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A Direct Imaging Search for Substellar and Planetary Mass Companions around White Dwarfs

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Declaration

I hereby declare that no part of this thesis has been previously submitted to this or any other University as part of the requirement for a higher degree. The work described herein was conducted by the undersigned, except for contributions from colleagues as acknowledged in the text.

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Abstract

Even though the radial velocity technique has detected almost all of the 269 extrasolar planets discovered to date, this method does not directly observe the light from the planet. The ability to directly detect this light would allow spectra of extrasolar planets to be obtained, providing information about their formation and evolution through the investigation of their composition and structure. To date, none of the extrasolar planets found using the radial velocity technique have been directly imaged, as these faint companions are too close to their bright parent stars. White dwarfs are intrinsically faint objects and can be up to 10,000 times less luminous than their main sequence progenitors, substantially increasing the probability of directly imaging an extrasolar planet in orbit around them.

The Degenerate Objects around Degenerate Objects (DODO) survey aims to obtain a direct image of an extrasolar planet in a wide orbit around a white dwarf. By acquiring J band images of 26 equatorial and northern hemisphere white dwarfs a year or two apart, common proper motion companions to the white dwarfs can be identified. The discovery of such a system could supply new information on the frequency and mass distribution of extrasolar planets around intermediate mass main sequence stars and confirm whether these companions can survive the final stages of stellar evolution. In addition, the direct detection of an extrasolar planet in orbit around a white dwarf would allow the spectroscopic investigation of planets much older than any previously found.

Using the 24 white dwarfs in the DODO survey within ~ 20 pc, the frequency of substellar companions with effective temperatures $\gtrsim 500$ K and projected physical separations from the white dwarf between 60 – 200 AU is estimated to be $\lesssim 5\%$. For the same range of projected physical separations, the frequency of substellar companions with masses $\gtrsim 10 M_{\text{Jup}}$ is estimated to be $\lesssim 9\%$.

Publications

A significant amount of work contained in this thesis has been published in the following papers:

Hogan, E., Burleigh, M. R. and Clarke, F. J. (2008), ‘The DODO Survey II: A Gemini Direct Imaging Search for Substellar and Planetary Mass Companions around Nearby Equatorial and Northern Hemisphere White Dwarfs’, *MNRAS* in prep.

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Maxted, P. F. L., Napiwotzki, R., Marsh, T. R., Burleigh, M. R., Dobbie, P. D., **Hogan, E.** and Nelemans, G. (2007), ‘Follow-up Observations of SPY White Dwarf + M-Dwarf Binaries’, *ASPC* 372, 471.

Hogan, E., Burleigh, M. R. and Clarke, F. J. (2007), ‘The DODO Survey: Imaging Planets Around White Dwarfs’, *ASPC* 372, 349.

Burleigh, M. R., **Hogan, E.**, Dobbie, P. D., Napiwotzki, R. and Maxted, P. F. L. (2006), ‘A near-infrared spectroscopic detection of the brown dwarf in the post common envelope binary WD0137 – 349’, *MNRAS* 373L, 55.

Burleigh, M. R., **Hogan, E.** and Clarke, F. J. (2006), ‘Direct imaging searches for planets around white dwarf stars’, *IAUS* 232, 344.

Burleigh, M. R., **Hogan, E.**, Levan, A., Clarke, F. and Hodgkin, S. (2005), ‘White Dwarfs and Extra-Solar Planets: Observing the Final State of a Solar System’, *Proto-stars and Planets V, Proceedings of the Conference held October 24–28, 2005, in Hilton Waikoloa Village, Hawai’i. LPI Contribution No. 1286.*, p.8490.

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Chapter 1

Introduction

1.1 Overview

White dwarfs, brown dwarfs and planets largely contribute to the lowest luminosity objects in the Universe. White dwarfs represent the most common endpoint of stellar evolution, with approximately 98% of all stars formed eventually ending up in this state (Wood, 1992). These faint stellar remnants are extremely dense, compact objects, with masses between $\sim 0.17 M_{\odot}$ (Kilic et al., 2007b) and a maximum mass of $\sim 1.4 M_{\odot}$ (Chandrasekhar, 1931). The peak of the mass distribution of white dwarfs lies at $\sim 0.6 M_{\odot}$ (Weidemann and Koester, 1984). Brown dwarfs are often described as failed stars and are thought to be formed similarly to stars. However, the cores of brown dwarfs do not reach a large enough mass and temperature to sustain hydrogen fusion, the source of energy for stars. The lowest mass at which hydrogen fusion can be sustained ranges between $0.07 - 0.092 M_{\odot}$ (Burrows and Liebert, 1993; Burrows et al., 2001) and

defines the boundary between brown dwarfs and stars. Brown dwarfs can burn deuterium and this fact is used to distinguish between these objects and planets, which are of a lower mass. The mass at which deuterium burning occurs is $\sim 13 M_{\text{Jup}} \approx 0.012 M_{\odot}$ and is generally used to define the boundary between planets and brown dwarfs. This chapter will introduce white dwarfs, brown dwarfs and planets in turn. The introduction of stellar spectral classification will explain the initial classification of white dwarfs and help with the understanding of the discovery of these objects. The formation and internal structure of white dwarfs will also be discussed. The discovery of brown dwarfs, along with the need for further stellar spectral classes to identify these objects, will follow. Finally, the discovery and properties of extrasolar planets will be covered, including the definition of a planet and current detection methods.

1.2 Stellar Spectral Classification

The basic classification of stars, known as the Harvard spectral classification scheme, was used to distinguish between the spectra of different stars and was first employed by Annie Jump Cannon. In 1890 while working for Edward Charles Pickering at the Harvard College Observatory, Annie Jump Cannon classified the spectra of hundreds of thousands of stars for the Henry Draper Memorial Catalogue using the letters A–I and L–Q (Pickering, 1890). At the beginning of the 20th century, Annie Jump Cannon re–ordered the spectral classes, using the temperature of the star as the main distinguishing feature, and dropped the redundant letters (Cannon and Pickering, 1901). The resulting

Table 1.1. The Harvard spectral classification scheme

Spectral Type	Temperature [K]	Colour	Characteristics
O	> 25,000	Blue	Strong HeII absorption (sometimes emission) lines HeI absorption lines becoming stronger
B	11,000 – 25,000	Blue–White	HeI absorption lines strongest HI (Balmer) absorption lines becoming stronger
A	7,500 – 11,000	White	HI (Balmer) absorption lines strongest CaII absorption lines becoming stronger
F	6,000 – 7,500	Yellow–White	HI (Balmer) absorption lines becoming weaker CaII absorption lines becoming stronger Neutral metal absorption lines (FeI, CrI)
G	5,000 – 6,000	Yellow	CaII absorption lines becoming stronger Neutral metal absorption lines becoming stronger
K	3,500 – 5,000	Orange	CaII absorption lines strongest Spectra dominated by neutral metal absorption lines
M	< 3,500	Red	Spectra dominated by molecular absorption bands, especially TiO Neutral metal absorption lines remain strong

spectral classification scheme consisted of the 7 well known classes of O B A F G K M (Table 1.1). Annie Jump Cannon further subdivided these spectral classes using the numbers 0 to 9, where, for example, A0 is the hottest A type star, while A9 is the coolest.

In the early part of the 20th century, Ejnar Hertzsprung and Henry Norris Russell separately discovered a relationship between the spectral class of a star and its luminosity. This relationship can be displayed on what is now known as a Hertzsprung–Russell (H–R) diagram. The x-axis of the H–R diagram can be given in terms of the spectral class of a star, with O on the left running through to M on the right, or in terms of decreasing temperature from the left to the right. The y-axis is generally given in terms of luminosity, increasing from the bottom to the top. The first H–R diagram was published by Henry Norris Russell (Figure 1.1; Russell, 1914) and shows the majority of stars in the so called “main sequence”, where the hottest O type stars are the brightest and are positioned in the top left corner of the diagram, while the coolest M type stars are the faintest and are positioned in the bottom right corner of the diagram. In 1924 Arthur Stanley Eddington showed that the luminosity, L , and the mass, M , of stars along the main sequence in the H–R diagram were related (Eddington, 1924). This mass–luminosity relation is commonly given as

$$\frac{L}{L_{\odot}} \approx \left(\frac{M}{M_{\odot}} \right)^a \quad (1.1)$$

where a ranges between 3 and 5 when $M > 0.3 M_{\odot}$ (Burrows and Liebert, 1993). As a result, the brighter O type stars are more massive than the fainter M type stars.

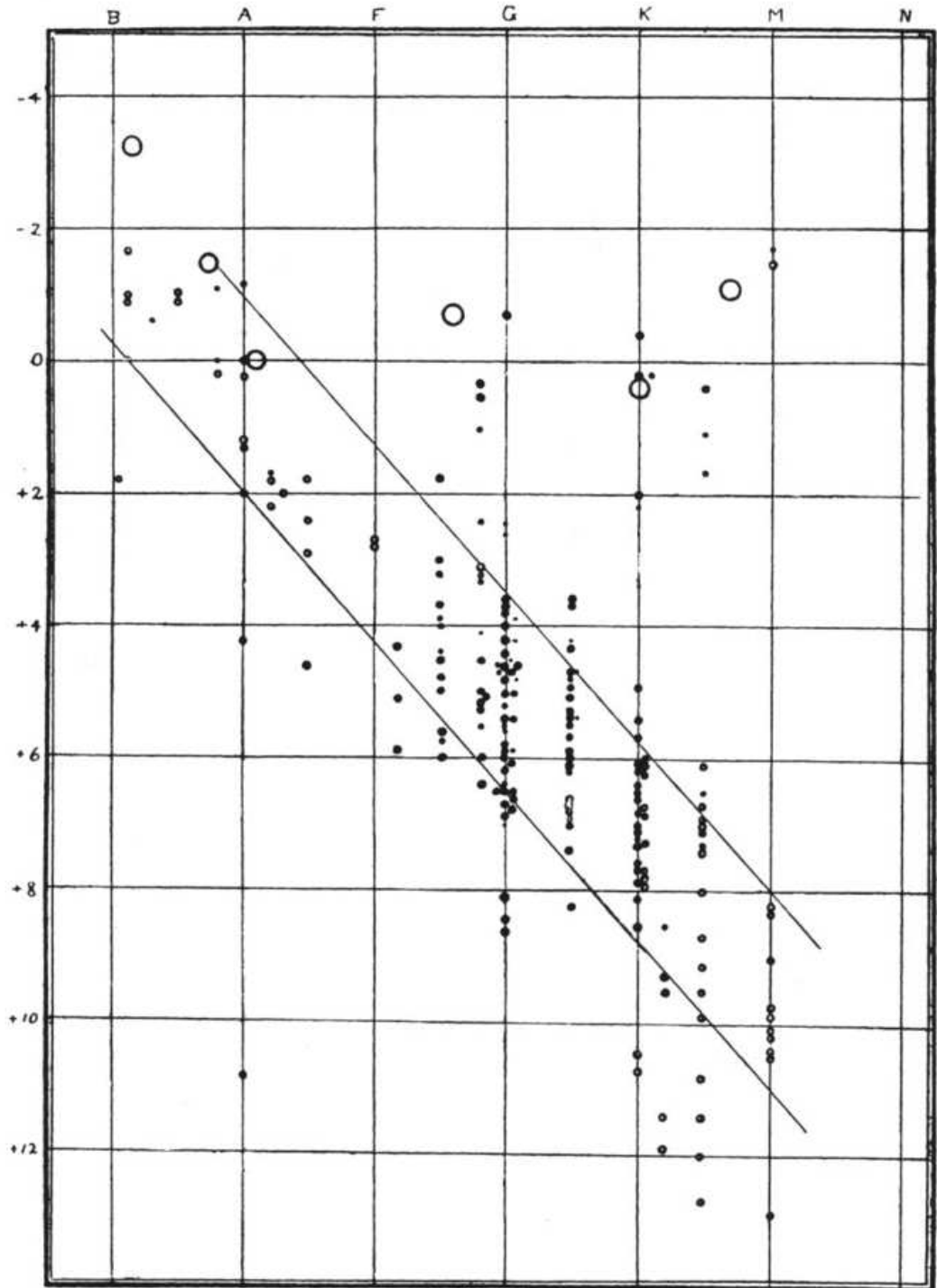


FIGURE 1.1. The first H-R diagram published by Henry Norris Russell in 1914. The x-axis is given in terms of spectral class and the y-axis is given in terms of absolute magnitude. The main sequence is marked and runs from the hot, bright O type stars in the top left corner to the cool, faint M type stars in the bottom right corner.

1.3 White Dwarfs

1.3.1 Discovery

During the early part of the 20th century Williamina Fleming, an assistant to Charles Pickering, was one of the many ladies, along with Annie Jump Cannon, working on classifying stellar spectra. In 1910 Henry Norris Russell, Pickering and Fleming discovered that the spectral class of the faint star 40 Eridani B did not have the expected M type spectral class given to faint stars, but was unusually of spectral class A (Schatzman, 1958). This spectral class is normally used to describe hot, white stars. Since 40 Eridani B was so hot yet so faint, it solely occupied the bottom left corner of the H–R diagram (Figure 1.1). Luyten (1922) first coined the term “white dwarf” to describe peculiar hot, faint objects, such as 40 Eridani B.

Even though Sirius B is widely regarded as the first white dwarf to have been discovered, its subluminescent nature was not confirmed until after 40 Eridani B. In 1844 Friedrich Bessel reported on the regular change in the celestial trajectory of Sirius since 1755, leading him to predict the existence of a companion in orbit around Sirius (Bessel, 1844). On 31 January 1862, Alvan Graham Clark finally observed this previously unseen companion with his new 18.5 inch telescope (*Discovery of a Companion of Sirius*, 1862). However, it wasn't until 1915, when Walter Sydney Adams obtained a spectrum of Sirius B, that it was confirmed to be of the same spectral class as Sirius A (Adams, 1915); an A type star. Only then did Sirius B join 40 Eridani B in the bottom left corner of the

H–R diagram.

1.3.2 Properties

In 1879 Josef Stefan showed that the luminosity, L , of a blackbody, measured in Watts (W), with a surface area A and a temperature T , measured in meters² and Kelvin (K), respectively, is given by

$$L = A \sigma T^4 \quad (1.2)$$

In 1884 Ludwig Boltzmann derived what is now known as the Stefan–Boltzmann equation. For a spherical star with a surface area of $A = 4 \pi R^2$, the Stefan–Boltzmann equation takes the form

$$L = 4 \pi R^2 \sigma T_e^4 \quad (1.3)$$

where σ is the Stefan–Boltzmann constant and T_e is defined as the effective temperature of the star, which is used instead of the temperature, T , since stars are not perfect blackbodies. Both 40 Eridani B and Sirius B were hotter yet considerably fainter than their companions. Both of these factors reduce their radii (Equation 1.3), which, when combined with their masses, calculated from the orbit of their companions, implied extremely high densities that could not be explained using the ordinary gas law. At the time, there were no theories available to explain the extremely dense nature of white dwarfs.

Considerable progress in the understanding of the structure of white dwarfs resulted

from the application of the quantum statistical theory of electrons by Pauli, Fermi and Dirac. The Pauli Exclusion principle states that no two electrons can occupy the same quantum state at the same time, i.e., have the same momentum and the same spin. As the electron density increases, the electrons are forced into higher available momentum states, increasing the number of electrons in a given volume. When all the states are filled, the electrons cannot be pushed closer together and this generates a pressure known as electron degeneracy pressure. Fowler (1926) showed that this pressure could support a white dwarf against gravitational collapse, maintaining hydrostatic equilibrium in a white dwarf.

By equating the gravitational potential energy and the energy supplied by the electron degeneracy pressure, it can be shown that for a degenerate object, $R \propto M^{-1/3}$. This inverse mass–radius relation implies that more massive degenerate objects have smaller radii. Electron degeneracy pressure depends strongly on the density, but is almost independent of the temperature. This pressure can only support against gravitational collapse if the mass of the white dwarf is below a certain limit. In 1931 Subrahmanyan Chandrasekhar calculated the maximum non–rotating mass which can be supported against gravitational collapse by electron degeneracy pressure (Chandrasekhar, 1931). This maximum mass, known as the Chandrasekhar Limit, is $\sim 1.4 M_{\odot}$ for objects with solar metallicity. Stars with a mass greater than this limit will become neutron stars or black holes.

1.3.3 The Life and Death of a Star

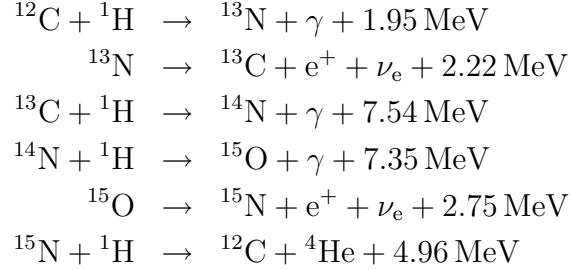
Stars are formed from interstellar clouds of gas and dust grains, consisting primarily of hydrogen and helium. Gravitational instabilities can cause regions in these clouds to collapse, occurring when the internal gas pressure of the cloud can no longer counteract the force of gravity. The critical mass, above which gravity will dominate and the cloud will collapse, is called the Jeans mass, and is given by

$$M_{\text{Jeans}} = \left(\frac{5 k T}{G \mu m_H} \right)^{3/2} \left(\frac{3}{4 \pi \rho} \right)^{1/2} \quad (1.4)$$

where T and ρ are the cloud temperature and density, m_H is the atomic mass of hydrogen, μ is the mean atomic weight of the cloud material relative to hydrogen and k is Boltzmann's constant. When the Jeans mass is exceeded, runaway collapse occurs and the beginnings of a star, also known as a protostar, are formed. The exact details of the formation of these protostars are not well understood. As the cloud fragments and contracts, regions of the cloud increase in mass, temperature and pressure as material accumulates towards the central protostar. The small percentage of matter that has not yet fallen into the protostar is distributed in a thin circumstellar disk. When the temperature and the pressure at the very centre of the protostar is sufficiently high, nuclear fusion of hydrogen nuclei occurs, which counteracts the force of gravity. Hydrostatic equilibrium is attained and the star is born. Detailed discussions of the formation of stars are beyond the scope of this thesis.

If such a star has an initial mass $\lesssim 8 M_{\odot}$, it will end its life as a white dwarf (Weidemann

FIGURE 1.2. The Carbon–Nitrogen–Oxygen cycle equations



and Koester, 1983). Intermediate mass stars with masses between $\sim 1.1 - 8 M_{\odot}$ have convective cores (Hurley, Pols and Tout, 2000), which allow them to burn hydrogen in their cores predominantly via the temperature sensitive Carbon–Nitrogen–Oxygen (CNO) cycle (Figure 1.2). The net effect of the CNO cycle is to convert hydrogen into helium via nuclear fusion. These so called main sequence stars are named after the region in which these stars lie on the H–R diagram (Figure 1.1). Main sequence stars spend the majority of their lives burning hydrogen in this manner, which creates a hydrogen deficient helium core.

As the main sequence phase advances, the core becomes completely depleted of hydrogen. When this happens, hydrogen burning in the core ceases. Since there is no longer any thermal pressure from nuclear fusion to counteract the force of gravity, the core begins to contract. This contraction increases the temperature of the core which in turn increases the temperature of the surrounding matter, allowing hydrogen burning to continue in a shell around the core. The mass of the core continues to increase as more helium is introduced from the hydrogen burning shell (Prialnik, 2000). As the core

contracts, the relatively cool region outside the hydrogen burning shell, known as the envelope, expands to conserve gravitational potential energy. This envelope can reach distances between $\sim 20 - 300 R_{\odot}$, depending on the initial mass of the main sequence star (Hurley et al., 2000). At the same time, the increasing core temperature results in a decrease in temperature of the envelope, to conserve thermal energy. This decrease in the surface temperature of the star causes the envelope to become convective. The star has now entered the red giant phase of stellar evolution and moves from the main sequence to the right on the H–R diagram. This region is called the Red Giant Branch (RGB). Overall, the transformation from a main sequence star to a red giant occurs on very short timescales, which is reflected in the low number of stars observed undergoing this transition (Hurley et al., 2000).

During the red giant phase, the hydrogen burning shell consumes the hydrogen readily available at the base of the envelope, producing helium which adds to the growing core. The core continues to increase in mass and temperature until it reaches the point at which helium can ignite. This occurs via the triple- α process (Figure 1.3), which converts helium into carbon via nuclear fusion, forming oxygen in the process (Figure 1.4). However, for stars with masses $\lesssim 2 M_{\odot}$, degenerate helium cores develop before helium burning can begin. When the temperature of these degenerate cores becomes sufficiently high and the core reaches a mass of $\sim 0.5 M_{\odot}$ (Prialnik, 2000), all the helium in the core ignites simultaneously in an explosion due to the degeneracy of the core, lifting the degeneracy. This is known as a helium flash. When helium burning begins, the thermal pressure increases and the core expands, slowing the rate of core helium burning and

FIGURE 1.3. The Triple-Alpha Process equations

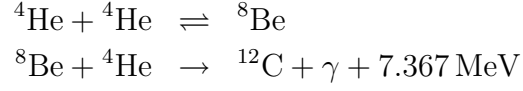
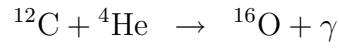


FIGURE 1.4. The oxygen forming equation



hydrogen burning in the surrounding shell.

When the helium in the core is exhausted, another phase of core contraction and envelope expansion begins, moving the star into the Asymptotic Giant Branch (AGB) phase. The AGB star can have a radius between $\sim 300 - 1500 R_{\odot}$, depending on the initial mass of the main sequence star (Hurley et al., 2000). The dense core of the star now consists mainly of carbon and oxygen (C-O), surrounded by a helium burning shell. A helium layer lies between this internal helium burning shell and the external hydrogen burning shell. These two shells supply energy during the asymptotic giant phase in a cyclic manner. For the majority of the time, hydrogen burning in the external shell occurs, increasing the mass of the helium layer, while the inner shell is extinct. This causes the helium layer to contract and heat until the temperature at its base becomes sufficiently high for helium to ignite in the internal shell. As the helium layer contracts, the hydrogen burning shell expands and cools, which extinguishes the hydrogen burning temporarily. The helium burning front advances through the helium layer, turning helium into carbon

and oxygen, until it catches up with the now extinct hydrogen shell. The proximity of the hot helium burning front causes the hydrogen in the shell to reignite. At the same time, helium burning is quenched as a result of the relatively low temperature in the region of the hydrogen burning shell, and a new cycle begins. The lasting result of each cycle is the growth of the C–O core, which gradually raises the density of the core to the point where the electrons become degenerate.

Due to the increased radius of the star during the AGB phase and the predicted development of a strong stellar wind, mass loss of the less tightly bound envelope occurs. The stellar wind phenomenon is not yet well understood theoretically. The end of mass loss is brought about by the dissipation of the entire envelope, creating a planetary nebula. This occurs at a random phase of shell burning. If mass loss occurs during the hydrogen burning phase, the star will be left with a thin atmosphere of hydrogen rich material. If it occurs during the helium burning phase, the atmosphere of the star will be composed predominantly of helium. Since hydrogen burning takes up a large fraction of the cyclic shell burning, the probability of a star ending the AGB phase with a hydrogen, rather than a helium, atmosphere is ~ 11 times more likely (Eisenstein et al., 2006).

The remnants of these stellar evolution phases have masses between $\sim 0.17 - 1.4 M_{\odot}$ and effective temperatures of $\sim 100,000$ K. These white dwarfs consist of a compact, degenerate, hot C–O core, containing almost all of the mass of the white dwarf, surrounded by a thin non-degenerate atmosphere. Since they no longer have a source of energy, white dwarfs continually cool to the point where they are almost impossible to

detect. At this point, they are known as black dwarfs.

In a white dwarf, energy is transported through the degenerate core by the efficient process of electron conduction, while in the non-degenerate atmosphere, energy is transported by the much less efficient method of photon diffusion. The thermal energy stored in the core of a white dwarf is eventually released via its atmosphere, which decreases the effective temperature and the luminosity of the white dwarf. However, the radius of the white dwarf remains approximately the same as it cools, since the electron degeneracy pressure in the core is almost independent of its temperature. White dwarf cooling occurs over a long period of time due to their low surface area. Several effects are now known to be very important in the cooling rate of white dwarfs. One effect is cooling from neutrinos. Neutrinos are electrically neutral, almost massless elementary particles that are created in energetic collisions between ions in the core of a white dwarf. Energy is lost as the neutrinos are released from the white dwarf. When the white dwarf is extremely hot during the early stages of its life, more energy is radiated through the release of a high number of neutrinos than through photon emission, resulting in a white dwarf cooling rate that is proportional to its temperature.

The cooling rate of white dwarfs is also affected by crystallisation. As a white dwarf cools, a point is reached where the kinetic energy of the ions in its core is no longer sufficient to prevent them from becoming localised. Coulomb interactions become dominant and the ions form a periodic lattice structure (van Horn, 1968). For the conditions characteristic of the interior of white dwarfs, with central densities of order 10^6 g cm^{-3} ,

oxygen crystallises at $\sim 3.4 \times 10^6$ K, while carbon crystallises at $\sim 2.1 \times 10^6$ K. These central temperatures are reached when the white dwarf has been cooling for ~ 1 Gyr (Kawaler, 1998). As the star crystallises it releases latent heat, providing an additional energy source that slows the cooling process. Once the bulk of the star is crystalline, energy is transported through the white dwarf more efficiently, which speeds up the cooling process.

The initial final mass relation (IFMR) describes the relationship between the mass of the main sequence progenitor, M_{MS} , and the mass of the white dwarf, M_{WD} . This relationship has been explored in detail (e.g., Wood, 1992) and is determined using white dwarfs in open clusters, where the total age of the white dwarf is assumed to be equal to the age of the cluster. Throughout this thesis, the linear IFMR equation of Dobbie et al. (2006a) is used, which is based on the measurements of a small number of white dwarfs found in young open clusters;

$$M_{\text{WD}} = 0.133 M_{\text{MS}} + 0.289 \quad (1.5)$$

Recent observations of white dwarfs in older open clusters have placed constraints on the low mass end of the IFMR, suggesting that this equation is valid down to white dwarf masses of $0.54 M_{\odot}$ (Kalirai et al., 2007).

1.3.4 Classification

Main sequence stars are classified using the Harvard spectral classification scheme (Section 1.2), which is based on the temperature of the stars and specific features present in their spectra. Kuiper (1941) was the first investigator to attempt to systematically classify white dwarfs using their spectra in a similar fashion. In 1960 Greenstein suggested a system that was in use for over 20 years. This system, which was an elaboration of the system proposed by Luyten (1952), involved comparing the spectrum of a white dwarf to that of main sequence stars. The white dwarf was then given a spectral class, taken from the Harvard spectral classification scheme, equal to the spectral class of the main sequence star it most resembled. To distinguish between main sequence stars and white dwarfs, the spectral class of the white dwarf was prefixed with an uppercase D, which stands for degenerate. However, a new classification of white dwarfs was finalised in 1983 after investigators in the field expressed their dissatisfaction with this old system, which was proposed at a time when the diversity of atmospheric compositions existing among white dwarfs was unknown (Sion et al., 1983). This new classification system is still in use (Table 1.2) and consists of

1. an uppercase D which stands for degenerate,
2. an uppercase letter for primary or dominant spectroscopic type in the optical spectrum,
3. an uppercase letter for secondary spectroscopic features, if present in any part of

the electromagnetic spectrum,

4. a temperature index from 0 to 9, defined by $50,400/T_{\text{eff}}$.

Since the majority of white dwarfs have a hydrogen rich atmosphere (Section 1.3.3), their spectra would show mainly hydrogen lines. Therefore, most white dwarfs are DA white dwarfs.

Table 1.2. The white dwarf spectral classification scheme

Primary and Secondary Features	
A	Only Balmer lines; no HeI or metals present
B	HeI lines; no H or metals present
C	Continuous spectrum, no lines deeper than 5%
O	HeII strong: HeI or H present
Z	Metal lines only; no H or He
Q	Carbon features, either atomic or molecular
X	Peculiar or unclassifiable spectra
Secondary Features Only	
P	Magnetic white dwarfs showing polarisation
H	Magnetic white dwarfs showing no detectable polarisation
V	Variable

1.4 Brown Dwarfs

1.4.1 Discovery

In 1963 Shiv S. Kumar predicted the existence of objects with masses insufficient to sustain hydrogen burning, the main source of energy for main sequence stars. The lack of stable hydrogen burning in these objects would make them intrinsically much dimmer. He gave these low mass, faint, cool objects the provisional name of “black dwarfs” (Kumar, 1963). However, this name had already been used to describe extremely old, cool white dwarfs (Section 1.3.3). In 1975 Jill Tarter coined the alternative name of “brown dwarfs” to describe these substellar mass objects (Tarter, 1975). Searches for these objects began in earnest in the 1980s, but with no success (e.g., Probst, 1983; Jameson, Sherrington and Giles, 1983; Shipman, 1986). Then, in 1988, during their infrared (IR) photometric survey to search for low mass companions to white dwarfs, Eric E. Becklin and Ben Zuckerman directly imaged a faint object in orbit around the DA white dwarf GD 165 (Becklin and Zuckerman, 1988). The temperature of the companion, known as GD 165 B, was determined to be ~ 2100 K, the coolest object ever reported at the time, with a mass between $0.06 - 0.08 M_{\odot}$. The lowest mass at which hydrogen fusion can be sustained, M_{limit} , also known as the hydrogen burning main sequence edge mass (HBMM), can be estimated using the equation

$$M_{\text{limit}} \sim 0.0865 \left(\frac{10^{-2} \text{ cm}^2 \text{ g}^{-1}}{\kappa_{\text{R}}} \right)^{1/9} M_{\odot} \quad (1.6)$$

where κ_R is the Rosseland mean opacity and is a function of metallicity. The HBMM is generally thought of as the boundary between brown dwarfs and very low mass (VLM) main sequence stars and ranges between $0.07 - 0.092 M_\odot$ (Burrows and Liebert, 1993; Burrows et al., 2001). The mass of GD 165 B was very close to the hydrogen burning mass limit, which made it hard to confirm whether it was a brown dwarf or a VLM star. Over a decade later, GD 165 B was spectroscopically confirmed to be a brown dwarf (Kirkpatrick et al., 1999b) by identifying absorption features due to metal hydrides in its spectrum, which are not present in any known faint VLM stars. However, the first spectroscopically confirmed brown dwarf was found in orbit around Gliese 229 (Oppenheimer et al., 1995). The brown dwarf Gliese 229 B has absorption features in its near infrared (NIR) spectrum attributable to methane, which are not present in any known faint VLM stars, implying a temperature of ~ 1000 K.

1.4.2 Classification

Brown dwarfs could not be classified using the current Harvard spectral classification scheme (Section 1.2), since their spectra were much different to those of main sequence stars. The increasing number of objects fainter and cooler than stars with spectral class M led to the introduction of two entirely new stellar spectroscopic classes. The majority of the letters in the alphabet were already in use for classifying different astronomical objects, so two of the remaining unused letters, L and T, were chosen (Kirkpatrick et al., 1998; Kirkpatrick et al., 1999a).

L dwarfs have effective temperatures between $\sim 1300 - 2500$ K (Kirkpatrick, 2005) and a red $J - K$ colour ($J - K > 0$). They are characterised spectroscopically by the clear depletion of titanium oxide (TiO) and vanadium oxide (VO) absorption lines, which are typical of the lowest mass M type stars. These metallic oxide absorption lines are replaced by metallic hydride lines, such as iron hydride (FeH) and chromium hydride (CrH), and neutral alkali metal lines, such as lithium (Li), sodium (Na), potassium (K), rubidium (Rb) and caesium (Cs), along with a carbon monoxide (CO) edge at $\sim 2.3\mu\text{m}$, as the major optical and NIR spectroscopic signatures (Kirkpatrick et al., 1999a). The spectrum of GD 165 B contains weakened TiO and VO absorption features, along with features due to FeH and CrH. Strong absorption features due to Na, K, Rb and Cs are also present. Therefore, GD 165 B was the first L dwarf discovered (Kirkpatrick et al., 1999b).

T dwarfs have effective temperatures between $\sim 700 - 1400$ K and a blue $J - K$ colour ($J - K < 0$). They are characterised spectroscopically by strong water (H_2O) and hydrogen (H_2) absorption lines, while the onset and growth of methane (CH_4) absorption in the H ($1.6 - 1.7\mu\text{m}$) and K ($2.15\mu\text{m}$) bands appear in place of the CO absorption lines, particularly at 2.3 and $4.7\mu\text{m}$, as the main form of carbon (Burrows et al., 2001). Gliese 229 B was the first T dwarf discovered as its IR spectrum contains CH_4 absorption features, implying temperatures of ~ 1000 K. Over 490 L dwarfs and 120 T dwarfs have been discovered to date¹.

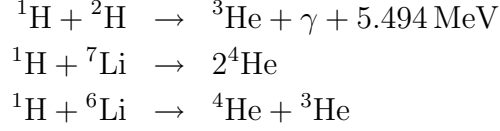
¹<http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/>

The brown dwarf ULAS J003402.77 – 005206.7 was recently discovered by the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS; Lawrence et al., 2007) and has a spectral class of T8.5 and an effective temperature of $600 < T_{\text{eff}} < 700$ K (Warren et al., 2007). This T dwarf has the latest spectral class and the coolest effective temperature known to date. In comparison, Jupiter has an effective temperature of ~ 125 K (Burrows et al., 2001). Another proposed spectral class for objects with temperatures between the coolest T dwarfs and planets have been provisionally given the letter Y (Kirkpatrick, 2005). The spectra of these Y dwarfs will show absorption lines due to ammonia, if such objects exist. Alternatively, if no obvious spectral change suggests the use of a new spectral class, then the T dwarfs will continue down into the planetary regime, covering all effective temperatures.

1.4.3 Properties

Brown dwarfs are often described as failed stars. They are thought to be formed similarly to stars (Section 1.3.3), but they cannot sustain hydrogen burning, since the core of the protostar does not attain the high temperatures and masses required. Brown dwarfs instead will undergo short periods of primordial deuterium burning very early in their evolution (Figure 1.5), which maintains hydrostatic equilibrium. When all the deuterium is consumed, the fusion processes needed to counteract gravitational collapse disappear and the brown dwarf contracts and cools. As the density in the core rises, electron degeneracy pressure becomes the dominant process in stabilising the radius of the brown

FIGURE 1.5. Deuterium and lithium burning equations



dwarf (Section 1.3.2).

The temperature required to sustain hydrogen burning in VLM stars is only slightly higher than the temperature required to burn lithium (Figure 1.5). VLM stars and brown dwarfs will never have more than their primordial abundance of lithium in their cores as this element is not easily manufactured. This gave rise to a simple indirect test called the “lithium test”, which was devised to distinguish between brown dwarfs and VLM stars (Rebolo, Martin and Magazzu, 1992). If the spectrum of an object contained an atomic lithium absorption line at 6708 Å, then the object was unable to burn lithium and in turn hydrogen, confirming that it was indeed a brown dwarf. However, three important points must be considered when applying the lithium test. Firstly, the age of the object must be known before the lithium test is applied, since lithium will not have been depleted in VLM stars with ages $\lesssim 100$ Myr. Secondly, brown dwarfs with masses $\gtrsim 63 M_{\text{Jup}}$ will reach a high enough core temperature (2.5×10^6 K) to burn its primordial supply of lithium (Rebolo et al., 1992). Finally, in the lower mass brown dwarfs with temperatures $\lesssim 1525$ K, lithium is found in the molecular form of LiCl, with LiH and LiOH increasing in abundance with decreasing temperature (Lodders, 1999). However, any object with such a low temperature will be a brown dwarf regardless. The lithium test is less useful

now as the determination of L and T dwarfs is achieved more easily from other spectral features (Section 1.4.2).

Even though deuterium burning and, for the more massive L dwarfs, lithium burning, can play interesting roles in the evolution of brown dwarfs, thermonuclear processes do not dominate their evolution. Brown dwarfs will begin to contract and cool once their supply of deuterium and lithium has been exhausted, since there is no longer any thermal pressure from nuclear fusion to counteract the force of gravity. Evolutionary models for brown dwarfs can predict the luminosity of these objects (Figure 1.6; Burrows et al., 2001). These models take into account the composition, scattering properties and absorption effects of the molecular atmospheres of brown dwarfs, all of which depend on their temperature.

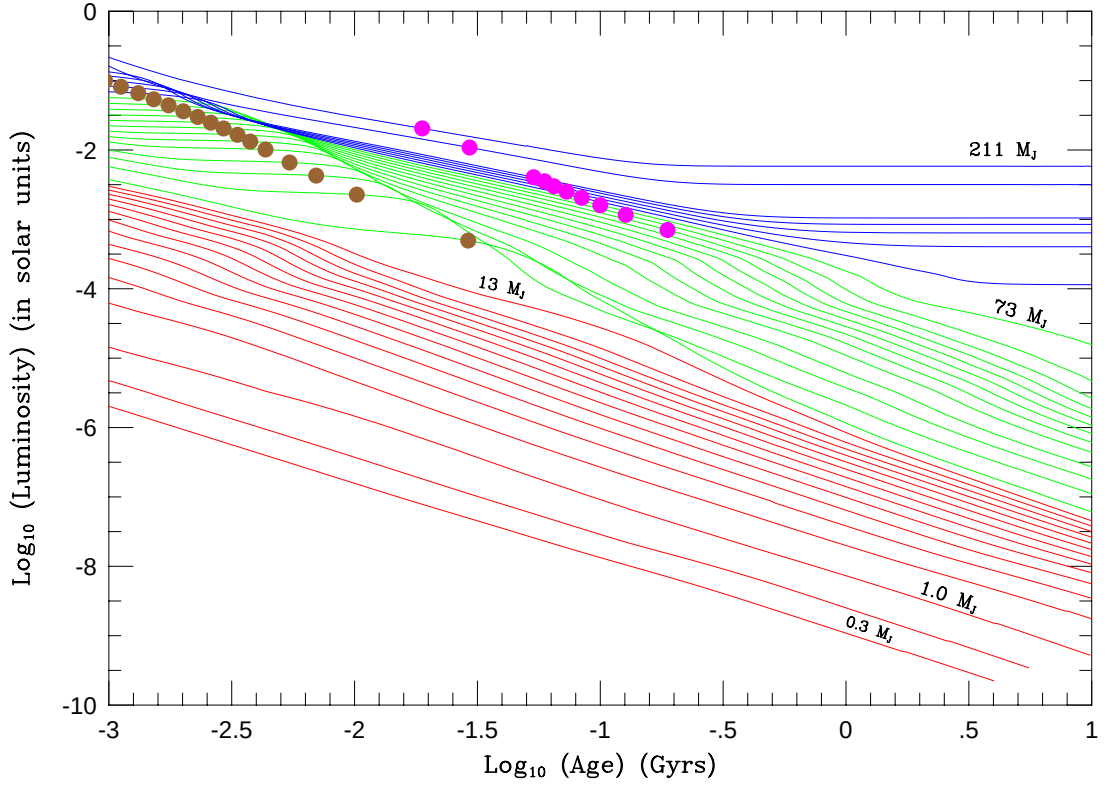


FIGURE 1.6. Evolution of the luminosity of isolated solar metallicity VLM stars and substellar mass objects, measured in terms of $L_{\odot}$, against their age, measured in years. The VLM stars are shown in blue, objects above $13 M_{\text{Jup}}$ are shown in green and objects equal to or below $13 M_{\text{Jup}}$ are shown in red. The masses of the objects from bottom to top are $0.3, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0$ and $15.0 M_{\text{Jup}}$ and $0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.085, 0.09, 0.095, 0.1, 0.15, 0.2 M_{\odot}$ ($\equiv 211 M_{\text{Jup}}$). For a given object, the gold dots mark when 50% of the deuterium has burned and the magenta dots mark when 50% of the lithium has burned. Note that the lithium sequence penetrates into the brown dwarf regime near $0.065 M_{\odot}$, below the HBMM (Burrows et al., 2001).

1.5 Extrasolar Planets

1.5.1 Definition

The definition of a planet is a highly disputed topic. The Working Group on Extrasolar Planets (WGESp) has agreed to the following statements regarding substellar mass objects (Boss et al., 2007);

1. Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are “planets” (no matter how they formed). The minimum mass / size required for an extrasolar object to be considered a planet should be the same as that used in the Solar System.
2. Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are “brown dwarfs”, no matter how they formed nor where they are located.
3. Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not “planets”, but are “sub-brown dwarfs” (or whatever name is most appropriate).

Due to the increasing number of detections of planets with low masses, methods to ascertain the lower mass limit of planets have also been discussed, based on the knowledge

of the Solar System²;

1. A "planet"³ is a celestial body that
 - (a) is in orbit around the Sun,
 - (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape,
 - (c) has cleared the neighbourhood around its orbit.
2. A "dwarf planet" is a celestial body that
 - (a) is in orbit around the Sun,
 - (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape⁴,
 - (c) has not cleared the neighbourhood around its orbit,
 - (d) is not a satellite.
3. All other objects⁵ except satellites orbiting the Sun shall be referred to collectively as "Small Solar System Bodies".
4. Pluto is a "dwarf planet" by the above definition and is recognised as the prototype of a new category of Trans-Neptunian Objects.

²<http://www.iau.org/iau0603.414.0.html>

³The eight "planets" are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

⁴An IAU process will be established to assign borderline objects into either dwarf planet and other categories.

⁵These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies.

1.5.2 Discovery

The first planetary mass object to be confirmed outside the Solar System was discovered in orbit around the millisecond pulsar PSR1257+12 in 1992 (Wolszczan and Frail, 1992). Pulsars are rapidly spinning, highly magnetised neutron stars, which emit narrow beams of radio emission parallel to their magnetic dipole axis. These beams are seen as intense pulses at the spin frequency of the pulsar due to a misalignment of the magnetic and spin axes. Normal pulsars have spin periods of ~ 1 second. Millisecond pulsars are neutron stars that have been spun-up to very short spin periods during mass and angular momentum transfer from a binary companion. Two planetary mass companions were discovered from the periodic variation in the precise timing measurements of the 6.2 ms pulses from PSR1257 + 12. Three planetary mass companions are now known to exist around this pulsar and have masses of $0.022 M_{\oplus}$, $4.1 M_{\oplus}$ and $3.8 M_{\oplus}$ and orbital radii of 0.19, 0.36 and 0.46 AU, respectively. It is thought that these planets formed after the neutron star was created, since it is unlikely that a planet born around the pulsar progenitor would survive the supernova explosion that created the pulsar.

The first definitive extrasolar planet discovered around a star like the Sun was in 1995 (Mayor and Queloz, 1995). The star, which has a spectral class of G2, is known as 51 Pegasi and is located 14.7 pc away. The planet 51 Pegasi b⁶ has a minimum mass of $0.468 \pm 0.007 M_{\text{Jup}}$ and an orbital radius of 0.052 AU⁷. The presence of this planet

⁶The capital letter “B” is generally used to denote a companion. Keeping with this method, the lower-case “b” is used to denote a planetary mass companion

⁷The Extrasolar Planets Encyclopaedia; <http://exoplanet.eu/planet.php?p1=51+Peg&p2=b>

was confirmed only a few weeks afterwards (Marcy and Butler, 1995). 51 Pegasi b was found using a method known as the radial velocity technique.

1.5.3 Detection Methods

Radial Velocity

The radial velocity technique, which takes advantage of the Doppler effect, has detected 255 of the 269 extrasolar planets discovered to date⁸. A planet and its parent star will orbit around their common centre of mass. As the star moves along its orbit away from the Earth, the light detected from the star is redshifted, while light detected from the star is blueshifted as the star moves towards the Earth. The measured wavelengths of absorption lines in the spectrum obtained from the star oscillate around the rest wavelength of the lines as the star orbits the centre of mass of the system. This systematic change in the measured wavelength can be used to calculate the radial velocity of the star by using the equation

$$\Delta\lambda = \lambda' - \lambda = \frac{\lambda v_r}{c} \quad (1.7)$$

where λ' is the measured wavelength of the line, λ is the rest wavelength of the line and v_r is the radial velocity. By convention, a positive radial velocity indicates the object is receding (redshifted). The systematic variation in the radial velocity of 51 Pegasi (Figure 1.7; Marcy et al., 1997) confirmed the presence of 51 Pegasi b, the first extrasolar planet to be discovered. The velocity amplitude, K , which can be determined from the

⁸The Extrasolar Planets Encyclopaedia; <http://exoplanet.eu/>

velocity curve, is given by

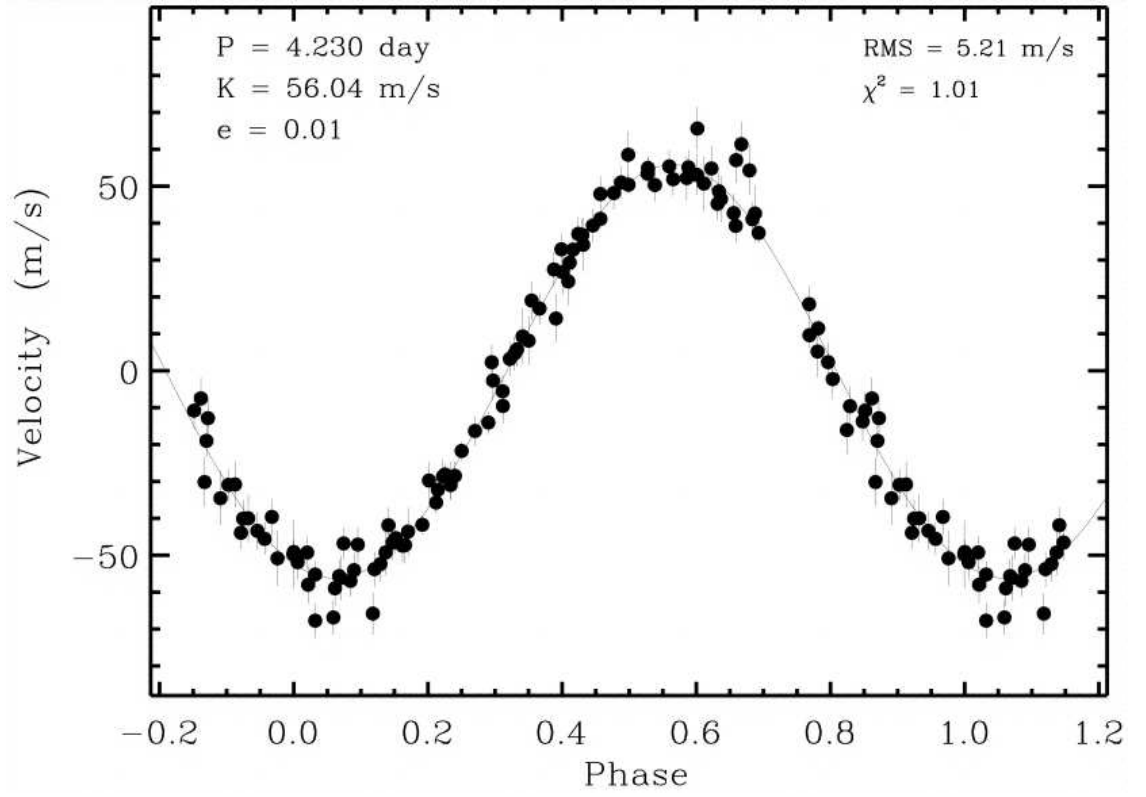


FIGURE 1.7. The velocity curve obtained from the spectrum of 51 Pegasi (Marcy et al., 1997).

$$K = \left(\frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_p + M_*)^{2/3}} \frac{1}{(1 - e^2)^{1/2}} \quad (1.8)$$

where P is the orbital period, M_p is the mass of the planet, i is the inclination of the orbit with respect to the line of sight of the observer, M_* is the mass of the parent star and e is the eccentricity of the orbit of the planet (Cumming, Marcy and Butler, 1999).

In a circular orbit the velocity variations are sinusoidal and for $M_p \ll M_*$ the velocity amplitude reduces to

$$K = 28.4 \left(\frac{P}{1 \text{ year}} \right)^{-1/3} \left(\frac{M_p \sin i}{M_{\text{Jup}}} \right) \left(\frac{M_*}{M_{\odot}} \right)^{-2/3} \quad (1.9)$$

where K is measured in ms^{-1} and P is related to the orbital radius, a , by Kepler's third law

$$P = 2\pi \left(\frac{a^3}{GM_*} \right)^{1/2}, \quad M_p \ll M_* \quad (1.10)$$

Determining the velocity amplitude, K , enables the calculation of certain parameters, such as the period and eccentricity of the orbit of the planet (Equation 1.8). However, the $\sin i$ dependence results in no measurable radial velocity perturbation for planets which orbit their parent stars in the plane perpendicular to the line of sight of the observer ($i = 0^\circ$). As a consequence, radial velocity measurements can only determine a minimum mass of $M_p \sin i$, since the orbital inclination is generally unknown. The velocity amplitude obtained from the velocity curve of 51 Pegasi is $\sim 56 \text{ ms}^{-1}$ (Figure 1.7), leading to a planet with a minimum mass of $0.468 \pm 0.007 M_{\text{Jup}}$. In comparison, Jupiter causes the Sun to have a velocity amplitude of $\sim 12.5 \text{ ms}^{-1}$.

Massive extrasolar planets with short orbital periods and therefore small orbital radii (Equation 1.10) result in larger radial velocities (Equation 1.9). Hence, the radial velocity technique is most sensitive to these systems. The extrasolar planets present in such systems are known as “Hot Jupiters”, since the excessive irradiation from their parent stars causes a large increase in the effective temperatures of these planets. However, the number of discoveries of extrasolar planets with orbital radii comparable to the orbital radius of Jupiter is gradually increasing due to the increasing length of radial velocity surveys. In addition, the improved sensitivity of the spectrographs currently used to measure radial velocities, compared to the first spectrographs used, has increased dramatically. The High Accuracy Radial velocity Planet Searcher (HARPS) on the ESO

3.6 meter telescope on La Silla in Chile, which is sensitive to radial velocities as small as $\sim 1 \text{ ms}^{-1}$ (Pepe et al., 2000), has allowed the detection of one of the lowest mass extra-solar planets at the time of writing. This planet, known as GL 581 c, is one of the three planets known to orbit the star GL 581 and has a mass of $\sim 5.0 M_{\oplus}$ (Udry et al., 2007).

Transits

Extrasolar planets discovered using the radial velocity technique are not generally open to further direct study due to their proximity to the much brighter parent star. However, if the planet passes in front of its parent star in a plane close to the line of sight of the observer, the observed luminosity of the star will decrease temporarily. This drop in luminosity approximates to

$$\frac{\Delta L_*}{L_*} \approx \left(\frac{R_p}{R_*} \right)^2 \quad (1.11)$$

under the assumption that the star has a uniform surface brightness (Deeg, 1998). $\Delta L_*/L_*$ is the fractional drop in luminosity of the star, R_p is the radius of the planet and R_* is the radius of the star. By measuring the depth of the eclipse of the light curve and inferring R_* from the spectral class of the star, the radius of the planet can be determined (Equation 1.11). This allows the determination of the true mass of the planet, as well as its density, when combined with radial velocity measurements (Equation 1.8), since these transiting systems must have an inclination, $i \sim 90^\circ$.

The first extrasolar planet found to transit its parent star was HD 209458 b. However,

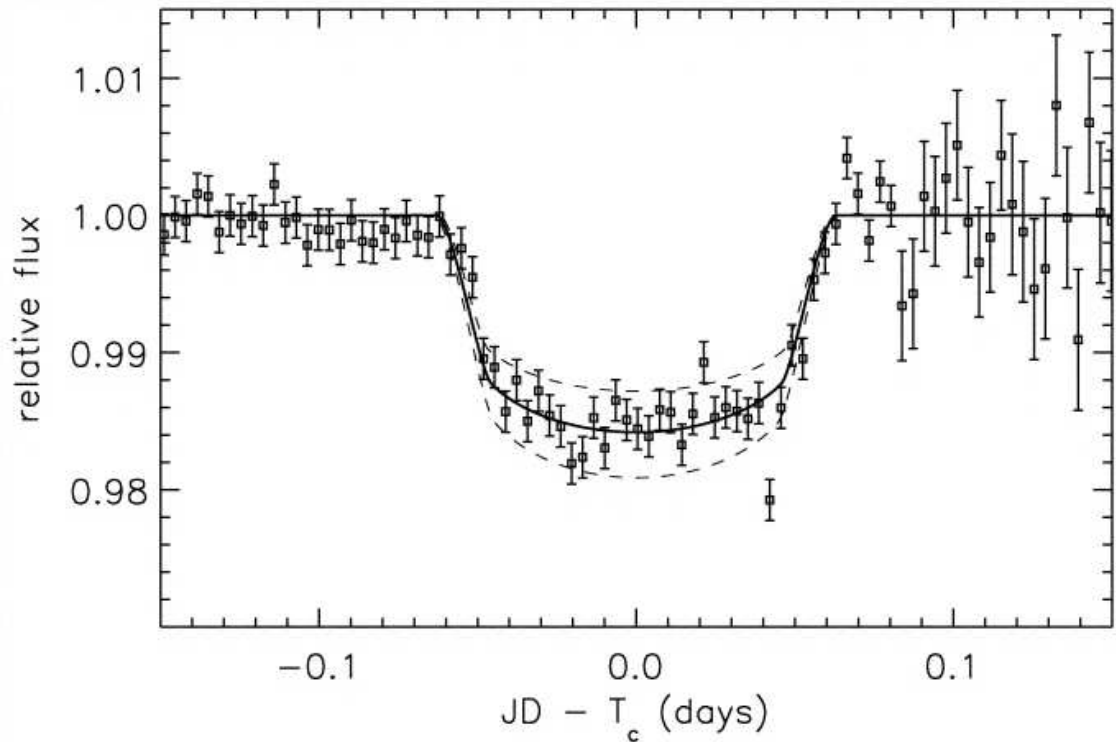


FIGURE 1.8. Light curve for HD 209458 (Charbonneau et al., 2000).

HD 209458 b was initially discovered using the radial velocity technique in August 1999 (Mazeh et al., 2000) and was only found to transit its parent star during subsequent observations in September 1999 (Charbonneau et al., 2000; Henry et al., 2000). The change in the observed luminosity of the star HD 209458, due to the planet blocking some of the light from the star, can be seen in its light curve (Figure 1.8).

Wavelength dependent changes in the spectra acquired of the star–planet system when the planet transits its parent star, known as the primary eclipse, and when the planet disappears behind the star, known as the secondary eclipse, present a unique opportunity to study the atmospheres of transiting extrasolar planets. The decrease in the observed luminosity specifically in the region of 589.3 nm relative to other wavelengths

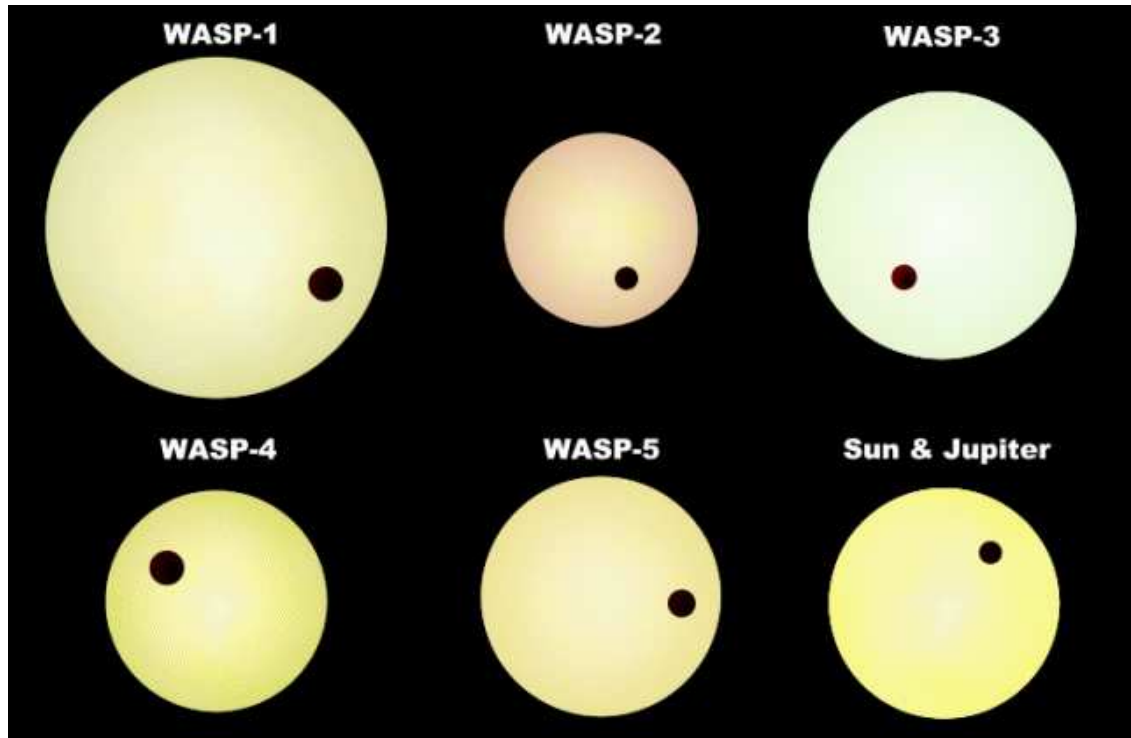


FIGURE 1.9. A scale diagram to compare the ratios of the radii of the 5 transiting planets discovered by WASP with their parent stars.

during the primary eclipse has been interpreted as absorption of sodium by the planetary atmosphere (Charbonneau et al., 2002). An IR spectrum of the extrasolar planet HD 209458 b has also been observed by obtaining the difference between the spectra of the star–planet system when the planet disappears behind the parent star and when the planet later reemerges (Richardson, Deming and Seager, 2003).

To date, 34 extrasolar planets are known to transit their parent stars, all of which have also been detected using the radial velocity technique. Half of these planets have been discovered in 2007, showing the dramatic increase in the detection of transiting planets. The Wide Angle Search for Planets (WASP; Pollacco et al., 2006), which utilises 2 robotic observatories in South Africa and La Palma, each consisting of eight wide an-

gle cameras, monitors both hemispheres of the sky to search for planetary transit events. WASP has detected 5 of these transiting planets⁹ (Cameron et al., 2007), all of which have radii similar to that of Jupiter (Figure 1.9).

Gravitational Microlensing

The mass of an object can curve the structure of space in its immediate vicinity, causing the path followed by light to be bent around the object (Einstein, 1936). The gravitational microlensing technique takes advantage of this effect and was first suggested by Mao and Paczynski (1991). As seen from the Earth, hundreds of stars each year pass in front of background stars as they orbit the Galaxy. This effect is more noticeable when looking towards the galactic centre, where the density of stars is greater. When an object passes in front of a background star, the mass of the object acts as a lens, bending and focussing the light from the background star towards the Earth. This leads to the apparent brightening and subsequent dimming of the observed luminosity of the background star, which creates a smooth symmetric light curve. If the object acting as the lens is a solitary star, a single luminosity peak would be observed. When the lens consists of two objects, such as a star–planet system, the planet acts like a defect in the lens, making a detectable contribution to the microlensing effect. Additional sharp peaks, lasting for ~ 1 day (Gould and Loeb, 1992), appear in the light curve of the background star, which can be used to establish the mass of the planet. This technique is sensitive to terrestrial mass planets around stars that are large distances (kpc) away, without actually

⁹http://www.superwasp.org/wasp_planets.htm

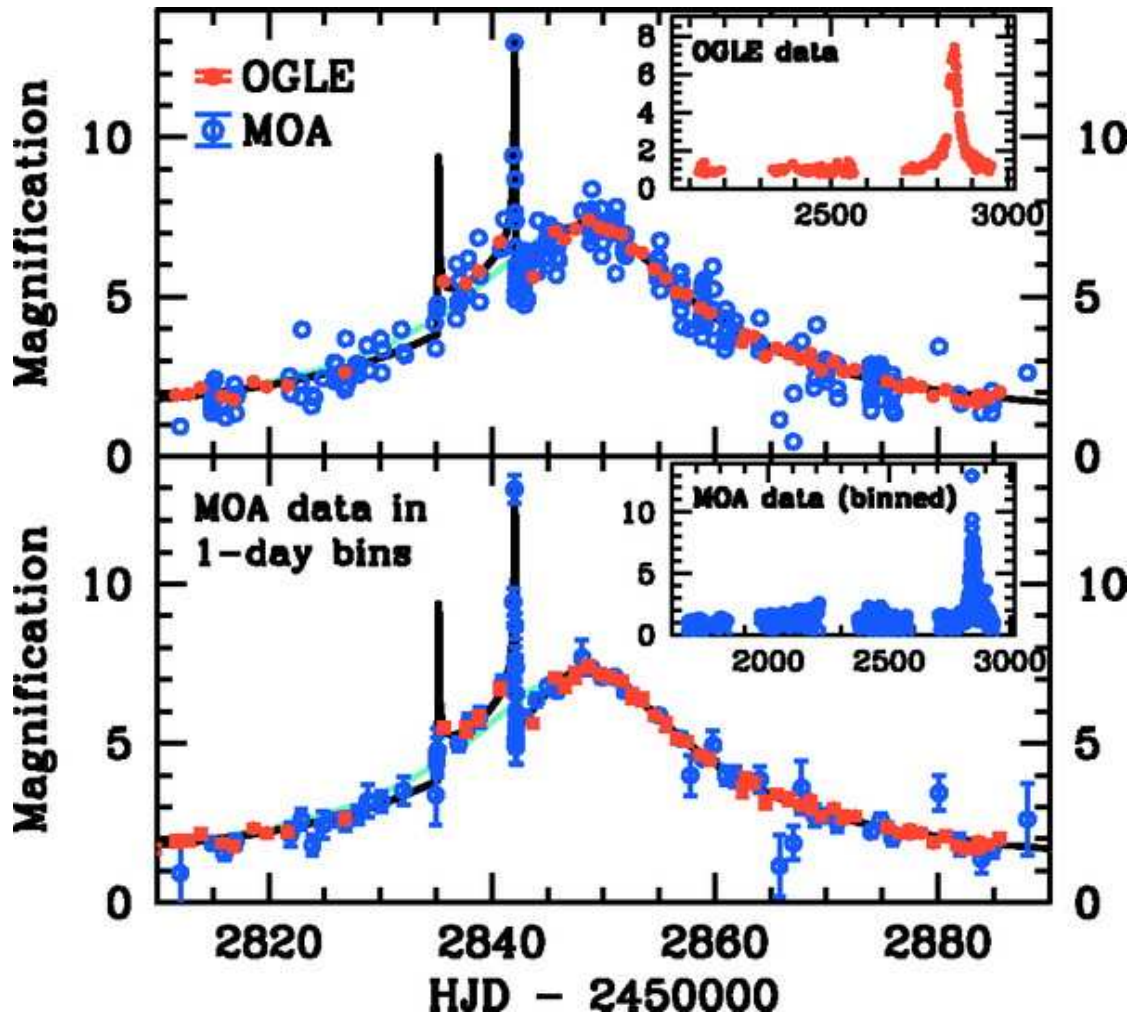


FIGURE 1.10. Light curves obtained from observations of the gravitational microlensing event OGLE235–MOA53 (Bond et al., 2004).

detecting the light from the planet or the parent star. However, due to the precise alignment required for detectable brightening, which will only occur once as seen from the Earth, combined with the distance to the star–planet system, planets discovered using the microlensing technique cannot be selected for further study. In addition, a very large number of background stars must be continuously monitored in order to detect planetary microlensing events at a reasonable rate.

The first extrasolar planet found using the gravitational microlensing technique was OGLE235–MOA53 b in 2004 (Bond et al., 2004). The planet, which has a mass of $\sim 1.5 M_{\text{Jup}}$, was discovered from the light curve of the background star, indicating that the lens was not a single star, but a star–planet system (Figure 1.10). Even though only 4 extrasolar planets have been discovered using the gravitational microlensing technique to date, this method has detected one of the lowest mass extrasolar planets at the time of writing. This extrasolar planet, OGLE–2005–BLG–390L b, has a mass of $\sim 5.5 M_{\oplus}$ (Beaulieu et al., 2006), only slightly more massive than the lowest mass planet found using the radial velocity technique.

Astrometry

All the stars in the Galaxy move across the night sky as seen from the Earth. One component of this motion is known as parallax and is due to the orbit of the Earth around the Sun. The remainder of this motion is due to the orbit of the stars around the center of mass of the Galaxy and consists of a radial component and a transverse component. The radial component, or radial velocity, is the motion along the line of sight of the observer, while the transverse component is the motion perpendicular to this, along the plane of the celestial sphere. The accurate measurement of this transverse component of motion, also known as proper motion, can be achieved using astrometry. The proper motion of a solitary star follows a straight line, after accounting for the motion due to parallax. However, a star–planet system will orbit around their common centre of mass, leading to an oscillation of the star around the expected straight trajectory of the star

alone. The amplitude of this oscillation, known as the astrometric signature, α , can be used to determine information about the planet and is given as

$$\alpha = \frac{M_p}{M_*} \frac{a}{d} \quad (1.12)$$

where α is measured in arc seconds (as) when the orbital radius, a , is measured in AU and the distance to the star, d , is measured in pc. The astrometric technique aims to detect this displacement by acquiring precise measurements of the position of a star relative to background stars. If the Sun was viewed at a distance of 10 pc, Jupiter alone would induce an astrometric signature of ~ 0.5 mas, while the effect of the Earth would lead to an astrometric signature of $\sim 0.3 \mu\text{as}$ (Casertano et al., 1996). Therefore, the astrometric accuracy required to detect extrasolar planets using this technique is typically in the sub-mas range. This technique is particularly sensitive to relatively long orbital periods, since the astrometric signature is directly proportional to the orbital radius of the planet (Equation 1.12).

In 1996 George Gatewood announced the discovery of two astrometrically detected planets in orbit around Lalande 21185 (Gatewood, 1996). This was over 20 years after he had disproved the existence of a single planet around Lalande 21185 (Gatewood, 1974), which had been proposed by Sarah Lippincott in 1960 (Lippincott, 1960). The masses of the two planets are predicted to be $0.9 M_{\text{Jup}}$ and $2 M_{\text{Jup}}$, orbiting at periods of 5.8 and 35 years, respectively (Mayor and Frei, 2003). However, these planets are yet to be confirmed. More recently, astrometric measurements obtained of ϵ Eridani have been combined with radial velocity measurements to determine the mass of the known companion ϵ Eridani b (Benedict et al., 2006).

The National Aeronautics and Space Administration (NASA) Space Interferometry Mission (SIM) PlanetQuest is the first space based long baseline interferometer designed for precision astrometry and is due for launch in 2015 (Shao et al., 2007). The instrument will operate at optical wavelengths using a 9 meter baseline and will monitor a few thousand stars within 30 pc to search for planets with masses as small as $\sim 1 M_{\oplus}$, with the hope of detecting a significant fraction of the expected population of planets around these stars. This will be achieved by using differential astrometry with an accuracy of $\sim 0.6 \mu\text{as}$ for a single measurement for stars brighter than $V = 7$, equivalent to a differential positional accuracy at the end of 5 years of $\lesssim 0.1 \mu\text{as}$ (Unwin et al., 2007). The European Space Agency (ESA) is currently developing the GAIA astrometric mission, which has a target launch date between 2010 and 2012. GAIA will provide astrometric measurements of $\sim 10^9$ stars with an accuracy of $\sim 10 \mu\text{as}$ for stars brighter than $V = 15$. This mission is expected to discover 10,000 – 20,000 massive planetary systems out to ~ 200 pc (Perryman, 2002).

Direct Imaging

If an extrasolar planet can be spatially resolved from its parent star, i.e., the planet is beyond the point spread function (PSF) of the star, then the probability of obtaining a direct image of the planet is greatly increased. However, the extrasolar planets already found using the radial velocity technique are too close to the bright parent star to be directly imaged. Current imaging efforts are working towards suppressing the amount of light detected from the parent star, leading to an increase in the likelihood of spatially resolv-

ing and directly detecting the faint planet. A technique known as nulling interferometry can be used to effectively prevent the detection of the light from the parent star. Nulling interferometry can be described by considering two separated mirrors that acquire the light from a single star. When the light from both mirrors are combined, if the light from one mirror arrives with an added phase shift of half a wavelength, the light will interfere destructively. A nulling interferometer can be tuned so that destructive interference of only the light from the parent star occurs. The ESA Darwin mission, which uses three 3 meter telescopes separated by up to 168 meters, and the NASA Terrestrial Planet Finder Interferometer (TPF-I) mission, which uses four 3.5 meter telescopes separated by up to 100 meters, are both due for launch at some point after 2015. These missions will use the nulling interferometry method combined with mid infrared (MIR) imaging to attempt to directly detect the light from Earth like planets around nearby stars. In addition, the TPF-I is being developed concurrently with the Terrestrial Planet Finder Coronagraph (TPF-C). Using a coronagraphic mask, so called since they were initially used to observe the corona of the Sun, is another way in which the amount of light detected from the parent star can be suppressed. Another technique, known as adaptive optics (AO), can decrease the size of the PSF of a star by minimising the effects of atmospheric turbulence. These effects are removed by using deformable mirrors to compensate and correct for the constant changes in the atmosphere.

Rather than use technology to block the light from the parent star, targeting intrinsically faint stars can improve the spatial resolution between the planet and its parent star, since the PSF of the star will be less prominent. This increases the probability of directly

detecting an extrasolar planet. In addition, observing at longer wavelengths enhances the contrast between the planet and the star. As the temperature of an object decreases, the peak of its emission occurs at longer wavelengths, as shown by Planck's Law

$$I(\lambda, T) = \frac{2 h c^2}{\lambda^5} \frac{1}{e^{\frac{h c}{\lambda k T}} - 1} \quad (1.13)$$

where $I(\lambda, T)$ is the spectral radiance, λ is the wavelength, T is the temperature of the object, h is Planck's constant and k is Boltzmann's constant. The contrast between a planet and its parent star is optimised when such a system is observed in the MIR, since the peak of the thermal emission of a planet occurs at these wavelengths.

Planets cannot sustain deuterium burning as their cores do not attain the high masses and temperatures required (Section 1.5.1). Therefore, thermonuclear processes do not dominate the evolution of planets. Planets will contract and cool continuously from the moment they form, since there is no thermal pressure from nuclear fusion to counteract the force of gravity. The evolutionary models used to predict the luminosity of brown dwarfs (Section 1.4.3) can also be used to predict the luminosity of extrasolar planets and show that younger planets have higher luminosities (Figure 1.6). Many groups have used this to their advantage, surveying young stars to find young, bright planetary companions (e.g., The Gemini Deep Planet Survey; GDPS; Lafrenière et al., 2007).

The first planetary mass object found using direct imaging was 2MASSW J1207334 – 393254 b (2M1207 b) in April 2004 (Figure 1.11; Chauvin et al., 2004; Chauvin et al., 2005a). 2M1207 b has a mass of $\sim 4 \pm 1 M_{\text{Jup}}$ (Ducourant et al., 2007) and was found in orbit around the intrinsically faint, young, $\sim 25 M_{\text{Jup}}$ brown dwarf member of the

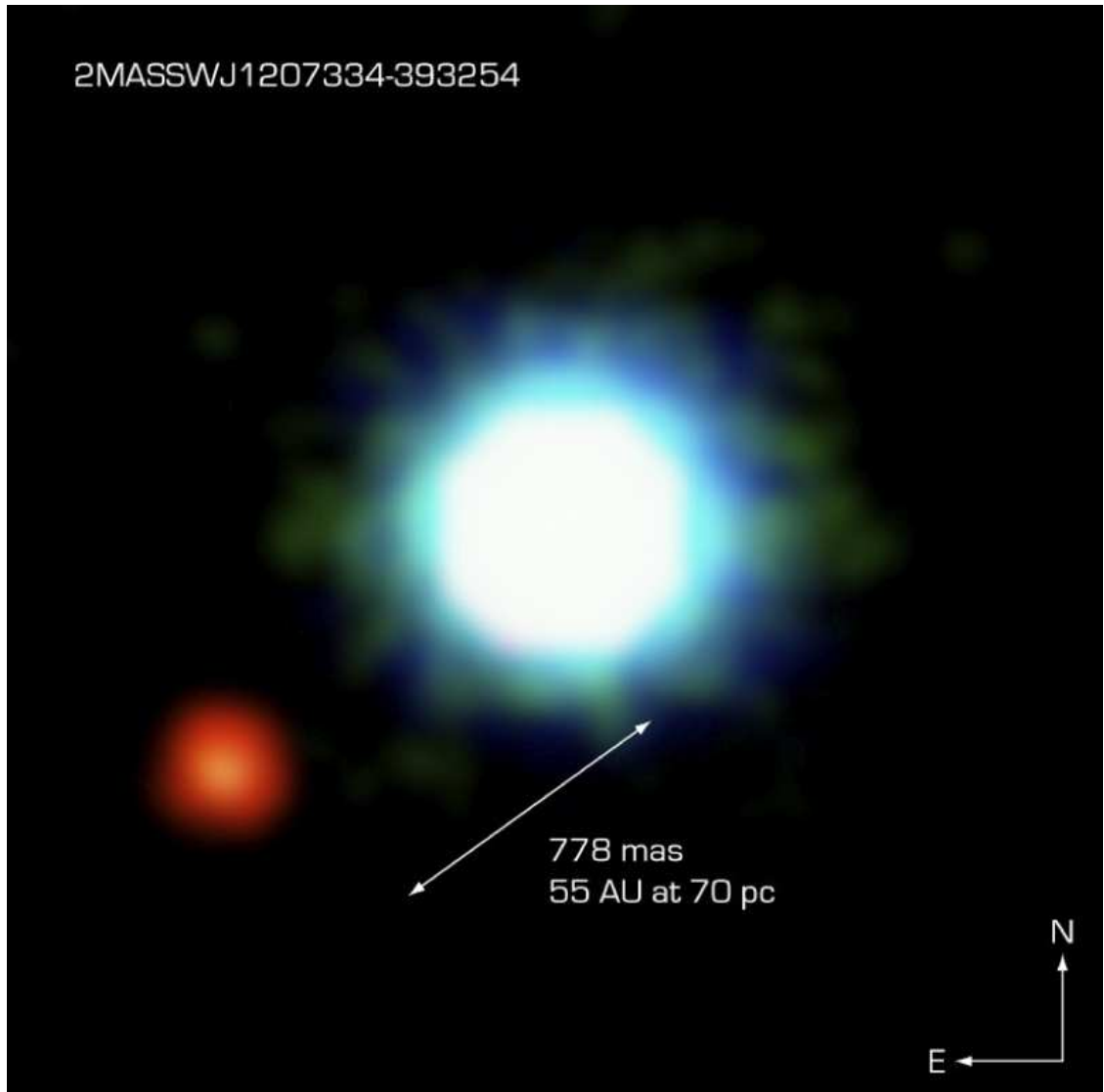


FIGURE 1.11. The first direct image of a planetary mass object ($\sim 4 \pm 1 M_{\text{Jup}}$), discovered in orbit around the $\sim 25 M_{\odot}$ brown dwarf 2MASSW J1207334–393254, composed of individual H (blue), K_s (green) and L' (red) band images (Chauvin et al., 2004).

TW Hydrae association known as 2MASSW J1207334–393254 (2M1207 A). The direct image of 2M1207 b was obtained using H , K_s and L' band imaging combined with AO.

There are currently only 4 objects listed under “Candidates detected by imaging” in

The Extrasolar Planets Encyclopaedia¹⁰. However, with the exception of 2M1207 b, the masses of the other three objects are currently too uncertain to confidently classify them as extrasolar planets. The second directly imaged companion, announced in 2005 after the discovery of 2M1207 b, was found in orbit around the young, T Tauri star GQ Lup in the Lupus star forming region. This companion, which was detected through the use of K band imaging combined with AO, was initially estimated to have a mass between $\sim 1 - 42 M_{\text{Jup}}$ (Neuhäuser et al., 2005). However, recent J and H band spectroscopy obtained of the companion suggests a higher mass, between $\sim 10 - 42 M_{\text{Jup}}$ (McElwain et al., 2007). The planetary nature of this companion remains unconfirmed.

The third directly imaged companion, also announced in 2005, was found in orbit around the young, nearby star AB Pic, a member of the large Tucana–Horologium association. This companion, which was detected through the use of NIR imaging combined with coronagraphy, has a mass between $\sim 13 - 14 M_{\text{Jup}}$ (Chauvin et al., 2005b), placing it on the boundary of the limiting mass for the thermonuclear fusion of deuterium (Section 1.5.1). Again, the planetary nature of this companion is unconfirmed.

The fourth directly imaged companion, announced in 2006, was found in orbit around the nearby M type star SCR 1845 – 6357 (Biller et al., 2006). This companion was detected through the use of the Simultaneous Differential Imager (SDI) combined with AO, which was used to observe at wavelengths around $1.62\mu\text{m}$, exploiting the fact that cool substellar objects have strong CH_4 absorption at these wavelengths (Section 1.4.2).

¹⁰<http://exoplanet.eu/catalog-imaging.php>

This methane rich T dwarf was initially estimated to have a mass between $9 - 65 M_{\text{Jup}}$. However, recent NIR spectroscopy obtained of the companion constrains the mass to between $40 - 50 M_{\text{Jup}}$ (Kasper et al., 2007), providing evidence that this companion is in fact a brown dwarf.

1.5.4 Properties

Planetary formation theories have been developed using information acquired from the Solar System. It is known that planets are formed in orbit around their parent stars from the circumstellar disk of gas and dust that remains after the formation of the star. However, the exact details of the formation of planets within the circumstellar disk are unclear. Two competing theories have so far been used to explain planet formation. The generally accepted mechanism, not only for planet formation in the Solar System but also in extrasolar planetary systems, is known as core accretion (e.g., Pollack et al., 1996). This method can explain in an unified way the formation of both gas giants and rocky terrestrial planets. In the core accretion model, a solid core is formed by collisional accumulation of planetesimals, which themselves are formed by collisional coagulation of small dust grains. This is the basis of the formation of rocky terrestrial planets. As the core grows, its ability to accrete the gas present in the circumstellar disk increases, leading to the formation of a gaseous envelope around the core. When the core and the envelope masses become equal to each other, which occurs when the core reaches a critical mass of $\sim 10 - 30 M_{\oplus}$, subsequent growth occurs almost entirely by

gas accretion (Bodenheimer and Pollack, 1986). A massive gaseous envelope is formed through runaway accretion and the gas giant is born. However, the problem with this scenario is that the core accretion model requires several million years to form these gas giants, which is comparable to the estimated lifetime of circumstellar disks (Boss, 2000).

The disk instability model (e.g., Kuiper, 1951) is the second theory used to explain planet formation. If a marginally gravitationally unstable circumstellar disk is sufficiently massive, the disk fragments, forming dense regions. These regions can contract to form giant gaseous protoplanets in a few hundred years (Boss, 2000), before the gas in the circumstellar disk has depleted. Gas giants formed in this way are assumed to have a metallicity similar to that of the parent star, since the star and its circumstellar disk are formed from the same interstellar cloud. However, this is inconsistent with the indication that the envelope of Jupiter contains three times the solar abundance of heavy elements (Young, 2003). In addition, the stars hosting extrasolar planets appear to have a higher metallicity compared to average field stars (e.g., Gonzalez, 1997). Therefore, it is possible that the abundance of heavy elements present in the circumstellar disk assists in the formation of planets. Further detailed discussions of the formation of planets are beyond the scope of this thesis.

Chapter 2

The DODO Survey

2.1 Overview

Directly imaging the extrasolar planets found using the radial velocity technique is difficult as these faint companions are too close to their bright parent stars. By targeting intrinsically faint stars, the probability of obtaining a direct image of an extrasolar planet in orbit around them is substantially increased. White dwarfs are intrinsically faint stars and can be up to 10,000 times less luminous than their main sequence progenitors. This chapter will discuss whether extrasolar planets can survive stellar evolution and remain in orbit around the eventual white dwarf, along with an estimation of the likelihood of finding such old planetary systems. The advantages of the Degenerate Objects around Degenerate Objects (DODO) survey, which aims to obtain a direct image of an extrasolar planet in a wide orbit around a white dwarf, will be introduced. Finally, the reasons behind the selection of the targets chosen for the DODO survey, including their observa-

tions, will be covered.

Since the DODO survey aims to detect faint extrasolar planets, the survey will also be sensitive to brighter and more massive brown dwarfs. However, distinguishing between a massive extrasolar planet and a very low mass (VLM) brown dwarf is difficult. The current definition of an extrasolar planet states that an object less massive than the limiting mass for thermonuclear fusion of deuterium, currently calculated to be $\sim 13 M_{\text{Jup}}$, is a planet regardless of how it formed. However, this definition is highly debated, since it appears that the method of formation is the key in distinguishing between these two types of objects (Baraffe, private communication). Unfortunately, there is no physical way to distinguish between massive extrasolar planets and VLM brown dwarfs after they have formed. It is argued that 2M1207 Ab (Section 1.5.3) more likely formed as a binary brown dwarf system (Section 1.3.3), since the core accretion model, thought to be the most likely formation mechanism for gas giants like those in the Solar System (Section 1.5.4), is unable to account for the formation of 2M1207 b (Lodato, Delgado-Donate and Clarke, 2005). As a result, for the remainder of this thesis, the term “planet” will refer to “planetary mass object”, i.e., less than $\sim 13 M_{\text{Jup}}$. No distinction will be made on whether such an object formed as an extrasolar planet or a brown dwarf.

While the following chapter will focus on the discussion of extrasolar planets in particular, brown dwarfs will be considered where appropriate. The following sections are based on the publication by Burleigh, Clarke and Hodgkin (2002).

2.2 Can Extrasolar Planets Survive Stellar Evolution?

The discovery of an extrasolar planet in orbit around a white dwarf would suggest that the planet has survived the process of stellar evolution. The Red Giant Branch (RGB) and the Asymptotic Giant Branch (AGB) phases of evolution (Section 1.3.3) are the most influential, particularly the late stages of the AGB phase, since the main sequence progenitor will reach its maximum radius and lose most of its initial mass during this phase (Villaver and Livio, 2007). The main factor that determines whether a planet will survive the RGB and AGB phases is the initial orbital radius of the planet. During stellar evolution, the orbital radius of the planet will evolve, primarily due to mass loss from the parent star, which acts to increase the orbital radius. However, if the red giant envelope expands beyond the orbital radius of the planet, interactions between the planet and the red giant envelope will act to reduce the orbital radius. This leads to two different evolutionary scenarios, one where the orbital radius of the planet is inside the red giant envelope, known as common envelope evolution, and one where the orbital radius of the planet is outside the red giant envelope.

A planet with an orbital radius within the red giant envelope will lose angular momentum due to frictional drag, arising from the motion of the planet through the red giant envelope. As a result, the orbital radius of the planet will decrease (Livio and Soker, 1984). The final orbital radius, a_f , of a planet after the entirety of the red giant envelope has

been expelled can be estimated as

$$a_f \approx \left(\frac{\chi}{1 - \chi} \right) \frac{M_p}{M_{\text{rg}}} R_{\text{rg}} \quad (2.1)$$

where $\chi = M_{\text{core}}/M_{\text{rg}}$, M_{core} is the mass of the core of the red giant, equivalent to the white dwarf mass, $M_{\text{rg}} = M_{\text{core}} + M_{\text{env}}$ is the total mass of the red giant, equivalent to the total mass of the main sequence progenitor assuming no mass loss has occurred, M_{env} is the mass of the red giant envelope, M_p is the mass of the planet and R_{rg} is the radius of the red giant (Nelemans and Tauris, 1998). Depending on the initial mass of the planet, one of the following three events will occur (Livio and Soker, 1984);

1. The planet will evaporate before it reaches an orbital radius of a_f .
2. The orbital radius of the planet will continue to decrease until it collides with the core of the red giant.
3. The planet survives interactions with the red giant envelope and exists as a close companion to the newly formed white dwarf at an orbital radius of a_f .

The orbital radius at which a planet will evaporate, a_{evap} , can be estimated as

$$a_{\text{evap}} = \left[10 \left(\frac{M_{\text{Jup}}}{M_p} \right) \right]^{1.18} \quad (2.2)$$

where a_{evap} is measured in $R_{\odot}$. If $a_{\text{evap}} > a_f$, a planet with a mass of M_p will evaporate before the planet reaches its final orbital radius, which is assumed to occur when the entirety of the red giant envelope has been expelled. The mass of a planet that will completely evaporate exactly when the entirety of the red giant envelope is expelled is

known as the critical mass, M_{crit} . This mass can be estimated by equating Equations 2.1 and 2.2 (Nelemans and Tauris, 1998). If the planet has a mass less than M_{crit} , the planet will evaporate before the entirety of the red giant envelope has been expelled. M_{crit} is given as

$$M_{\text{crit}} = 10 \left[\left(\frac{1 - \chi}{\chi} \right) \left(\frac{M_{\text{rg}}}{M_{\odot}} \right) \left(\frac{100 R_{\odot}}{R_{\text{rg}}} \right) \right]^{0.46} \quad (2.3)$$

where M_{crit} is measured in M_{Jup} . For a main sequence progenitor mass of $1.5 M_{\odot}$, the initial final mass relation (IFMR) implies a white dwarf mass of $\sim 0.49 M_{\odot}$ (Equation 1.5; Dobbie et al., 2006a). The $1.5 M_{\odot}$ main sequence progenitor will reach a maximum radius of $\sim 300 R_{\odot}$ during the AGB phase of stellar evolution (Hurley et al., 2000), leading to a M_{crit} value of $\sim 10 M_{\text{Jup}}$. This indicates that a $\sim 10 M_{\text{Jup}}$ object, with an initial orbit within the red giant envelope of a $1.5 M_{\odot}$ main sequence progenitor, will not survive common envelope evolution and will evaporate before the red giant envelope has been expelled. Planets with an initial mass greater than M_{crit} will survive the RGB and AGB phases of stellar evolution and will orbit around the newly formed white dwarf at a radius of a_f . However, if at any point the orbital radius of the planet is smaller than the Roche lobe radius of the white dwarf, the planet will continue to spiral inwards, where it will collide with the core of the red giant and be completely destroyed. In addition, more massive planets deposit significant orbital angular momentum into the red giant envelope as they spiral inwards, increasing the rotation of the envelope. This could lead to the premature ejection of the red giant envelope by planets less massive than M_{crit} (Nelemans and Tauris, 1998).

This theoretical estimate of M_{crit} is highly uncertain, since it depends on factors which

are largely unknown, i.e., the efficiency of envelope ejection. However, the recently discovered $0.053 M_{\odot}$ brown dwarf companion to the white dwarf WD 0137 – 349 has survived common envelope evolution (Maxted et al., 2006; Burleigh et al., 2006), providing observational constraints to the theoretical estimate of M_{crit} . This system will be discussed in more detail in Chapter 6.

A planet with an orbital radius that avoids direct contact with the red giant envelope will have a greater chance of survival, migrating outwards as mass is lost from the central star. Assuming that the mass of the star, M_* , is much larger than the mass of the planet, M_p , the product $M_* a$ is constant, where a is the orbital radius of the planet (Jeans, 1924). Therefore,

$$a_f = \left(\frac{M_{\text{MS}}}{M_{\text{WD}}} \right) a_i \quad (2.4)$$

where M_{MS} is the mass of the main sequence progenitor, M_{WD} is the mass of the white dwarf and a_i is the initial orbital radius of the planet.

2.2.1 The Stability of Planetary Systems around White Dwarfs

Extrasolar planetary systems around stars more massive than the Sun, such as the $1.5 - 8 M_{\odot}$ main sequence progenitors of white dwarfs, may be destabilised due to mass loss during the RGB and AGB phases of stellar evolution (Duncan and Lissauer, 1998). Therefore, planets in previously marginally stable orbits can become unstable fairly rapidly after the star evolves into a white dwarf, or possibly as early as the AGB phase.

One of the following three events will occur once the orbits of the planets become unstable;

1. Planets in the system will collide.
2. One planet is ejected from the system.
3. The planets in the system settle into a different and more stable configuration.

The ejection of one planet from an extrasolar planetary system will decrease the orbital radii of the remaining planets, resulting in a system where the planets orbit much closer to the white dwarf than around the main sequence progenitor. For systems that are rearranged into a more stable configuration, one or two planets in the system will be left with highly eccentric orbits. For systems that contain only two planetary companions, in which one of the planets has an initial orbital radius of ~ 5 AU, the probability that the two planets will collide is $\sim 8\%$, while the probability that one planet will be ejected is 35% (Debes and Sigurdsson, 2002). This implies that even though planetary systems can become unstable due to mass loss during the RGB and AGB phases of stellar evolution, in most cases planetary systems will survive.

2.2.2 Evidence for the Existence of Old Planetary Systems

In ~ 5.5 Gyr, the Sun will evolve into a white dwarf. It is currently unclear whether the Earth will survive the final stages of stellar evolution and remain in orbit around

the eventual white dwarf. One model predicts that during the AGB phase, the red giant envelope will expand to a radius of $\sim 220 R_{\odot} \approx 1$ AU (Hurley et al., 2000). In this case, the Earth may be lost as a result of its interactions with the red giant envelope. If old extrasolar planetary systems around white dwarfs existed, observations of such systems may provide information on their formation and evolution, which could allow the future of the Solar System to be determined.

Companions with $a_i > R_{\text{rg}}$

Observations acquired of the post-red giant star V 391 Pegasi provides evidence that a planet with an initial orbital radius outside the maximum radius of the red giant envelope can survive the RGB phase of stellar evolution. In 2007 a planet was discovered in orbit around V 391 Pegasi from the periodic variation in the precise timing measurements of the extremely stable, short period pulsations from the post-red giant star (Silvotti et al., 2007). The planet has a minimum mass, $M_p \sin i \sim 3.2 M_{\text{Jup}}$, an orbital radius of ~ 1.7 AU and an estimated age of ~ 10 Gyr. V 391 Pegasi has a mass of $\sim 0.5 M_{\odot}$ and is currently burning helium in its core, suggesting that this star is yet to begin the AGB phase of stellar evolution (Section 1.3.3). The initial orbital radius of the planet around the $\sim 0.85 M_{\odot}$ main sequence progenitor is estimated to be ~ 1 AU. This indicates that the initial orbital radius of the planet was well beyond the extent of the red giant envelope, which has a predicted maximum radius of ~ 0.7 AU. This provides evidence that planets with an initial orbital radius beyond the extent of the red giant envelope can survive the RGB phase of stellar evolution. In addition, a number of extrasolar planets have been

discovered around evolved giant stars using the radial velocity technique. These stars have entered the red giant phase of stellar evolution, providing additional evidence that planets can survive the early stages of the RGB phase.

Companions with $a_i < R_{\text{rg}}$

Observations acquired of the white dwarf WD 0137 – 349 provides evidence that a brown dwarf with a mass of $\sim 53 M_{\text{Jup}}$ and an initial orbital radius inside the maximum radius of the red giant envelope can survive the RGB and AGB phases of stellar evolution (Maxted et al., 2006). This brown dwarf was discovered in orbit around WD 0137 – 349 in 2006 using the radial velocity technique (Section 1.5.3). The brown dwarf has an orbital radius of $\sim 0.65 R_{\odot} \approx 0.003 \text{ AU}$, indicating that the initial orbital radius of the brown dwarf was within the extent of the red giant envelope during stellar evolution. This provides evidence that objects with masses $\gtrsim 53 M_{\text{Jup}}$ within the extent of the red giant envelope can survive the RGB and AGB phases of stellar evolution. This system will be discussed in more detail in Chapter 6.

Dust Disks

The discovery of metal rich dust disks in close orbits around white dwarfs may indicate the presence of old, rocky planetary systems, suggesting that even terrestrial planets and asteroids can survive the final stages of stellar evolution. The first dust disk was discov-

ered in 1987, when the observed magnitudes of the white dwarf G 29 – 38, also known as WD 2326 + 049, at wavelengths between $2 - 5\mu\text{m}$ were discovered to be much brighter than the predicted magnitudes of a $T_{\text{eff}} = 11820 \pm 175$ K white dwarf (Zuckerman and Becklin, 1987b). This infrared (IR) excess was initially attributed to a spatially unresolved, $T_{\text{eff}} = 1200 \pm 200$ K brown dwarf companion to the white dwarf. Subsequent magnitude measurements in the K ($2.2\mu\text{m}$), L ($3.5\mu\text{m}$), L' ($3.8\mu\text{m}$), M ($4.8\mu\text{m}$) and N ($\sim 10\mu\text{m}$) bands suggested that the temperature relating to the blackbody-like IR excess was closer to ~ 800 K. However, based on the observed luminosity of the excess emission, combined with the distance to G 29 – 38 of ~ 14.1 pc, an unacceptably large radius of $\sim 0.4 R_{\odot}$ was determined for the brown dwarf. This problem was solved by assuming the IR excess was due to a dust disk rather than a brown dwarf (Tokunaga, Becklin and Zuckerman, 1990). More recently, a mid infrared (MIR) spectrum of G 29 – 38, obtained by the Spitzer Space Telescope, shows a strong emission feature in the spectrum between $9 - 11\mu\text{m}$, which indicates the presence of silicates (SiO_4) in the dust disk (Reach et al., 2005).

Over 18 years after the discovery of the dust disk around G 29 – 38, 4 additional white dwarfs are now known to have dust disks in orbit around them: GD 362 ($T_{\text{eff}} = 9740$ K; Becklin et al., 2005; Kilic et al., 2005), GD 56 ($T_{\text{eff}} = 14400$ K; Kilic et al., 2006), WD 1150 – 153 ($T_{\text{eff}} = 12800$ K; Kilic and Redfield, 2007a) and WD 2115 – 560 ($T_{\text{eff}} = 9700$ K; von Hippel et al., 2007). All 5 are classified as DAZ white dwarfs, which contain both hydrogen lines and metal lines in their spectra (Table 1.2). The fraction of known single DAZ white dwarfs with IR excesses, which can be attributed to a dust

disk, is 14% (Kilic et al., 2006). Before the discovery of dust disks around white dwarfs, the atmospheric metal abundances observed in DAZ white dwarfs were difficult to explain, since the diffusion timescales for heavy elements to sink below the atmosphere are short compared to the white dwarf cooling age. Therefore, the metals present in the atmospheres of DAZ white dwarfs could not be primordial and indicated that they were accreted from an external source. Accretion from the interstellar medium (ISM; Dupuis, Fontaine and Wesemael, 1993) and comets impacting onto the white dwarfs (Alcock, Fristrom and Siegelman, 1986) had previously been suggested to explain the presence of metals in the atmospheres of white dwarfs. Today, the generally accepted origin of these metals is accretion from a dust disk, formed from the tidal disruption of an asteroid that had strayed within the Roche lobe radius of the white dwarf after its orbital radius was altered during the AGB phase of stellar evolution (Graham et al., 1990; Debes and Sigurdsson, 2002; Jura, 2003). It is thought that $> 7\%$ of white dwarfs possess asteroid belts with masses between $\sim 7 \times 10^{-5} - 10^{-3} M_{\oplus}$. Since the current mass of the asteroid belt in the Solar System is $\sim 6 \times 10^{-4} M_{\oplus}$, the asteroid belts around white dwarfs are analogous to the asteroid belt in the Solar System (Jura, 2006). This implies that $> 7\%$ of white dwarfs could also possess planetary systems. In addition, the presence of silicates in the dust disk around G 29 – 38 also supports the idea that the disk was formed from the disruption of an asteroid. Therefore, the detection of a dust disk in orbit around a white dwarf represents a possible link to the existence of an old planetary system.

In addition to these dust disks, there have been metal rich gas disks found in orbit around 2 hotter DAZ white dwarfs; SDSS J122859.93 + 104032.0 ($T_{\text{eff}} = 22292$ K; Gänsicke

et al., 2006) and SDSS J104341.53 + 085558.2 ($T_{\text{eff}} = 18330$ K; Gänsicke, Marsh and Southworth, 2007). These gas disks could also indicate the presence of old planetary systems, since it is likely that the hot white dwarfs caused the dust in the disk to sublimate.

White Dwarfs as Companions to Planet Hosting Stars

No extrasolar planets have been discovered in orbit around a white dwarf to date¹. However, up to three white dwarfs are known to be wide companions to stars hosting extrasolar planets. In 1973 the well studied white dwarf WD 1620 – 391 was discovered to be a common proper motion companion to the solar type star HD 147513 (Wegner, 1973). Over 30 years later, a planetary mass companion, with a minimum mass, $M_p \sin i = 1.21 M_{\text{Jup}}$ and an orbital radius of 1.32 AU, was discovered in orbit around HD 147513 using the radial velocity technique (Mayor et al., 2004). Since WD 1620 – 391 and the parent star are separated by ~ 5360 AU, it is highly unlikely that the evolution of the main sequence progenitor of the white dwarf affected the mass and orbit of HD 147513 b.

It has been suggested that the faint companions to two other planet hosting stars are also white dwarfs. A planetary mass companion, with a minimum mass, $M_p \sin i = 1.28 M_{\text{Jup}}$ and an orbital radius of 1.18 AU, was discovered in orbit around HD 27442

¹Since the submission of this thesis, strong evidence for the existence of a planetary mass companion to the DAV white dwarf GD 66 has recently been found from the periodic variation in the precise timing measurements of the extremely stable non-radial pulsations from GD 66 (Mullally et al., 2008).

using the radial velocity technique (Butler et al., 2001). Further observations of this system revealed an additional faint common proper motion companion to HD 27442 A, which was most likely a white dwarf (Raghavan et al., 2006; Chauvin et al., 2006). HD 27442 B was later confirmed to be a white dwarf from the analysis of its optical and IR spectrum (Mugrauer et al., 2007; Chauvin et al., 2007). Since the white dwarf and the parent star are separated by ~ 240 AU, it is unlikely that the evolution of the main sequence progenitor of the white dwarf affected the mass and orbit of HD 27442 b.

Finally, a planetary mass companion, with a minimum mass, $M_p \sin i = 4.01 M_{\text{Jup}}$ and an orbital period of 15.8 days, was found in orbit around Gliese 86 using the radial velocity technique (Queloz et al., 2000). Further observations of this system revealed an additional faint common proper motion companion to Gliese 86 A. Near infrared (NIR) photometry of the companion suggested that this faint companion was a brown dwarf (Els et al., 2001). More recently, spectra acquired of the faint companion indicates that Gliese 86 B is more likely to be a white dwarf, with a mass between $0.48 M_{\odot} \leq M \leq 0.62 M_{\odot}$ and an orbital radius of ~ 20 AU (Mugrauer and Neuhauser, 2005; Lagrange et al., 2006). However, inconsistencies between the white dwarf cooling age, the age of the star and the presence of a planet makes it hard to understand how such a system can exist. The possible effects of the evolution of the main sequence progenitor on the mass and orbit of the planet remain to be investigated (Desidera and Barbieri, 2006).

Although the evolution of the main sequence progenitor is unlikely to have affected the planets in these systems, the discovery and study of such systems in the future could

provide additional evidence that extrasolar planets can survive stellar evolution.

2.3 Searches for Substellar Companions Around White Dwarfs

The first search for low mass substellar companions to white dwarfs was conducted by Probst (1983), who measured the IR magnitudes of ~ 100 white dwarfs to determine whether any excess emission was present, which could be attributed to a spatially unresolved low mass companion. No companions were found during this survey. Since then, a number of groups have unsuccessfully attempted to detect substellar companions to white dwarfs using the same method (e.g., Shipman, 1986; Zuckerman and Becklin, 1987a).

2.3.1 White Dwarf–Brown Dwarf Binaries

Only three substellar companions have been found in orbit around a white dwarf. The first substellar companion was discovered in 1988 around the DA white dwarf GD 165 (Section 1.4.1; Becklin and Zuckerman, 1988). Over 15 years later, a second substellar companion was confirmed. This L dwarf was discovered from the detection of excess emission present in the IR spectrum of the DA white dwarf GD 1400 (Farihi and Christopher, 2004; Dobbie et al., 2005). More recently, radial velocity measurements revealed a third substellar companion in a close orbit around the DA white dwarf WD 0137 – 349

(Maxted et al., 2006). This system will be discussed in more detail in Chapter 6. The L dwarf companion fraction, determined from a wide field, proper motion, NIR search for wide substellar companions to 261 white dwarfs, capable of detecting companions with projected physical separations between $\sim 100 - 5000$ AU with masses $> 0.05 M_{\odot}$, along with a deep search of 86 white dwarfs, capable of directly detecting companions with projected physical separations between $\sim 50 - 1100$ AU with masses $> 0.02 M_{\odot}$, is estimated to be $< 0.5\%$ (Farihi, Becklin and Zuckerman, 2005).

2.3.2 The Brown Dwarf Desert

The lack of brown dwarf companions to white dwarfs is most likely related to the so called brown dwarf desert. The brown dwarf desert is the term given to the deficit in the frequency of brown dwarf companions, relative to both the frequency of less massive planetary companions and the frequency of more massive stellar companions (Marcy and Butler, 2000). The brown dwarf desert is generally thought to exist for companions with orbital radii < 3 AU. Around 16% of solar type stars have companions with masses $> 1 M_{\text{Jup}}$ and orbital radii < 3 AU. Of these, $11\% \pm 3\%$ are stellar companions, $< 1\%$ are brown dwarf companions and $5\% \pm 2\%$ are planetary mass companions. The driest part of the desert has a mass range between $13 - 56 M_{\text{Jup}}$ (Grether and Lineweaver, 2006). It was initially thought that the brown dwarf desert did not exist for companions with large orbital radii. Observations of a number of known L and T dwarfs, which were discovered to be wide common proper motion companions to stars with spectral classes of F–M, in-

licated that brown dwarfs were $\gtrsim 10$ times more frequent at separations > 1000 AU than at close separations (Gizis et al., 2001). However, more recent observations suggest that the brown dwarf desert does exist at wide orbital radii. During an infrared coronagraphic search for substellar companions to several hundred nearby stars with spectral classes of G, K and M, only one brown dwarf companion was detected. The frequency of brown dwarf companions with projected physical separations between $75 - 300$ AU is $1\% \pm 1\%$. The frequency of massive brown dwarf companions with masses $> 30 M_{\text{Jup}}$ with projected physical separations between $120 - 1200$ AU is $0.7\% \pm 0.7\%$. The frequency of planetary mass companions with masses between $5 - 10 M_{\text{Jup}}$ with projected physical separations between $75 - 300$ AU is $< 3\%$ (McCarthy and Zuckerman, 2004). In addition, during a deep imaging search for wide companions to 132 VLM stars and brown dwarfs, no companions were found with projected physical separations between $40 - 1000$ AU. This null result implies a wide companion frequency $< 2.3\%$ for companions with masses between $0.03 - 0.05 M_{\odot}$ (Allen et al., 2007).

2.4 The Survey

The Degenerate Objects around Degenerate Objects (DODO) survey aims to obtain a direct image of an extrasolar planet in a wide orbit around a white dwarf. By acquiring images of a selection of target white dwarfs a year or two apart, the motion of all objects in the field of view of each white dwarf between the two epoch images can be determined. Any common proper motion companions to the white dwarfs can then be

identified. Directly imaging the extrasolar planets found using the radial velocity technique is difficult as these faint companions are too close to their bright parent stars. The DODO survey has the advantage of searching for extrasolar planets around intrinsically faint white dwarfs, which can be up to 10,000 times less luminous than their main sequence progenitors, significantly enhancing the contrast between any planets and the white dwarf. Also, the DODO survey aims to specifically image extrasolar planets that have avoided contact with the red giant envelope. The orbital radii of these planets will have increased due to mass loss from their parent stars (Section 2.2; Equation 2.4). For example, when the Sun evolves into a white dwarf, the orbital radius of Jupiter will increase by a factor of ~ 2.4 , leading to a final orbital radius around the eventual white dwarf of ~ 12.3 AU. At 10 pc, this is equivalent to a projected physical separation of $\sim 1.2''$. Planets with larger orbital radii will be even easier to spatially resolve from the PSF of the white dwarf (Section 1.5.3).

Radial velocity searches have concentrated mainly on stars with spectral classes between mid F and M, since the faster rotation and increased activity of early B, A and mid F type stars broadens the low number of absorption lines in their spectra. As a result, it is difficult to accurately measure the Doppler shift of stars with these earlier spectral classes. However, new methods in manipulating the measurements acquired when using the radial velocity technique has allowed extrasolar planets to be found around stars with spectral classes of A and F (e.g., Galland et al., 2005). Since the $1.5 - 8 M_{\odot}$ main sequence progenitors of white dwarfs have spectral classes of early B, A and mid F, searching for extrasolar planets in orbit around white dwarfs allows the examination of a

currently inadequately explored region of parameter space. Therefore, the DODO survey could supply new information on the frequency and mass distribution of extrasolar planets around intermediate mass main sequence stars. In addition, the direct detection of an extrasolar planet in orbit around a white dwarf would allow the spectroscopic investigation of planets much older and cooler than any previously found. Such a discovery could help provide constraints on models for the evolution of planets and planetary systems during the final stages of stellar evolution.

2.4.1 Target Selection

The ability to directly image a spatially resolved extrasolar planet in orbit around a white dwarf will depend on the apparent magnitude of the planet. The apparent magnitude, m , depends on the absolute magnitude of the planet, M , and its distance from the Earth, d , and is given by

$$m = M + 5[(\log_{10} d) - 1] \quad (2.5)$$

The absolute magnitude of the planet is determined from its intrinsic luminosity, which is dependant primarily on the age of the planet, since it will cool continuously from the moment it formed (Section 1.5.4). The age of an extrasolar planet found in orbit around a white dwarf is equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age.

Evolutionary models for cool brown dwarfs and extrasolar planets can be used to predict

the IR magnitudes of extrasolar planets. Throughout this thesis, the “COND” evolutionary models of Baraffe et al. (2003) are adopted, which assume irradiation effects from the parent star on the planet are negligible. These models, which exclude the presence of dust in the atmospheres, agree well with observed NIR photometric and spectroscopic properties of known T dwarfs at wavelengths $\gtrsim 1\mu\text{m}$. These models are therefore appropriate to describe the photometric properties of T dwarfs and extrasolar planets with effective temperatures, $T_{\text{eff}} \lesssim 1300\text{ K}$. The predicted absolute J band ($1.25\mu\text{m}$) magnitudes of a $3 M_{\text{Jup}}$, $5 M_{\text{Jup}}$ and $10 M_{\text{Jup}}$ extrasolar planet, depending on its age, have been estimated using these models (Figure 2.1). The models indicate that younger, more massive planets will have brighter absolute magnitudes. In addition, closer planets will have brighter apparent magnitudes (Equation 2.5). For example, a $5 M_{\text{Jup}}$ planet with an age of $\sim 2\text{ Gyr}$ will have an apparent magnitude of $J \sim 24\text{ mag}$ at 10 pc . This magnitude is comparable with the expected sensitivity of a one hour exposure acquired using an 8m telescope². Therefore, the DODO survey consists of white dwarfs that are as young and as close as possible. Nearby white dwarfs are also more likely to have large proper motions, requiring a smaller baseline between the observations of the two epoch images.

An initial sample of 41 white dwarfs were chosen. The 26 equatorial and northern hemisphere white dwarfs (Table 2.1) are presented in this thesis. The cooling age of a white dwarf, t_{WD} , is calculated using evolutionary models. When t_{WD} was unavailable in the literature, models from Fontaine, Brassard and Bergeron (2001) were used to estimate this value. The IFMR was used to determine the main sequence progenitor mass, M_{MS} ,

²For objects with a signal to noise ratio (SNR) > 3 , calculated using the NIRI Integration Time Calculator (<http://www.gemini.edu/sciops/instruments/itc/ITCniri.html>).

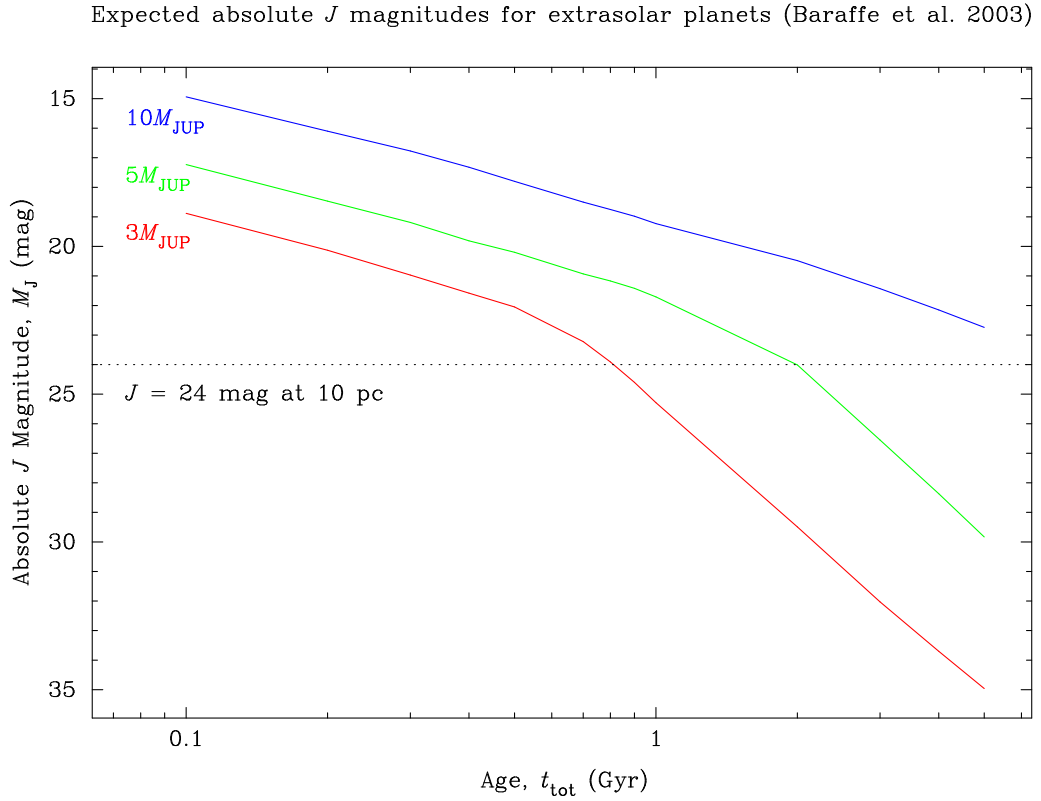


FIGURE 2.1. The predicted absolute J band ($1.25 \mu\text{m}$) magnitudes of a $3 M_{\text{Jup}}$, $5 M_{\text{Jup}}$ and $10 M_{\text{Jup}}$ extrasolar planet depending on its age.

for all 26 white dwarfs (Section 1.3.3; Equation 1.5). This IFMR is valid down to white dwarf masses of $0.54 M_{\odot}$. However, for the purpose of this thesis, this relationship was assumed to remain true for white dwarf masses below this limit. The main sequence progenitor lifetime, t_{MS} , is estimated using the equation

$$t_{\text{MS}} = 10 \left(\frac{M_{\text{MS}}}{M_{\odot}} \right)^{-2.5} \quad (2.6)$$

where t_{MS} is measured in Gyr (Wood, 1992).

Table 2.1: Parameters of the 26 white dwarfs

White Dwarf Number	Name	Spectral Class	μ [mas/yr]	θ [mas/yr]	d [pc]	T_{eff} [K]	$\log g$	M_{WD} [$M_{\odot}$]	t_{WD} [Gyr]	M_{MS}^a [$M_{\odot}$]	t_{MS}^b [Gyr]	t_{tot} [Gyr]	Ref
0046 + 051	vMA 2	DZ	1234 ¹	−2713 ¹	4.41 ²	6031	8.10	0.63	2.84*	2.6	0.93	3.8	3
0115 + 159	LHS 1227	DQ	−20 ⁴	−647 ⁴	15.41 ⁵	9050	8.19	0.69	1.02*	3.0	0.63	1.7	6
0148 + 467	GD 279	DA	1 ²	124 ²	15.85 ²	13990	7.89	0.53	0.21*	1.8	2.26	2.5	7
0208 + 396	G 74−7	DAZ	1031 ⁴	−497 ⁴	16.72 ⁵	7310	8.01	0.60	1.38	2.3	1.20	2.6	8
0341 + 182	Wolf 219	DQ	415 ⁴	−1125 ⁴	19.01 ⁵	6510	7.99	0.57	1.79*	2.1	1.54	3.3	6
0346 − 011	GD 50	DA	89 ⁹	−166 ⁹	31.0 ¹⁰	40540	9.22	1.27	0.076*	7.4	0.07	0.14	7
0435 − 088	L 879−14	DQ	243 ⁴	−1555 ⁴	9.51 ⁵	6300	7.93	0.53	1.79*	1.8	2.26	4.1	6
0438 + 108	HZ 14	DA	90 ¹¹	5 ¹¹	52 ¹²	27230	8.05	0.64	0.02*	2.6	0.88	0.90	7, h
0644 + 375	G 87−7	DA	−226 ²	−936 ²	15.41 ²	21060	8.10	0.54 ¹³	0.07*	1.9	2.04	2.1	7
0738 − 172	L 745−46A	DZ	1147 ⁴	−538 ⁴	8.90 ⁵	7710	8.09	0.63	1.45	2.6	0.95	2.4	8
0912 + 536	G 195−19	DCP	−1086 ⁴	−1125 ⁴	10.28 ⁵	7160	8.28	0.75	2.54	3.5	0.45	3.0	8
1055 − 072	LHS 2333	DC	−822 ⁴	91 ⁴	12.15 ⁵	7420	8.42	0.85	3.01	4.2	0.27	3.3	8
1121 + 216	Ross 627	DA	−1040 ⁴	−14 ⁴	13.44 ⁵	7490	8.20	0.72	1.76	3.2	0.53	2.3	8
1134 + 300	GD 140	DA	−147 ²	−6 ²	15.32 ²	21280	8.55	0.96	0.20	5.0	0.17	0.37	14
1344 + 106	LHS 2800	DAZ	−871 ¹	−181 ¹	20.04 ⁵	7110	8.10	0.65	1.67	2.7	0.82	2.5	8
1609 + 135	LHS 3163	DA	14 ⁴	−551 ⁴	18.35 ⁵	9080	8.75	1.07	2.71	5.9	0.12	2.8	8
1626 + 368	Ross 640	DZ	−469 ¹	709 ¹	15.95 ⁵	8640	8.03	0.60	1.02	2.3	1.20	2.2	8

Table 2.1: Parameters of the 26 white dwarfs

White Dwarf Number	Name	Spectral Class	μ [mas/yr]	θ [mas/yr]	d [pc]	T_{eff} [K]	$\log g$	M_{WD} [$M_{\odot}$]	t_{WD} [Gyr]	M_{MS}^a [$M_{\odot}$]	t_{MS}^b [Gyr]	t_{tot} [Gyr]	Ref
1633 + 433	G 180–63	DAZ	218 ⁴	−302 ⁴	15.11 ⁵	6650	8.14	0.68	2.28	2.9	0.67	3.0	8
1647 + 591	G 226–29	DAV	139 ²	−292 ²	10.97 ²	12260	8.31	0.80	0.56*	3.8	0.35	0.91	15
1900 + 705	G 260–15	DAP	105 ¹	479 ¹	12.99 ⁵	12070	8.58	0.95	0.94	5.0	0.18	1.1	8
1953 − 011	G 92–40	DAP	−442 ⁴	−699 ⁴	11.39 ⁵	7920	8.23	0.74	1.63	3.4	0.47	2.1	8
2007 − 219	LTT 7983	DA	109 ⁴	−313 ⁴	18.22 ¹⁶	9887	8.14	0.69	0.76*	3.0	0.63	1.4	17
2047 + 372	G 210–36	DA	160 ⁴	149 ⁴	18.16 ¹⁶	14630	8.13	0.69	0.26*	3.0	0.63	0.89	18
2140 + 207	LHS 3703	DQ	−207 ¹	−658 ¹	12.52 ⁵	8200	7.84	0.49	0.82*	1.5	3.56	4.4	6
2246 + 223	G 67–23	DA	580 ¹	13 ¹	19.05 ⁵	10330	8.57	0.97	1.56	5.1	0.17	1.7	8
2326 + 049	G 29–38	DAZ	−360 ¹	−302 ¹	13.62 ⁵	11820	8.15	0.70	0.55	3.1	0.60	1.1	14

Columns: μ and θ are the R.A. and Dec components of the proper motion of the white dwarf, respectively, measured in milli arc seconds per year; d is the distance to the white dwarf, measured in parsecs; T_{eff} is the effective temperature of the white dwarf, measured in Kelvin; $\log g$ is the log of the gravity of the white dwarf; M_{WD} is the mass of the white dwarf, measured in solar masses; t_{WD} is the cooling age of the white dwarf, measured in gigayears; M_{MS} is the mass of the main sequence progenitor, measured in solar masses; ^a M_{MS} is calculated using the IFMR (Equation 1.5; Dobbie et al., 2006a); t_{MS} is the main sequence progenitor lifetime, measured in gigayears; ^b t_{MS} is calculated using Equation 2.6 (Wood, 1992); t_{tot} is the total age of the white dwarf, measured in gigayears; Ref = References, which refer to the T_{eff} , $\log g$, M_{WD} and t_{WD} columns. (1) Bakos, Sahu and Németh (2002), (2) Perryman et al. (1997), (3) Burleigh et al. (2008), (4) Salim and Gould (2003), (5) van Alena, Lee and Hoffleit (1995), (6) Dufour, Bergeron and Fontaine (2005), (7) Bergeron, Saffer and Liebert (1992), (8) Bergeron, Leggett and Ruiz (2001), (9) Klemola, Jones and Hanson (1987), (10) Dobbie et al. (2006b), (11) McCook and Sion (2003), (12) Weidemann et al. (1992), (13) Fontaine, Bergeron and Brassard (2007), (14) Liebert, Bergeron and Holberg (2005), (15) Gianninas, Bergeron and Fontaine (2005), (16) Holberg, Oswalt and Sion (2002), (17) Koester et al. (2001), (18) Giovannini et al. (1998); * indicates that the white dwarf cooling age was calculated using models from Fontaine et al. (2001); h indicates that the white dwarf is a member of the Hyades cluster.

2.4.2 Observations

The data acquired for the DODO survey were obtained using a very efficient observing mode called *queue scheduling*. Observations were executed by staff based at the telescopes in an order dependant upon the Time Allocation Committees (TAC) ranking, provided that the conditions at the time were equal or better to the conditions requested for the observation. The majority of the observations proposed for the DODO survey were awarded the top ranking (Band 1) by the TAC. The observing conditions requested for the DODO survey observations were an Image Quality (IQ) in the 70th percentile ($< 0.60''$ at zenith) and a Cloud Cover (CC) in the 50th percentile (photometric). As the Water Vapour (WV) and the Sky Background (SB) parameters do not significantly affect the quality of J band data, the observations were acquired with any value of WV or SB.

Observations of the 26 equatorial and northern hemisphere white dwarfs (Table 2.2) were acquired in the J band primarily using Gemini North (GN) and the Near InfraRed Imager (*NIRI*) between 2003 and 2005, while a small number of observations of equatorial targets were acquired in 2002, using Gemini South (GS) and the FLoridA Multi-object Imaging Near-IR Grism Observational Spectrometer (*FLAMINGOS*). GN is an 8.1 meter altitude-azimuth telescope situated at an elevation of 13,824 feet on Mauna Kea in Hawai'i. *NIRI* consists of a 1024×1024 pixel Indium Antimonide (InSb) ALADDIN-II array. When combined with the f/6 camera, *NIRI* supplies a pixel scale of $0.117'' \text{ pixel}^{-1}$ and a wide field of view of $120'' \times 120''$. GS is an 8.1 meter altitude-azimuth telescope situated at an elevation of 8,895 feet on Cerro Pachón in Chile. *FLAMINGOS* consists

of a 2048×2048 pixel Mercury Cadmium Telluride (HgCdTe) HAWAII-II array. When combined with the f/16 camera, *FLAMINGOS* supplies a pixel scale of $0.078'' \text{ pixel}^{-1}$ and a wide field of view of $160'' \times 160''$.

The *FLAMINGOS* data contributes to only 3 first epoch observations, while the remainder of the data were obtained using *NIRI*. The science data were acquired using a dither pattern, which involved systematically offsetting the telescope, to allow the effective removal of the sky background³. A standard 9 point dither pattern was used during the acquisition of the *FLAMINGOS* data, while a more random 54 point dither pattern was used during the acquisition of the *NIRI* data. The total exposure time given in Table 2.2 was achieved by obtaining 60 second and 90 second individual exposures per dither position for *NIRI* and *FLAMINGOS*, respectively. Dome flats were acquired for the calibration of the *NIRI* science data; “Lamps on” dome flats were acquired by imaging a uniformly illuminated screen within the dome, while “Lamps off” dome flats were acquired using the same method, except with no illumination of the screen. High and low twilight flats were acquired for the calibration of the *FLAMINGOS* data. Short dark frames were also acquired to help with the identification of bad pixels.

³The details of the sky background removal, along with the rest of the data reduction procedure, will be discussed in Chapter 3.

Table 2.2: Details of the observations of the 26 white dwarfs

White Dwarf Number	Date Observed	Epoch	ET [min]	FWHM ["]	IQ [%-ile]	CC [%-ile]	WV [%-ile]	SB [%-ile]	TW	Notes
0046 + 051	2004-12-25	1st	54	0.39	70	50	Any	Any	GN+N	1
	2005-08-25	2nd	75	0.69	70	50	20	80	GN+N	1, 2
0115 + 159	2003-08-17	1st	20	0.65	70	50	Any	Any	GN+N	
	2004-08-25	2nd	55	0.73	70	50	Any	Any	GN+N	
0148 + 467	2003-08-09	1st	13	0.57	70	50	Any	80	GN+N	1, 3
	2003-08-10		41		70	50	Any	80	GN+N	1, 3
	2005-08-28	2nd	75	0.48	20	50	20	80	GN+N	1
0208 + 396	2004-08-25	1st	55	0.57	70	50	Any	Any	GN+N	1
	2005-08-29	2nd	75	0.66	70	50	80	80	GN+N	1
0341 + 182	2004-12-21	1st	55	0.62	70	50	80	80	GN+N	
	2005-09-04	2nd	74	0.58	70	50	50	50	GN+N	
0346 - 011	2003-11-02	1st	54	0.68	70	50	Any	Any	GN+N	
	2005-09-26	2nd	74	0.74	70	50	80	80	GN+N	
0435 - 088	2004-12-24	1st	39	0.55	70	70	Any	Any	GN+N	
	2005-11-13	2nd	65	0.58	20	50	20	Any	GN+N	
	2005-11-24		10		20	50	Any	80	GN+N	
0438 + 108	2003-11-05	1st	54	0.44	20	50	Any	80	GN+N	1
	2005-11-23	2nd	75	0.45	70	50	Any	80	GN+N	1
0644 + 375	2003-11-03	1st	52	0.59	70	50	Any	80	GN+N	2
	2004-11-02	2nd	54	0.65	70	50	Any	Any	GN+N	

Table 2.2: Details of the observations of the 26 white dwarfs

White Dwarf Number	Date Observed	Epoch	ET [min]	FWHM ["]	IQ [%-ile]	CC [%-ile]	WV [%-ile]	SB [%-ile]	TW	Notes
0738 – 172	2004–12–24	1st	53	0.56	70	70	Any	Any	GN+N	1
	2005–11–13	2nd	32	0.71	70	50	20	50	GN+N	1
	2005–11–15		43		70	50	Any	Any	GN+N	1
0912 + 536	2003–03–22	1st	54	0.63	70	50	Any	80	GN+N	1, 2
	2004–02–09	2nd	37	0.64	70	70	Any	Any	GN+N	1
	2005–01–28	3rd	27	0.56	70	50	80	80	GN+N	1
1055 – 072	2004–12–24	1st	49	0.58	70	70	Any	Any	GN+N	
	2005–11–16	2nd	63	0.77	Any	Any	Any	Any	GN+N	
1121 + 216	2003–03–24	1st	54	0.63	70	50	80	80	GN+N	2
	2004–02–04	2nd	28	0.77	50	50	50	50	GN+N	3
	2004–02–10		24		70	50	Any	Any	GN+N	3
	2005–01–20	3rd	19	0.48	70	50	Any	Any	GN+N	2
1134 + 300	2003–03–22	1st	40	0.73	70	50	Any	80	GN+N	2
	2005–02–21	2nd	52	0.66	70	50	50	Any	GN+N	
1344 + 106	2003–03–22	1st	54	0.62	70	50	Any	80	GN+N	2
	2004–02–03	2nd	54	0.68	50	50	50	50	GN+N	3
1609 + 135	2003–06–10	1st	53	0.44	20	50	Any	80	GN+N	2
	2004–02–11	2nd	51	0.53	70	50	50	80	GN+N	3
1626 + 368	2003–06–10	1st	46	0.43	20	50	Any	80	GN+N	1, 2
	2004–04–01	2nd	47	0.50	70	50	20	80	GN+N	1

Table 2.2: Details of the observations of the 26 white dwarfs

White Dwarf Number	Date Observed	Epoch	ET [min]	FWHM ["]	IQ [%-ile]	CC [%-ile]	WV [%-ile]	SB [%-ile]	TW	Notes
1633 + 433	2003-06-09	1st	53	0.61	70	50	Any	80	GN+N	1, 2
	2004-04-01	2nd	54	0.52	70	50	20	80	GN+N	1, 4
1647 + 591	2003-05-17	1st	54	0.58	70	50	Any	80	GN+N	1
	2004-02-12	2nd	40	0.57	70	50	Any	80	GN+N	1
	2005-02-20	3rd	54	0.81	70	50	50	50	GN+N	1
1900 + 705	2003-05-17	1st	20	0.58	70	50	Any	80	GN+N	3
	2003-05-20		34		70	50	Any	80	GN+N	3
	2004-04-06	2nd	16	0.54	70	50	Any	80	GN+N	
	2004-04-07		38		20	50	20	80	GN+N	
1953 - 011	2002-06-23	1st	39	0.53	50	50	50	50	GS+F	
	2002-07-07		21		50	20	Any	Any	GS+F	
	2002-07-09		67.5		20	50	Any	50	GS+F	
	2003-08-10	2nd	51	0.52	70	50	Any	80	GN+N	1, 3
2007 - 219	2002-06-21	1st	73.5	0.47	50	50	50	50	GS+F	1
	2002-06-22		63		50	50	50	50	GS+F	1
	2003-08-15	2nd	53	0.53	20	50	Any	Any	GN+N	1
2047 + 372	2002-06-16	1st	51	0.53	50	50	Any	80	GN+N	1
	2003-08-10	2nd	54	0.51	70	50	Any	80	GN+N	1, 3
	2004-06-06	3rd	54	0.64	70	50	Any	80	GN+N	1
2140 + 207	2003-08-11	1st	52	0.53	70	50	Any	Any	GN+N	3
	2004-06-07	2nd	47	0.80	70	50	Any	80	GN+N	

Table 2.2: Details of the observations of the 26 white dwarfs

White Dwarf Number	Date Observed	Epoch	ET [min]	FWHM ["]	IQ [%-ile]	CC [%-ile]	WV [%-ile]	SB [%-ile]	TW	Notes
2246 + 223	2003-08-09	1st	57	0.43	70	50	Any	80	GN+N	3
	2004-06-07	2nd	53	0.70	70	50	Any	80	GN+N	
2326 + 049	2002-06-23		39		50	50	50	50	GS+F	3
	2002-07-07	1st	55.5	0.58	50	20	Any	Any	GS+F	
	2002-07-08		54		50	50	Any	50	GS+F	
	2003-08-09	2nd	54	0.49	70	50	Any	80	GN+N	

Columns: ET is the total exposure time, measured in minutes; FWHM is the full-width at half-maximum, calculated as the average FWHM of stars in the field using SExtractor, measured in arc seconds; IQ is the image quality percentile; CC is the cloud cover percentile; WV is the water vapour percentile; SB is the sky background percentile; TW is the telescope and instrument the data were taken with; GN+N indicates Gemini North and *NIRI* were used; GS+F indicates Gemini South and *FLAMINGOS* were used; Notes (information about the specifics of these notes can be found in Chapter 3): (1) Persistence present, (2) Moderate 60Hz signal, (3) Severe 60Hz signal, (4) Streak across the image due to a bright source just outside the field of view.

Chapter 3

Data Reduction and Analysis

3.1 Data Reduction

All the data acquired for the DODO survey were reduced using the Image Reduction and Analysis Facility (IRAF¹; Tody, 1986) and the GEMINI package, versions 2.12.2a and 1.8, respectively. Raw *NIRI* images are in the form of multi-extension fits (MEF) files with most of the header information in the Primary Header Unit (PHU), “[0]” extension and the raw image data in the second, “[1]” extension. Raw *FLAMINGOS* images are in the form of single extension fits files. The NPREPARE and FPREPARE tasks in the GEMINI package were applied to all raw data acquired with *NIRI* and *FLAMINGOS*, respectively. These tasks add certain essential keywords to the header of each data file, allowing the subsequent data reduction tasks to be applied. In addition, the FPREPARE task converted

¹IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

all the *FLAMINGOS* images into MEF files. This made it possible for both the *NIRI* and the *FLAMINGOS* data to be reduced in a homogeneous manner, using the *NIRI* tasks in the GEMINI package.

3.1.1 Dark Subtraction

Thermal excitation processes in the semiconductor materials of the ALADDIN-II and HAWAII-II arrays can generate electron-hole pairs in the same way as real photons. The extra signal detected due to this effect is known as the dark current and is exponentially dependant on the array temperature and linearly dependant on the wavelength response of the array. The dark current of the *NIRI* and the *FLAMINGOS* arrays are 0.25 and $6.3 \text{ e}^- \text{ s}^{-1} \text{ pixel}^{-1}$, respectively. Additional photons are detected from warmer objects surrounding the array, which creates a signal called the dark background. The dark background of the *NIRI* array is $0.5 \text{ e}^- \text{ s}^{-1} \text{ pixel}^{-1}$. The dark background for the *FLAMINGOS* array was not recorded, since it was a visiting instrument on Gemini South. For the *NIRI* and the *FLAMINGOS* data, a sky frame was used instead of a dark frame to remove these dark signals. This sky frame was created by average combining the individual science images after masking all the objects in each image. Using a sky frame gives a much better dark measurement as it was acquired concurrently with the science data. The sky frame also removes any constant additions to the science data due to the sky or bias levels. The NISKY task in the GEMINI package was used to create the sky frame, while the NIREDUCE task in the GEMINI package was used to subtract the sky frame from the

individual science images.

3.1.2 Flat Division

Effects due to illumination variations in the optical system, anomalies in the optical path and sensitivity variations between pixels in the array can be removed by dividing the individual science images by an image known as a flat field. The “lamps off” and low twilight flat field images (Section 2.4.2), equivalent to a dark measurement, were average combined to create a single “dark” flat field image for the *NIRI* and the *FLAMINGOS* data, respectively. This combined image was subtracted from each of the individual “lamps on” and high twilight flat field images (Section 2.4.2), which were then average combined. Finally, the combined flat field images were divided by their mean pixel value to create a normalised flat field image for both the *NIRI* and the *FLAMINGOS* data. These normalised flat field images have an average pixel value equal to 1 ADU. The NIFLAT task in the GEMINI package was used to create this normalised flat field image. The NIREDUCE task in the GEMINI package was then used to divide the individual science images by the normalised flat field image. The NIFLAT task also created a bad pixel mask by identifying bad pixels, which have extremely high or low values, from the individual flat field images and the short dark images (Section 2.4.2).

3.1.3 Sky Background Subtraction

The near infrared (NIR; $1 - 2.5\mu\text{m}$) sky background is dominated by emission from hydroxyl radicals (OH^-) in the upper atmosphere of the Earth. Disturbances in the upper atmosphere cause local variations in the temperature and density of the atmospheric gases, which in turn affects the intensity of the OH^- emission. The intensity of this emission varies on short timescales between 5 – 15 minutes (Ramsay, Mountain and Geballe, 1992). By acquiring images using a dither pattern (Section 2.4.2), background photons enter every pixel in the array. This enables an accurate sky background image to be created, which is used to remove this short term variation. Firstly, the shift of each individual image, with respect to the first image, was calculated. An initial stacked image was created by average combining the individual science images after aligning the images to the first image. An object mask, created using this initial stacked image, was used to mask out all the objects in each individual science image. A sky background image was then created for each individual science image by median combining the previous and subsequent 5 and 4 science images for the *NIRI* and the *FLAMINGOS* data, respectively. This sky background image was subtracted from its respective science image. The XMOSAIC task in the XDIMSUM package was used to create and subtract each sky background image from each individual science image. This task also corrected the bad pixels and cosmic rays events in each sky subtracted image before creating an average combined final stacked image.

3.1.4 Persistence

The well depth of the pixels in the ALADDIN-II and HAWAII-II arrays determines how many photons each pixel can receive. When there is a bright star in the field, the number of photons entering each pixel can exceed the well depth, causing the pixel to become saturated. Residual charge will be left in these saturated pixels after the array has been reset. As the science data are acquired using a dither pattern, an affect known as electronic persistence becomes apparent. Persistence manifests itself as a faint object in an image where a bright star was in the previous image. This faint object can remain for several frames depending on how bright the star is. For the ALADDIN-II *NIRI* array, a highly saturated star will leave a faint object at the level of $\sim 1\%$ in the subsequent exposure and $\sim 0.2\%$ in the next one (Hodapp et al., 2003). Persistence affects $\sim 43\%$ of the *NIRI* and the *FLAMINGOS* data acquired for the DODO survey (Table 2.2). To remove these persistence effects from the sky background image and from the final stacked image, a mask consisting of the cores of the bright stars in the field from the previous three science images was created for each individual science image and added to the object mask used in the XMOSAIC task.

3.1.5 Interference

Intermittent pattern noise substantially degraded a large amount of the *NIRI* data throughout 2003, although some data from 2004 and 2005 were also affected. A diagonal her-

ringbone pattern due to 60 Hz interference (Hodapp et al., 2003) is seen in $\sim 39\%$ of the *NIRI* data (Table 2.2). This pattern is reflected symmetrically in each quadrant (Figure 3.1), due to the fact that the readout of the quadrants, from each corner of the array to the centre of the array along each row, is symmetrical. This pattern is not present in the lab and has been eliminated at times on the telescope, indicating that it arises from the telescope environment and not from the *NIRI* electronics. This noise was not corrected for in the *NIRI* data.

Another form of intermittent pattern noise found in the *NIRI* data is due to 50 Hz interference, which creates a horizontal pattern (Figure 3.2). A task called NIRICLEAN² was applied to all data to remove constant variations in the rows and columns of each image. This was achieved by collapsing each quadrant along rows and columns and then subtracting the median value from each row and each column separately for each of the quadrants.

The NIRICLEAN task also removed another form of intermittent pattern noise found in the *NIRI* data, which manifests itself as a combined quadrant pattern plus a vertical pattern (Figure 3.3). The quadrant pattern occurs due to mismatched bias levels between the quadrants and the vertical pattern has a periodicity of 8 pixels, which corresponds to the 32 amplifier channels reading out each quadrant.

²NIRICLEAN was created by Fraser Clarke.

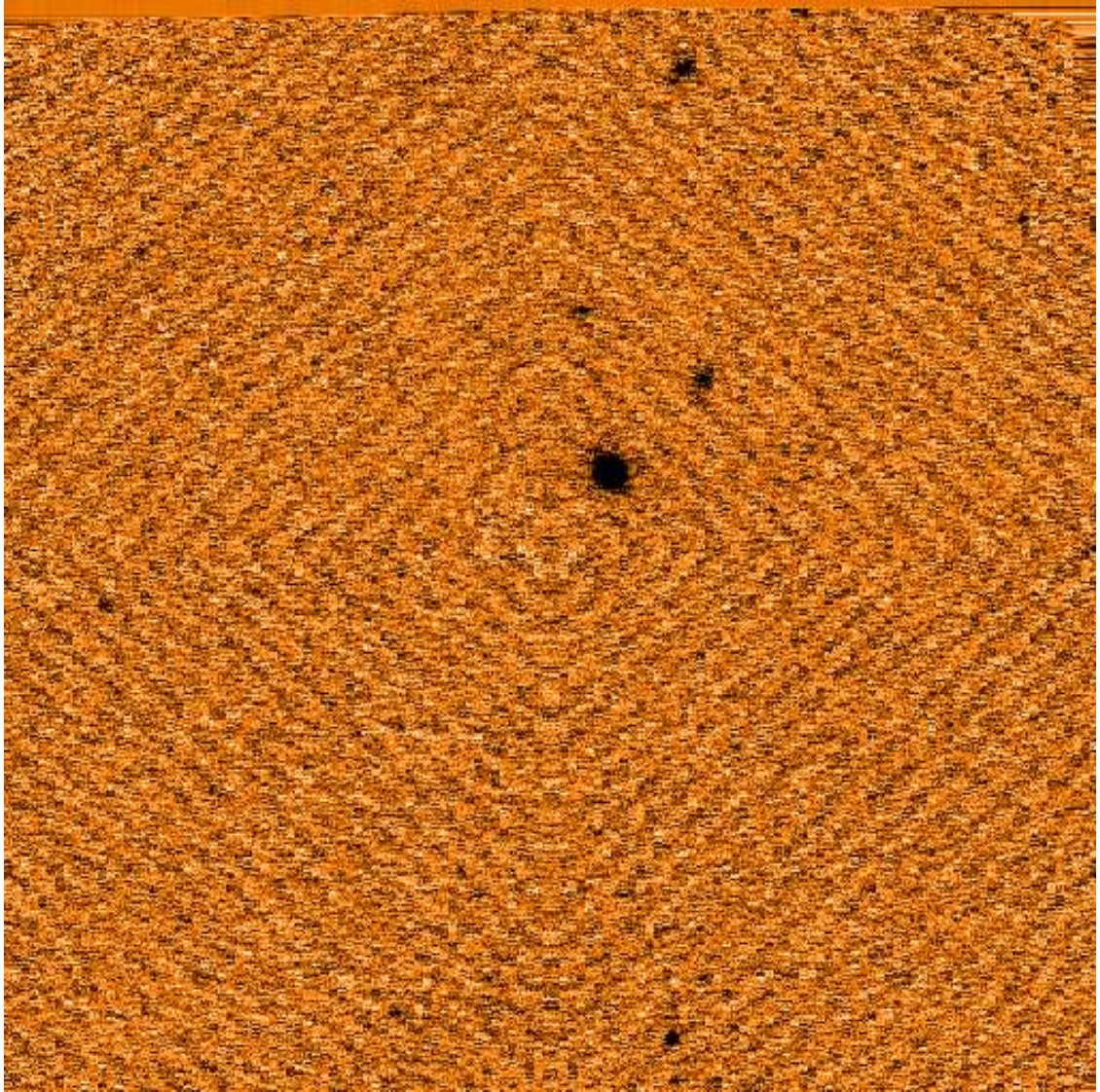


FIGURE 3.1. A 60 second sky frame subtracted, flat divided and sky background subtracted *NIRI* image of the white dwarf WD 1134 + 300, acquired in 2003. The diagonal herringbone pattern due to 60 Hz interference can be clearly seen.

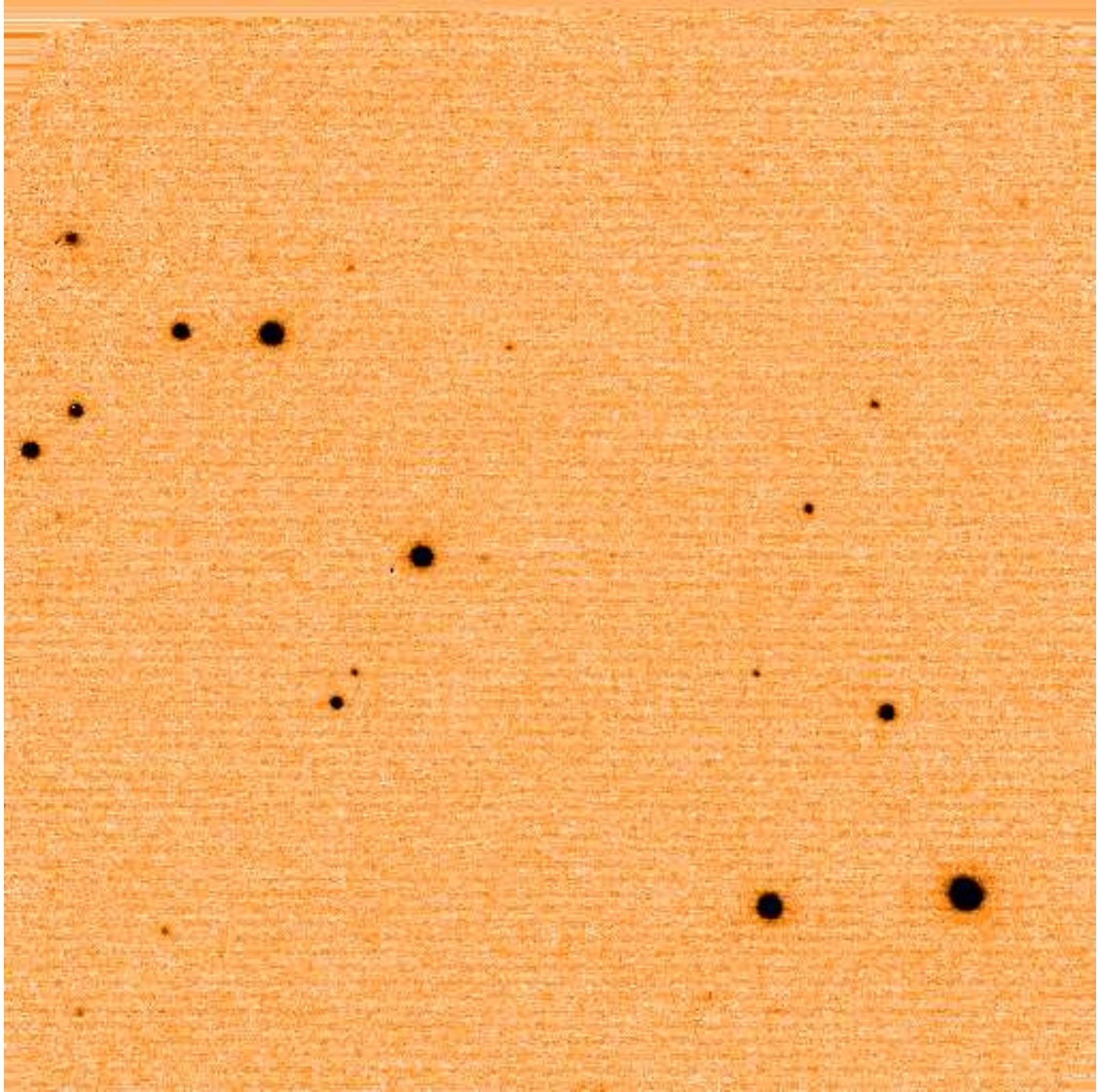


FIGURE 3.2. A 60 second sky frame subtracted, flat divided and sky background subtracted *NIRC2* image of the white dwarf WD 2246 + 223, observed in 2003. The horizontal pattern due to 50 Hz interference can be clearly seen.

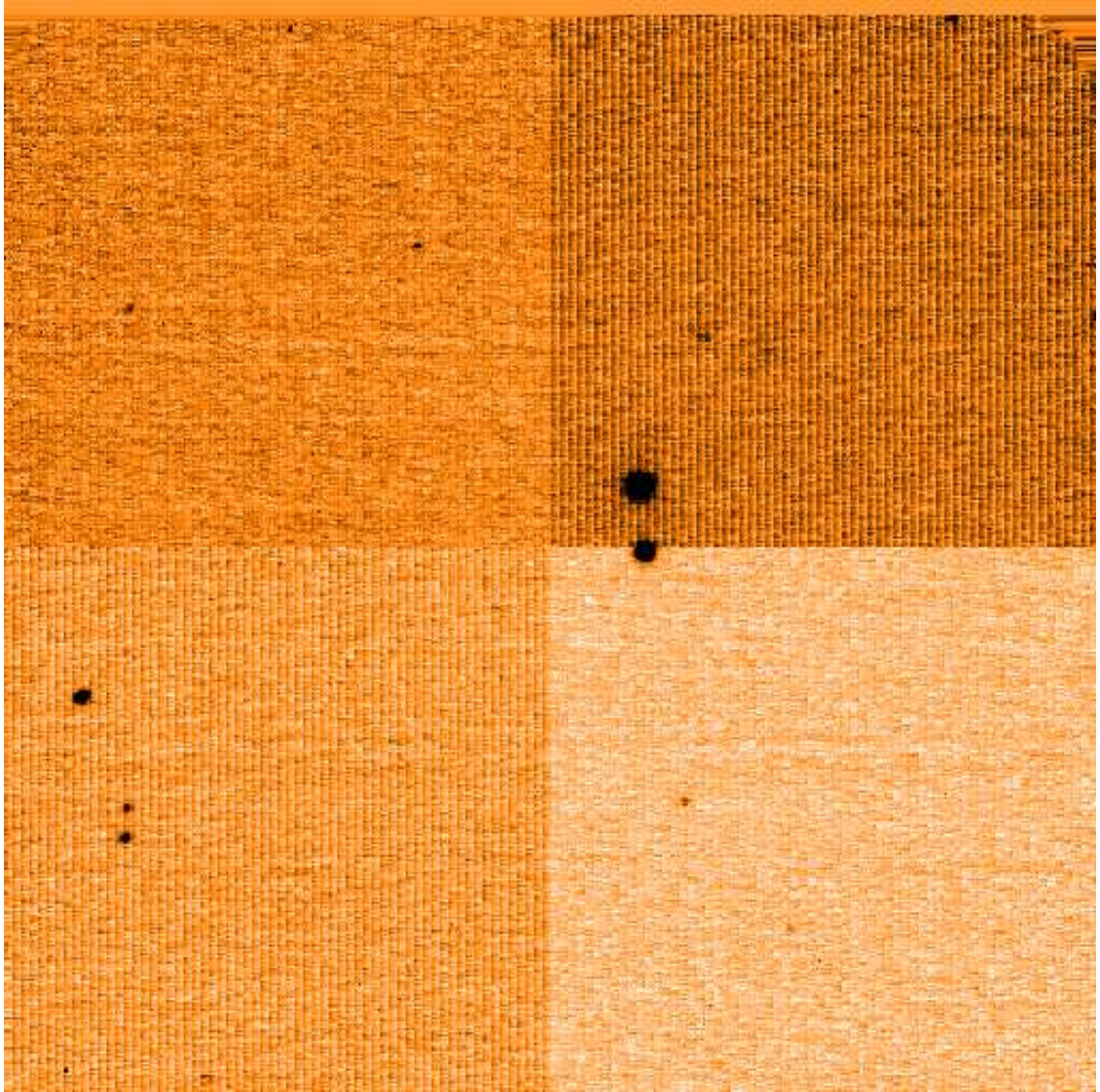


FIGURE 3.3. A 60 second sky frame subtracted, flat divided and sky background subtracted *NIRI* image of the white dwarf WD 1344 + 106, observed in 2004. The quadrant pattern along with the vertical pattern can be clearly seen.

3.2 Data Analysis

3.2.1 Astrometry

The cleaned final stacked images created using XMOSAIC were astrometrically calibrated to within $\sim 1 - 2''$ using Two Micron All Sky Survey (2MASS³; Skrutskie et al., 2006) objects in the field of each white dwarf. The 2MASS catalogue acquired observations of the entire sky in the NIR J ($1.35\mu\text{m}$), H ($1.65\mu\text{m}$) and K_s ($2.17\mu\text{m}$) bands between 1997 and 2001. The limiting magnitudes of 2MASS are $J = 15.8$, $H = 15.1$ and $K_s = 14.3$ mag, respectively, corresponding to a signal to noise ratio (SNR) equal to 10. The IRAF tasks CCFIND and CCMAP in the IMAGES package were used to calculate the transformation required to match the positions of the objects in each final stacked image with the positions of the objects in the 2MASS catalogue. Objects near the edge of each final stacked image were removed from the transformation calculations. The CCSETWCS task was then used to apply this transformation to each final stacked image.

3.2.2 Photometry

The astrometrically calibrated final stacked images were then photometrically calibrated using aperture photometry. The SExtractor program (Bertin and Arnouts, 1996) was

³This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

used to detect all objects in the final stacked images with a $\text{SNR} > 3$. As the individual science images were acquired using a dither pattern, only the central region of each final stacked image contained information from all of the individual science images. As a result, a “weight map”, created by the XMOSAIC task (Section 3.1.3), was used to give importance to the pixels where all of the individual science images contributed to each final stacked image. This led to a significant decrease in the detection of spurious sources around the edges of each final stacked image, where only a few of the individual science images contribute. The first pass of SExtractor used apertures with diameters ranging from 1 to 20 pixels to determine the aperture size that delivered the highest SNR. The SNR, equivalent to the flux divided by the error on the flux, was estimated using the values calculated by SExtractor. Internal flags are produced by the various detection and measurement processes within SExtractor (Table 3.1). Only objects with an internal flag equal to 0, indicating that no problems were found with the detection, were used in the determination of the optimum aperture size. In addition, the ellipticity of the objects, given as $1 - B/A$, where A and B are the semi-major and semi-minor axes of the object, respectively, was chosen to be < 0.2 . This excluded objects with high ellipticities, such as background galaxies, from the determination of the optimum aperture size. Also, only those objects within the central region of each final stacked image that had a full width at half maximum (FWHM) $< 1''$ were used. This further assisted in removing extended objects. Once the ideal aperture size had been determined, SExtractor was used to detect objects for a second time. These objects, which have an instrumental magnitude, calculated by SExtractor, of m_i , were then matched with objects in the 2MASS catalogue. The m_i of each object could then be associated with its apparent magnitude, m , using

Table 3.1. SExtractor internal flags

FLAG	Description
1	The object has neighbours, bright and close enough to significantly bias the MAG_AUTO photometry, or bad pixels (more than 10% of the integrated area affected)
2	The object was originally blended with another one
4	At least one pixel of the object is saturated (or very close to)
8	The object is truncated (too close to an image boundary)
16	Object's aperture data are incomplete or corrupted
32	Object's isophotal data are incomplete or corrupted
64	A memory overflow occurred during deblending
128	A memory overflow occurred during extraction

the linear formula

$$m = m_i + zp \quad (3.1)$$

The zeropoint, zp , is therefore equal to the y intercept of the line of best fit to the points in the plot of m_i against m . Only photometric 2MASS stars, with a J band photometric quality flag equal to “A”⁴, were used to determine the zp . In addition, objects near the edge of each final stacked image or that were saturated were excluded from this step. SExtractor was then run for the third and final time with the newly calculated zp , allowing the correct determination of the apparent magnitudes of all the objects in the field.

⁴A 2MASS photometric quality flag of “A” is given to objects with a SNR > 10 and a photometric uncertainty, $\sigma < 0.109$.

3.2.3 Completeness Limit Measurements

The completeness limit for each final stacked image was estimated by determining the magnitudes at which 90% and 50% of inserted artificial stars were recovered from each image. The STARLIST task was used to create a list of 200 randomly positioned artificial stars at a magnitude of $J = 19.0$ mag. The MKOBJECTS task was used to insert the artificial stars into each final stacked image. SExtractor was then used to detect all objects in each image, including the artificial stars. The calculated magnitudes of the artificial stars were checked to ensure they were equal to $J = 19.0$ mag. Using the same artificial star list, the MKOBJECTS and SExtractor steps were repeated for magnitudes between $19.1 \leq J \leq 24.0$ mag in 0.1 magnitude steps. The entire process was then repeated a further 50 times, equivalent to a total of 10,000 inserted artificial stars. Plots of the percentage of artificial stars recovered against the apparent J magnitudes of the artificial stars were created (Chapter 4). The number of artificial stars recovered was often much less than 100% at the brighter J magnitudes as some stars were lost either completely behind or within the point spread function (PSF) of other real objects or artificial stars. The motion of an object can be calculated only when the object is detected in both epochs. Assuming that the probability of detecting an object in the first epoch image, P_1 , is independent from the probability of detecting an object in the second epoch image, P_2 , the probability of detecting an object in both epochs is $P_1 \times P_2$. Therefore, by multiplying the individual completeness limits for each epoch, a combined completeness limit for both epoch images can be determined. This assumption is very likely to be valid for objects near the completeness limit. However, it is not valid for the bright objects not

detected due to the fact that they are within the PSF of other real objects or artificial stars.

3.2.4 Proper Motion Measurements

The motion of the objects in the field of each white dwarf between the first epoch and second (or third) epoch images was calculated. Since the white dwarf is rarely positioned on the same pixels in each epoch, distortion effects can be seen around the edges of the final stacked images. These effects are due to spherical aberrations of the mirrors of the Gemini telescopes. As a result, non-moving objects positioned near the edges of the final stacked images appear to have a large motion between the two epoch images. The GEOMAP and GEOXYTRAN tasks in the IMAGES package were used to correct for these distortion effects. Objects from the first epoch image were matched to the closest object present in the second (or third) epoch image only if

1. their magnitudes are within 1 mag,
2. the SExtractor internal flag ≤ 3 (Table 3.1),
3. the ellipticity of the object is < 0.5 .

This excluded objects with very high ellipticities, such as background galaxies, from the matching procedure. In some cases, the closest object was too far away to be a true match, so a clipping factor was introduced to remove these mismatches.

Chapter 4

Results

4.1 Overview

This chapter will present the results for each of the 26 equatorial and northern hemisphere white dwarfs in the DODO survey. The first figure for each white dwarf will show the completeness limit in terms of the percentage of artificial stars recovered against the apparent J magnitude of the artificial stars. The second figure for each white dwarf will show the motion of all objects between the first epoch and the second (or third) epoch images. Using the combined completeness limit for each white dwarf, an estimate of the minimum mass of a companion which could be detected in both epoch images is calculated. The range of projected physical separations at which a companion of this mass could be found around each white dwarf and the corresponding range of projected physical separations around each main sequence progenitor is determined.

4.2 WD 0046 + 051

Completeness limits for the images of WD0046+051

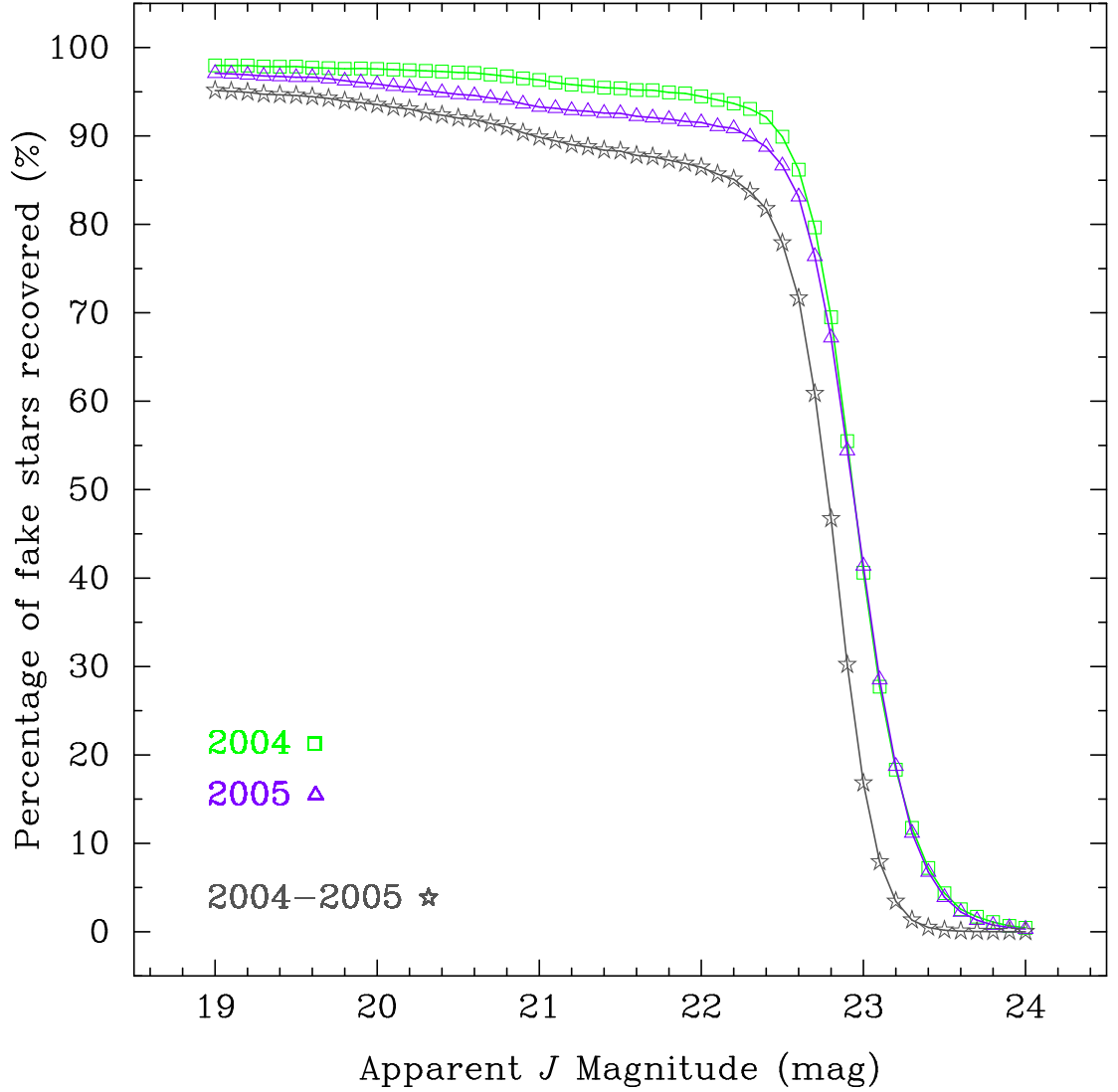


FIGURE 4.1. The percentage of artificial stars recovered by SExtractor from the 2004 first epoch image (green squares) and the 2005 second epoch image (purple triangles) acquired of the closest, single white dwarf to the Sun, WD 0046 + 051 (van Maanen’s star; vMA 2). The 90% and 50% completeness limits taken from the combined 2004–2005 curve (grey stars) are $J = 20.9$ mag and $J = 22.7$ mag, respectively.

Proper Motion Diagram for WD0046+051

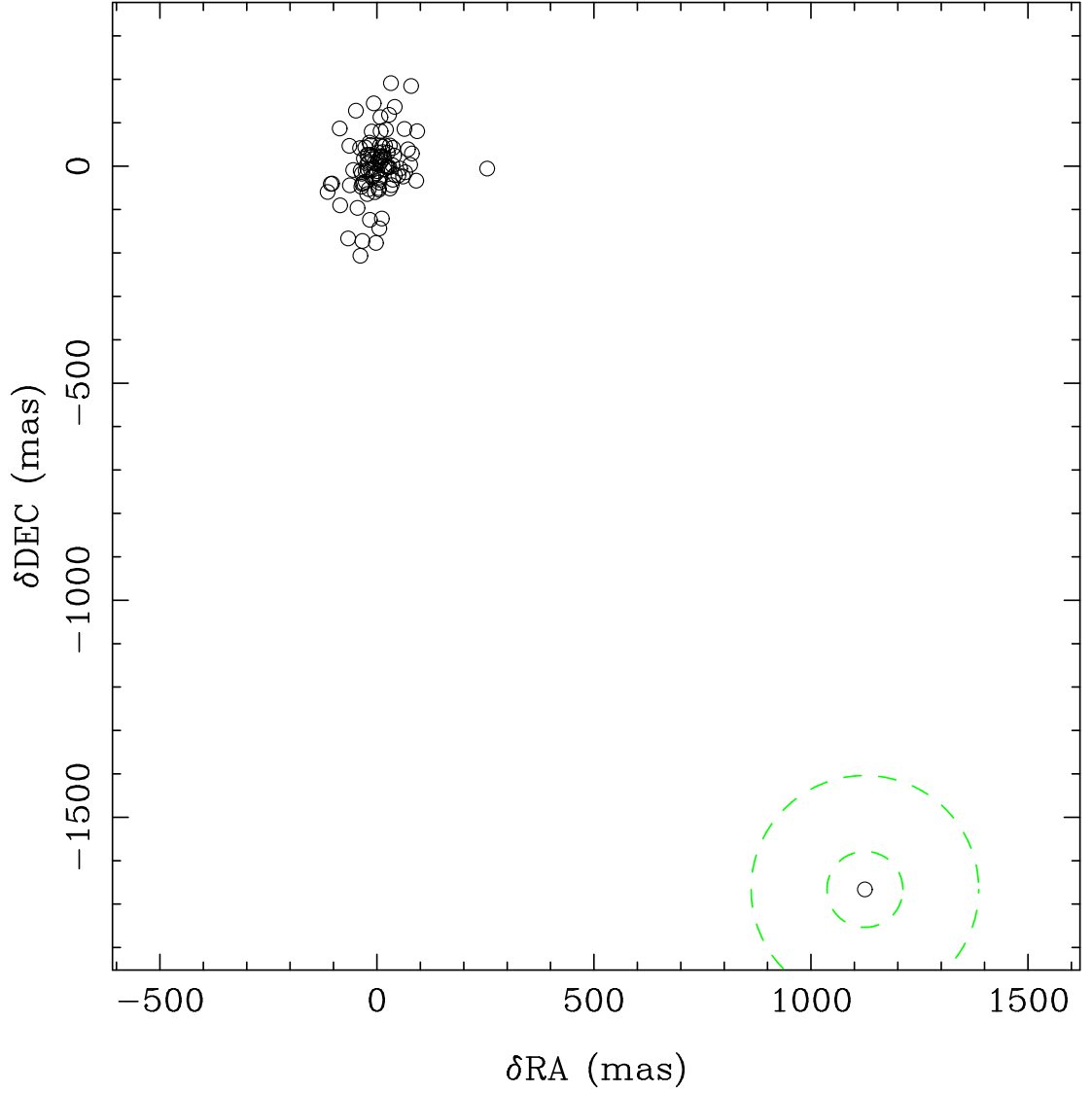


FIGURE 4.2. The motion of all objects between the 2004 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0046 + 051. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD0046 + 051.

4.3 WD 0115 + 159

Completeness limits for the images of WD0115+159

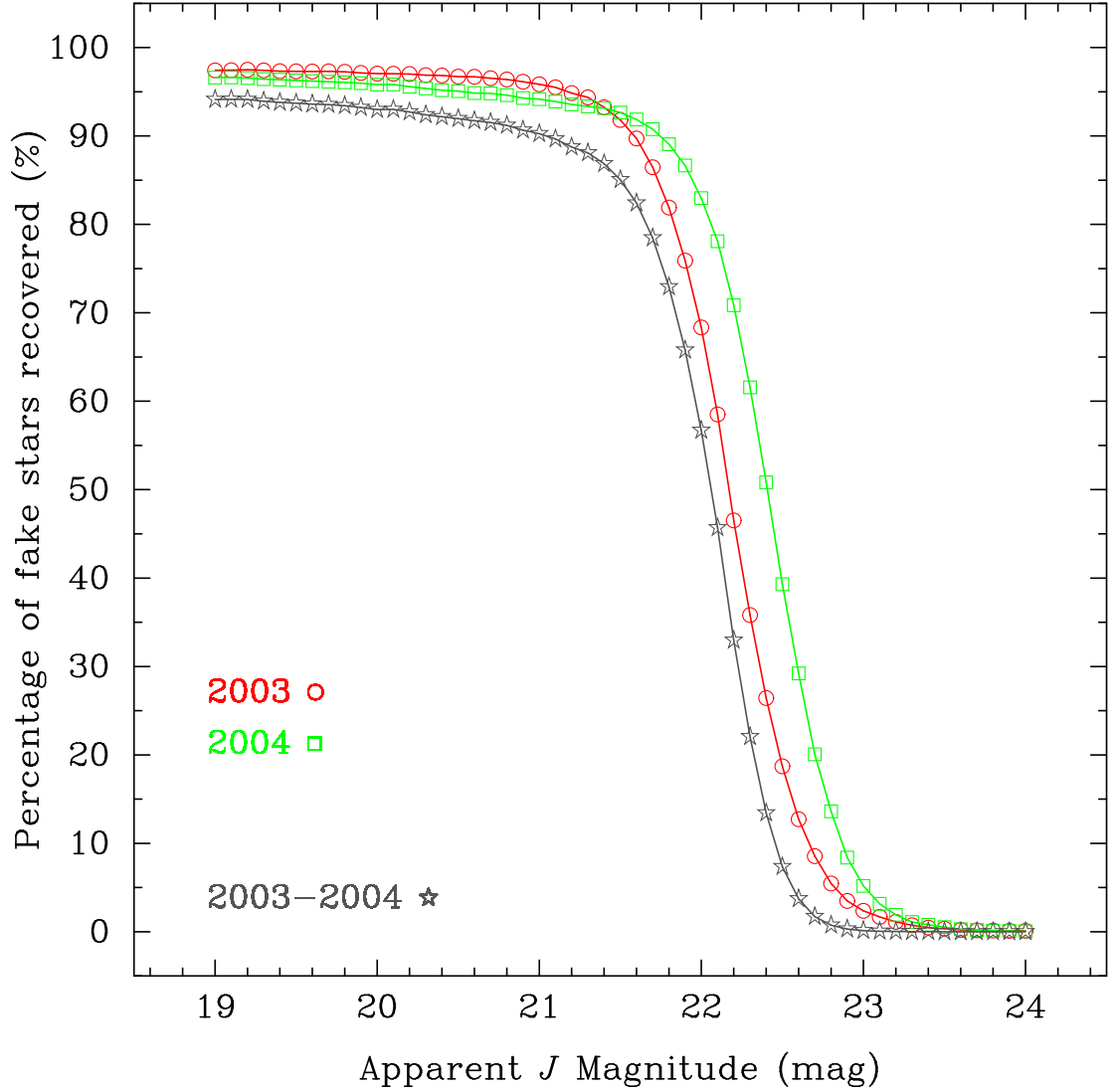


FIGURE 4.3. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 0115 + 159. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 21.0$ mag and $J = 22.0$ mag, respectively.

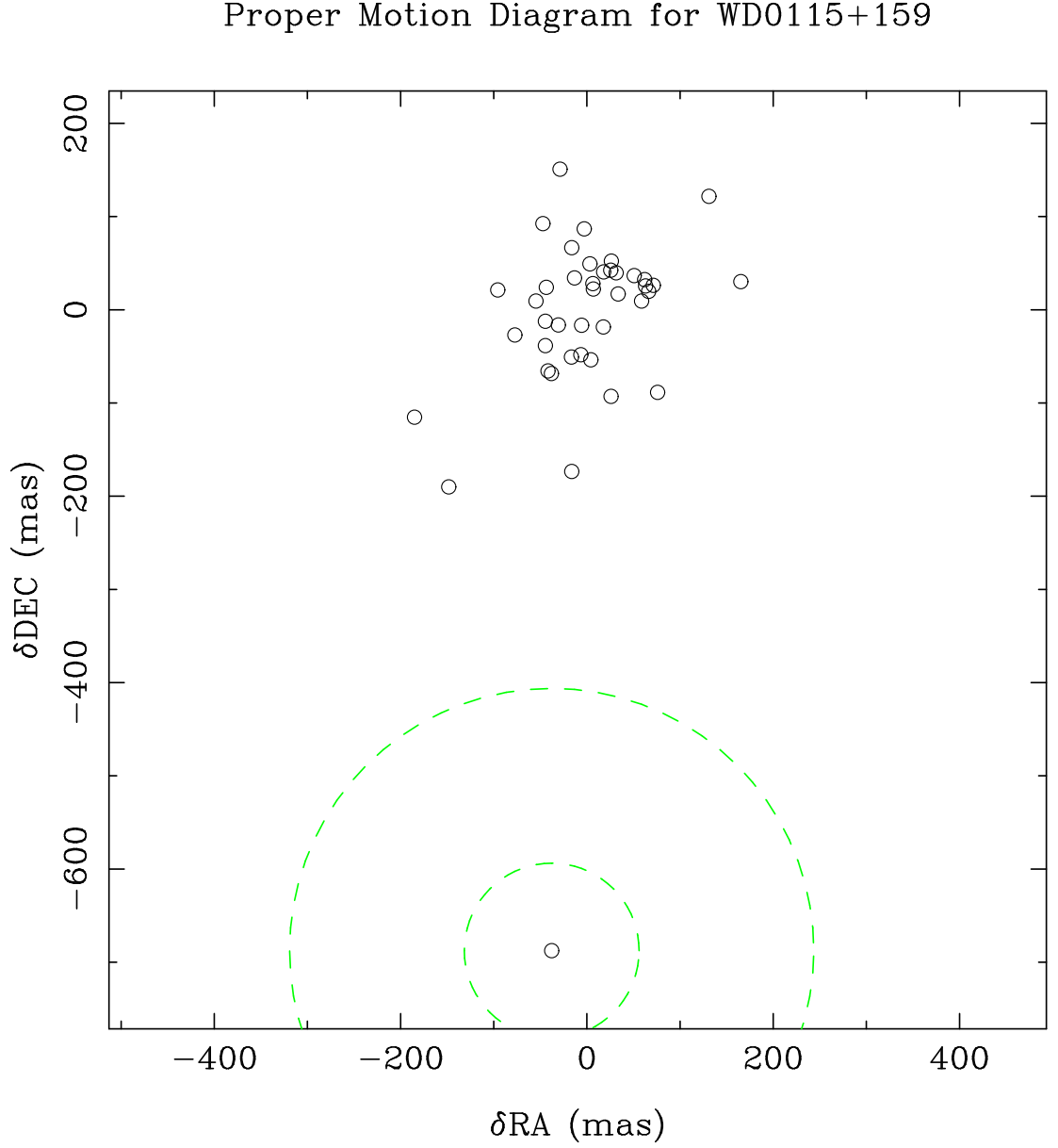


FIGURE 4.4. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 0115 + 159. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 0115 + 159.

4.4 WD 0148 + 467

Completeness limits for the images of WD0148+467

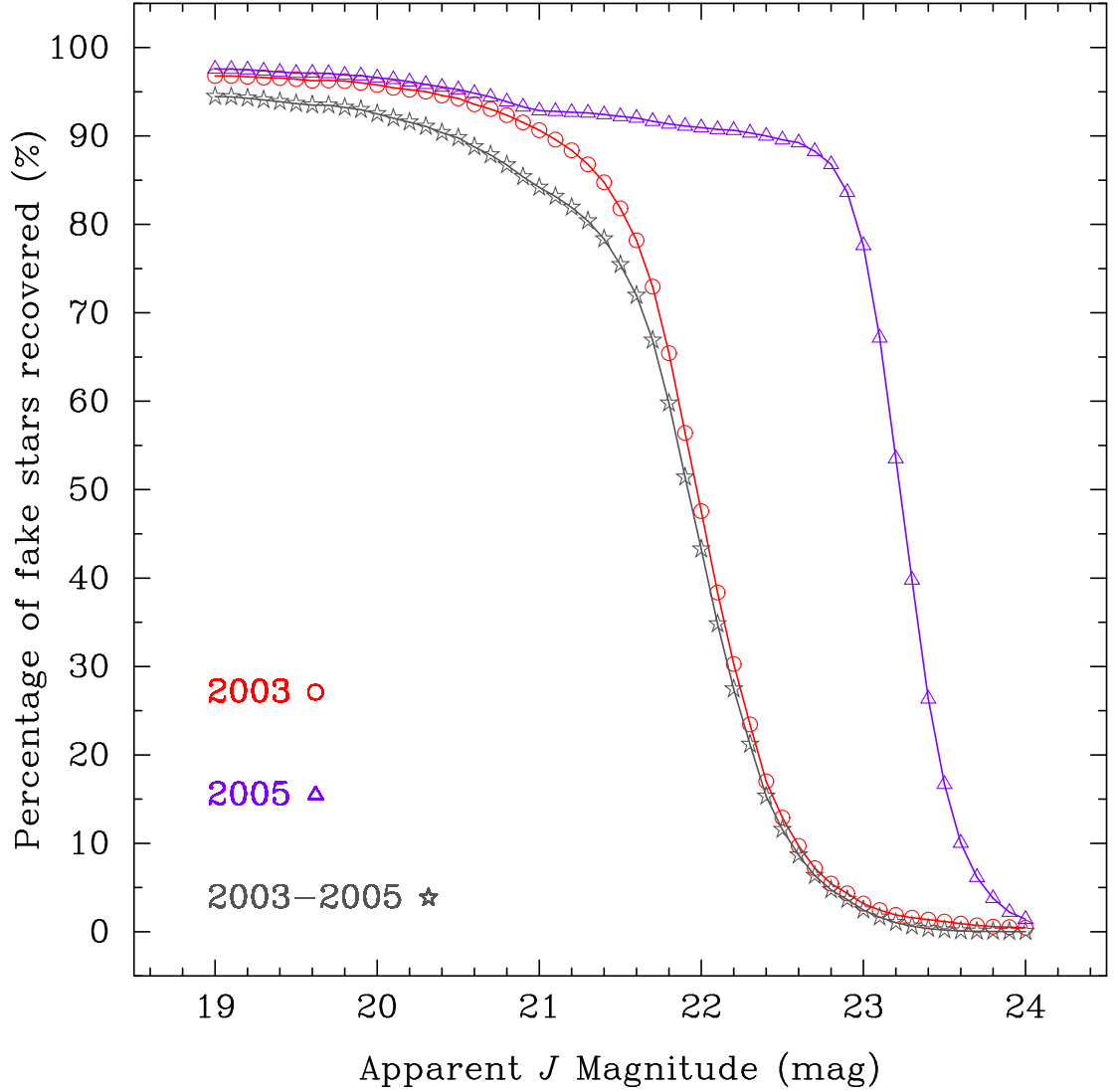


FIGURE 4.5. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 0148 + 467. The 90% and 50% completeness limits taken from the combined 2003–2005 curve (grey stars) are $J = 20.4$ mag and $J = 21.9$ mag, respectively.

Proper Motion Diagram for WD0148+467

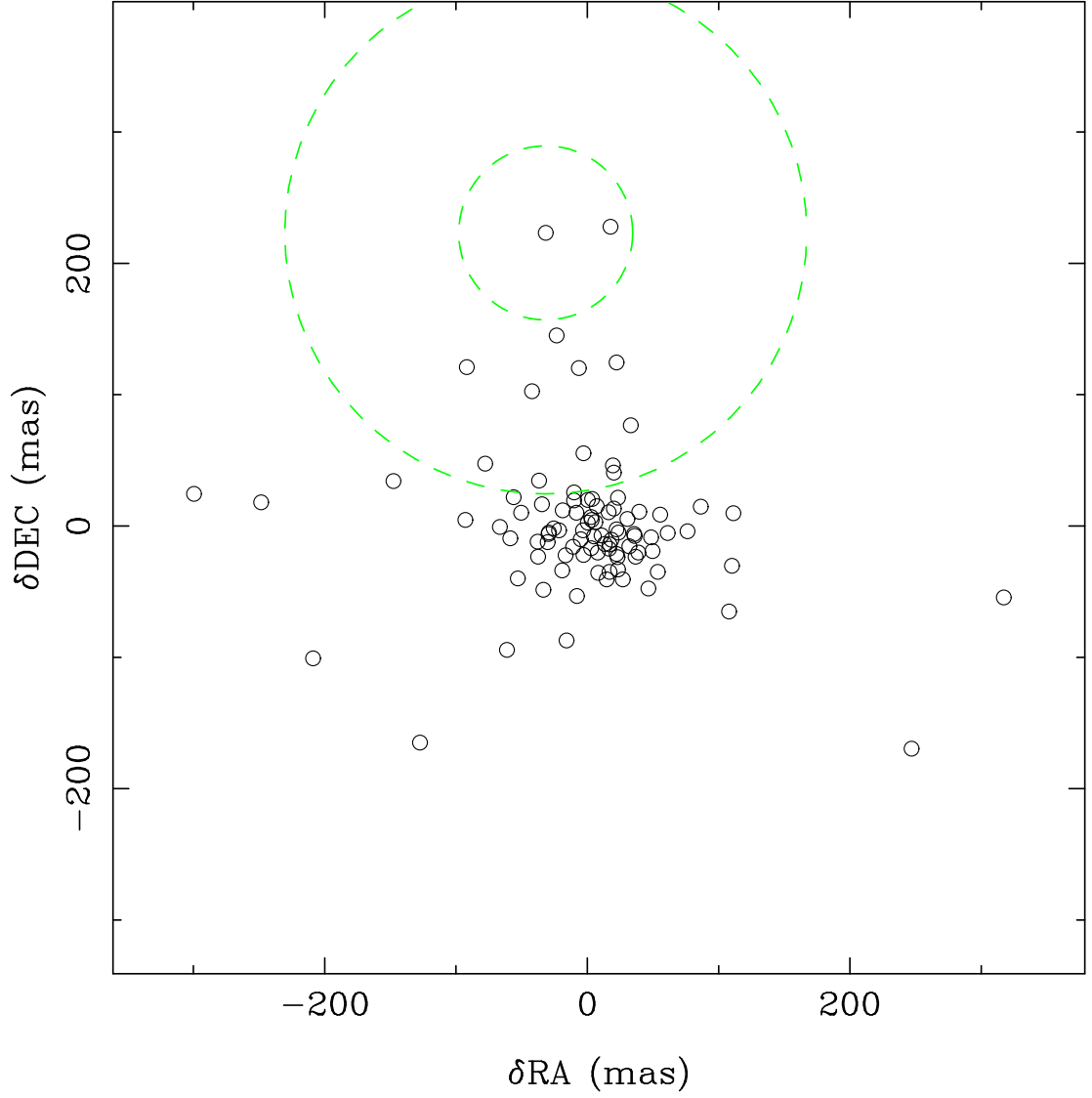


FIGURE 4.6. The motion of all objects between the 2003 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0148 + 467. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.5 WD 0208 + 396

Completeness limits for the images of WD0208+396

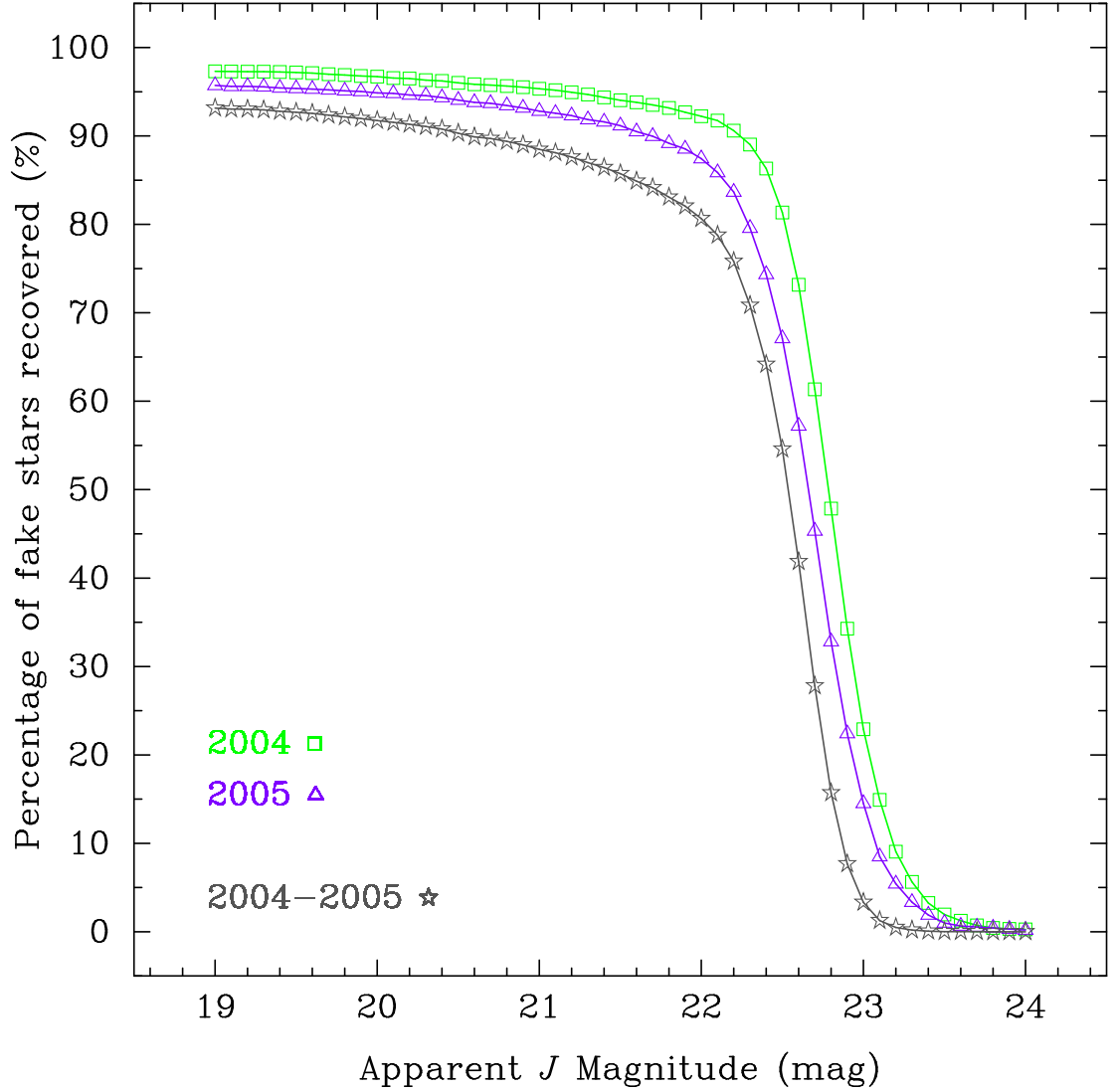


FIGURE 4.7. The percentage of artificial stars recovered by SExtractor from the 2004 first epoch image (green squares) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 0208 + 396. The 90% and 50% completeness limits taken from the combined 2004–2005 curve (grey stars) are $J = 20.5$ mag and $J = 22.5$ mag, respectively.

Proper Motion Diagram for WD0208+396

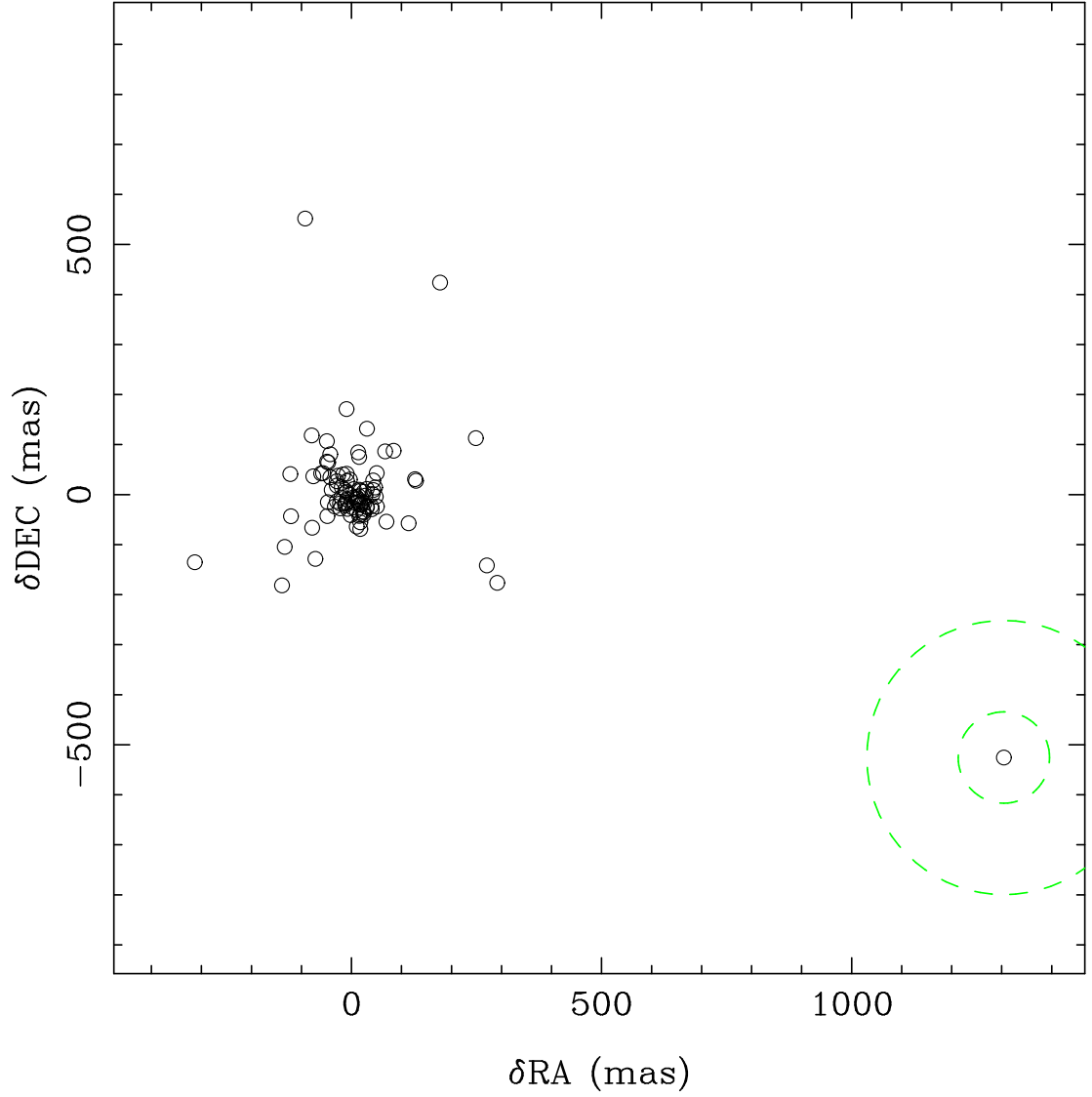


FIGURE 4.8. The motion of all objects between the 2004 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0208 + 396. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 0208 + 396.

4.6 WD 0341 + 182

Completeness limits for the images of WD0341+182

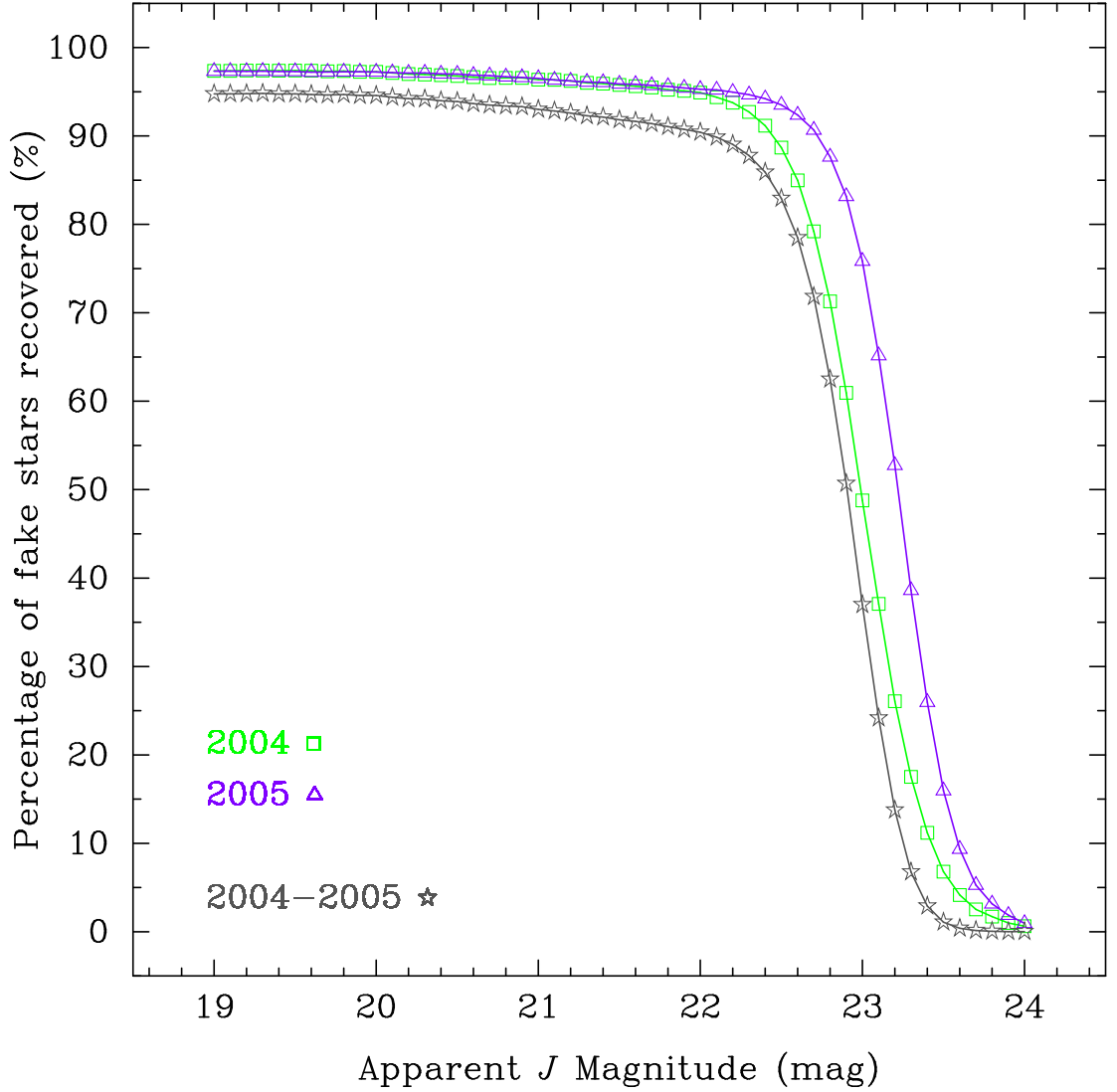


FIGURE 4.9. The percentage of artificial stars recovered by SExtractor from the 2004 first epoch image (green squares) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 0341 + 182. The 90% and 50% completeness limits taken from the combined 2004–2005 curve (grey stars) are $J = 22.0$ mag and $J = 22.9$ mag, respectively.

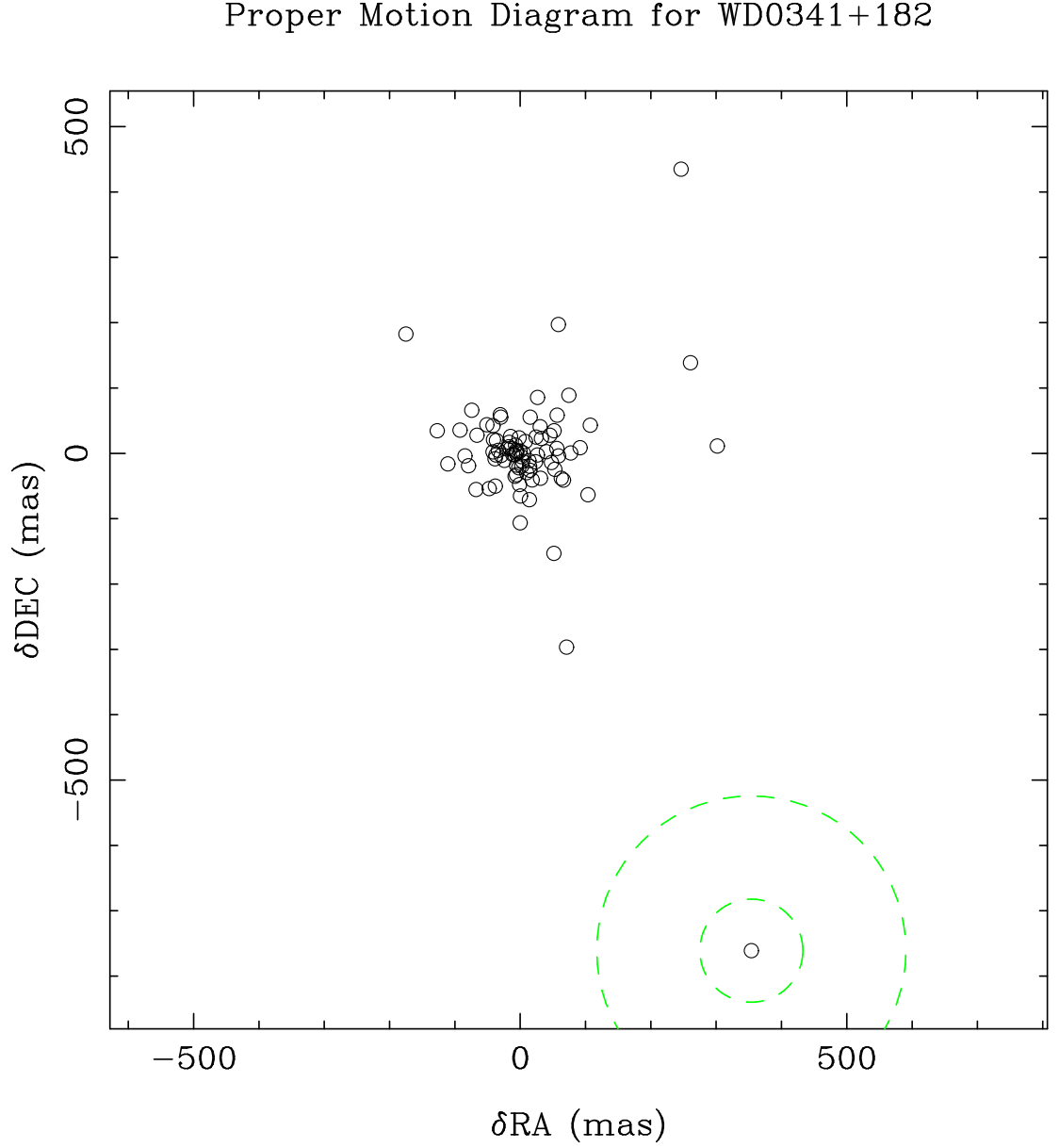


FIGURE 4.10. The motion of all objects between the 2004 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0341 + 182. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 0341 + 182.

4.7 WD 0346 – 011

Completeness limits for the images of WD0346–011

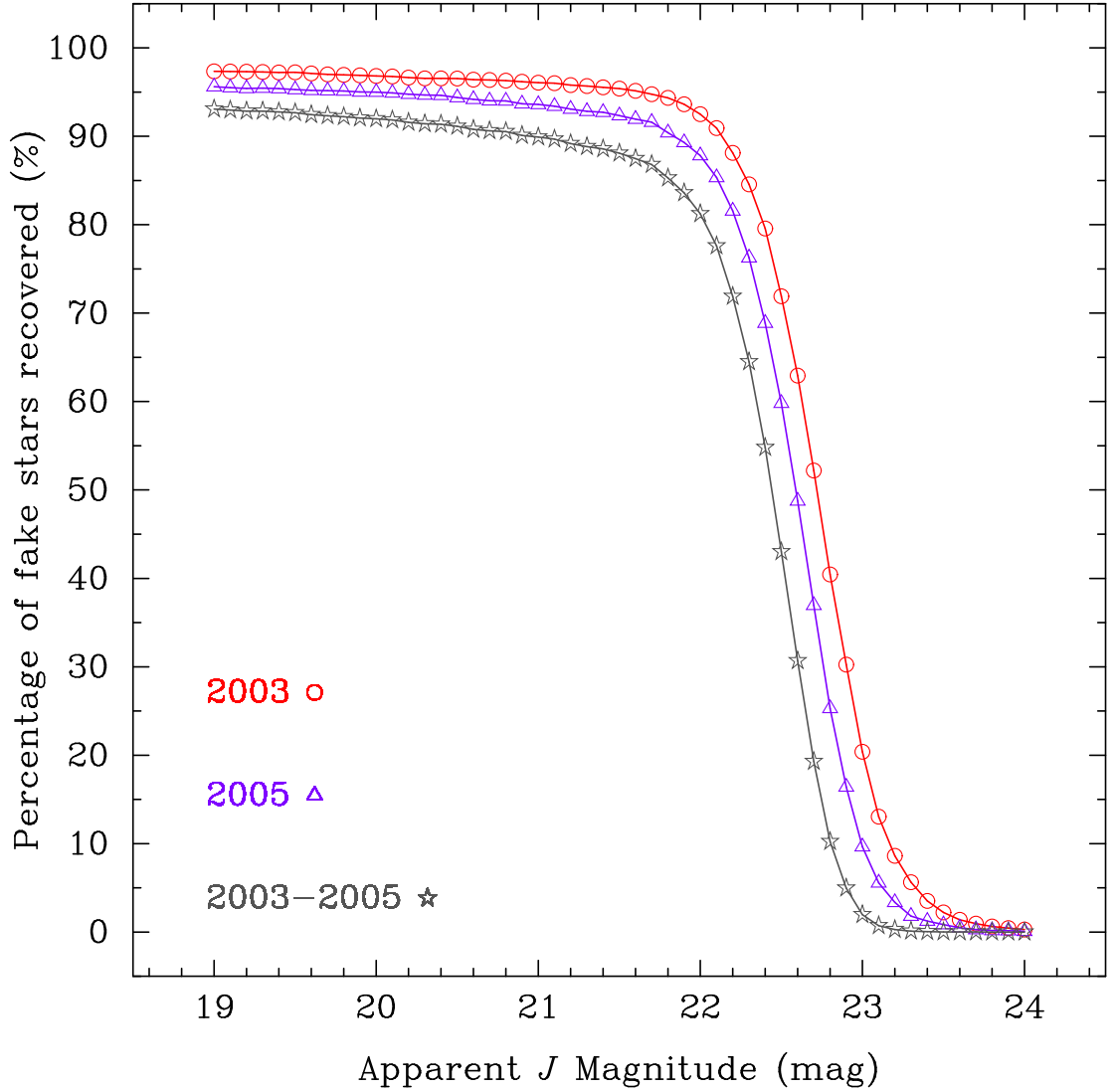


FIGURE 4.11. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2005 second epoch image (purple triangles) acquired of the youngest and most massive white dwarf observed for the DODO survey, WD 0346 – 011 (GD 50). The 90% and 50% completeness limits taken from the combined 2003–2005 curve (grey stars) are $J = 20.9$ mag and $J = 22.4$ mag, respectively.

Proper Motion Diagram for WD0346–011

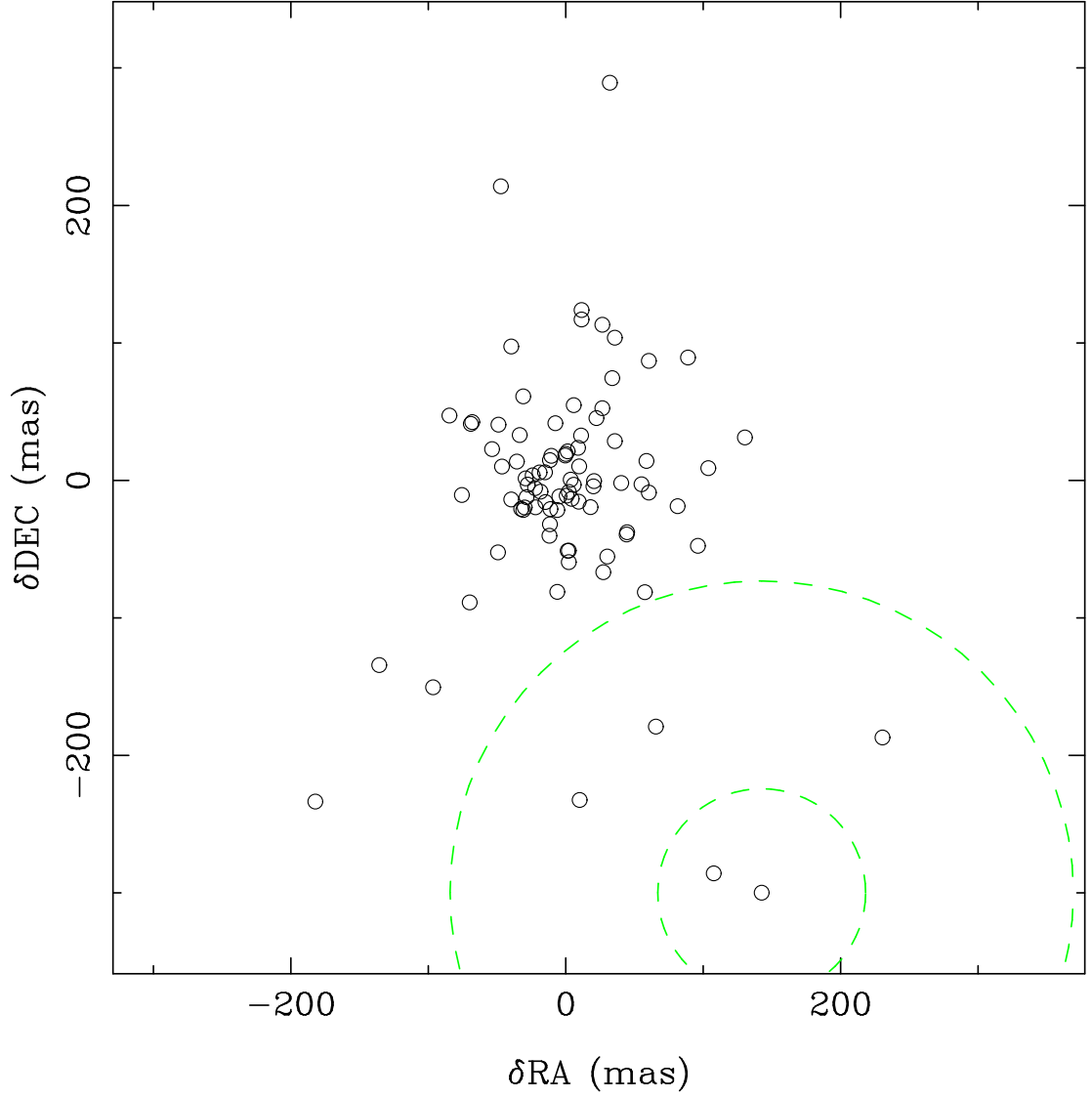


FIGURE 4.12. The motion of all objects between the 2003 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0346 – 011. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.8 WD 0435 – 088

Completeness limits for the images of WD0435–088

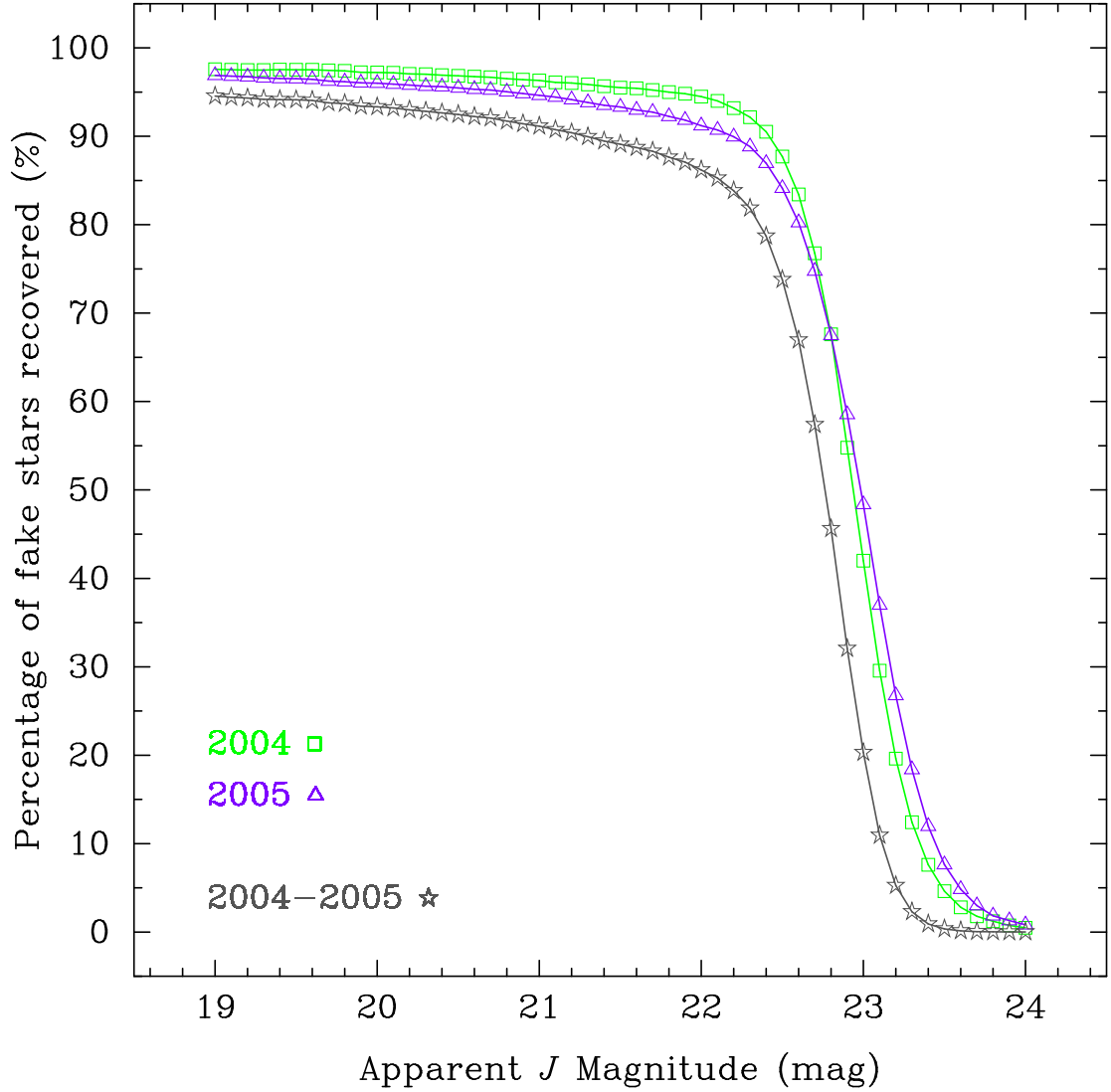


FIGURE 4.13. The percentage of artificial stars recovered by SExtractor from the 2004 first epoch image (green squares) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 0435 – 088. The 90% and 50% completeness limits taken from the combined 2004–2005 curve (grey stars) are $J = 21.2$ mag and $J = 22.7$ mag, respectively.

Proper Motion Diagram for WD0435–088

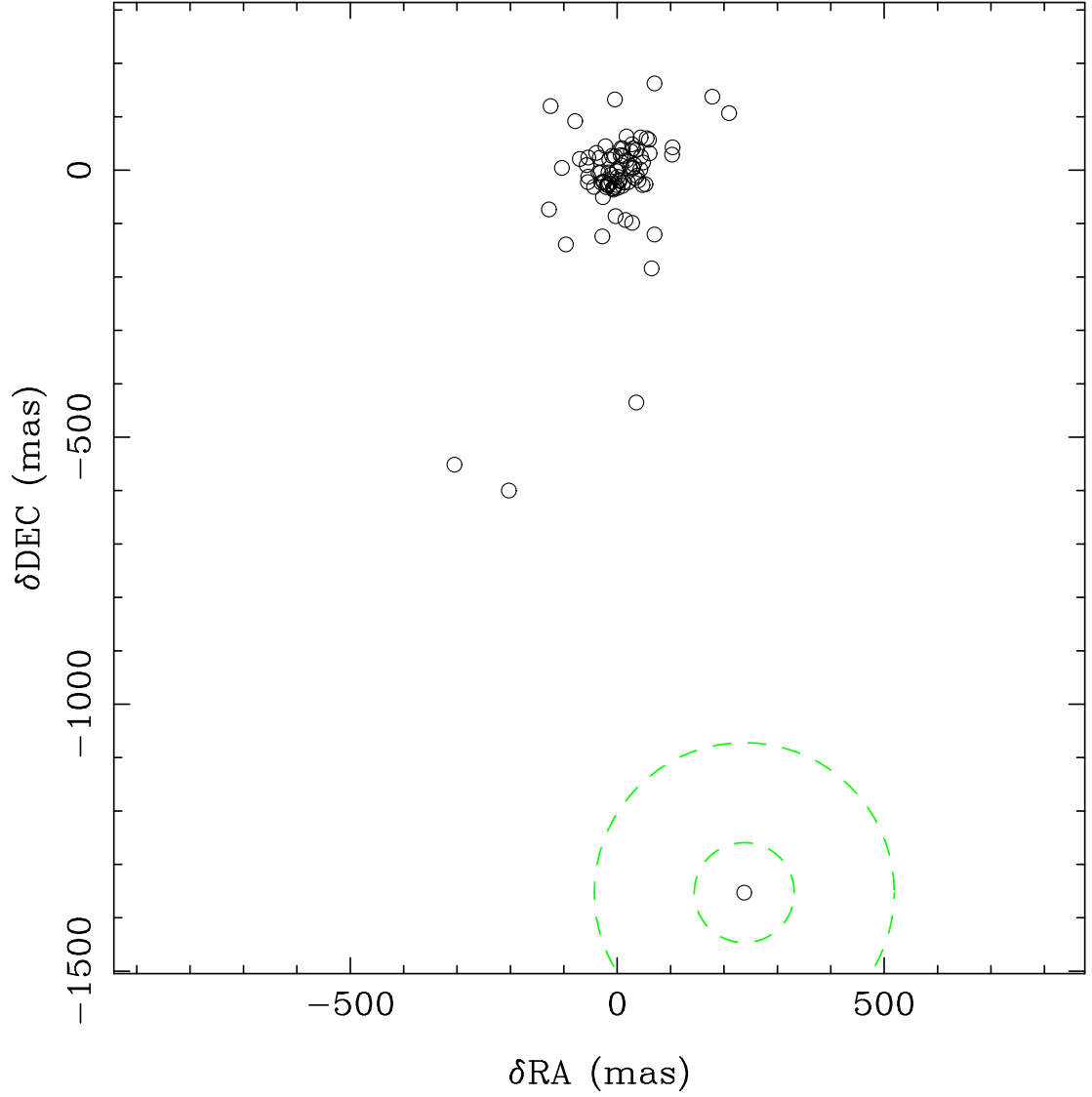


FIGURE 4.14. The motion of all objects between the 2004 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0435 – 088. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 0435 – 088.

4.9 WD 0438 + 108

Completeness limits for the images of WD0438+108

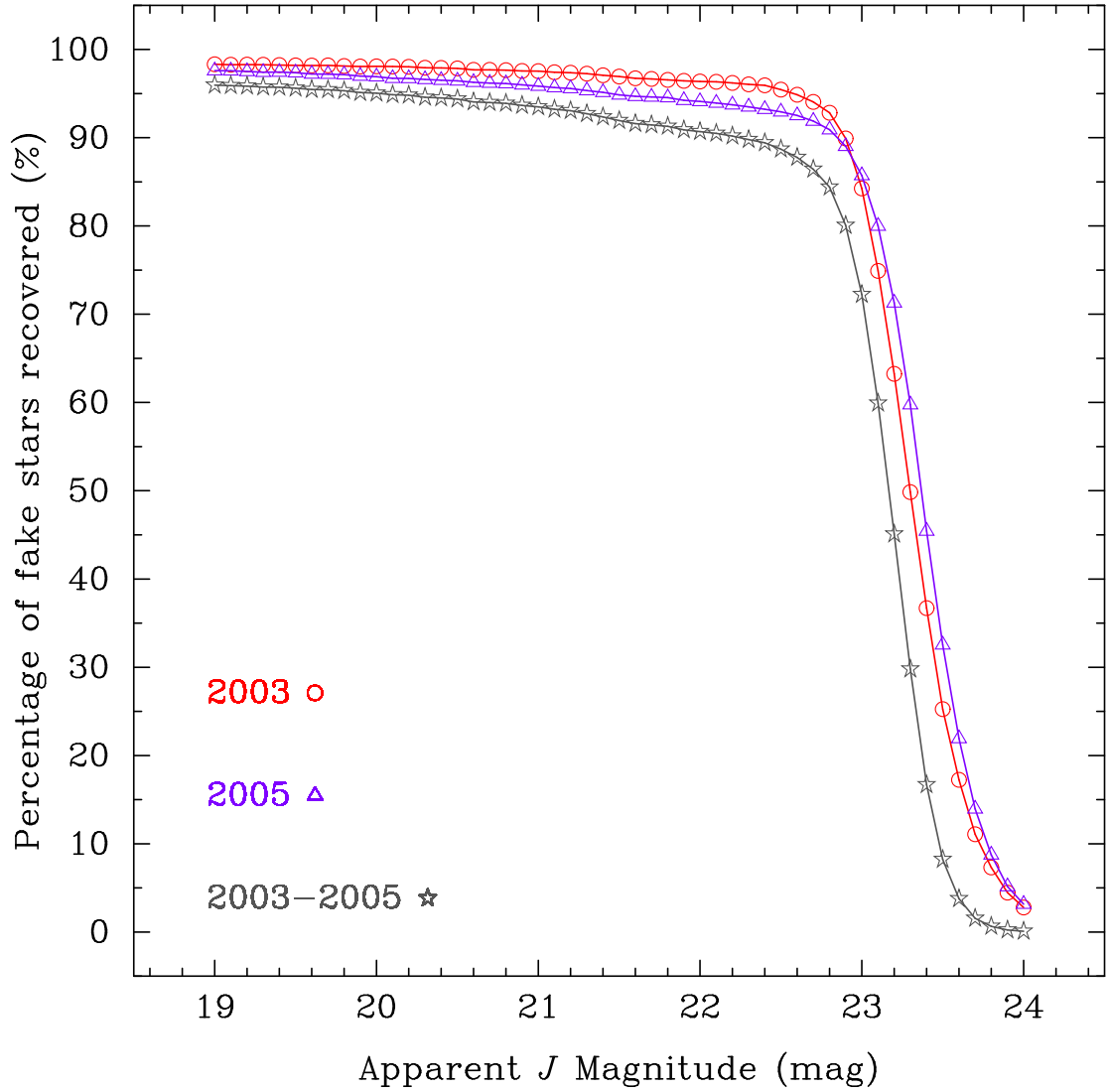


FIGURE 4.15. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 0438 + 108. The 90% and 50% completeness limits taken from the combined 2003-2005 curve (grey stars) are $J = 22.2$ mag and $J = 23.1$ mag, respectively.

Proper Motion Diagram for WD0438+108

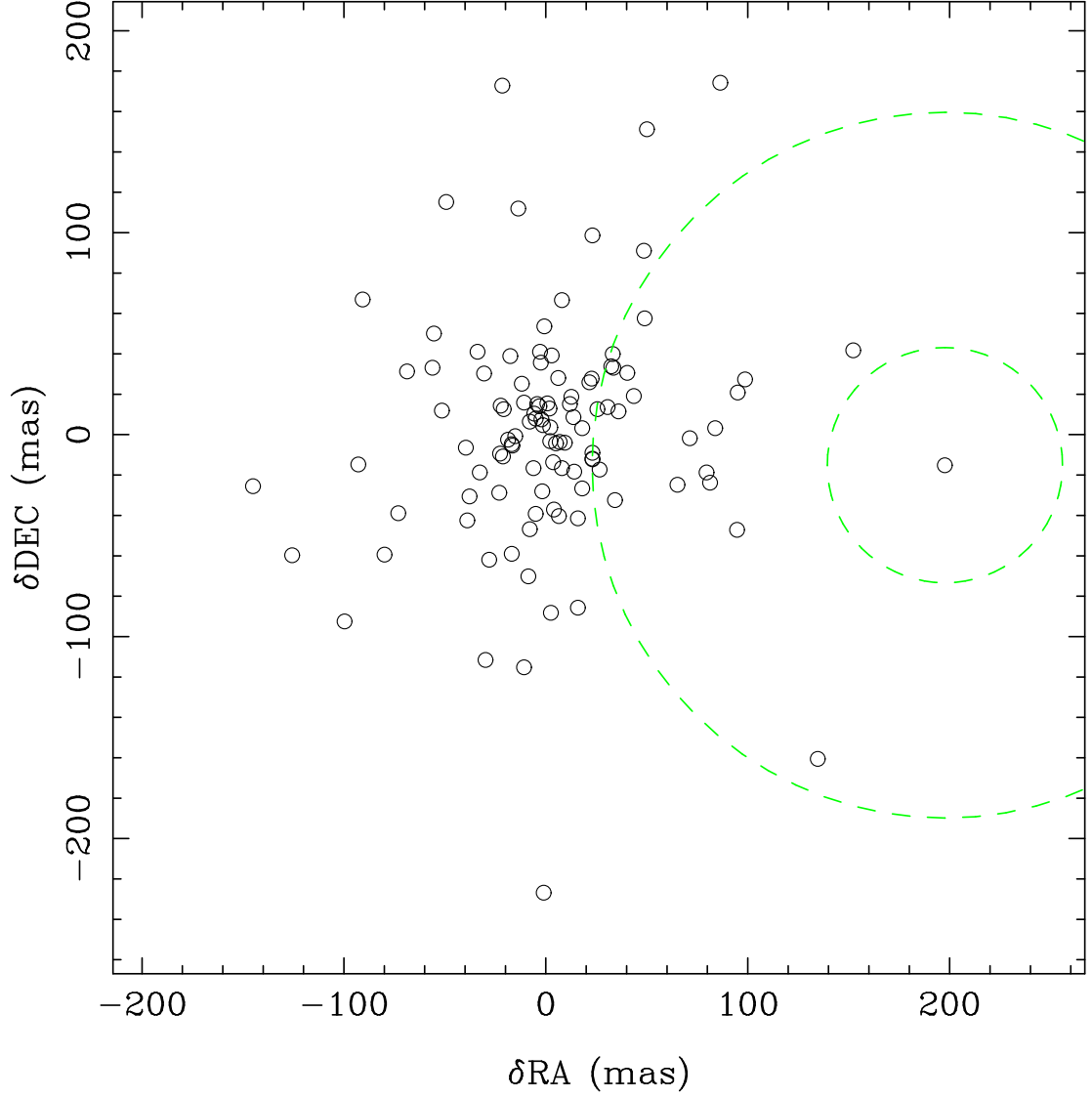


FIGURE 4.16. The motion of all objects between the 2003 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0438 + 108. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.10 WD 0644 + 375

Completeness limits for the images of WD0644+375

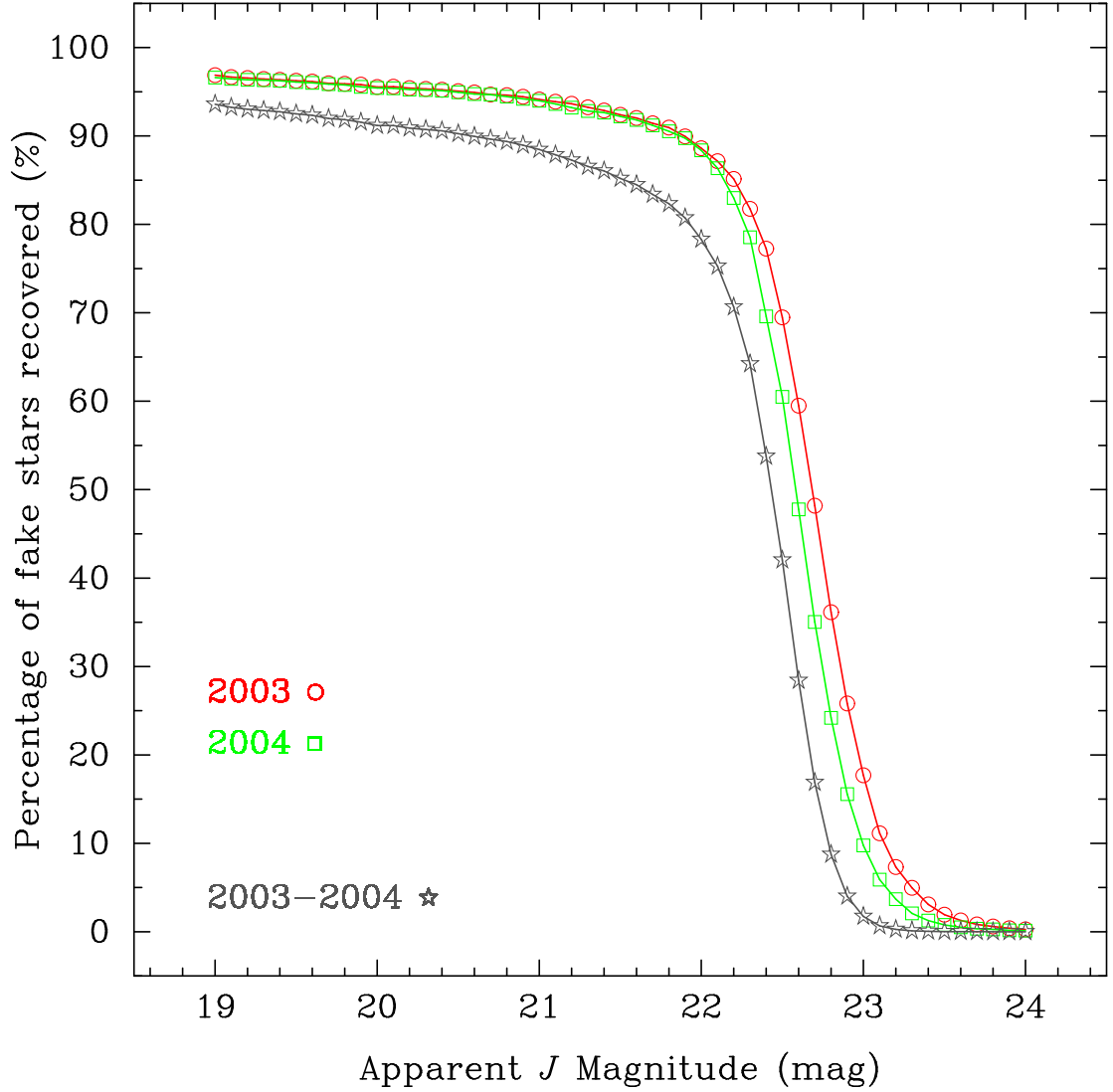


FIGURE 4.17. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 0644 + 375. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 20.5$ mag and $J = 22.4$ mag, respectively.

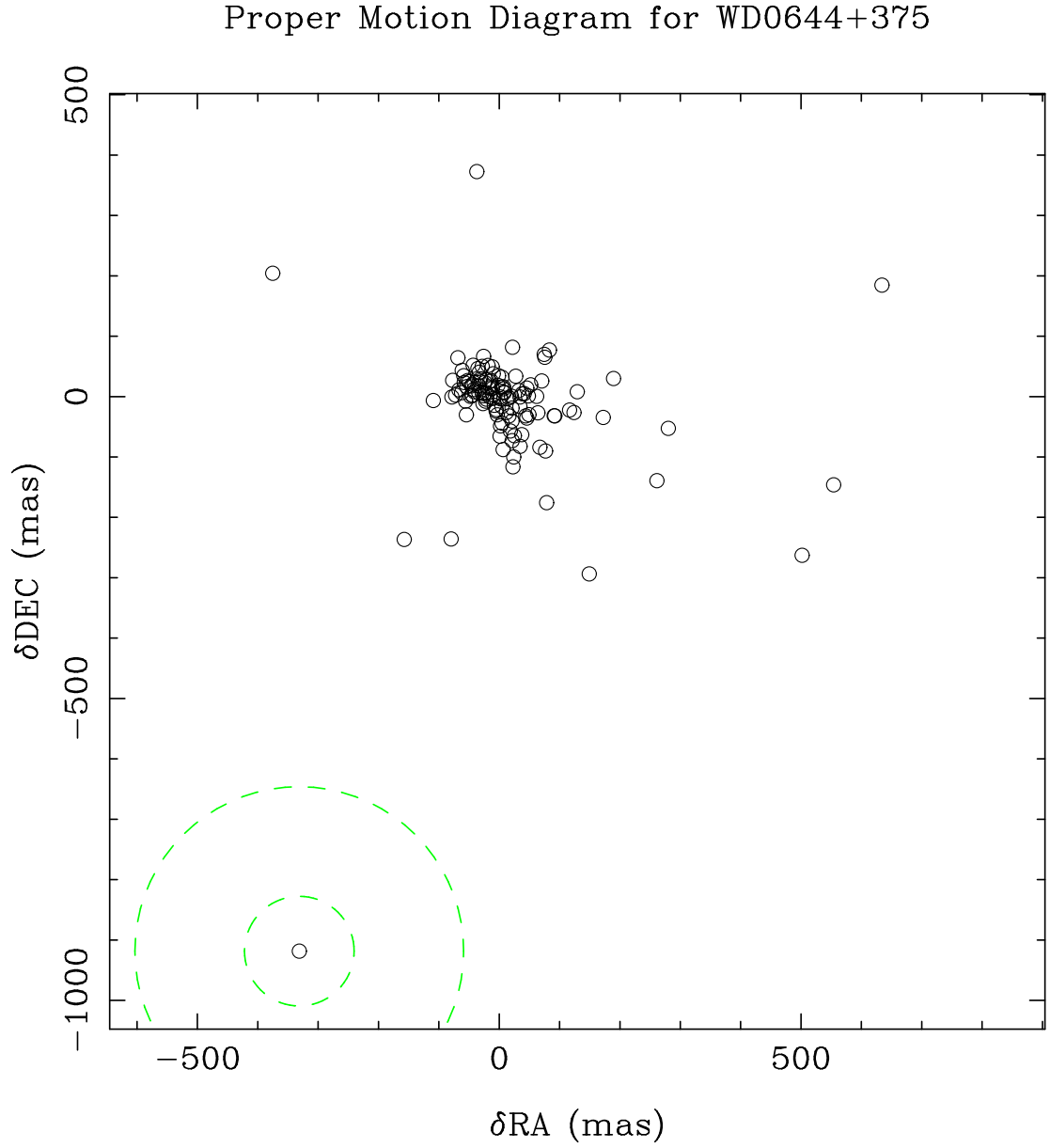


FIGURE 4.18. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 0644 + 375. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 0644 + 375.

4.11 WD 0738 – 172

Completeness limits for the images of WD0738–172

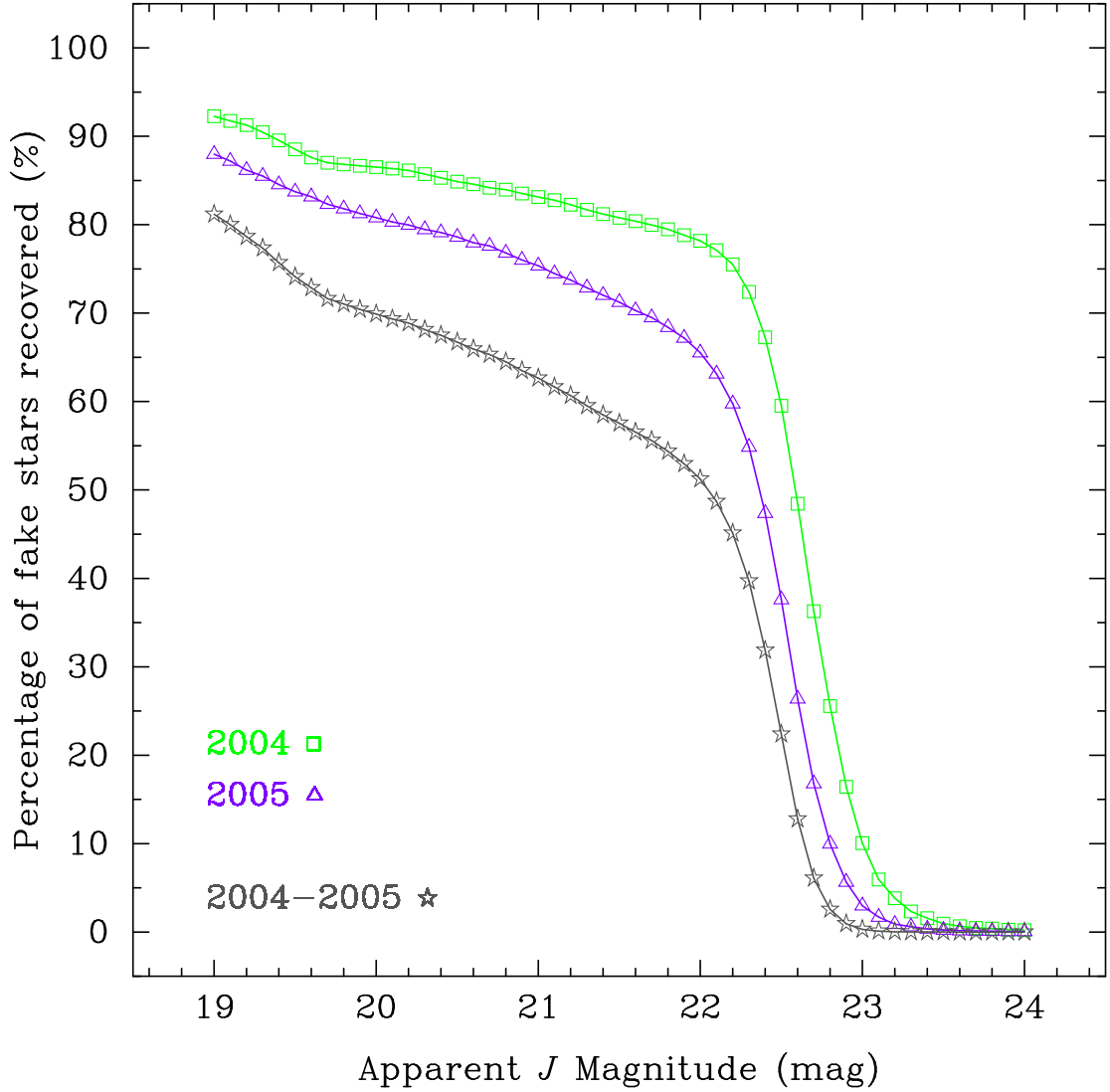


FIGURE 4.19. The percentage of artificial stars recovered by SExtractor from the 2004 first epoch image (green squares) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 0738 – 172. The 50% limiting magnitude taken from the combined 2004–2005 curve (grey stars) is $J = 22.0$ mag.

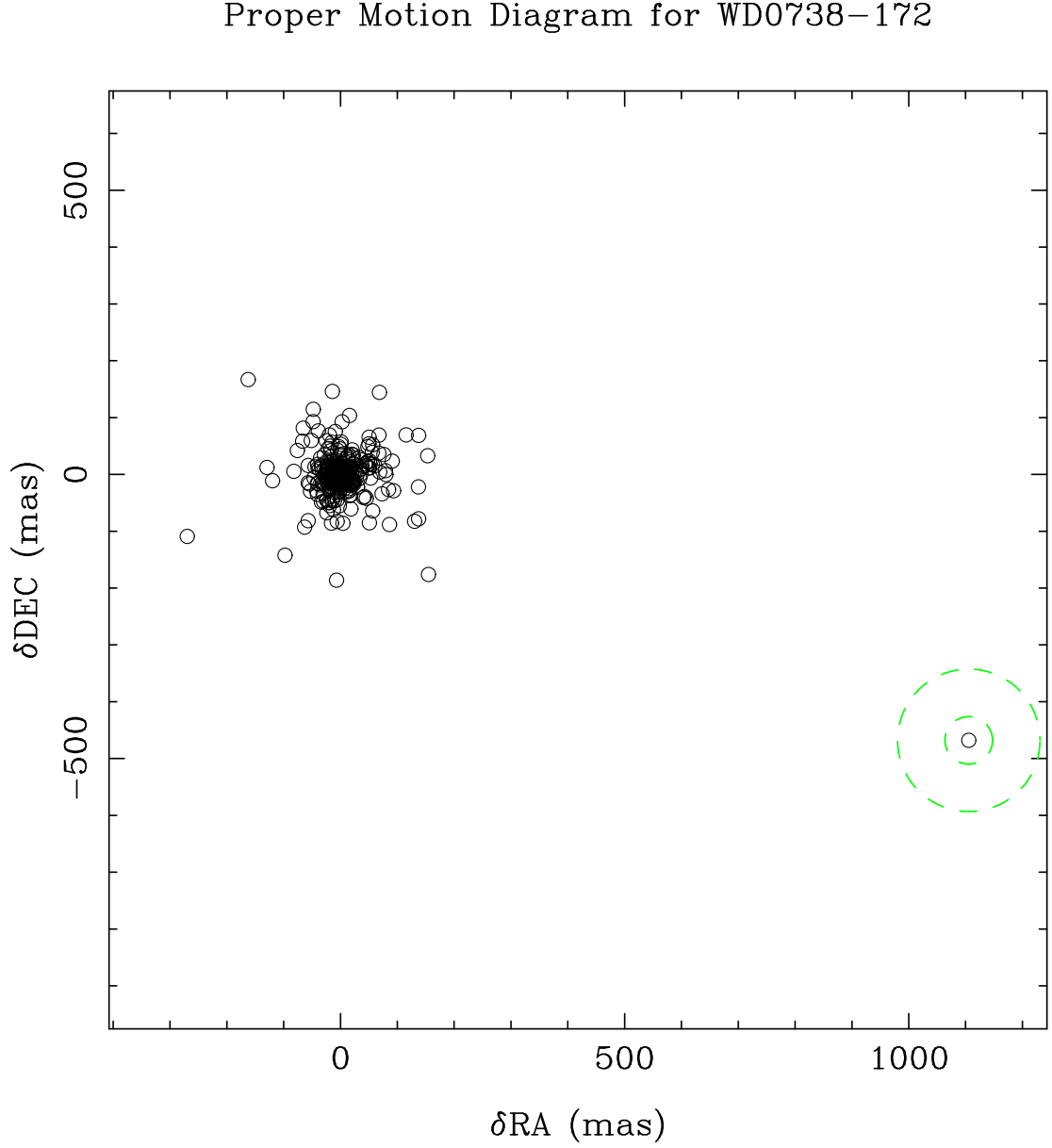


FIGURE 4.20. The motion of all objects between the 2004 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 0738 – 172. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 0738 – 172.

4.12 WD 0912 + 536

Completeness limits for the images of WD0912+536

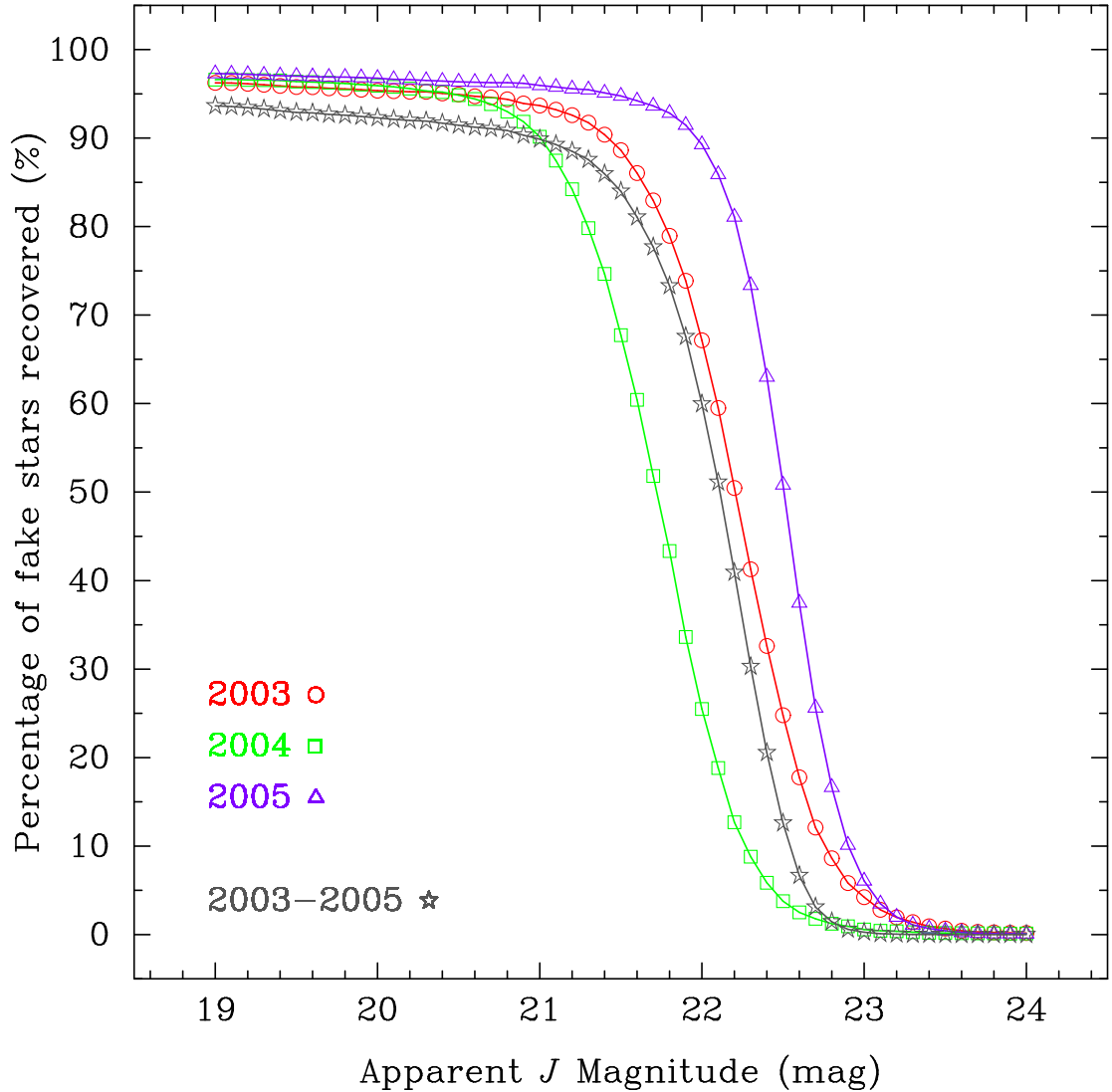


FIGURE 4.21. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles), the 2004 second epoch image (green squares) and the 2005 third epoch image (purple triangles) acquired of the white dwarf WD 0912 + 536. The 90% and 50% completeness limits taken from the combined 2003–2005 curve (grey stars) are $J = 20.9$ mag and $J = 22.1$ mag, respectively.

Proper Motion Diagram for WD0912+536

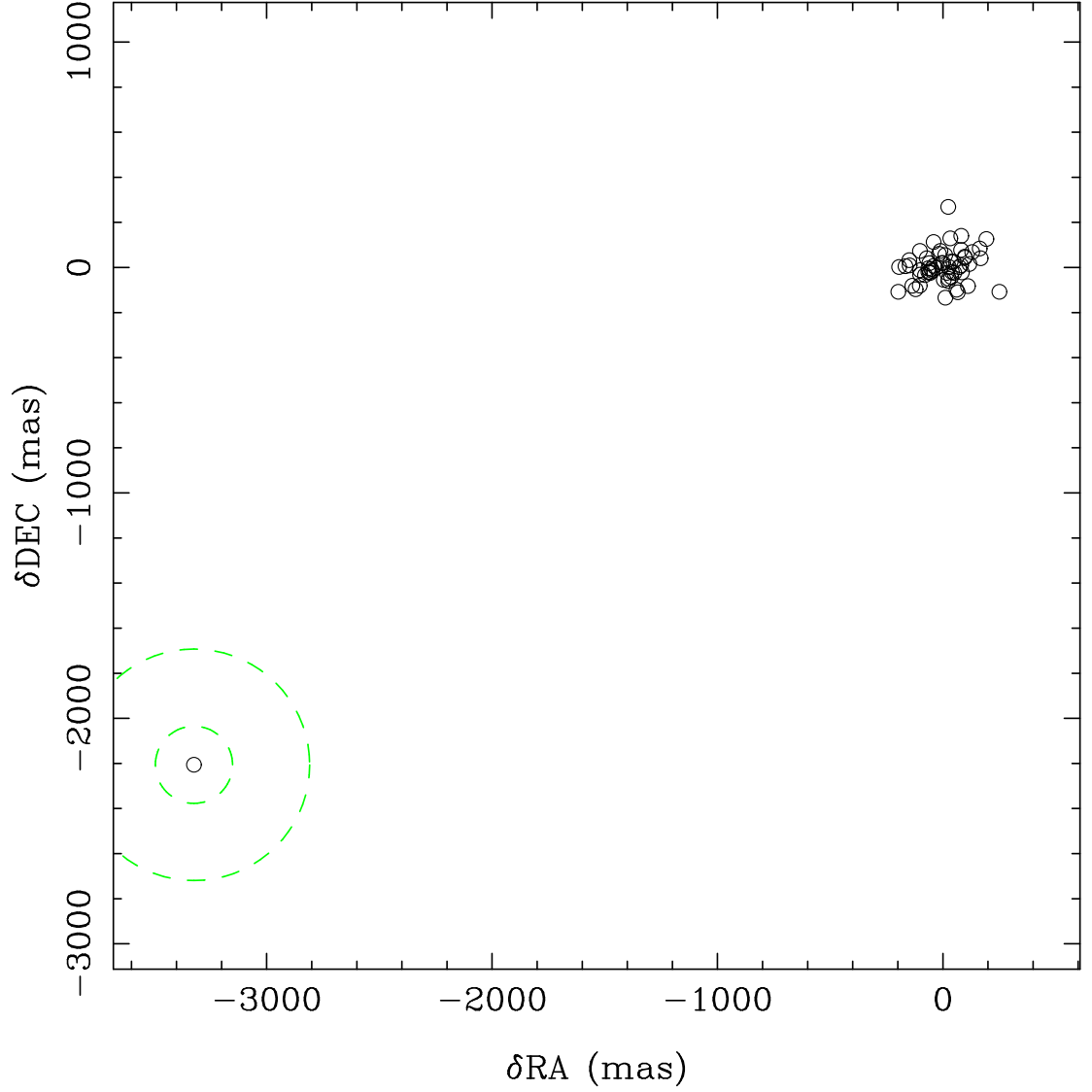


FIGURE 4.22. The motion of all objects between the 2003 first epoch image and the 2005 third epoch image acquired of the white dwarf WD 0912 + 536. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 0912 + 536.

4.13 WD 1055 – 072

Completeness limits for the images of WD1055–072

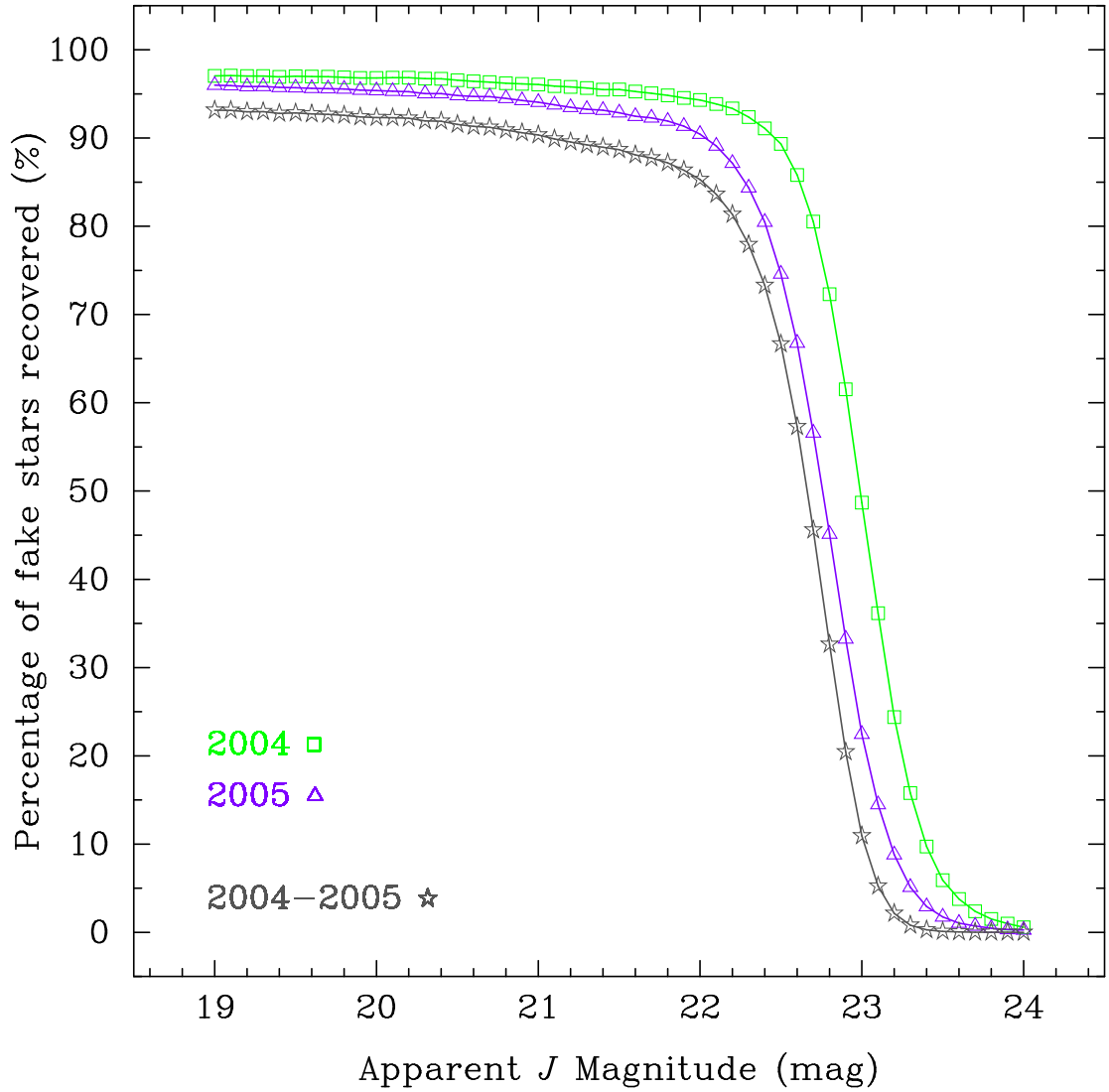


FIGURE 4.23. The percentage of artificial stars recovered by SExtractor from the 2004 first epoch image (green squares) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 1055 – 072. The 90% and 50% completeness limits taken from the combined 2004–2005 curve (grey stars) are $J = 21.0$ mag and $J = 22.6$ mag, respectively.

Proper Motion Diagram for WD1055–072

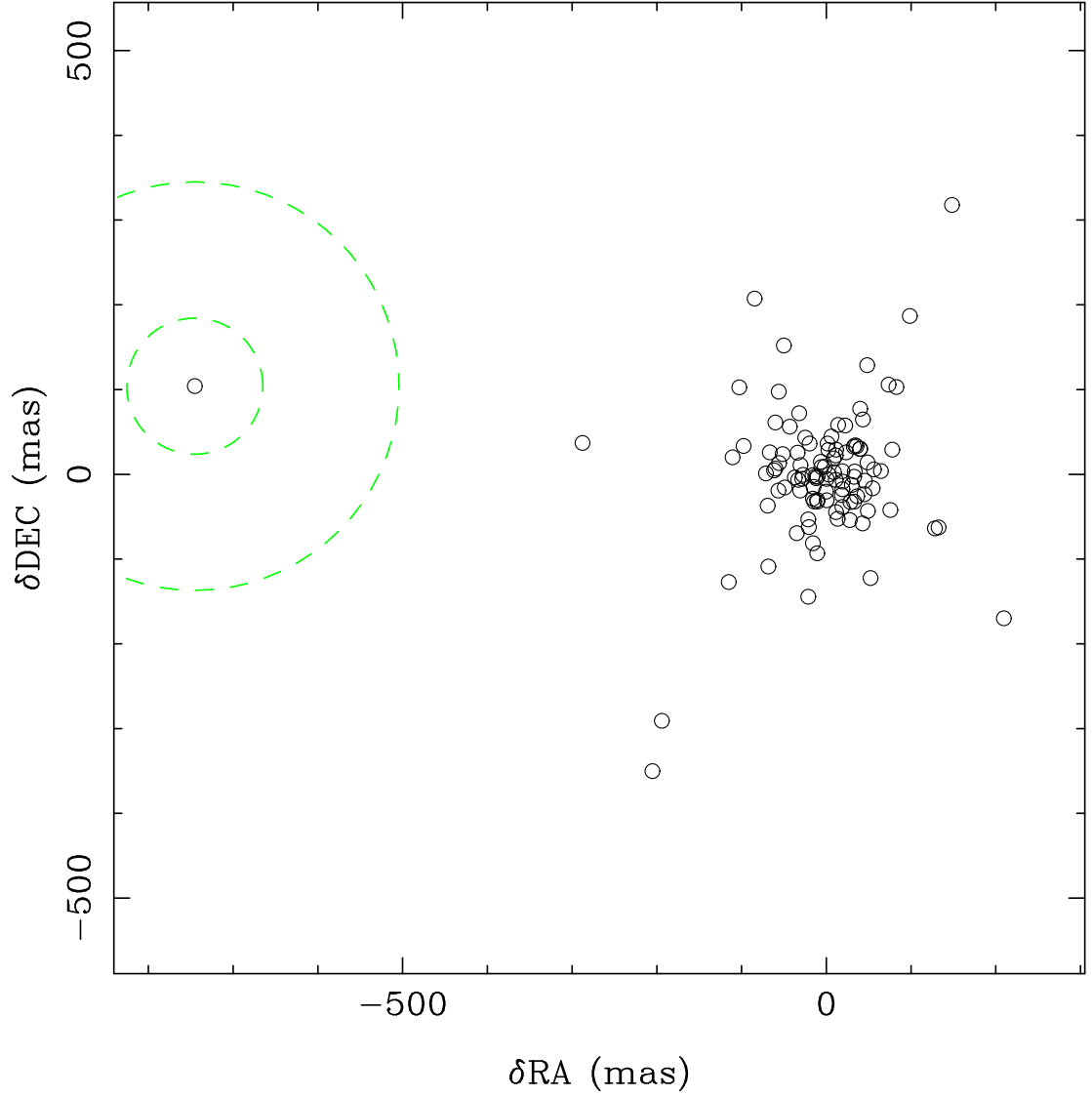


FIGURE 4.24. The motion of all objects between the 2004 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 1055 – 072. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 1055 – 072.

4.14 WD 1121 + 216

Completeness limits for the images of WD1121+216

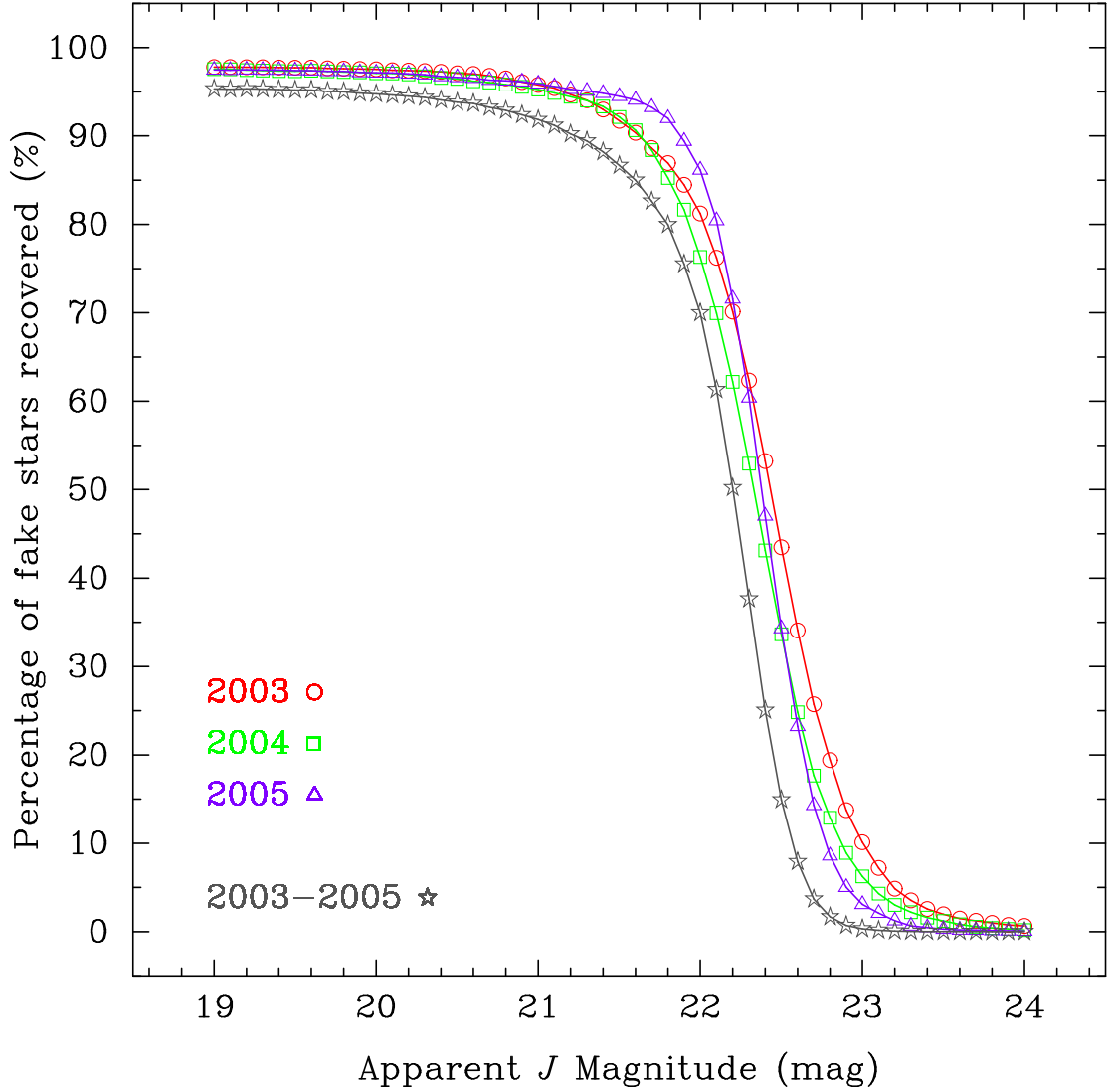


FIGURE 4.25. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles), the 2004 second epoch image (green squares) and the 2005 third epoch image (purple triangles) acquired of the white dwarf WD 1121 + 216. The 90% and 50% completeness limits taken from the combined 2003–2005 curve (grey stars) are $J = 21.2$ mag and $J = 22.2$ mag, respectively.

Proper Motion Diagram for WD1121+216

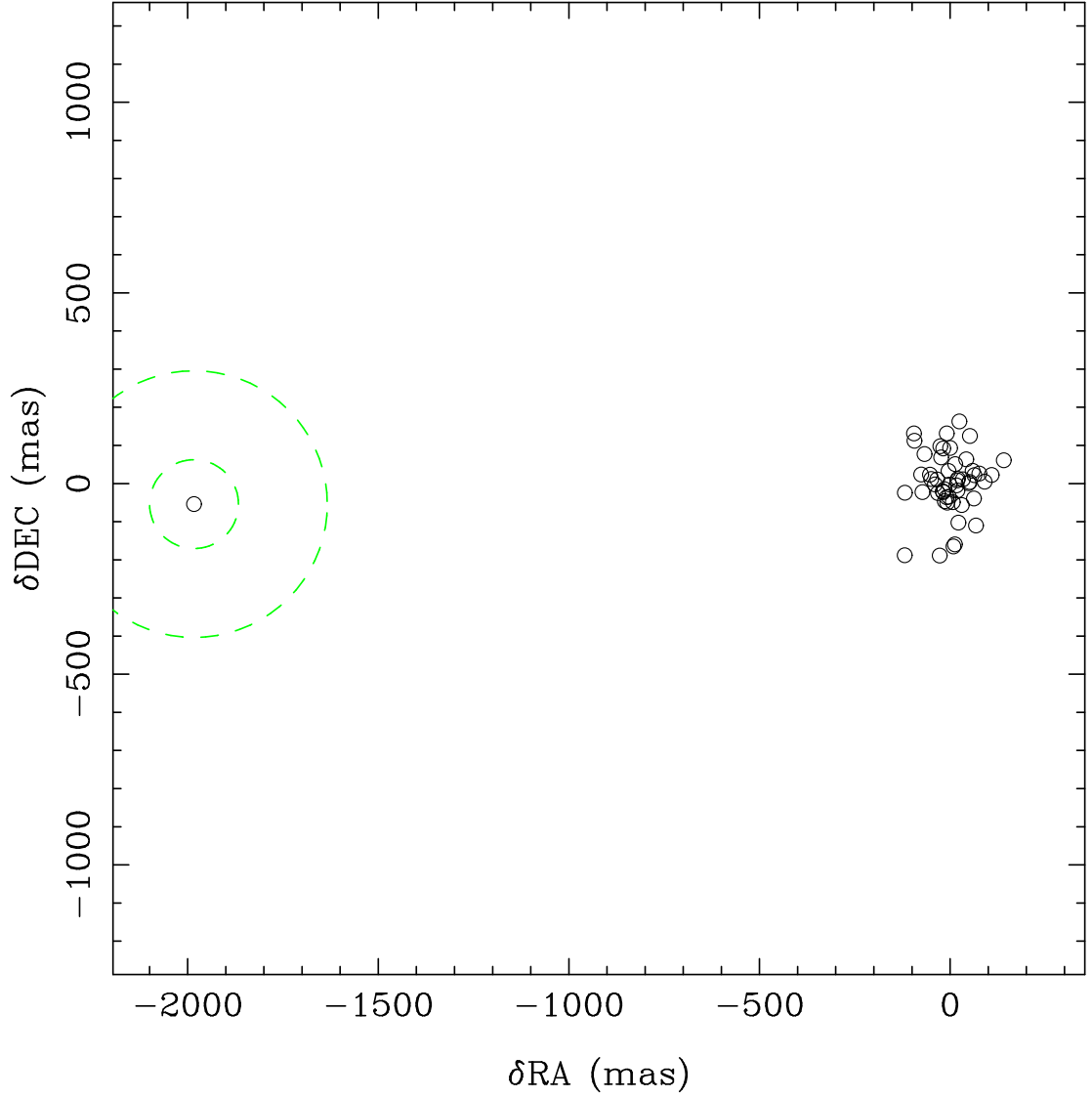


FIGURE 4.26. The motion of all objects between the 2003 first epoch image and the 2005 third epoch image acquired of the white dwarf WD 1121 + 216. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 1121 + 216.

4.15 WD 1134 + 300

Completeness limits for the images of WD1134+300

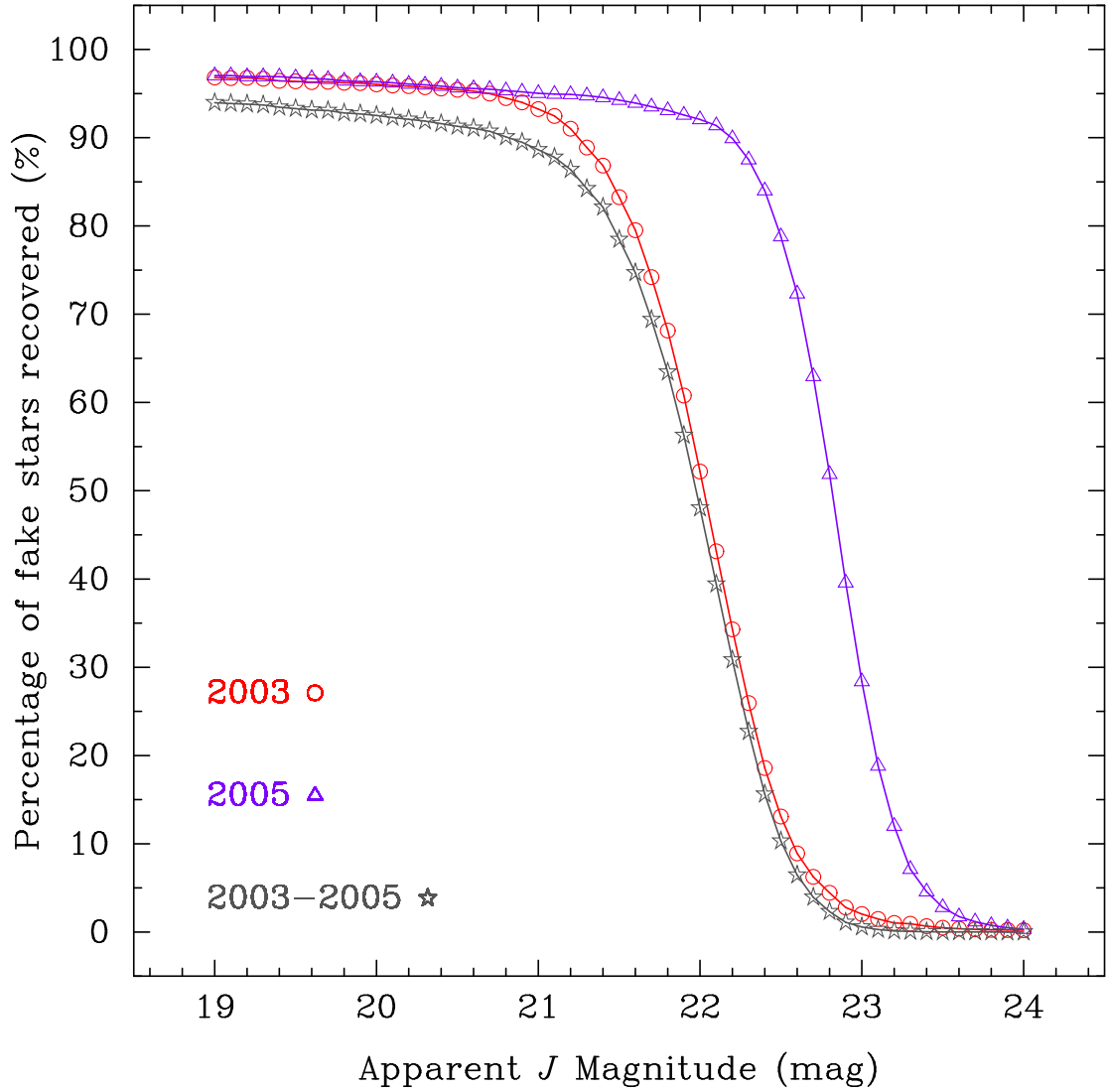


FIGURE 4.27. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2005 second epoch image (purple triangles) acquired of the white dwarf WD 1134 + 300. The 90% and 50% completeness limits taken from the combined 2003–2005 curve (grey stars) are $J = 20.8$ mag and $J = 21.9$ mag, respectively.

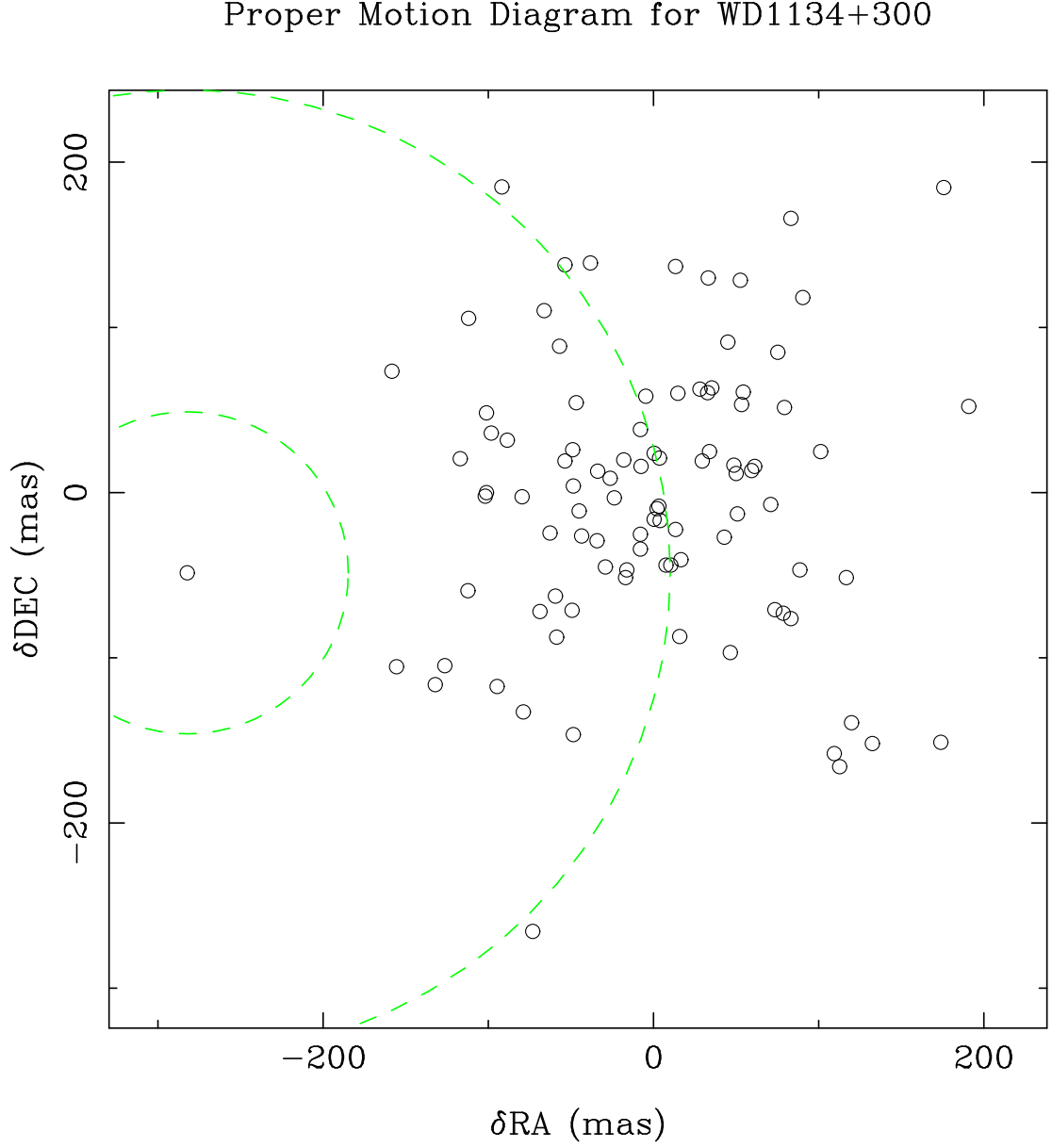


FIGURE 4.28. The motion of all objects between the 2003 first epoch image and the 2005 second epoch image acquired of the white dwarf WD 1134 + 300. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.16 WD 1344 + 106

Completeness limits for the images of WD1344+106

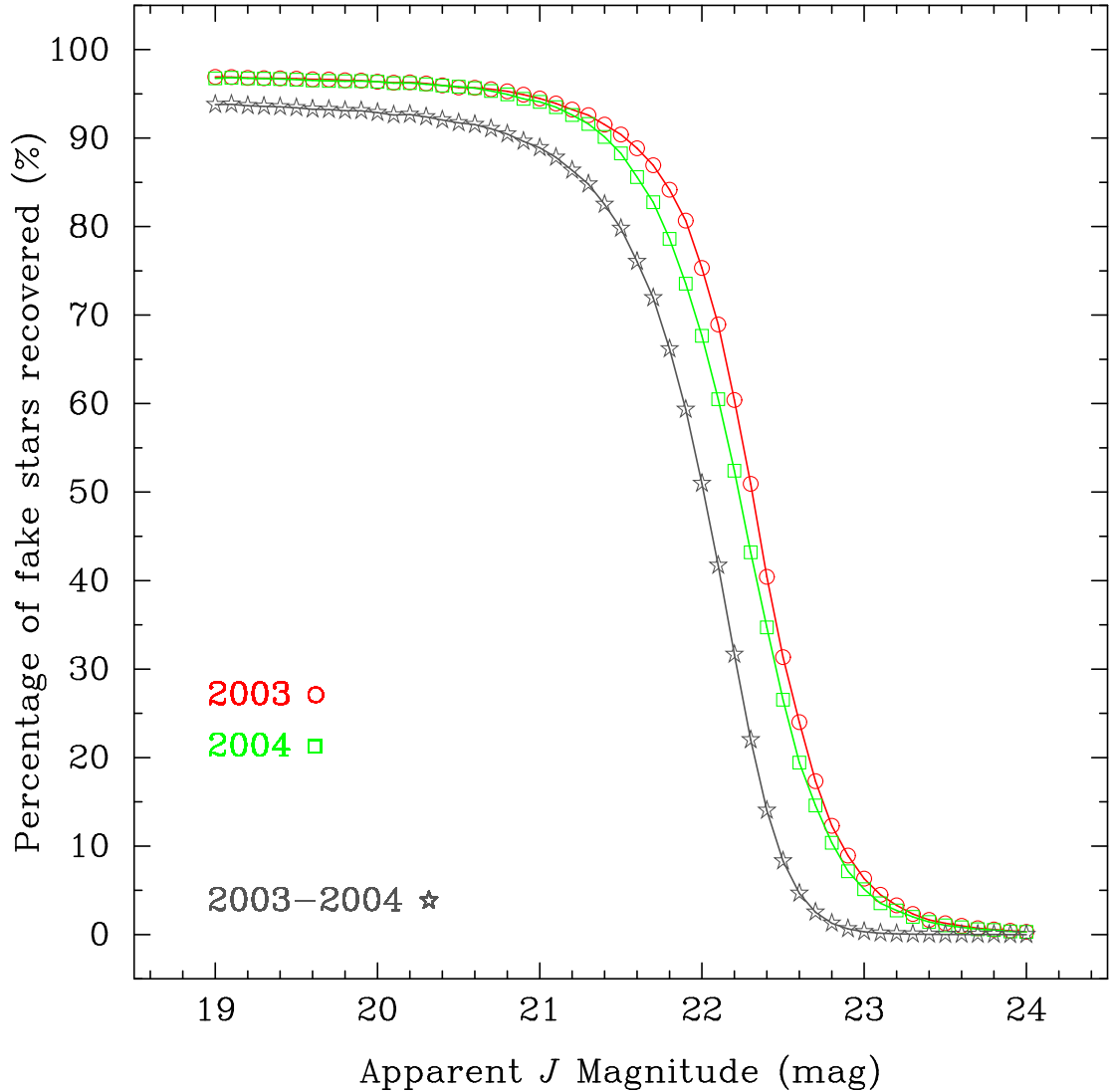


FIGURE 4.29. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 1344 + 106. The 90% and 50% completeness limits taken from the combined 2004–2005 curve (grey stars) are $J = 20.8$ mag and $J = 22.0$ mag, respectively.

Proper Motion Diagram for WD1344+106

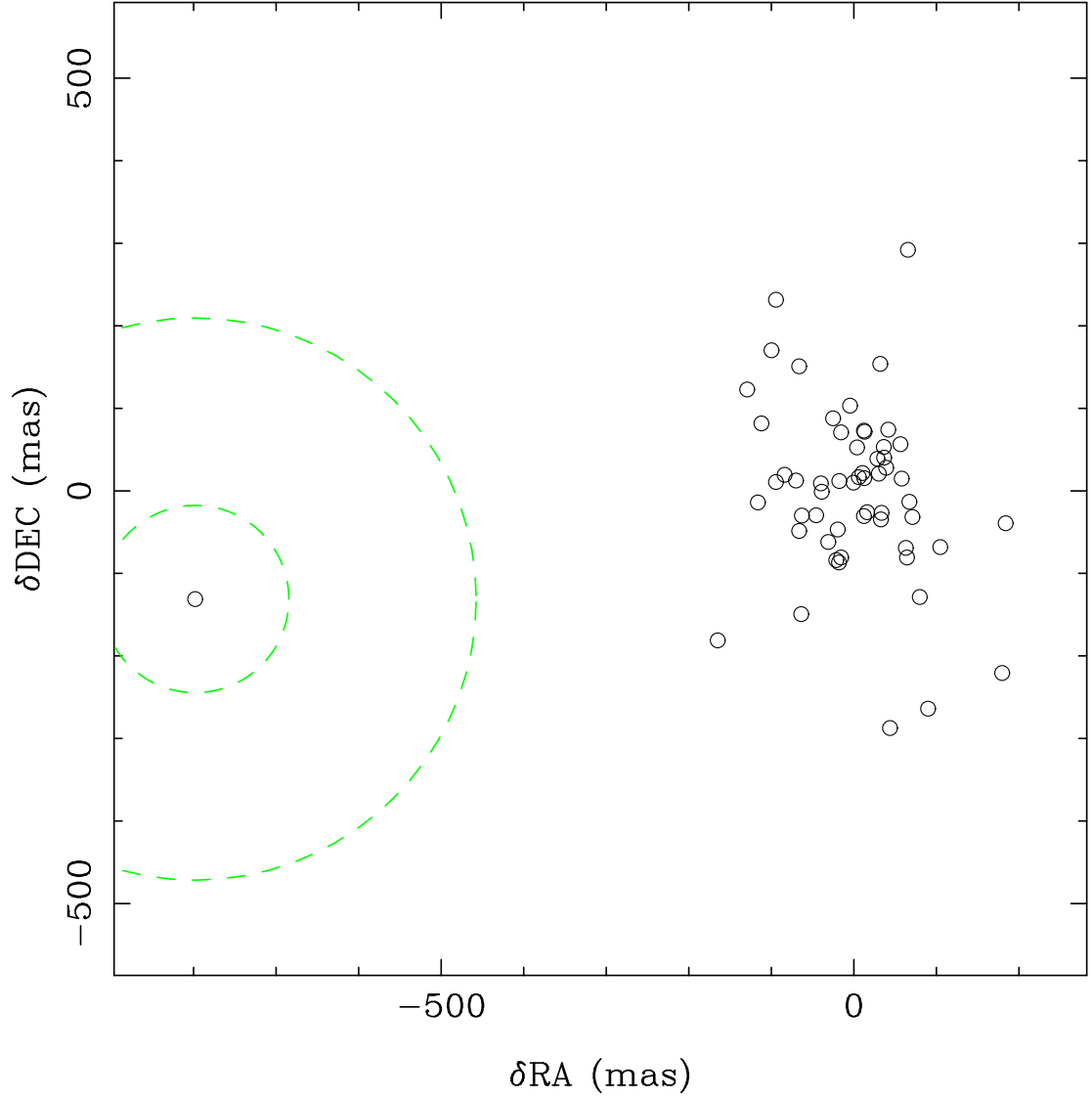


FIGURE 4.30. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 1344 + 106. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 1344 + 106.

4.17 WD 1609 + 135

Completeness limits for the images of WD1609+135

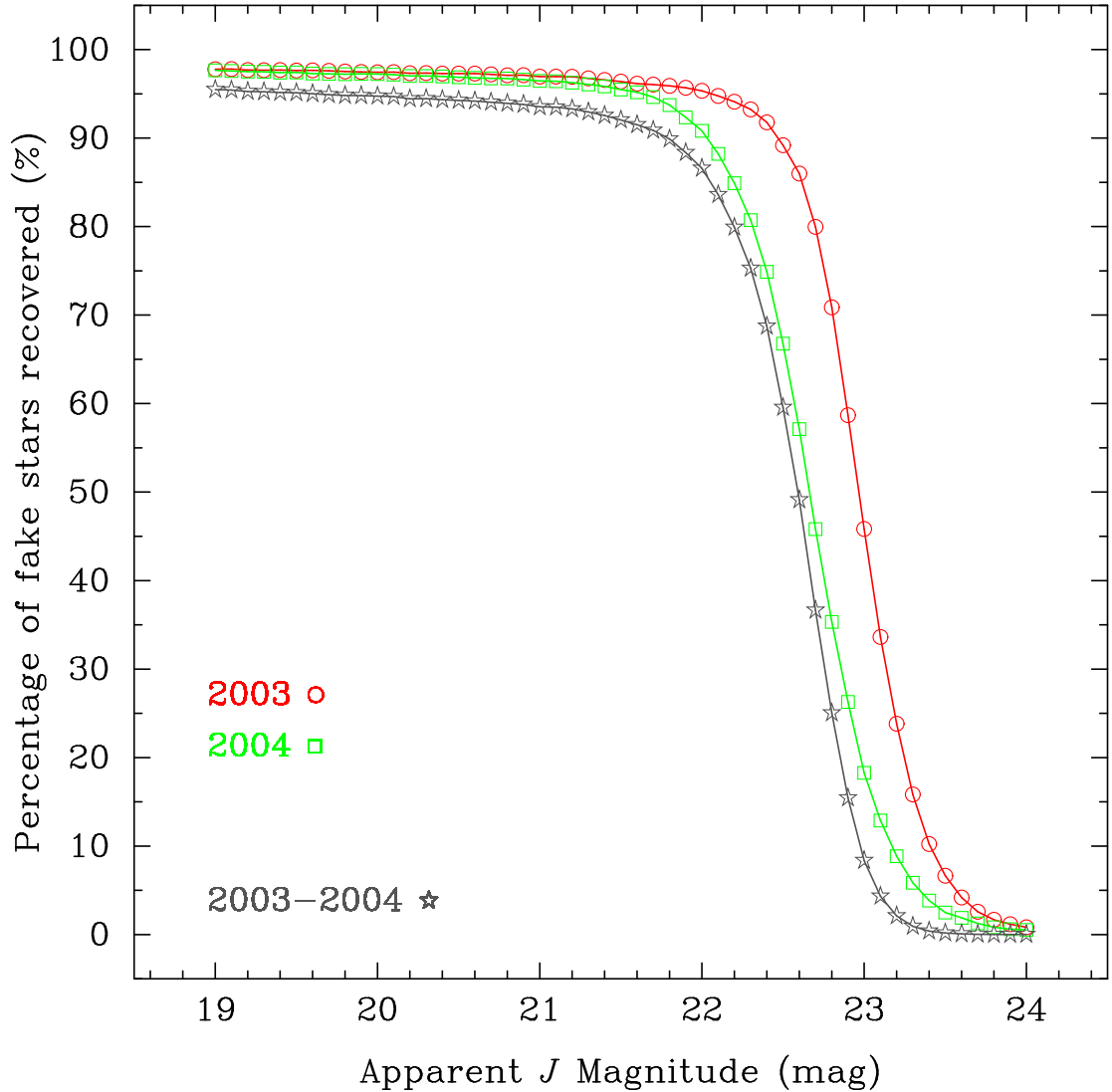


FIGURE 4.31. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 1609 + 135. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 21.7$ mag and $J = 22.5$ mag, respectively.

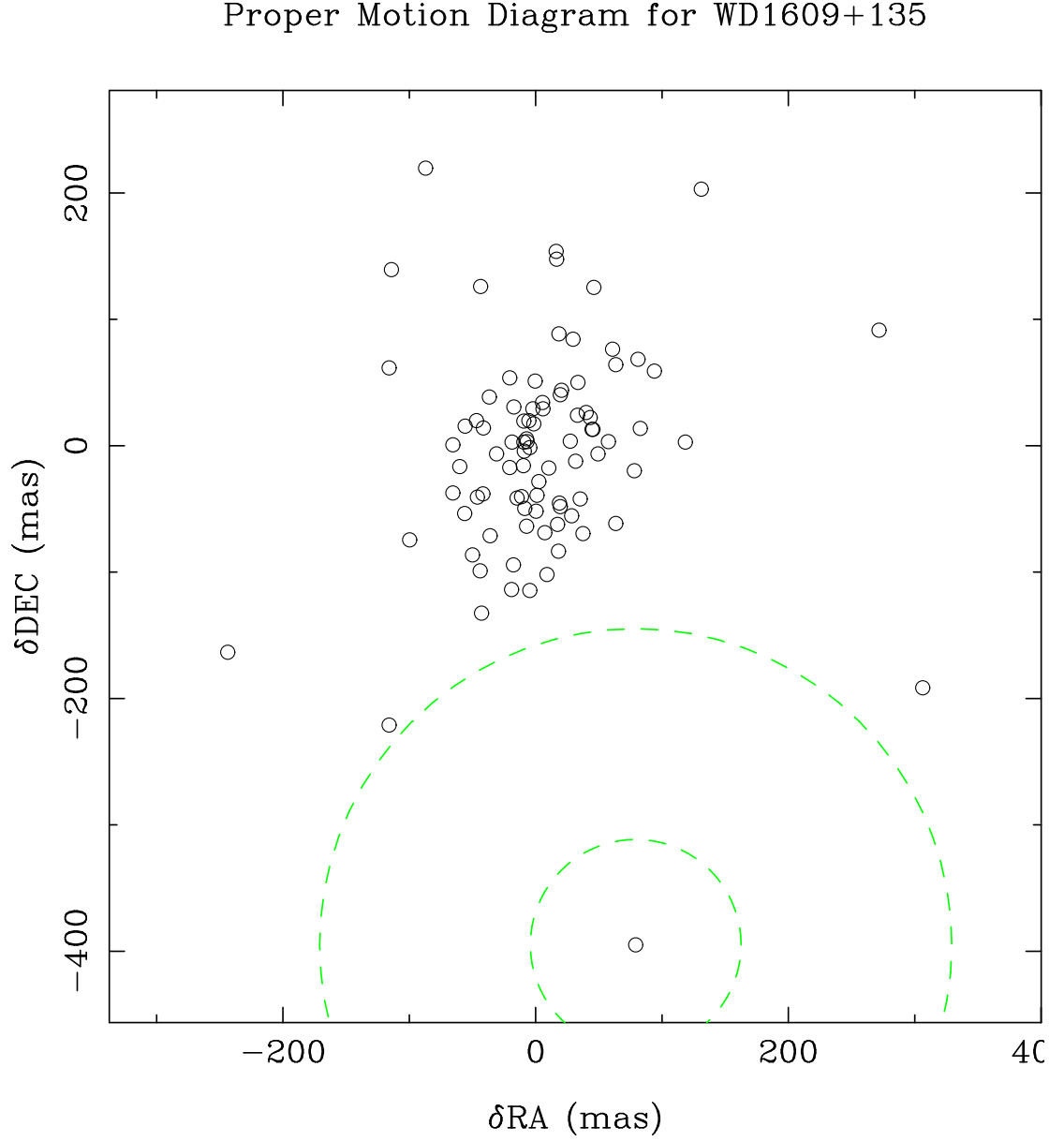


FIGURE 4.32. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 1609 + 135. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 1609 + 135.

4.18 WD 1626 + 368

Completeness limits for the images of WD1626+368

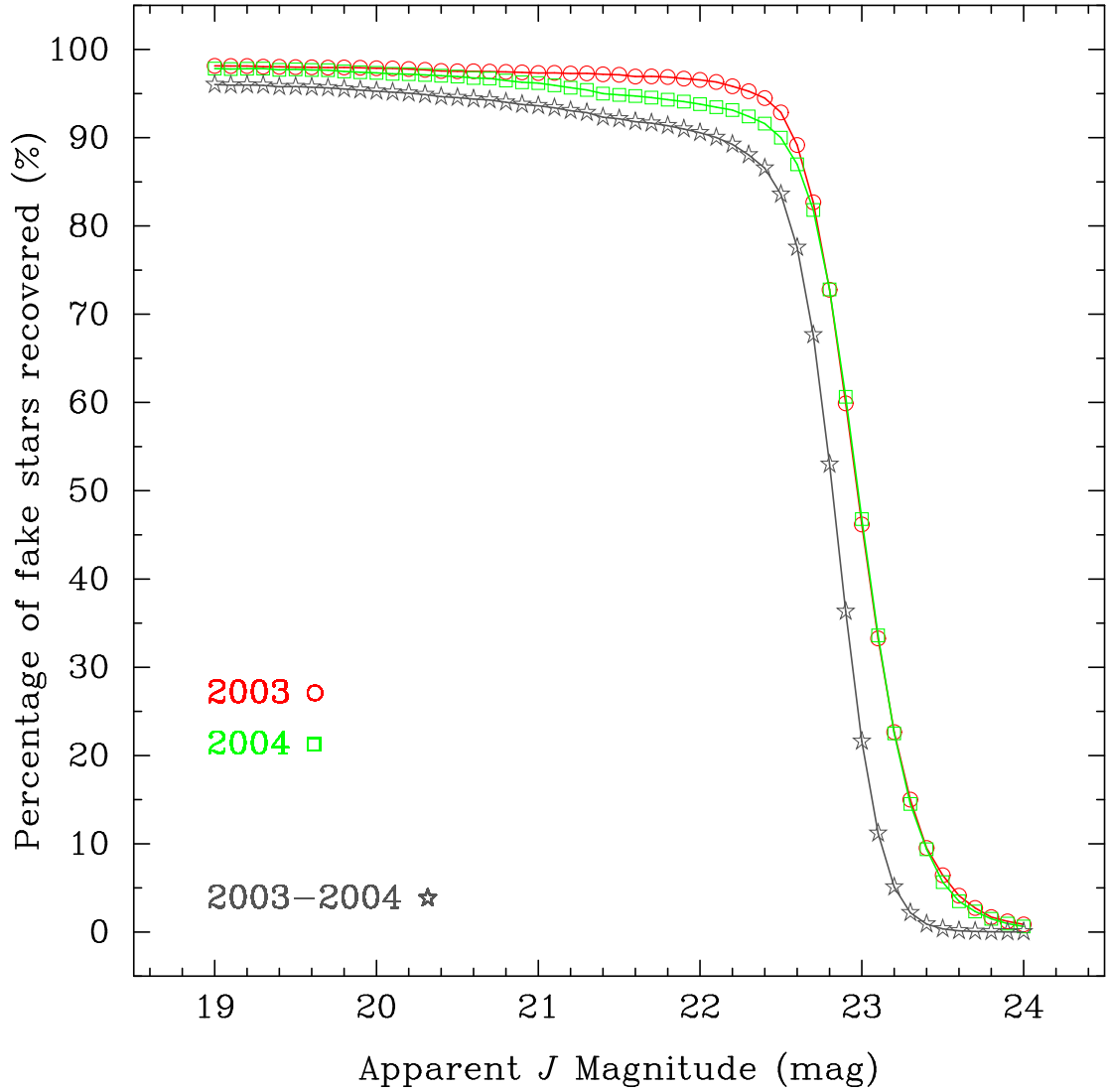


FIGURE 4.33. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 1626 + 368. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 22.1$ mag and $J = 22.8$ mag, respectively.

Proper Motion Diagram for WD1626+368

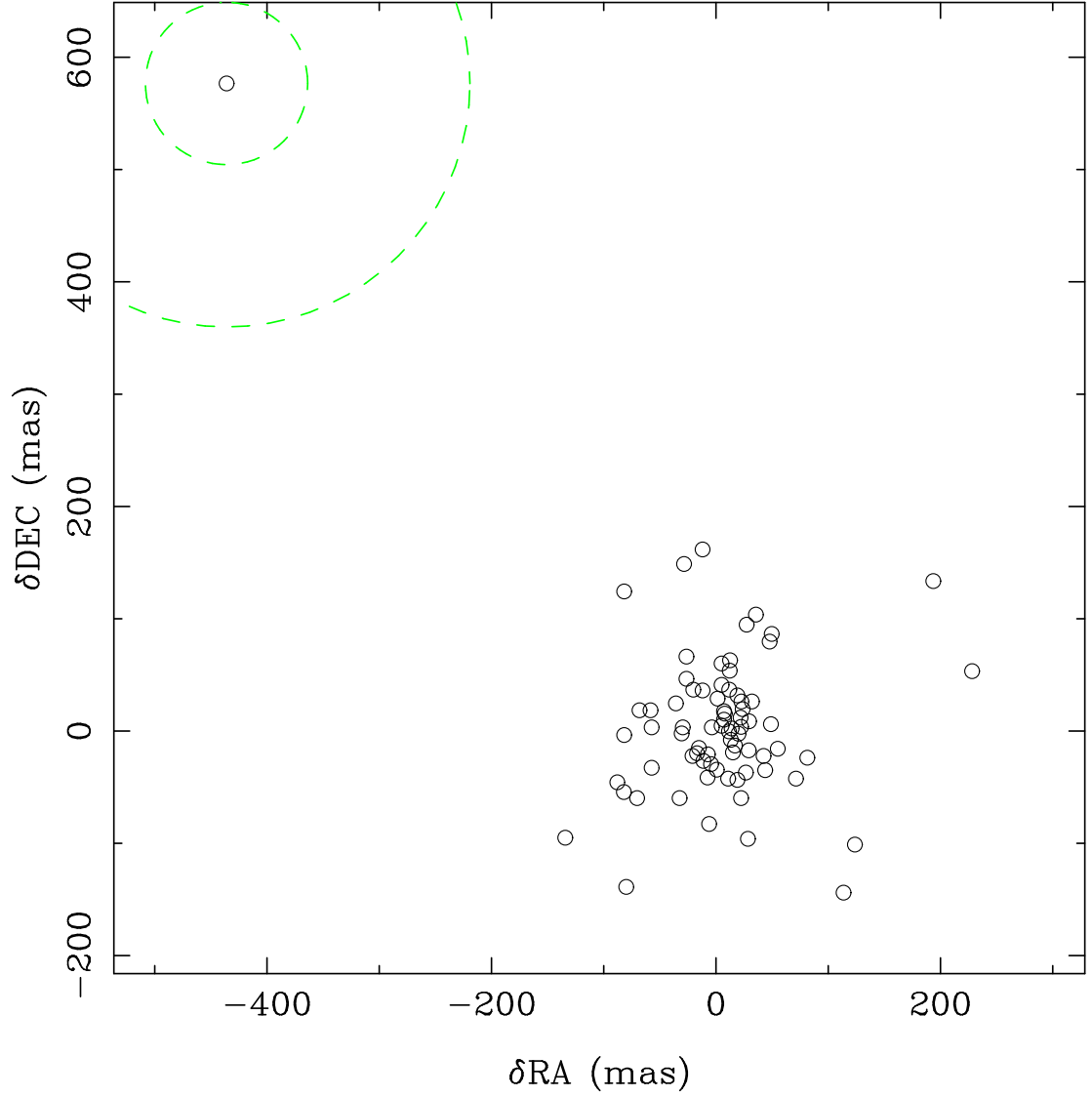


FIGURE 4.34. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 1626 + 368. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 1626 + 368.

4.19 WD 1633 + 433

Completeness limits for the images of WD1633+433

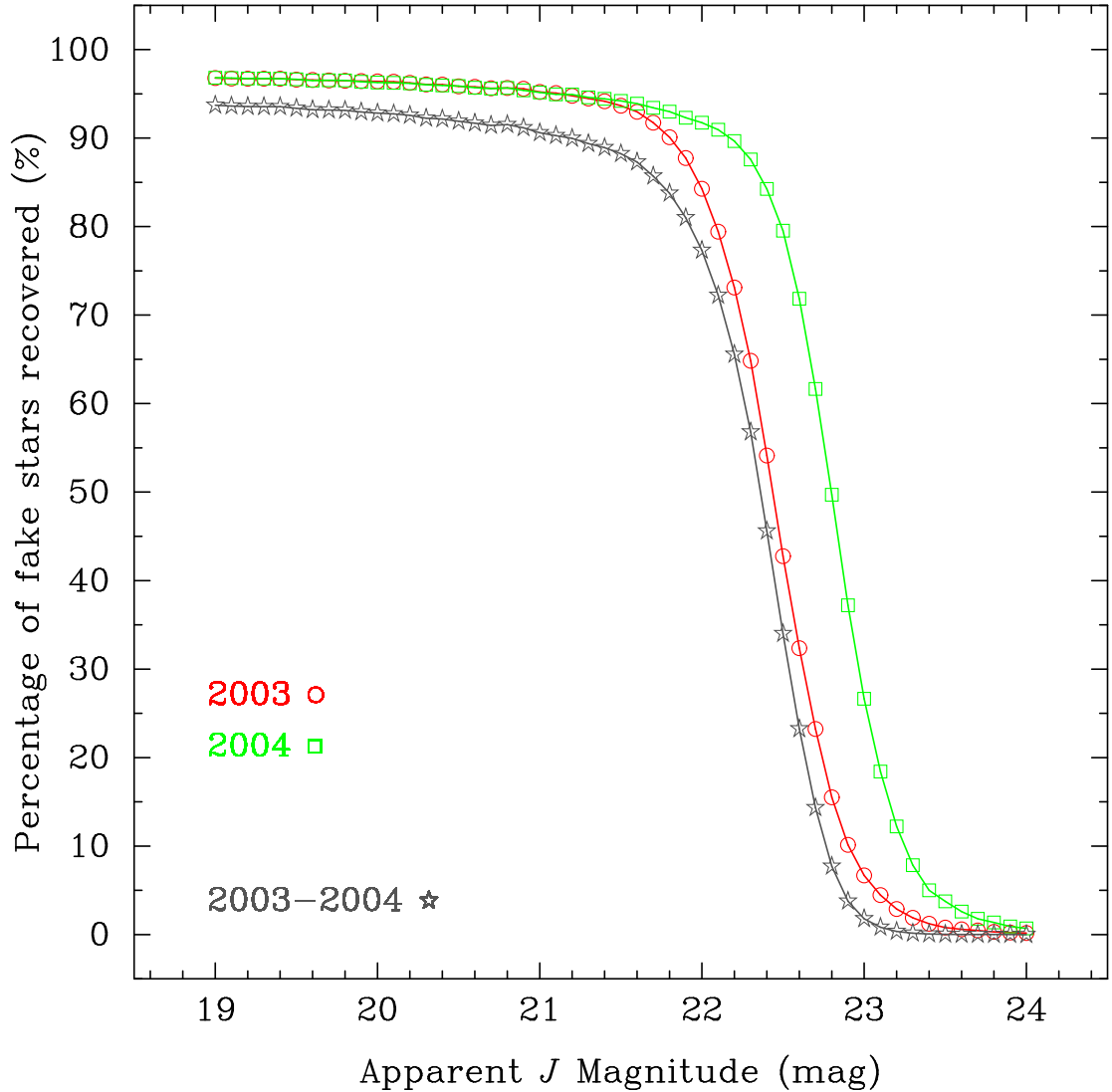


FIGURE 4.35. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 1633 + 433. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 21.1$ mag and $J = 22.3$ mag, respectively.

Proper Motion Diagram for WD1633+433

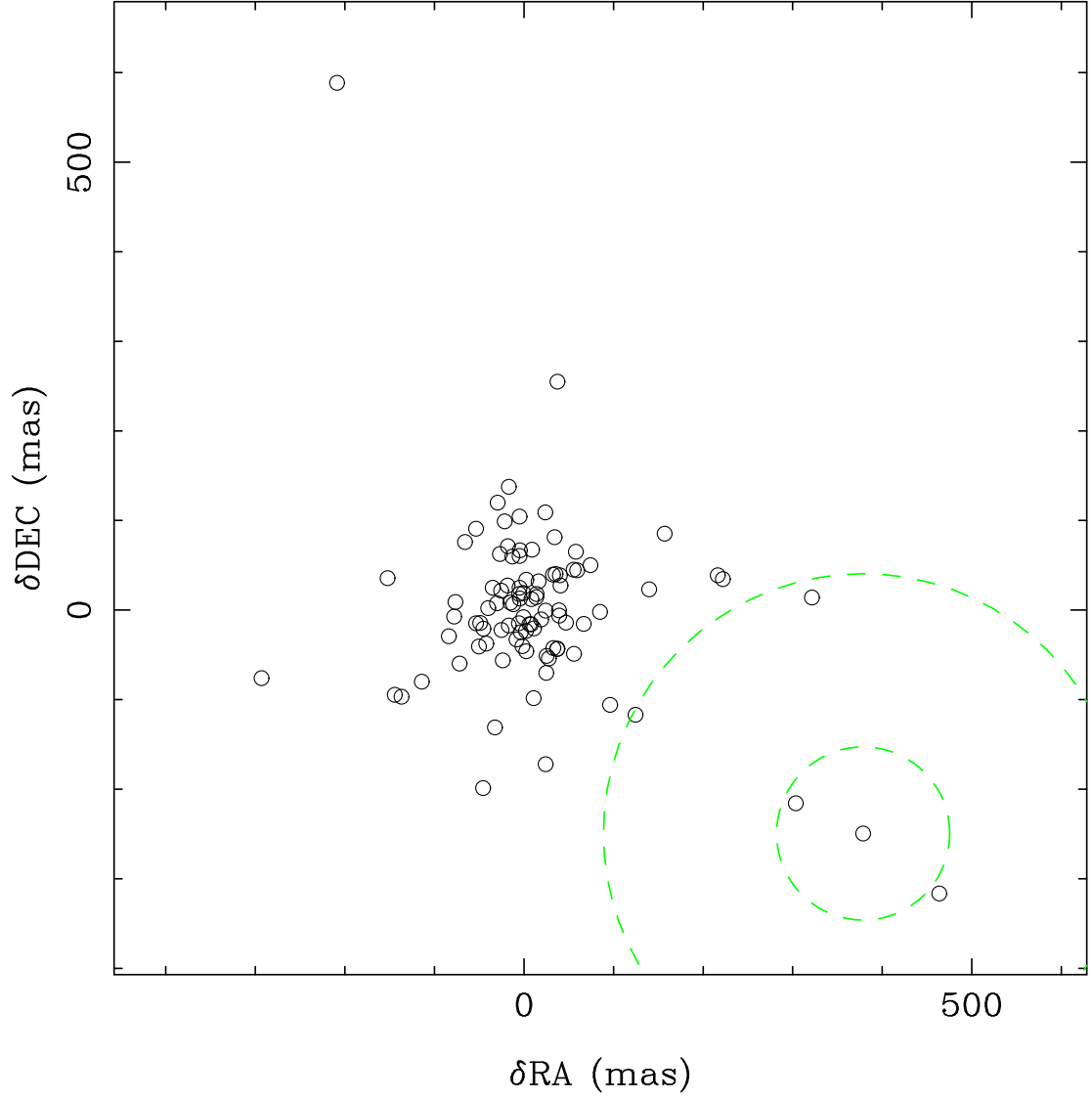


FIGURE 4.36. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 1633 + 433. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.20 WD 1647 + 591

Completeness limits for the images of WD1647+591

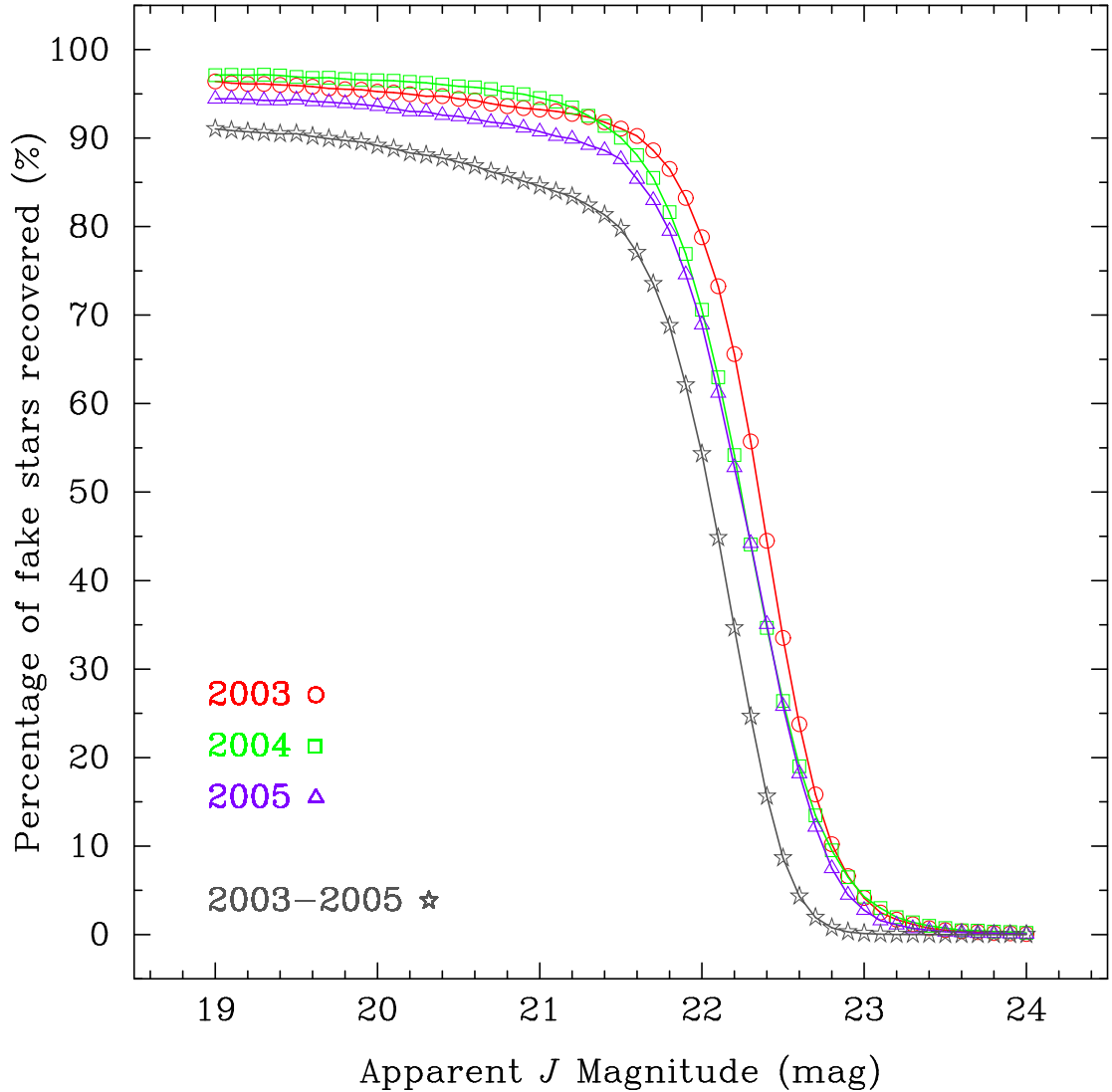


FIGURE 4.37. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles), the 2004 second epoch image (green squares) and the 2005 third epoch image (purple triangles) acquired of the white dwarf WD 1647 + 591. The 90% and 50% completeness limits taken from the combined 2003–2005 curve (grey stars) are $J = 19.6$ mag and $J = 22.0$ mag, respectively.

Proper Motion Diagram for WD1647+591

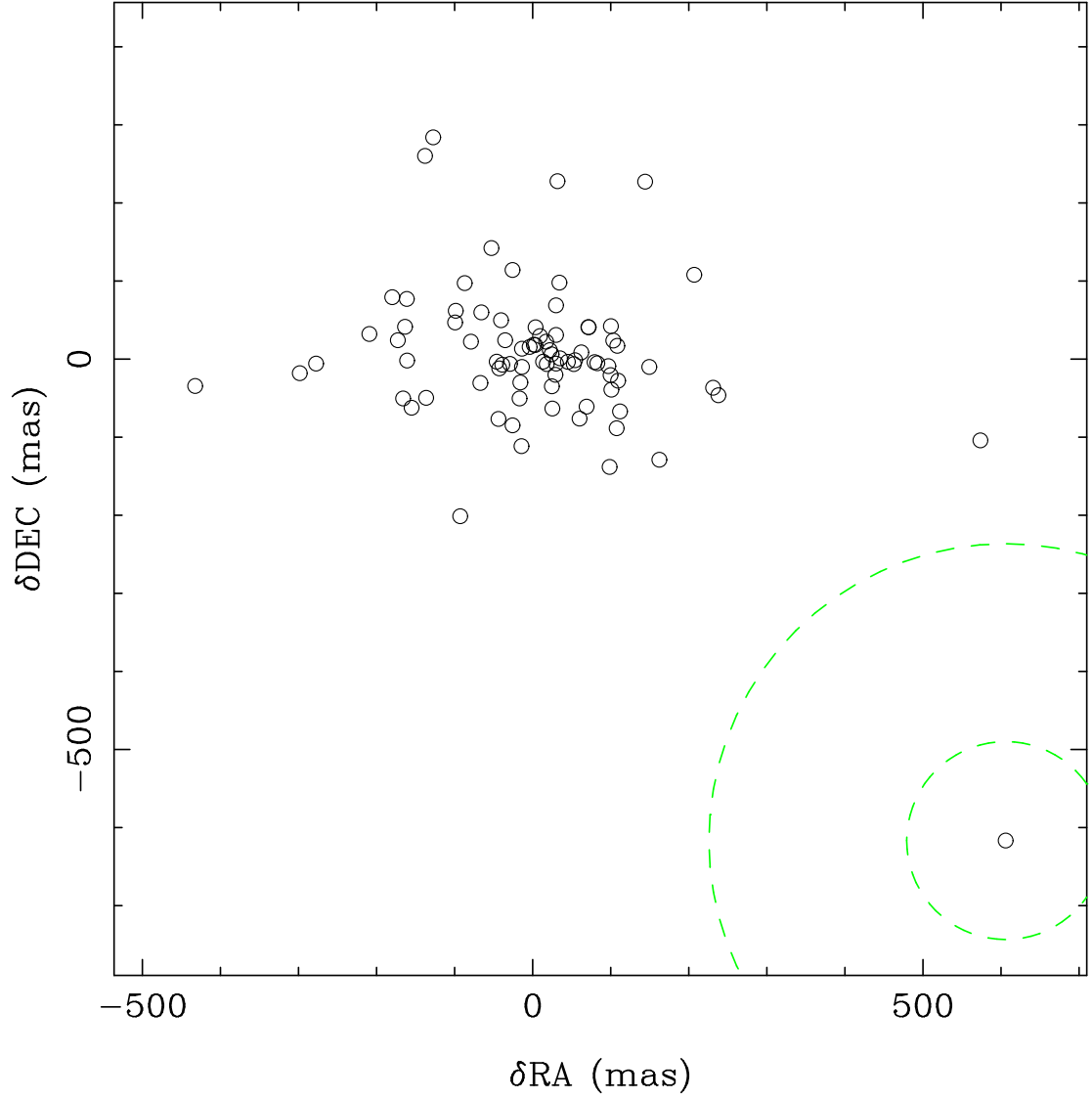


FIGURE 4.38. The motion of all objects between the 2003 first epoch image and the 2005 third epoch image acquired of the white dwarf WD 1647 + 591. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 1647 + 591.

4.21 WD 1900 + 705

Completeness limits for the images of WD1900+705

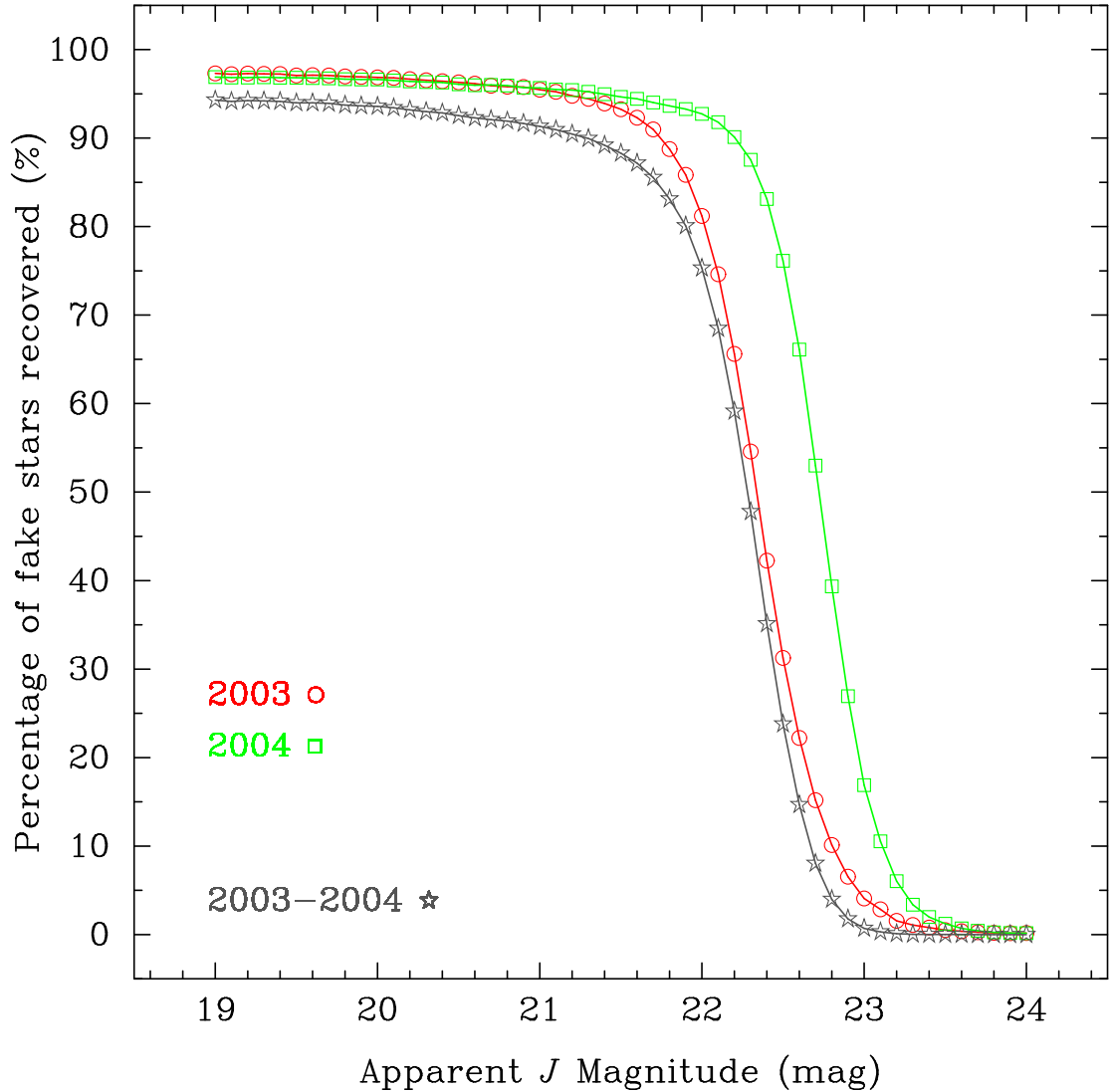


FIGURE 4.39. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 1900 + 705. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 21.2$ mag and $J = 22.2$ mag, respectively.

Proper Motion Diagram for WD1900+705

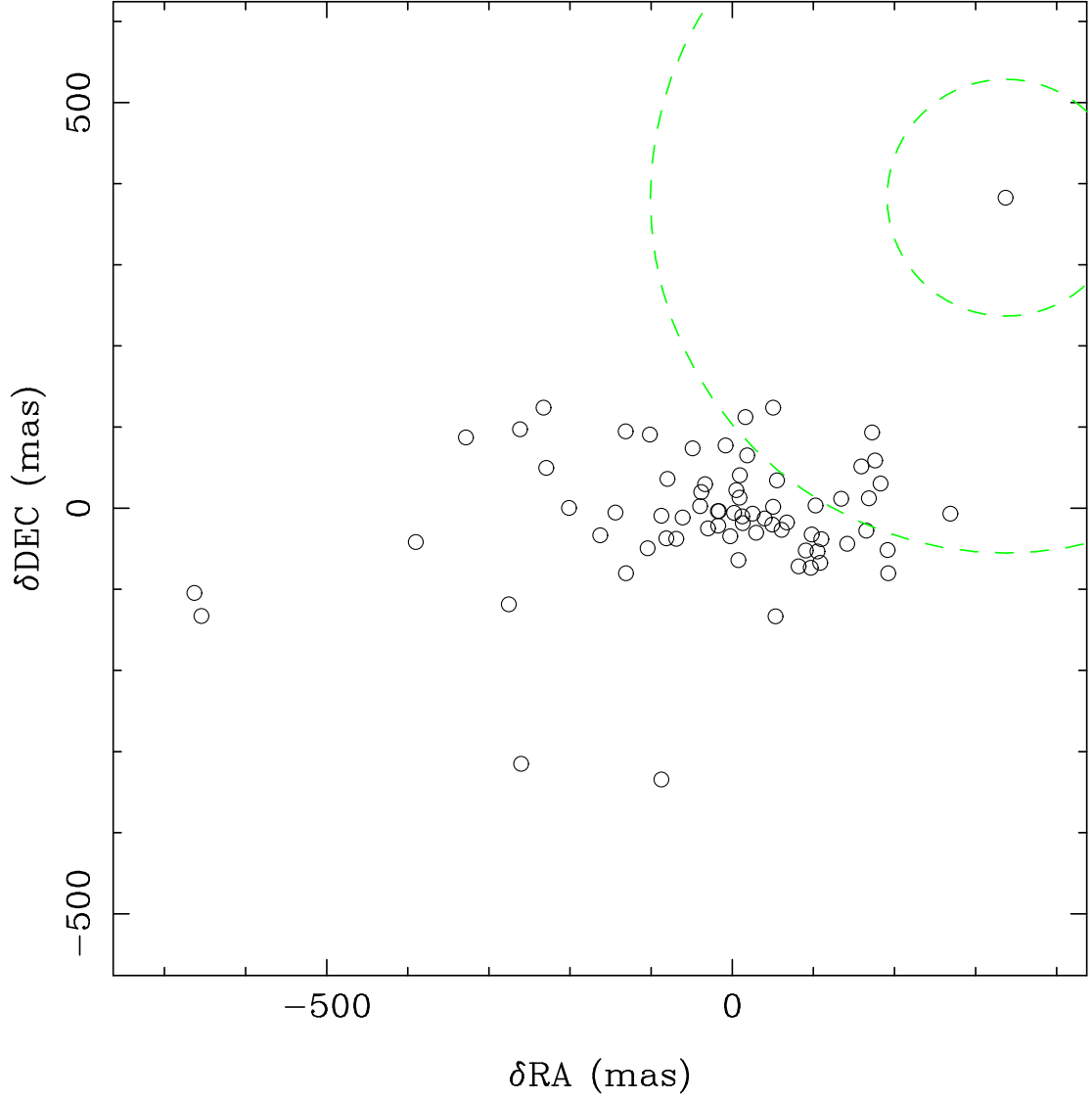


FIGURE 4.40. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 1900 + 705. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.22 WD 1953 – 011

Completeness limits for the images of WD1953–011

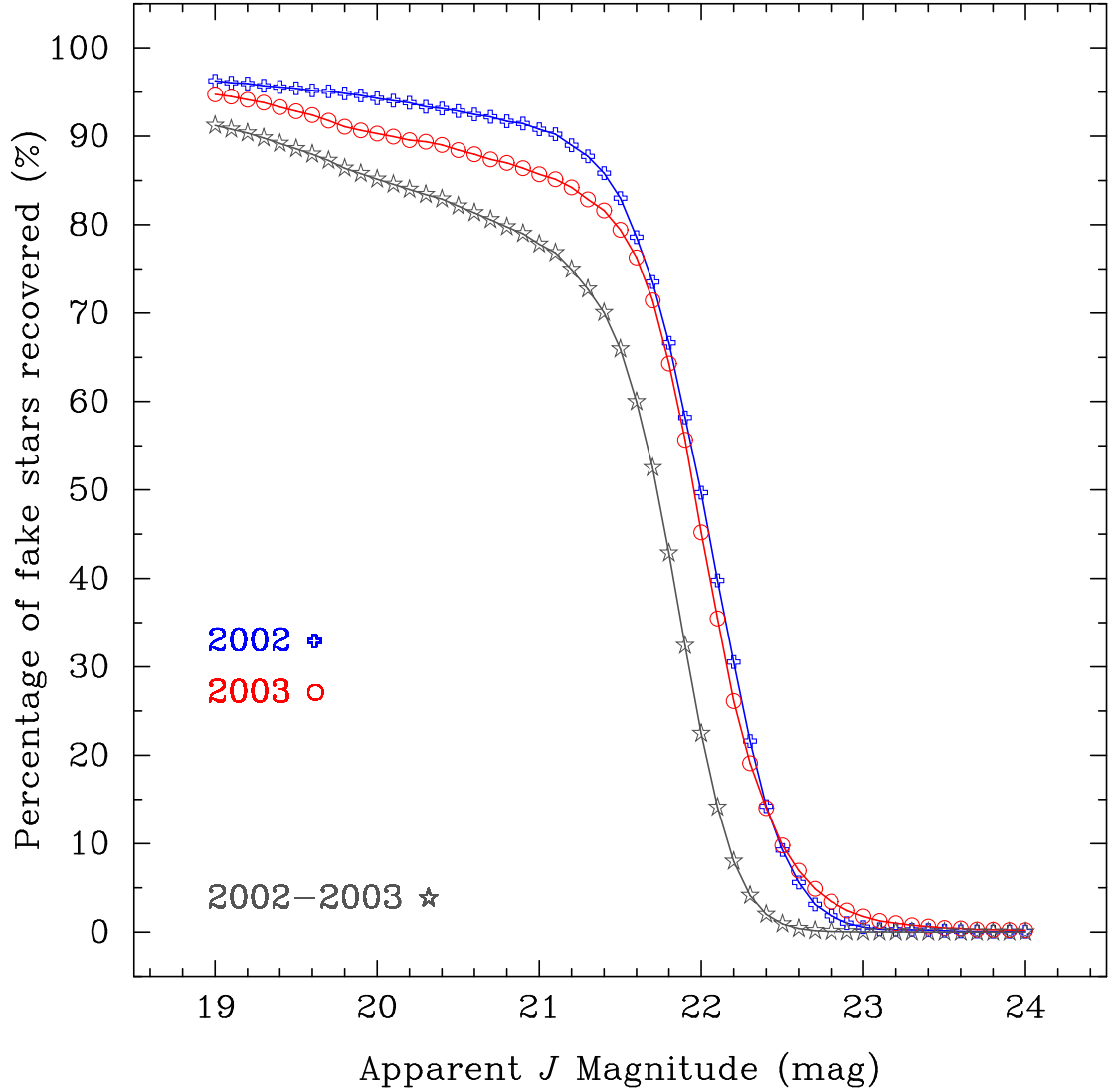


FIGURE 4.41. The percentage of artificial stars recovered by SExtractor from the 2002 first epoch image (blue crosses) and the 2003 second epoch image (red circles) acquired of the white dwarf WD 1953 – 011. The 90% and 50% completeness limits taken from the combined 2004–2005 curve (grey stars) are $J = 19.2$ mag and $J = 21.7$ mag, respectively.

Proper Motion Diagram for WD1953–011

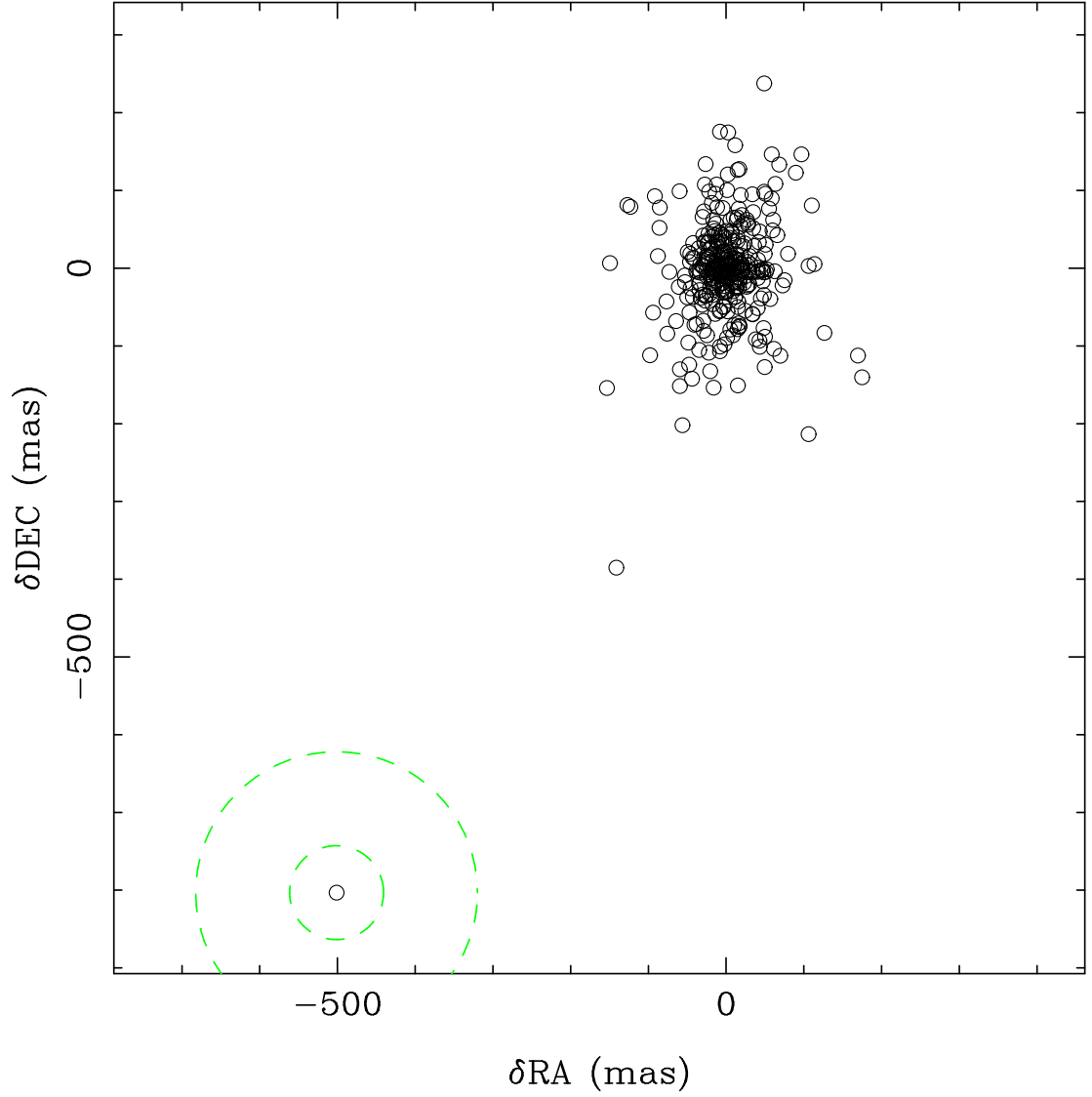


FIGURE 4.42. The motion of all objects between the 2002 first epoch image and the 2003 second epoch image acquired of the white dwarf WD 1953 – 011. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 1953 – 011.

4.23 WD 2007 – 219

Completeness limits for the images of WD2007–219

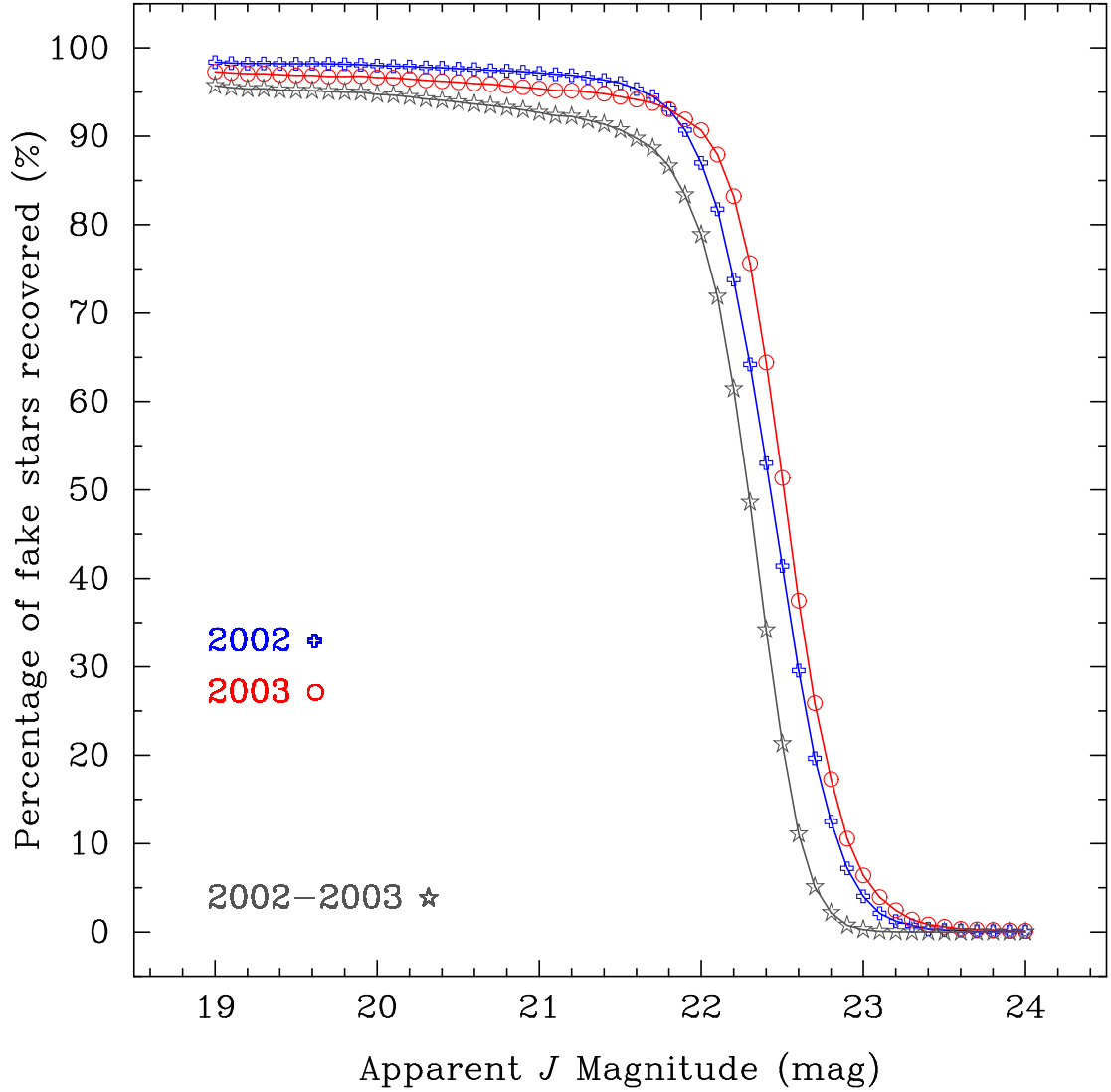


FIGURE 4.43. The percentage of artificial stars recovered by SExtractor from the 2002 first epoch image (blue crosses) and the 2003 second epoch image (red circles) acquired of the white dwarf WD 2007 – 219. The 90% and 50% completeness limits taken from the combined 2002–2003 curve (grey stars) are $J = 21.5$ mag and $J = 22.2$ mag, respectively.

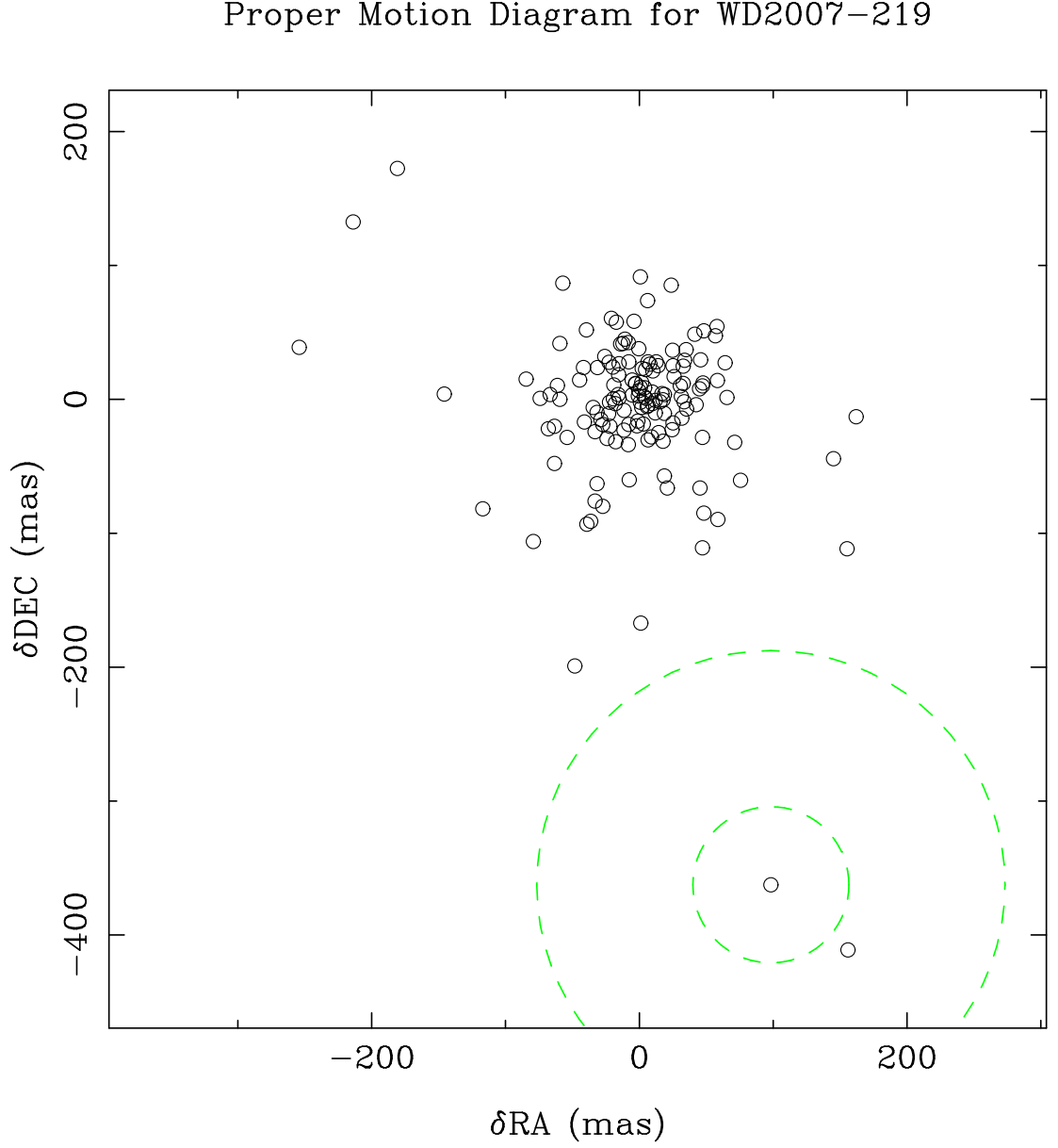


FIGURE 4.44. The motion of all objects between the 2002 first epoch image and the 2003 second epoch image acquired of the white dwarf WD 2007 – 219. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.24 WD 2047 + 372

Completeness limits for the images of WD2047+372

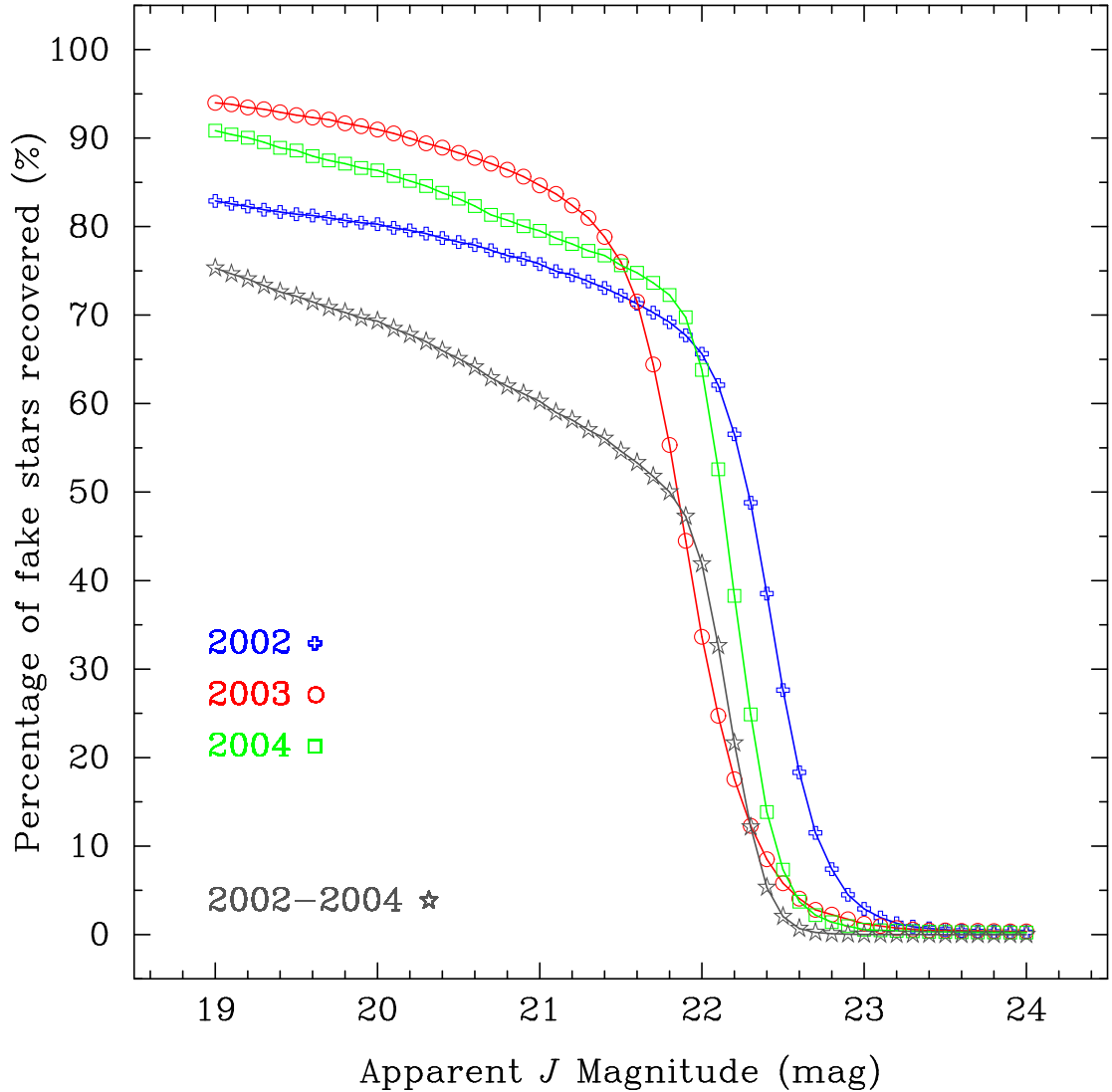


FIGURE 4.45. The percentage of artificial stars recovered by SExtractor from the 2002 first epoch image (blue crosses), the 2003 second epoch image (red circles) and the 2004 third epoch image (green squares) acquired of the white dwarf WD 2047 + 372. The 50% limiting magnitude taken from the combined 2002–2004 curve (grey stars) is $J = 21.8$ mag.

Proper Motion Diagram for WD2047+372

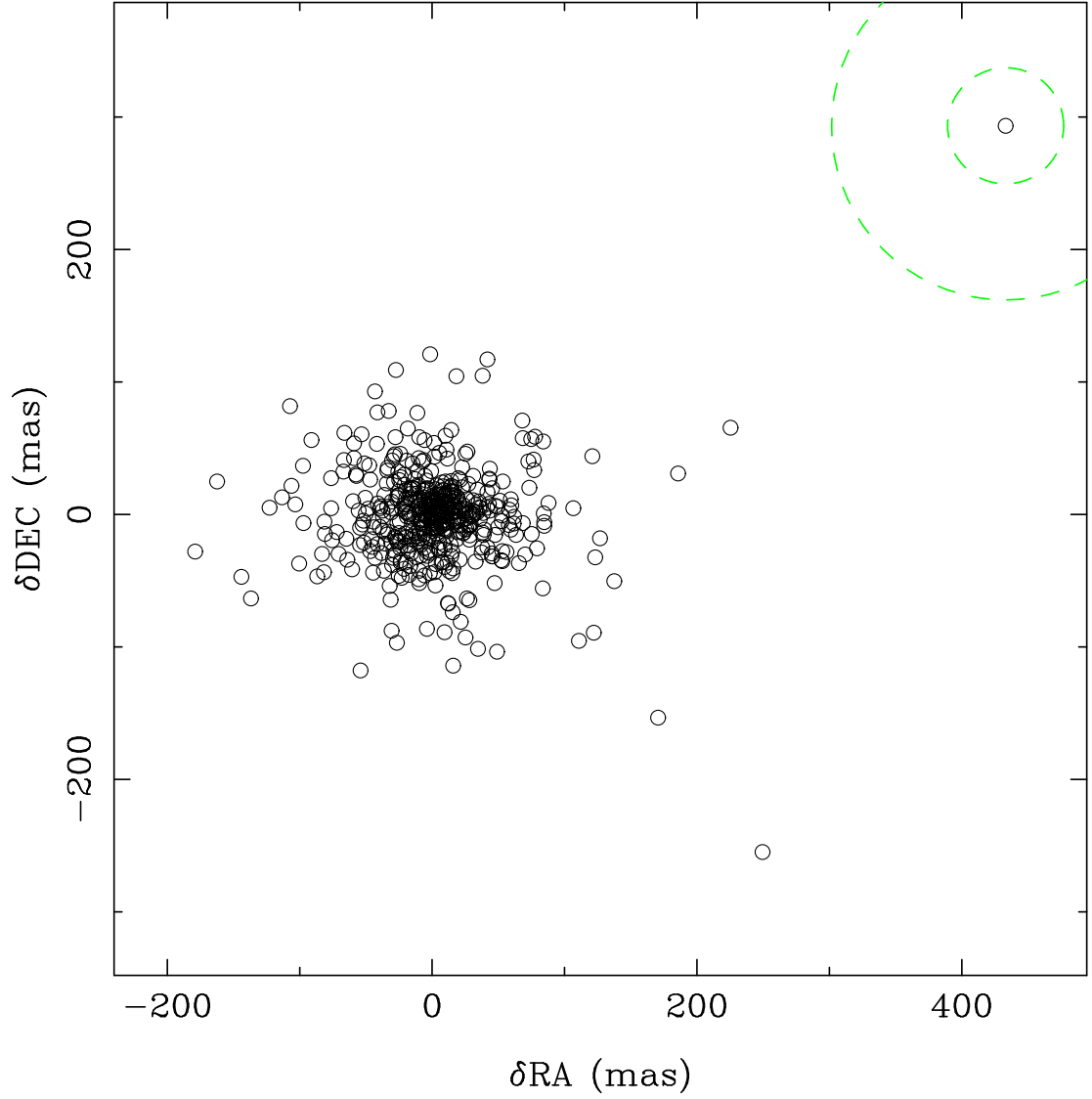


FIGURE 4.46. The motion of all objects between the 2002 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 2047 + 372. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 2047 + 372.

4.25 WD 2140 + 207

Completeness limits for the images of WD2140+207

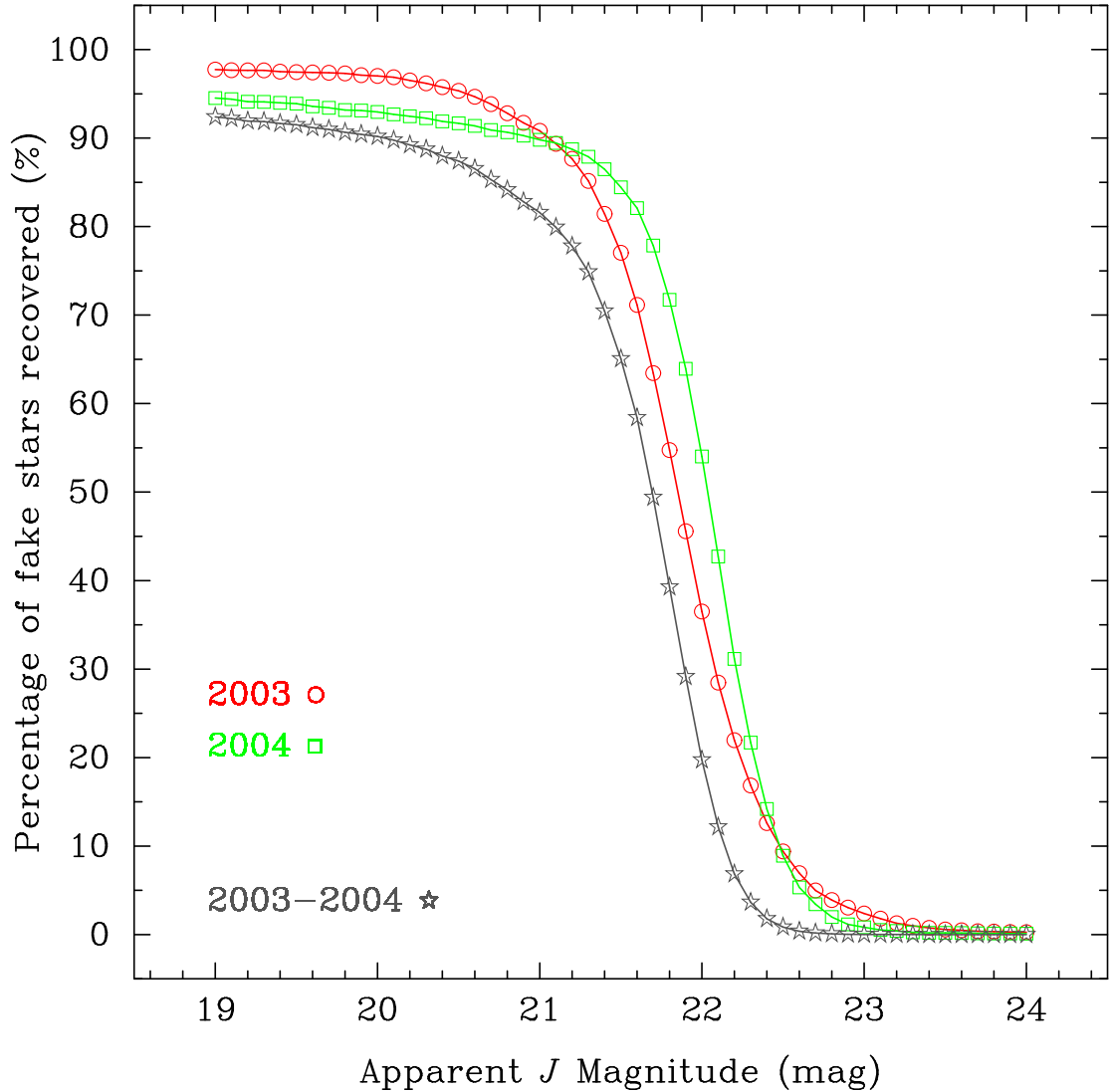


FIGURE 4.47. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 2140 + 207. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 20.0$ mag and $J = 21.6$ mag, respectively.

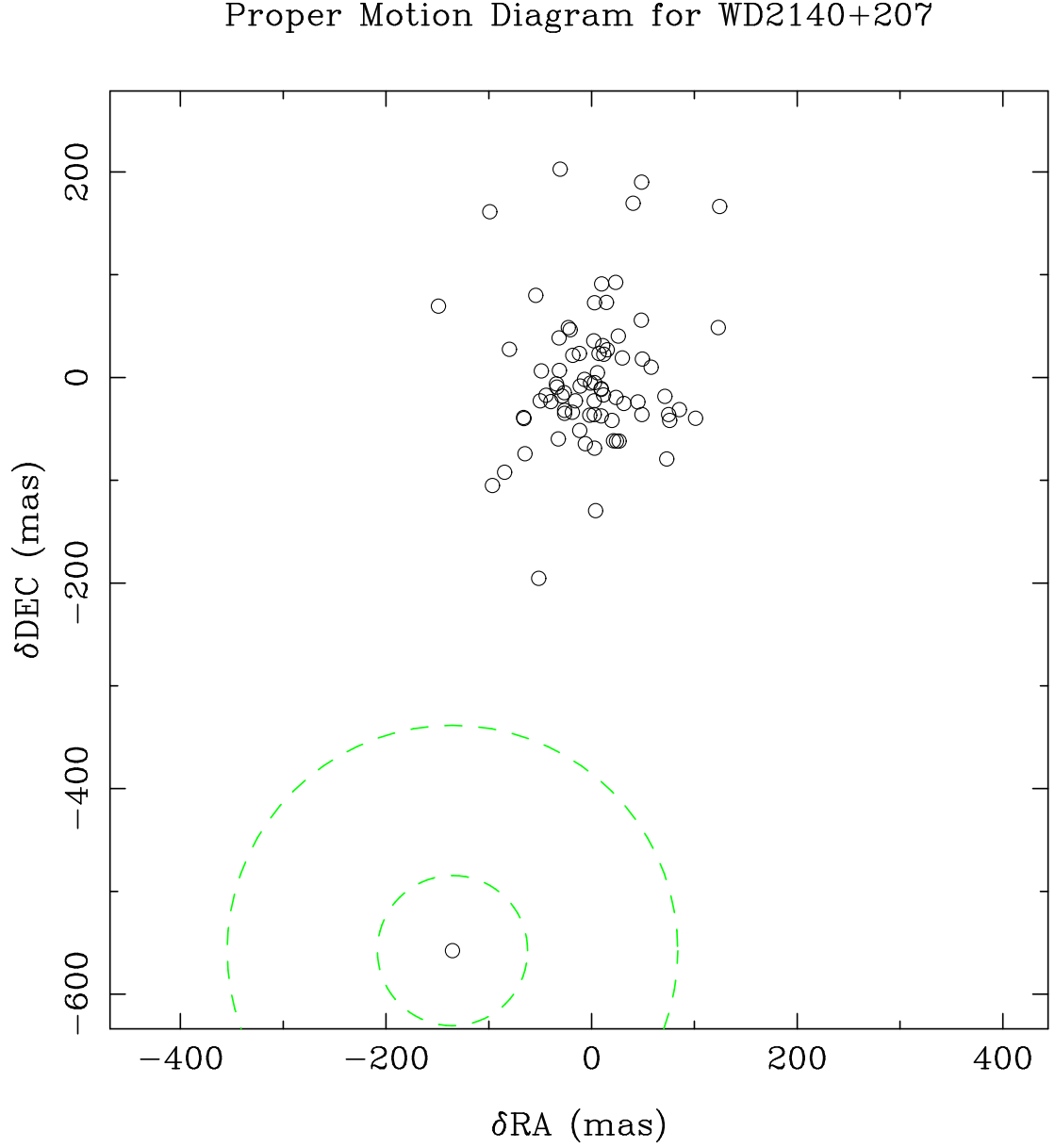


FIGURE 4.48. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 2140 + 207. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 2140 + 207.

4.26 WD 2246 + 223

Completeness limits for the images of WD2246+223

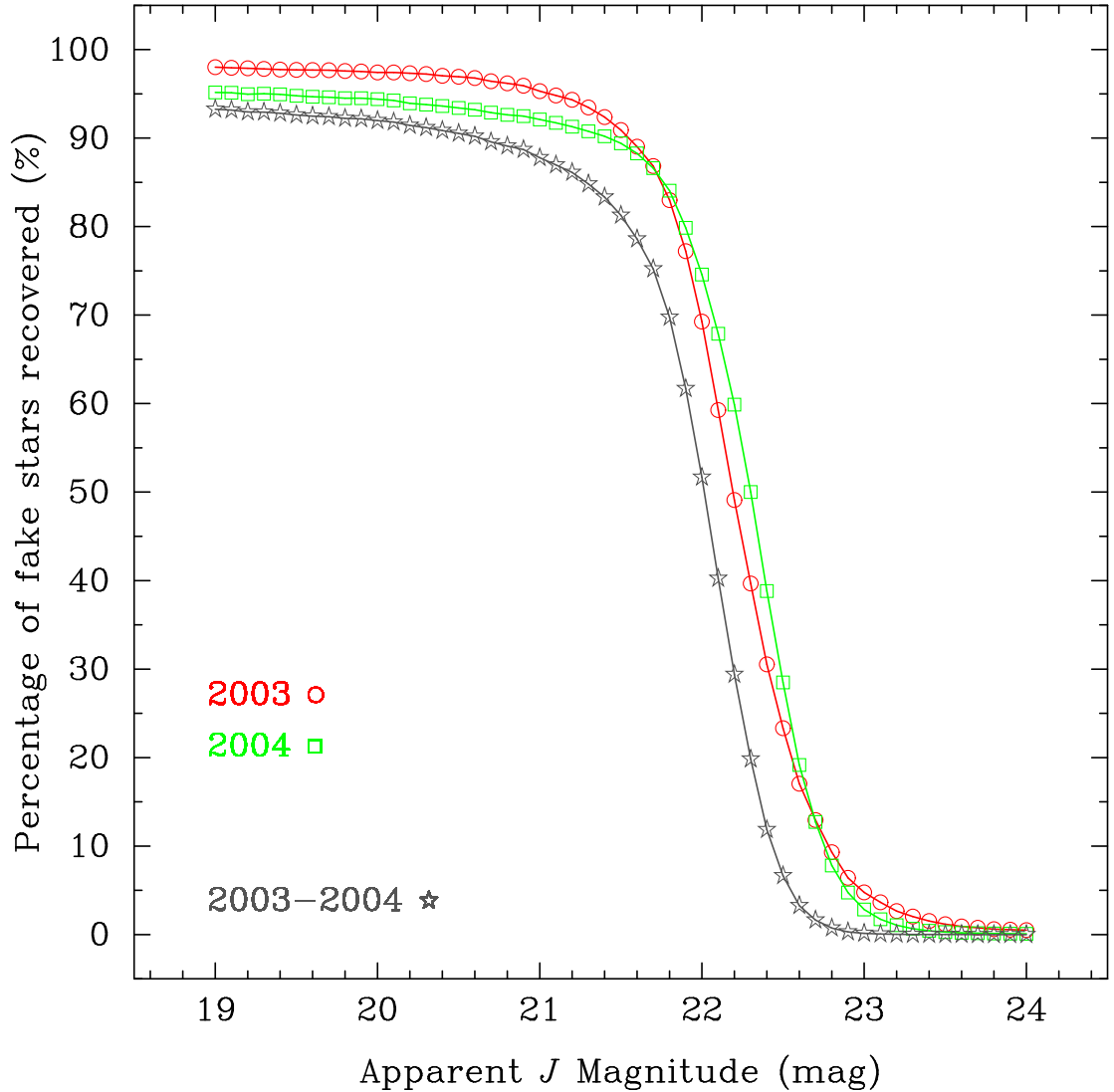


FIGURE 4.49. The percentage of artificial stars recovered by SExtractor from the 2003 first epoch image (red circles) and the 2004 second epoch image (green squares) acquired of the white dwarf WD 2246 + 223. The 90% and 50% completeness limits taken from the combined 2003–2004 curve (grey stars) are $J = 20.6$ mag and $J = 22.0$ mag, respectively.

Proper Motion Diagram for WD2246+223

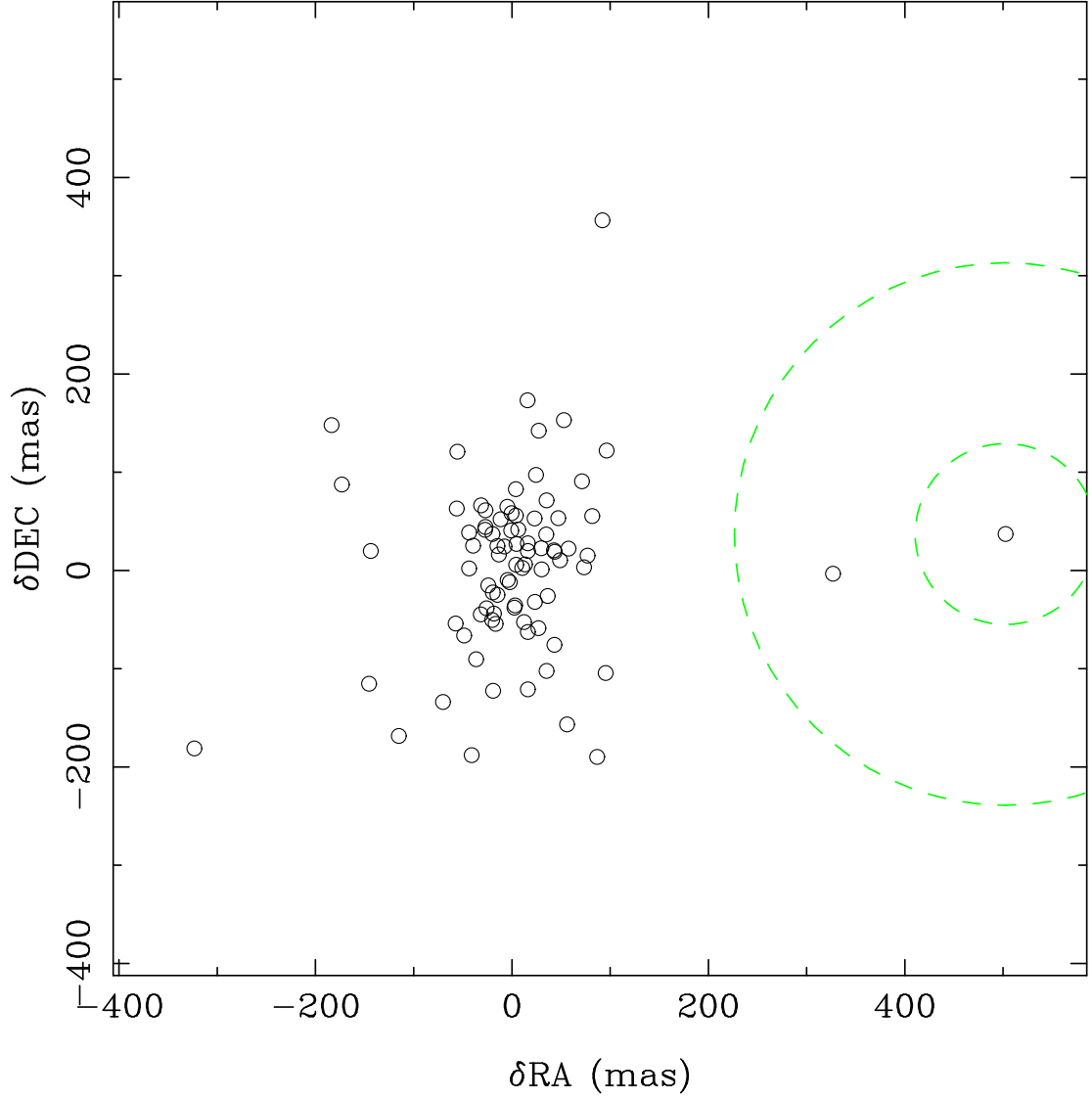


FIGURE 4.50. The motion of all objects between the 2003 first epoch image and the 2004 second epoch image acquired of the white dwarf WD 2246 + 223. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf.

4.27 WD 2326 + 049

Completeness limits for the images of WD2326+049

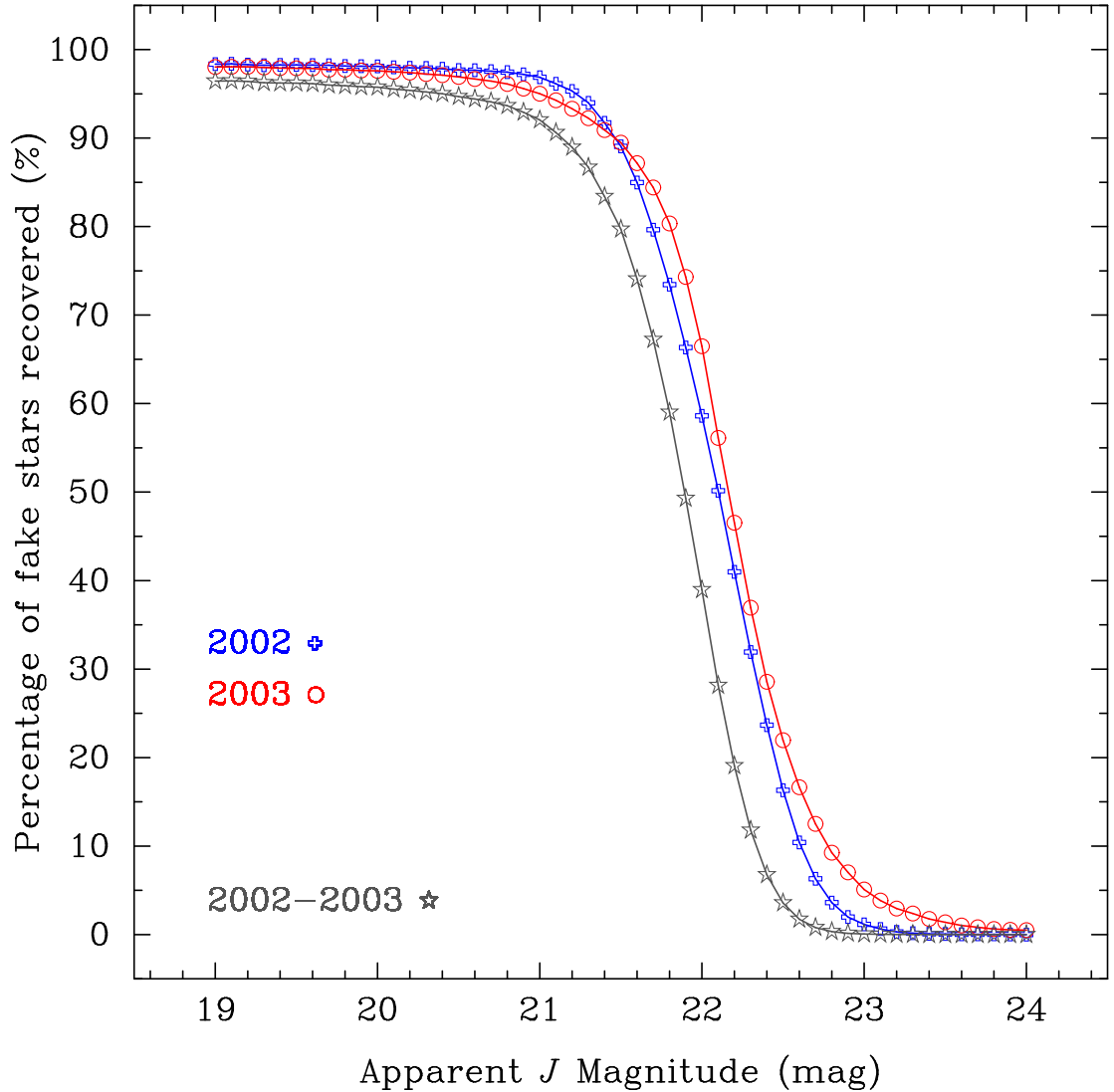


FIGURE 4.51. The percentage of artificial stars recovered by SExtractor from the 2002 first epoch image (blue crosses) and the 2003 second epoch image (red circles) acquired of the white dwarf WD 2326 + 049. The 90% and 50% completeness limits taken from the combined 2002–2003 curve (grey stars) are $J = 21.1$ mag and $J = 21.8$ mag, respectively.

Proper Motion Diagram for WD2326+049

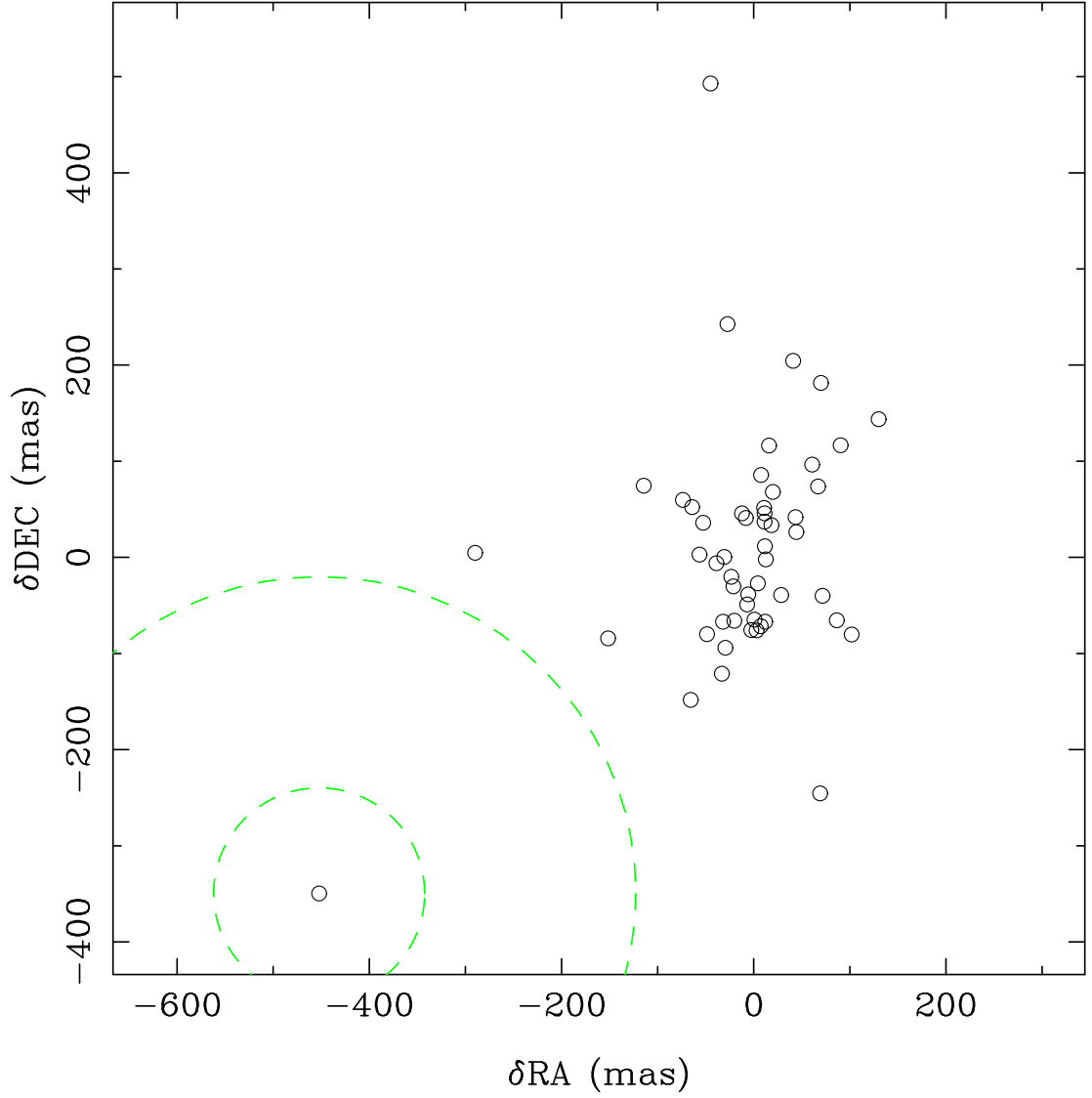


FIGURE 4.52. The motion of all objects between the 2002 first epoch image and the 2003 second epoch image acquired of the white dwarf WD 2326 + 049. The green dashed circles represent the 1σ and 3σ scatter of the distribution of the motions of all objects excluding the white dwarf, centred on the white dwarf, to help determine possible common proper motion companions to the white dwarf. There are no objects with a similar proper motion to WD 2326 + 049.

4.28 Limits

The “COND” evolutionary models for cool brown dwarfs and extrasolar planets (Baraffe et al., 2003), along with the magnitudes at which 90% and 50% of artificial stars were recovered, were used to estimate the minimum mass of a companion which could be detected in both epoch images. These models predict the absolute magnitudes of substellar objects depending upon their age. The age of a companion found in orbit around a white dwarf is equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, both of which depend upon evolutionary models. While the cooling age errors are relatively well constrained, the main sequence progenitor lifetimes are notoriously difficult to calculate. In addition, the initial final mass relation (IFMR; Equation 1.5) is an empirical relation based on the measurements of a small number of white dwarfs found in open clusters and has only been determined down to white dwarf masses of $0.54 M_{\odot}$. To take all these uncertainties into account, a conservative error of $\pm 25\%$ is applied to the total age of each white dwarf. However, at ages > 1 Gyr, the “COND” evolutionary models indicate that the absolute magnitudes of substellar objects are relatively insensitive to changes in their age, implying that even with a $\pm 25\%$ error, the resulting error on the mass of a companion is small (Table 4.1). It is noted that the masses predicted by the evolutionary models of Burrows, Sudarsky and Lunine (2003) are very similar to the masses predicted by the “COND” evolutionary models (Baraffe et al., 2003).

The detection of a companion with a mass equal to the minimum mass determined using

the completeness limit will only be possible if the companion is outside the extent of the point spread function (PSF) of the white dwarf. PSF subtraction was not attempted, since recent mid infrared (MIR) photometry of a number of the white dwarfs in the DODO survey, acquired using the Spitzer Space Telescope (Werner et al., 2004), would have detected any unresolved companions (Mullally et al., 2007). In addition, it is expected that the orbital radius of any companions that avoid direct contact with the red giant envelope will expand (Section 2.2), which would increase the projected physical separation between the companion and the white dwarf. The majority of the DODO survey observations were acquired in good seeing conditions, so the minimum projected physical separation at which a companion could be found around each white dwarf is taken to be $3''$. Beyond this distance, the contribution of the flux from the white dwarf is assumed to be minimal. The maximum projected physical separation at which a companion could be found around each white dwarf is limited by the field of view covered by both epochs. The completeness limit is only valid in the central region of each final stacked image, where all the individual images contribute. The useable field of view decreases further when the two epoch images are matched as the white dwarf is rarely positioned on the same pixels in each epoch image. The minimum and maximum projected physical separations at which a companion could be found around the main sequence progenitor can also be estimated, since the orbital radius of any companions around the main sequence progenitor will expand during stellar evolution (Section 2.2; Equation 2.4).

Table 4.1: Results for the 26 white dwarfs

White Dwarf Number	t_{mod} [Gyr]	90% J [J mag]	90% M [M_{Jup}]	90% T [K]	50% J [J mag]	50% M [M_{Jup}]	50% T [K]	WD Orbit [AU]	MS Orbit [AU]
0046 + 051	3.8	20.9	9_{-2}^{+0}	330	22.7	7_{-1}^{+0}	280	13 - 190	3 - 48
0115 + 159	1.7	21.0	10_{-1}^{+2}	430	22.0	8_{-1}^{+1}	380	46 - 675	11 - 160
0148 + 467	2.5	20.4	16_{-3}^{+5}	480	21.9	10_{-1}^{+2}	390	48 - 457	14 - 138
0208 + 396	2.6	20.5	16_{-3}^{+5}	480	22.5	9_{-1}^{+1}	360	50 - 758	13 - 194
0341 + 182	3.3	22.0	13_{-2}^{+3}	400	22.9	10_{-1}^{+2}	360	57 - 801	16 - 222
0346 − 011	0.14	20.9	4_{-0}^{+1}	520	22.4	3_{-1}^{+0}	460	93 - 1323	16 - 230
0435 − 088	4.1	21.2	13_{-2}^{+3}	380	22.7	9_{-2}^{+1}	320	28 - 408	9 - 124
0438 + 108	0.90	22.2	10_{-1}^{+2}	510	23.1	9_{-2}^{+1}	480	156 - 2488	40 - 629
0644 + 375	2.1	20.5	13_{-0}^{+3}	460	22.4	8_{-1}^{+1}	360	46 - 652	17 - 236
0738 − 172	2.4	—	—	—	22.0	7_{-1}^{+1}	320	27 - 379	7 - 96
0912 + 536	3.0	20.9	13_{-2}^{+0}	410	22.1	9_{-2}^{+1}	350	31 - 419	7 - 93
1055 − 072	3.3	21.0	13_{-2}^{+3}	400	22.6	9_{-1}^{+1}	340	36 - 503	8 - 103
1121 + 216	2.3	21.2	10_{-1}^{+2}	390	22.2	8_{-1}^{+2}	350	40 - 605	9 - 134
1134 + 300	0.37	20.8	5_{-1}^{+0}	440	21.9	3_{-0}^{+1}	350	46 - 664	9 - 127
1344 + 106	2.5	20.8	16_{-3}^{+5}	480	22.0	13_{-2}^{+0}	440	60 - 865	14 - 208
1609 + 135	2.8	21.7	13_{-2}^{+3}	420	22.5	10_{-1}^{+2}	380	55 - 642	10 - 117
1626 + 368	2.2	22.1	9_{-1}^{+1}	380	22.8	8_{-1}^{+1}	360	48 - 535	13 - 141

Table 4.1: Results for the 26 white dwarfs

White Dwarf Number	t_{mod} [Gyr]	90% J [J mag]	90% M [M_{Jup}]	90% T [K]	50% J [J mag]	50% M [M_{Jup}]	50% T [K]	WD Orbit [AU]	MS Orbit [AU]
1633 + 433	3.0	21.1	13^{+3}_{-0}	410	22.3	10^{+2}_{-2}	370	45 - 533	10 - 123
1647 + 591	0.91	19.6	9^{+1}_{-1}	480	22.0	5^{+0}_{-1}	350	33 - 372	7 - 77
1900 + 705	1.1	21.2	7^{+1}_{-1}	400	22.2	5^{+1}_{-0}	330	39 - 452	8 - 89
1953 - 011	2.1	19.2	16^{+5}_{-0}	510	21.7	8^{+1}_{-1}	360	34 - 509	7 - 111
2007 - 219	1.4	21.5	9^{+1}_{-2}	430	22.2	7^{+1}_{-1}	370	55 - 831	12 - 189
2047 + 372	0.89	—	—	—	21.8	6^{+1}_{-0}	390	54 - 202	12 - 46
2140 + 207	4.4	20.0	21^{+0}_{-0}	490	21.6	13^{+3}_{-0}	370	38 - 542	13 - 181
2246 + 223	1.7	20.6	13^{+3}_{-0}	490	22.0	9^{+1}_{-1}	400	57 - 835	11 - 157
2326 + 049	1.1	21.1	7^{+1}_{-1}	400	21.8	6^{+1}_{-1}	370	41 - 396	9 - 89

Columns: t_{mod} is the “COND” evolutionary model age used; 90% and 50% gives the 90% and 50% completeness limits in terms of apparent J magnitude, mass (measured in Jupiter masses) and effective temperature (measured in Kelvin), respectively; WD Orbit is the range of projected physical separations at which a companion of that mass could be found around the white dwarf, measured in AU; MS Orbit is the range of projected physical separations at which a companion of that mass could be found around the main sequence progenitor, measured in AU (Equation 2.4).

Chapter 5

Discussion

5.1 Overview

The DODO survey aims to obtain a direct image of an extrasolar planet in a wide orbit around a white dwarf. Any companion found in orbit around a white dwarf would have an age equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age (Section 2.4.1). The combined completeness limit, calculated from the individual completeness limits of the first epoch and second (or third) epoch images, can be used to determine the magnitude of the faintest companion that could be found in the field of view of each white dwarf (Section 3.2.3). The corresponding completeness limit in terms of Jupiter masses can then be estimated using evolutionary models for cool brown dwarfs and extrasolar planets, which can predict the mass of these substellar objects depending on their age and magnitude (Baraffe et al., 2003). This chapter will discuss the results shown in Chapter 4 for each white dwarf in turn.

5.2 WD 0046 + 051

WD 0046 + 051, also known as van Maanen’s star (vMa 2), is the closest, single white dwarf to the Sun, situated at a distance of 4.41 pc (Perryman et al., 1997). WD 0046+051 is classified as a DZ white dwarf due to the presence of metals in its atmosphere. These metals could be from the accretion of cometary material or asteroids, in a similar way to DAZ white dwarfs (Section 2.2.2), increasing the probability of the existence of an old planetary system around this white dwarf. In 2004 the presence of a substellar companion to WD 0046 + 051 was predicted from measurements of the astrometric signature (Section 1.5.3) of the white dwarf, obtained from Hipparcos data (Makarov, 2004). This alleged $0.06 \pm 0.02 M_{\odot}$ companion was separated from WD 0046 + 051 by $0.3''$ and was estimated to have an orbital period of 1.57 years. Later that year, direct L' band imaging of WD 0046 + 051, combined with adaptive optics (AO), refuted the existence of this companion (Farihi, Becklin and Macintosh, 2004). In addition, observations of WD 0046 + 051 acquired with the Infrared Space Observatory (ISO) showed no infrared (IR) excess. These observations suggest that no resolved or unresolved substellar companions exist around WD 0046 + 051. An upper limit of ~ 500 K was placed on the effective temperature of any possible companion in orbit around WD 0046 + 051 (Farihi et al., 2004).

WD 0046 + 051 is a $0.633 \pm 0.022 M_{\odot}$ white dwarf with an effective temperature, $T_{\text{eff}} = 6031 \pm 240$ K and a $\log g = 8.10 \pm 0.04$ (Burleigh et al., 2008). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 2.84 Gyr (Fontaine

et al., 2001). An object with a magnitude of $J = 22.7$ mag can be detected with a 50% probability in both the 2004 first epoch and the 2005 second epoch images of WD 0046 + 051 (Figure 4.1). If such an object was determined to be a companion to WD 0046 + 051, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 3.8 ± 0.95 Gyr. Therefore, it would be possible to detect a companion with a mass of $7_{-1}^{+0} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 280 K (Baraffe et al., 2003), in orbit around WD 0046 + 051 between a projected physical separation of $13 - 190$ AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.2) is large enough to confidently state that there are no common proper motion companions to WD 0046 + 051 within these limits. These results place a new upper limit of ~ 290 K on the effective temperature of any possible companion in orbit around WD 0046 + 051. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.3 WD 0115 + 159

WD 0115 + 159 is a $0.69 \pm 0.04 M_{\odot}$ DQ white dwarf with an effective temperature, $T_{\text{eff}} = 9050 \pm 310$ K and a $\log g = 8.19 \pm 0.07$ (Dufour et al., 2005). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 1.02 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 22.0$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 0115 +

159 (Figure 4.3). If such an object was determined to be a companion to WD 0115 + 159, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 1.7 ± 0.43 Gyr. Therefore, it would be possible to detect a companion with a mass of $8 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 380 K (Baraffe et al., 2003), in orbit around WD 0115 + 159 between a projected physical separation of 46 – 675 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.4) is large enough to confidently state that there are no common proper motion companions to WD 0115 + 159 within these limits.

5.4 WD 0148 + 467

WD 0148 + 467 is a $0.53 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 13990$ K and a $\log g = 7.89$ (Bergeron et al., 1992). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.21 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 21.9$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2005 second epoch images of WD 0148 + 467 (Figure 4.5). If such an object was determined to be a companion to WD 0148 + 467, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.5 ± 0.63 Gyr. Therefore, it would be possible to detect a companion with a mass of $10^{+2}_{-1} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 390 K (Baraffe et al., 2003), in orbit around WD 0148 + 467 between a projected

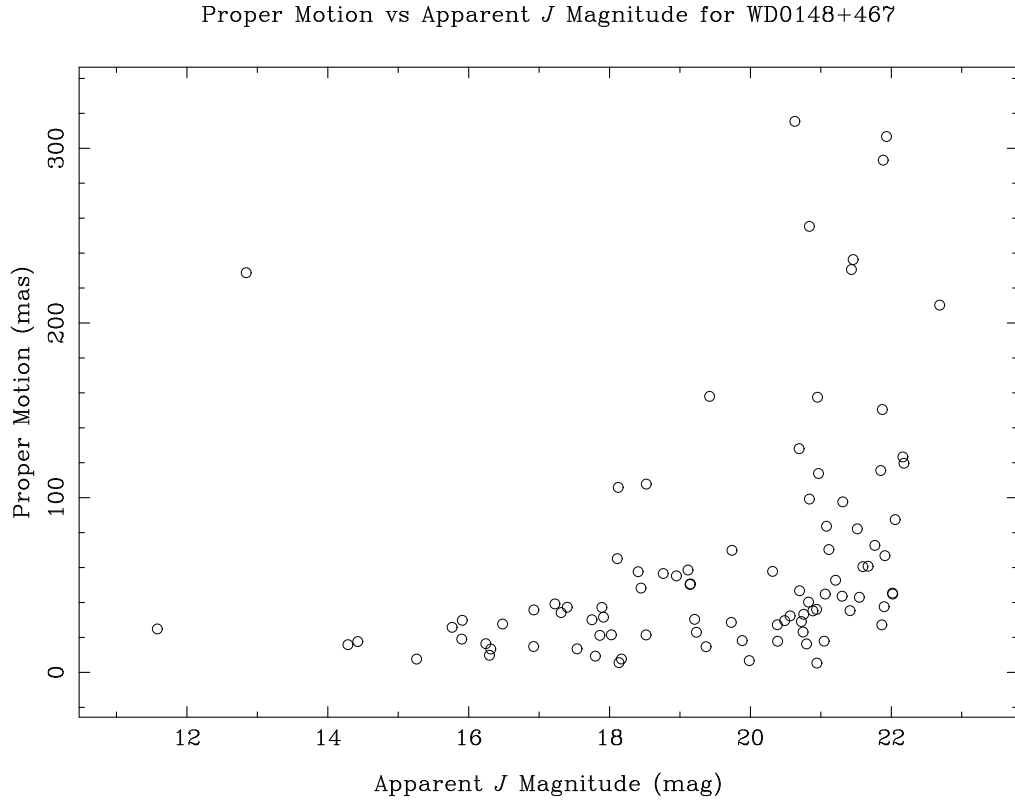


FIGURE 5.1. The motion of the objects between the 2003 first epoch and 2005 second epoch images of WD 0148 + 467. The white dwarf has a magnitude of $J \sim 13$ mag.

physical separation of 48 – 457 AU with a 50% probability (Table 4.1).

The 2003 first epoch image of WD 0148+467 was degraded by severe 60 Hz interference (Table 2.2; Section 3.1.5), which significantly decreased the completeness limit of this image (Figure 4.5). It is likely that this interference has introduced the large scatter in the motions of objects with magnitudes $J > 18$ mag between the 2003 first epoch and 2005 second epoch images (Figure 5.1). This suggests that the error on the motion of these faint objects is comparable to the motion of WD 0148 + 467. As a result, multiple

objects appear to have motions similar to the motion of the white dwarf (Figure 4.6). Real common proper motion companions to WD 0148 + 467 cannot be distinguished from non-moving background objects. Therefore, a third epoch image is required to determine if any of these objects are genuine common proper motion companions.

5.5 WD 0208 + 396

WD 0208 + 396 is a $0.60 \pm 0.05 M_{\odot}$ DAZ white dwarf with an effective temperature, $T_{\text{eff}} = 7310 \pm 180$ K, a $\log g = 8.01 \pm 0.09$ and a white dwarf cooling age, $t_{\text{WD}} = 1.38 \pm 0.17$ Gyr (Bergeron et al., 2001). Although no dust disk has been found in orbit around WD 0208 + 396, the presence of metals in its atmosphere may indicate the existence of an old planetary system (Section 2.2.2). A previous imaging search in the IR using the Hubble Space Telescope (HST) suggests that no substellar companions with a mass $> 10 M_{\text{Jup}}$ exist around WD 0208 + 396 between $0.9 - 10''$ (Debes, Sigurdsson and Woodgate, 2005b). At a distance of 16.72 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 15 – 167 AU.

An object with a magnitude of $J = 22.5$ mag can be detected with a 50% probability in both the 2004 first epoch and the 2005 second epoch images of WD 0208 + 396 (Figure 4.7). If such an object was determined to be a companion to WD 0208 + 396, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.6 ± 0.65 Gyr. Therefore, it would be possible to

detect a companion with a mass of $9 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 360 K (Baraffe et al., 2003), in orbit around WD 0208 + 396 between a projected physical separation of 50 – 758 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.8) is large enough to confidently state that there are no common proper motion companions to WD 0208 + 396 within these limits. These results place a new upper limit of $9 \pm 1 M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 0208 + 396. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.6 WD 0341 + 182

WD 0341 + 182 is a $0.57 \pm 0.06 M_{\odot}$ DQ white dwarf with an effective temperature, $T_{\text{eff}} = 6510 \pm 130$ K and a $\log g = 7.99 \pm 0.10$ (Dufour et al., 2005). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 1.79 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 22.9$ mag can be detected with a 50% probability in both the 2004 first epoch and the 2005 second epoch images of WD 0341 + 182 (Figure 4.9). If such an object was determined to be a companion to WD 0341 + 182, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 3.3 ± 0.83 Gyr. Therefore, it would be possible to detect a companion with a mass of $10^{+2}_{-1} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 360 K (Baraffe et al., 2003), in orbit around WD 0341 + 182 between a projected

physical separation of $57 - 801$ AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.10) is large enough to confidently state that there are no common proper motion companions to WD 0341 + 182 within these limits.

5.7 WD 0346 – 011

WD 0346 – 011, also known as GD 50, is the youngest, hottest and most massive white dwarf in the DODO survey. This $1.27 M_{\odot}$ DA white dwarf has an effective temperature, $T_{\text{eff}} = 40540$ K and a $\log g = 9.22$ (Bergeron et al., 1992). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.076 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 22.4$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2005 second epoch images of WD 0346 – 011 (Figure 4.11). If such an object was determined to be a companion to WD 0346 – 011, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 0.14 ± 0.035 Gyr. Therefore, it would be possible to detect a companion with a mass of $3_{-1}^{+0} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 460 K (Baraffe et al., 2003), in orbit around WD 0346 – 011 between a projected physical separation of $93 - 1323$ AU with a 50% probability (Table 4.1).

Due to the low proper motion of WD 0346 – 011 (Table 2.1), multiple objects appear

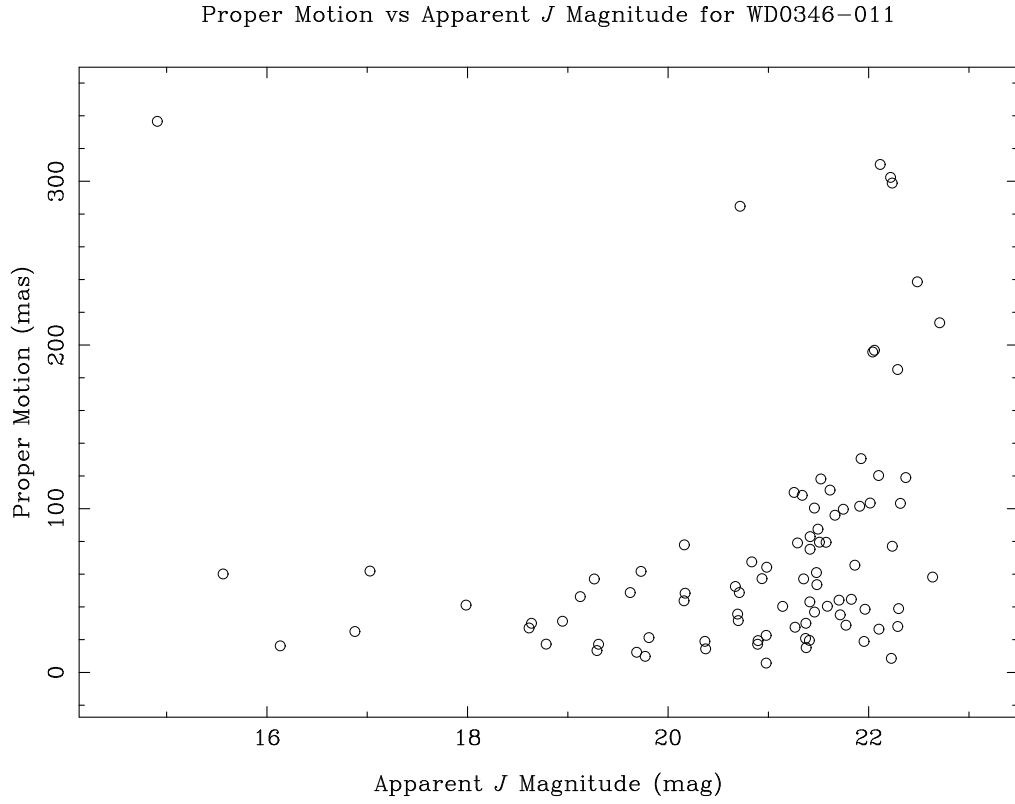


FIGURE 5.2. The motion of the objects between the 2003 first epoch and 2005 second epoch images of WD 0346 – 011. The white dwarf has a magnitude of $J \sim 15$ mag.

to have motions similar to the motion of the white dwarf (Figure 4.12). As a result, real common proper motion companions to WD 0346 – 011 cannot be distinguished from non-moving background objects (Figure 5.2). Therefore, a third epoch image is required to determine if any of these objects are genuine common proper motion companions.

5.8 WD 0435 – 088

WD 0435 – 088 is a $0.53 \pm 0.02 M_{\odot}$ DQ white dwarf with an effective temperature, $T_{\text{eff}} = 6300 \pm 110$ K and a $\log g = 7.93 \pm 0.04$ (Dufour et al., 2005). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 1.79 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 22.7$ mag can be detected with a 50% probability in both the 2004 first epoch and the 2005 second epoch images of WD 0435 – 088 (Figure 4.13). If such an object was determined to be a companion to WD 0435 – 088, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 4.1 ± 1.03 Gyr. Therefore, it would be possible to detect a companion with a mass of $9_{-2}^{+1} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 320 K (Baraffe et al., 2003), in orbit around WD 0435 – 088 between a projected physical separation of 28 – 408 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.14) is large enough to confidently state that there are no common proper motion companions to WD 0435 – 088 within these limits.

5.9 WD 0438 + 108

WD 0438 + 108 is a $0.64 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 27230$ K and a $\log g = 8.05$ (Bergeron et al., 1992). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.02 Gyr (Fontaine et al., 2001).

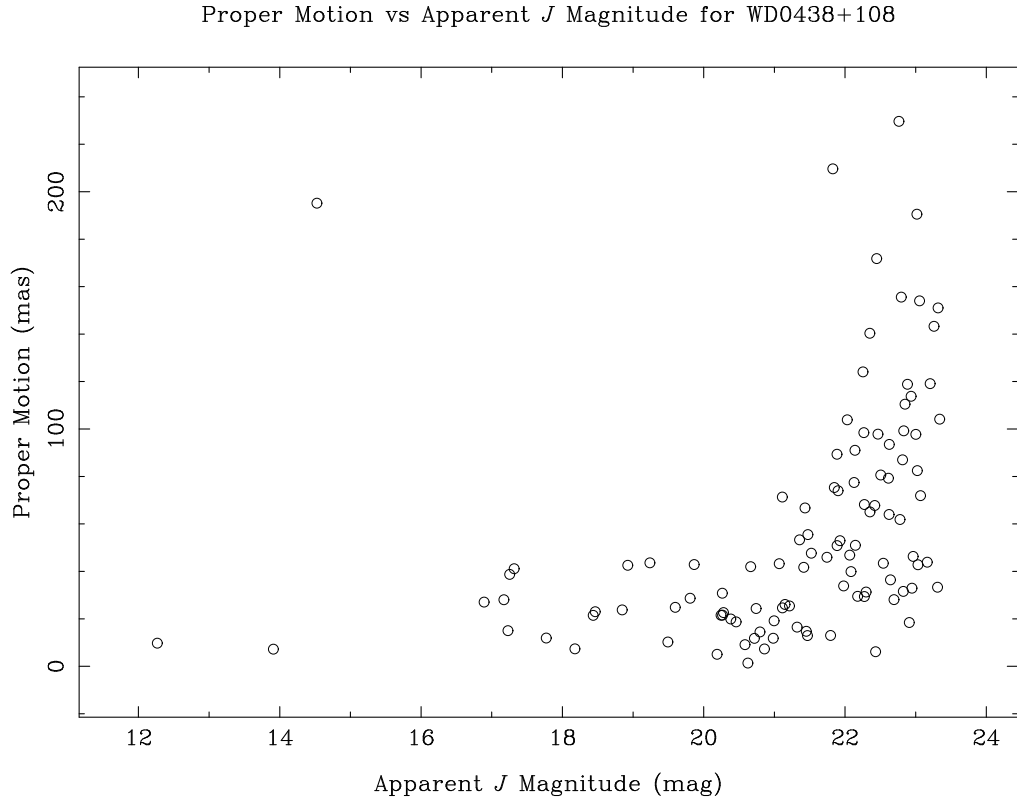


FIGURE 5.3. The motion of the objects between the 2003 first epoch and 2005 second epoch images of WD 0438 + 108. The white dwarf has a magnitude of $J \sim 14.5$ mag.

WD 0438 + 108 is a known member of the Hyades open cluster, which is situated at a distance of ~ 46 pc and has an age of 0.625 ± 0.050 Gyr (Perryman et al., 1998). An object with a magnitude of $J = 23.1$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2005 second epoch images of WD 0438 + 108 (Figure 4.15). If such an object was determined to be a companion to WD 0438 + 108, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 0.90 ± 0.225 Gyr. Therefore, it would be possible to detect a companion with a mass of $9_{-2}^{+1} M_{\text{Jup}}$, corresponding to an effective temperature

of ~ 480 K (Baraffe et al., 2003), in orbit around WD 0438 + 108 between a projected physical separation of $156 - 2488$ AU with a 50% probability (Table 4.1).

Due to the low proper motion of WD 0438 + 108 (Table 2.1), multiple objects appear to have motions similar to the motion of the white dwarf (Figure 4.16). As a result, real common proper motion companions to WD 0438 + 108 cannot be distinguished from non-moving background objects (Figure 5.3). Therefore, a third epoch image is required to determine if any of these objects are genuine common proper motion companions.

5.10 WD 0644 + 375

WD 0644 + 375 is a $0.54 M_{\odot}$ (Fontaine et al., 2007) DA white dwarf with an effective temperature, $T_{\text{eff}} = 21060$ K and a $\log g = 8.10$ (Bergeron et al., 1992). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.07 Gyr (Fontaine et al., 2001). The mass of WD 0644 + 375 was determined by assuming that the core of this white dwarf is made partly of strange matter (Mathews et al., 2006). This unusual core composition was suggested as a way to explain the inconsistency between the radius determined from the parallax of WD 0644 + 375, obtained from Hipparcos data, and the radius predicted using a mass-radius relation, which assumes the core of the white dwarf is composed primarily of carbon (Provencal et al., 1998). The mass of the white dwarf, originally determined by Bergeron et al. (1992) to be $0.66 M_{\odot}$, predicted a radius that was significantly larger than predicted using the parallax. Therefore, the slightly lower

mass of $0.54 M_{\odot}$ (Fontaine et al., 2007) is used to determine the total age of the white dwarf, since this mass provides a radius consistent with observations. An object with a magnitude of $J = 22.4$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 0644 + 375 (Figure 4.17). If such an object was determined to be a companion to WD 0644 + 375, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.1 ± 0.53 Gyr. Therefore, it would be possible to detect a companion with a mass of $8 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 360 K (Baraffe et al., 2003), in orbit around WD 0644 + 375 between a projected physical separation of $46 - 652$ AU with a 50% probability (Table 4.1). In contrast, it would be possible to detect a companion with a mass of $5 \pm 1 M_{\text{Jup}}$ if a white dwarf mass of $0.66 M_{\odot}$ (Bergeron et al., 1992) is used to determine the total age of the white dwarf. The motion of this white dwarf between the first epoch and second epoch images (Figure 4.18) is large enough to confidently state that there are no common proper motion companions to WD 0644 + 375 within these limits.

5.11 WD 0738 — 172

WD 0738 — 172 is a member of a known common proper motion binary. The secondary star of this binary system is an M6 main sequence star (Monteiro et al., 2006) with an orbital radius of ~ 262 AU (Poveda et al., 1994). This $0.63 \pm 0.02 M_{\odot}$ DZ white dwarf has an effective temperature, $T_{\text{eff}} = 7710 \pm 220$ K, a $\log g = 8.09 \pm 0.03$ and a white

dwarf cooling age, $t_{\text{WD}} = 1.45 \pm 0.05$ Gyr (Bergeron et al., 2001). An object with a magnitude of $J = 22.0$ mag can be detected with a 50% probability in both the 2004 first epoch and the 2005 second epoch images of WD 0738 – 172 (Figure 4.19). If such an object was determined to be a companion to WD 0738 – 172, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.4 ± 0.6 Gyr. Therefore, it would be possible to detect a companion with a mass of $7 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 320 K (Baraffe et al., 2003), in orbit around WD 0738 – 172 between a projected physical separation of 27 – 379 AU with a 50% probability (Table 4.1). The main sequence secondary does not appear in the proper motion diagram as it was saturated in the 2005 second epoch image, making it unavailable for proper motion measurements. The overall decrease in the completeness limit, compared to the other white dwarfs, of the images acquired of WD 0738 – 172 is due to the higher proportion of artificial stars inserted within the point spread function (PSF) of the bright secondary. The motion of this white dwarf between the first epoch and second epoch images (Figure 4.20) is large enough to confidently state that there are no other common proper motion companions to WD 0738 – 172 within these limits.

5.12 WD 0912 + 536

WD 0912 + 536 is a $0.75 \pm 0.02 M_{\odot}$ DCP white dwarf with a magnetic field strength, $B = 100$ MG, a rotation period, $P = 1.3$ days (Wickramasinghe and Ferrario, 2000), an

effective temperature, $T_{\text{eff}} = 7160 \pm 190$ K, a $\log g = 8.28 \pm 0.03$ and a white dwarf cooling age, $t_{\text{WD}} = 2.54 \pm 0.16$ Gyr (Bergeron et al., 1992). A previous imaging search in the near infrared (NIR) using the Canada France Hawaii Telescope (CFHT) suggests that no substellar companions with a mass $> 12 M_{\text{Jup}}$ exist around WD 0912 + 536 between $1 - 7''$ (Debes, Ge and Ftaclas, 2006). At a distance of 10.28 pc (van Altena et al., 1995), this corresponds to a projected physical separation between $10 - 72$ AU.

An object with a magnitude of $J = 22.1$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2005 third epoch images of WD 0912 + 536 (Figure 4.21). If such an object was determined to be a companion to WD 0912 + 536, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 3.0 ± 0.75 Gyr. Therefore, it would be possible to detect a companion with a mass of $9_{-2}^{+1} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 350 K (Baraffe et al., 2003), in orbit around WD 0912 + 536 with a projected physical separation between $31 - 419$ AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.22) is large enough to confidently state that there are no common proper motion companions to WD 0912 + 536 within these limits. These results place a new upper limit of $9_{-2}^{+1} M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 0912 + 536. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.13 WD 1055 – 072

WD 1055 – 072 is a $0.85 \pm 0.04 M_{\odot}$ DC white dwarf with an effective temperature, $T_{\text{eff}} = 7420 \pm 200$ K, a $\log g = 8.42 \pm 0.06$ and a white dwarf cooling age, $t_{\text{WD}} = 3.01 \pm 0.22$ Gyr (Bergeron et al., 2001). A previous imaging search in the NIR using the CFHT suggests that no substellar companions with a mass $> 14 M_{\text{Jup}}$ exist around WD 1055 – 072 between $1 - 7''$ (Debes et al., 2006). At a distance of 12.15 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 12 – 85 AU.

An object with a magnitude of $J = 22.6$ mag can be detected with a 50% probability in both the 2004 first epoch and the 2005 second epoch images of WD 1055 – 072 (Figure 4.23). If such an object was determined to be a companion to WD 1055 – 072, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 3.3 ± 0.83 Gyr. Therefore, it would be possible to detect a companion with a mass of $9 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 340 K (Baraffe et al., 2003), in orbit around WD 1055 – 072 between a projected physical separation of 36 – 503 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.24) is large enough to confidently state that there are no common proper motion companions to WD 1055 – 072 within these limits. These results place a new upper limit of $9 \pm 1 M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 1055 – 072. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.14 WD 1121 + 216

WD 1121 + 216 is a $0.72 \pm 0.03 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 7490 \pm 180$ K, a $\log g = 8.20 \pm 0.05$ and a white dwarf cooling age, $t_{\text{WD}} = 1.76 \pm 0.22$ Gyr (Bergeron et al., 2001). A previous imaging search in the NIR using the CFHT suggests that no substellar companions with a mass $> 11 M_{\text{Jup}}$ exist around WD 1055–072 between $1-7''$ (Debes et al., 2006). At a distance of 13.44 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 13 – 94 AU.

An object with a magnitude of $J = 22.2$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2005 third epoch images of WD 1121 + 216 (Figure 4.25). If such an object was determined to be a companion to WD 1121 + 216, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.3 ± 0.58 Gyr. Therefore, it would be possible to detect a companion with a mass of $8_{-1}^{+2} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 350 K (Baraffe et al., 2003), in orbit around WD 1121 + 216 between a projected physical separation of 40 – 605 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.26) is large enough to confidently state that there are no common proper motion companions to WD 1121 + 216 within these limits. These results place a new upper limit of $8_{-1}^{+2} M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 1121 + 216. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.15 WD 1134 + 300

WD 1134 + 300 is a $0.96 \pm 0.03 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 21280 \pm 180$ K, a $\log g = 8.55 \pm 0.05$ and a white dwarf cooling age, $t_{\text{WD}} = 0.20 \pm 0.22$ Gyr (Liebert et al., 2005). An object with a magnitude of $J = 21.9$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2005 second epoch images of WD 1134 + 300 (Figure 4.27). If such an object was determined to be a companion to WD 1134 + 300, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 0.37 ± 0.093 Gyr. Therefore, it would be possible to detect a companion with a mass of $3_{-0}^{+1} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 350 K (Baraffe et al., 2003), in orbit around WD 1134 + 300 between a projected physical separation of $46 - 664$ AU with a 50% probability (Table 4.1).

The 2003 first epoch image of WD 1134 + 300 was degraded by 60 Hz interference (Table 2.2; Section 3.1.5), which significantly decreased the completeness limit of this image (Figure 4.27). It is likely that this interference has introduced the large scatter in the motions of objects with magnitudes $J > 19$ mag between the 2003 first epoch and 2005 second epoch images (Figure 5.4). This suggests that the error on the motion of these faint objects is comparable to the motion of WD 1134 + 300. As a result, multiple objects appear to have motions similar to the motion of the white dwarf (Figure 4.28). Real common proper motion companions to WD 1134 + 300 cannot be distinguished from non-moving background objects. Therefore, a third epoch image is required to

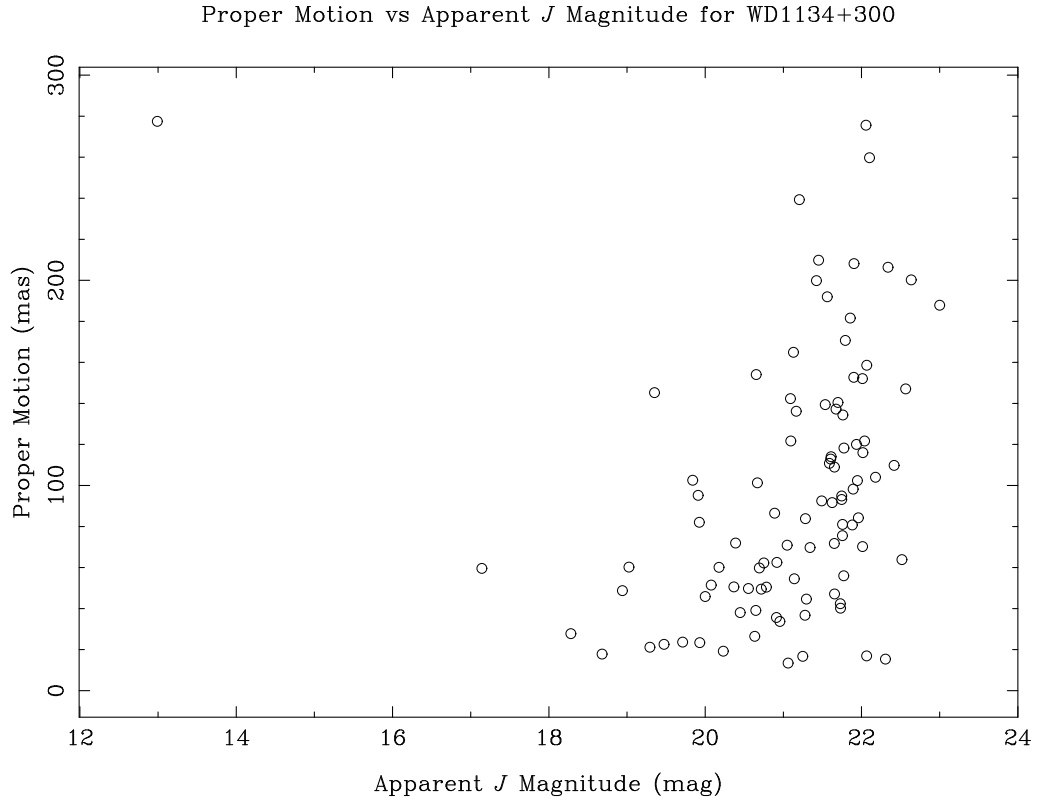


FIGURE 5.4. The motion of the objects between the 2003 first epoch and 2005 second epoch images of WD 1134 + 300. The white dwarf has a magnitude of $J \sim 13$ mag.

determine if any of these objects are genuine common proper motion companions.

5.16 WD 1344 + 106

WD 1344 + 106 is a $0.65 \pm 0.07 M_{\odot}$ DAZ white dwarf with an effective temperature, $T_{\text{eff}} = 7110 \pm 170$ K, a $\log g = 8.10 \pm 0.11$ and a white dwarf cooling age, $t_{\text{WD}} = 1.67 \pm 0.31$ Gyr (Bergeron et al., 2001). Although no dust disk has been found in orbit around WD 1344 + 106, the presence of metals in its atmosphere may indicate

the existence of an old planetary system (Section 2.2.2). An object with a magnitude of $J = 22.0$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 1344 + 106 (Figure 4.29). If such an object was determined to be a companion to WD 1344 + 106, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.5 ± 0.63 Gyr. Therefore, it would be possible to detect a companion with a mass of $13_{-2}^{+0} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 440 K (Baraffe et al., 2003), in orbit around WD 1344 + 106 between a projected physical separation of 60 – 865 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.30) is large enough to confidently state that there are no common proper motion companions to WD 1344 + 106 within these limits.

5.17 WD 1609 + 135

WD 1609+135 is a $1.07 \pm 0.06 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 9080 \pm 250$ K, a $\log g = 8.75 \pm 0.10$ and a white dwarf cooling age, $t_{\text{WD}} = 2.71 \pm 0.17$ Gyr (Bergeron et al., 2001). An object with a magnitude of $J = 22.5$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 1609 + 135 (Figure 4.31). If such an object was determined to be a companion to WD 1609 + 135, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.8 ± 0.7 Gyr. Therefore, it would be possible to detect a companion with a mass of $10_{-1}^{+2} M_{\text{Jup}}$, corresponding to

an effective temperature of ~ 380 K (Baraffe et al., 2003), in orbit around WD 1609 + 135 between a projected physical separation of 55 – 642 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.32) is large enough to confidently state that there are no common proper motion companions to WD 1609 + 135 within these limits.

5.18 WD 1626 + 368

WD 1626 + 368 is a $0.60 \pm 0.03 M_{\odot}$ DZ white dwarf with an effective temperature, $T_{\text{eff}} = 8640 \pm 280$ K, a $\log g = 8.03 \pm 0.05$ and a white dwarf cooling age, $t_{\text{WD}} = 1.02 \pm 0.07$ Gyr (Bergeron et al., 2001). Recent mid infrared (MIR) observations of WD 1626 + 368 show no evidence of a dust disk (Mullally et al., 2007). However, the abundance of carbon relative to iron in the atmosphere of WD 1626 + 368 is 10 times below the solar abundance, similar to the carbon deficient asteroids in the Solar System. Therefore, external pollution from such asteroids naturally explains the abundances of the metals in the atmosphere of this white dwarf (Jura, 2006). The possible presence of asteroids in orbit around WD 1626 + 368 represents an increased probability of the existence of an old planetary system. A previous imaging search in the NIR using the CFHT suggests that no substellar companions with a mass $> 14 M_{\text{Jup}}$ exist around WD 1626 + 368 between $1 - 7''$ (Debes et al., 2006). At a distance of 15.95 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 16 – 112 AU.

An object with a magnitude of $J = 22.8$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 1626 + 368 (Figure 4.33). If such an object was determined to be a companion to WD 1626 + 368, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.2 ± 0.55 Gyr. Therefore, it would be possible to detect a companion with a mass of $8 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 360 K (Baraffe et al., 2003), in orbit around WD 1626 + 368 between a projected physical separation of $48 - 535$ AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.34) is large enough to confidently state that there are no common proper motion companions to WD 1626 + 368 within these limits. These results place a new upper limit of $8 \pm 1 M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 1626 + 368. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.19 WD 1633 + 433

WD 1633 + 433 is a $0.68 \pm 0.04 M_{\odot}$ DAZ white dwarf with an effective temperature, $T_{\text{eff}} = 6650 \pm 150$ K, a $\log g = 8.14 \pm 0.07$ and a white dwarf cooling age, $t_{\text{WD}} = 2.28 \pm 0.34$ Gyr (Bergeron et al., 2001). Although no dust disk has been found in orbit around WD 1633 + 433, the presence of metals in its atmosphere may indicate the existence of an old planetary system (Section 2.2.2). A previous imaging search in the NIR using

the CFHT suggests that no substellar companions with a mass $> 14 M_{\text{Jup}}$ exist around WD 1633+433 between $1 - 7''$ (Debes et al., 2006). At a distance of 15.11 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 15 – 106 AU.

An object with a magnitude of $J = 22.3$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 1633 + 433 (Figure 4.35). If such an object was determined to be a companion to WD 1633 + 433, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 3.0 ± 0.75 Gyr. Therefore, it would be possible to detect a companion with a mass of $10 \pm 2 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 370 K (Baraffe et al., 2003), in orbit around WD 1633 + 433 between a projected physical separation of 45 – 533 AU with a 50% probability (Table 4.1). These results place a new upper limit of $10 \pm 2 M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 1633 + 433. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

The 2003 first epoch image of WD 1633 + 433 was degraded by 60 Hz interference (Table 2.2; Section 3.1.5), which has decreased the completeness limit of this image (Figure 4.35). In addition, the 2004 second epoch image of WD 1633 + 433 was degraded by a large streak across the image, due to a source just outside the field of view of WD 1633 + 433. However, this streak is not present in the first epoch image. It is likely that these effects have introduced the large scatter in the motions of objects

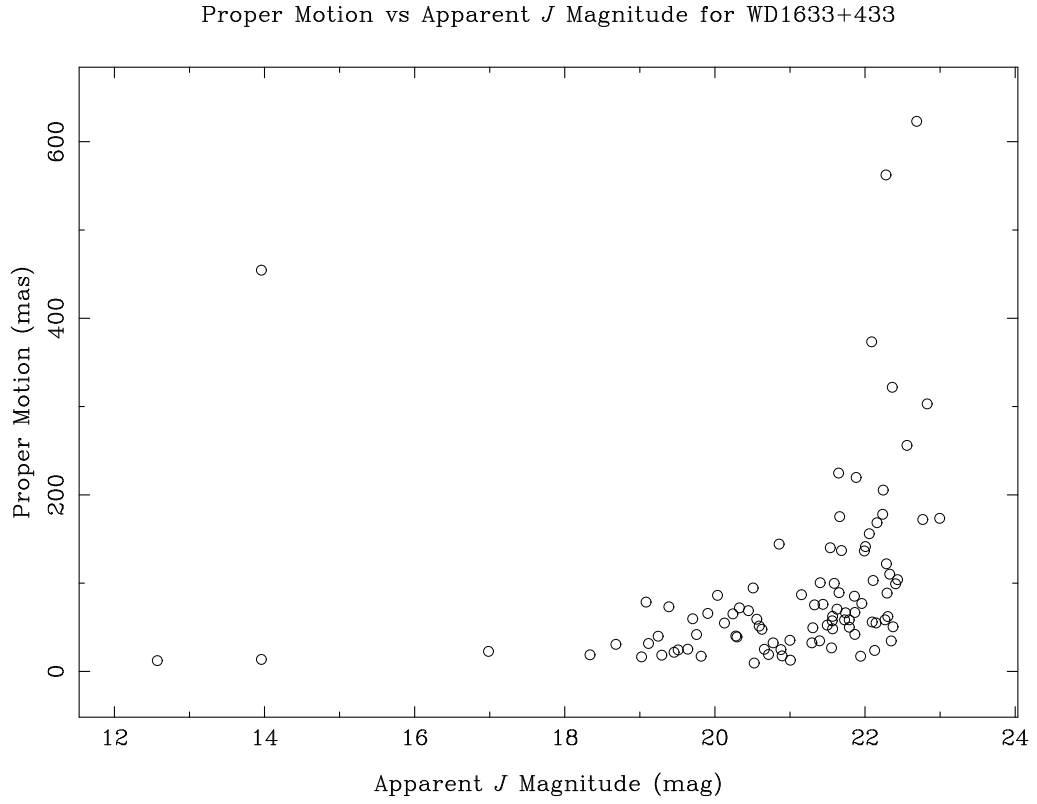


FIGURE 5.5. The motion of the objects between the 2003 first epoch and 2004 second epoch images of WD 1633 + 433. The white dwarf has a magnitude of $J \sim 14$ mag.

with magnitudes $J > 21$ mag between the 2003 first epoch and 2004 second epoch images, particularly in the region of the streak (Figure 5.5). This suggests that the error on the motion of these faint objects is comparable to the motion of WD 1633 + 433 (Table 2.1). As a result, multiple objects appear to have motions similar to the motion of the white dwarf (Figure 4.36), while the two objects with motions closest to the motion of WD 1633 + 433 lie on the streak. Real common proper motion companions to WD 1633 + 433 cannot be distinguished from non-moving background objects. Therefore, a third epoch image is required to determine if any of these objects are genuine

common proper motion companions.

5.20 WD 1647 + 591

WD 1647 + 591 is a $0.80 M_{\odot}$ pulsating DAV white dwarf with an effective temperature, $T_{\text{eff}} = 12260$ K and a $\log g = 8.31$ (Gianninas et al., 2005). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.56 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 22.0$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2005 third epoch images of WD 1647 + 591 (Figure 4.37). If such an object was determined to be a companion to WD 1647 + 591, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 0.91 ± 0.228 Gyr. Therefore, it would be possible to detect a companion with a mass of $5_{-1}^{+0} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 350 K (Baraffe et al., 2003), in orbit around WD 1647 + 591 between a projected physical separation of $33 - 372$ AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.38) is large enough to confidently state that there are no common proper motion companions to WD 1647 + 591 within these limits.

5.21 WD 1900 + 705

WD 1900+705 is a $0.95 \pm 0.02 M_{\odot}$ DAP white dwarf with a magnetic field strength, $B = 320$ MG (Wickramasinghe and Ferrario, 2000), an effective temperature, $T_{\text{eff}} = 12070 \pm 990$ K, a $\log g = 8.58 \pm 0.03$ and a white dwarf cooling age, $t_{\text{WD}} = 0.94 \pm 0.09$ Gyr (Bergeron et al., 2001). An object with a magnitude of $J = 22.2$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 1900 + 705 (Figure 4.39). If such an object was determined to be a companion to WD 1900 + 705, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 1.1 ± 0.28 Gyr. Therefore, it would be possible to detect a companion with a mass of $5_{-0}^{+1} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 330 K (Baraffe et al., 2003), in orbit around WD 1900 + 705 between a projected physical separation of $39 - 452$ AU with a 50% probability (Table 4.1).

The 2003 first epoch image of WD 1900+705 was degraded by severe 60 Hz interference (Table 2.2; Section 3.1.5), which decreased the completeness limit of this image (Figure 4.39). It is likely that this interference has introduced the large scatter in the motions of objects with magnitudes $J > 19$ mag between the 2003 first epoch and 2004 second epoch images (Figure 5.6). This suggests that the error on the motion of these faint objects is comparable to the motion of WD 1900 + 705 (Table 2.1). As a result, multiple objects appear to have motions similar to the motion of the white dwarf (Figure 4.40). Real common proper motion companions to WD 1900 + 705 cannot be distinguished

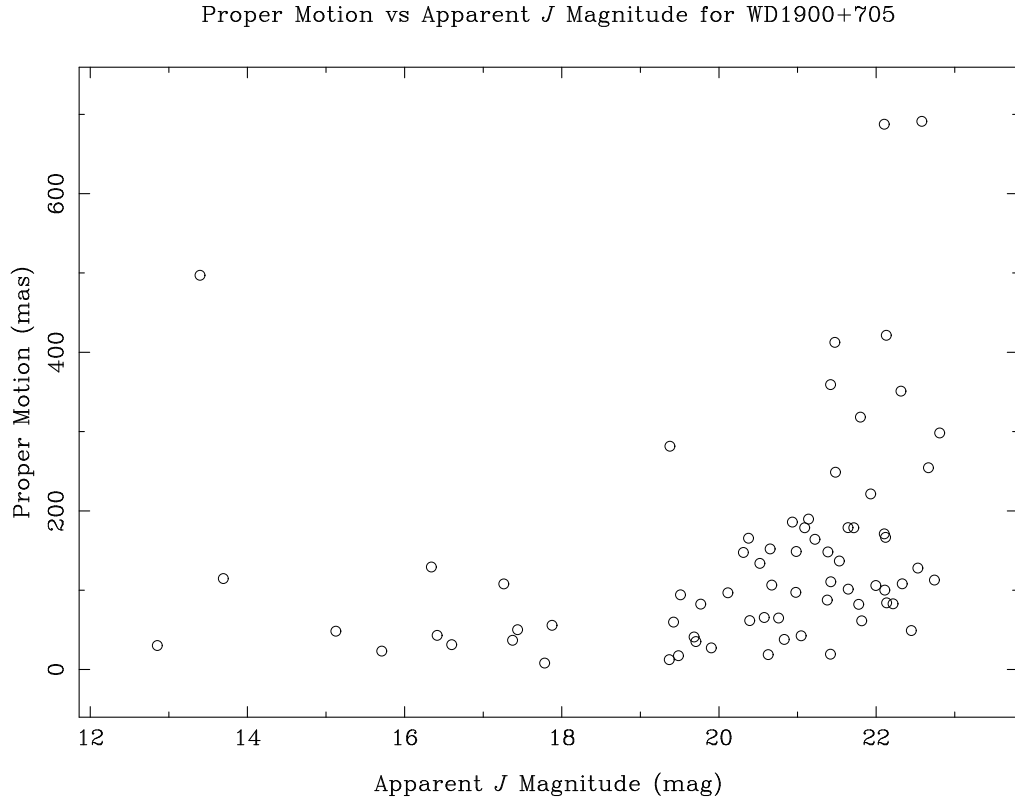


FIGURE 5.6. The motion of the objects between the 2003 first epoch and 2004 second epoch images of WD 1900 + 705. The white dwarf has a magnitude of $J \sim 13.5$ mag.

from non-moving background objects. Therefore, a third epoch image is required to determine if any of these objects are genuine common proper motion companions.

5.22 WD 1953 – 011

WD 1953 – 011 is a $0.74 \pm 0.03 M_{\odot}$ DAP white dwarf with a magnetic field strength, $B = 70$ kG, a rotation period, $P = 1.4418$ days (Brinkworth et al., 2005), an effective temperature, $T_{\text{eff}} = 7920 \pm 200$ K, a $\log g = 8.23 \pm 0.05$ and a white dwarf cooling

age, $t_{\text{WD}} = 1.63 \pm 0.16$ Gyr (Bergeron et al., 2001). WD 1953 – 011 is photometrically variable at the $\sim 2\%$ level, an effect which is believed to be caused by a star spot (Brinkworth et al., 2005). A previous imaging search in the NIR using the CFHT suggests that no substellar companions with a mass $> 10 M_{\text{Jup}}$ exist around WD 1953 – 011 between $1 - 7''$ (Debes et al., 2006). At a distance of 11.39 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 11 – 80 AU.

An object with a magnitude of $J = 21.7$ mag can be detected with a 50% probability in both the 2002 first epoch and the 2003 second epoch images of WD 1953 – 011 (Figure 4.41). If such an object was determined to be a companion to WD 1953 – 011, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 2.1 ± 0.53 Gyr. Therefore, it would be possible to detect a companion with a mass of $8 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 360 K (Baraffe et al., 2003), in orbit around WD 1953 – 011 between a projected physical separation of 34 – 509 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.42) is large enough to confidently state that there are no common proper motion companions to WD 1953 – 011 within these limits. These results place a new upper limit of $8 \pm 1 M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 1953 – 011. In addition, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.23 WD 2007 – 219

WD 2007 – 219 is a $0.69 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 9887 \pm 9$ K and a $\log g = 8.14 \pm 0.02$ (Koester et al., 2001). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.76 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 22.2$ mag can be detected with a 50% probability in both the 2002 first epoch and the 2003 second epoch images of WD 2007 – 219 (Figure 4.43). If such an object was determined to be a companion to WD 2007 – 219, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 1.4 ± 0.35 Gyr. Therefore, it would be possible to detect a companion with a mass of $7 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 370 K (Baraffe et al., 2003), in orbit around WD 2007 – 219 between a projected physical separation of 55 – 831 AU with a 50% probability (Table 4.1).

A single object with a magnitude of $J \sim 22$ mag appears to have a motion similar to the motion of WD 2007 – 219 (Figure 4.44). If the candidate is confirmed to be a common proper motion companion to WD 2007 – 219, it would have a mass of $7 \pm 1 M_{\text{Jup}}$ and a projected physical separation of ~ 980 AU¹. The candidate common proper motion companion is detected with a SNR of ~ 9 and ~ 11 in the first epoch (Figure 5.8) and second epoch (Figure 5.9) images, respectively. The magnitude of the motion of the candidate is ~ 440 mas. In comparison, the rms of the magnitude of the motion of the

¹This is marginally outside the maximum projected physical separation at which the completeness limit is valid, since only $\sim 54\%$ of the individual *FLAMINGOS* images contribute to this region of the 2002 final stacked image.

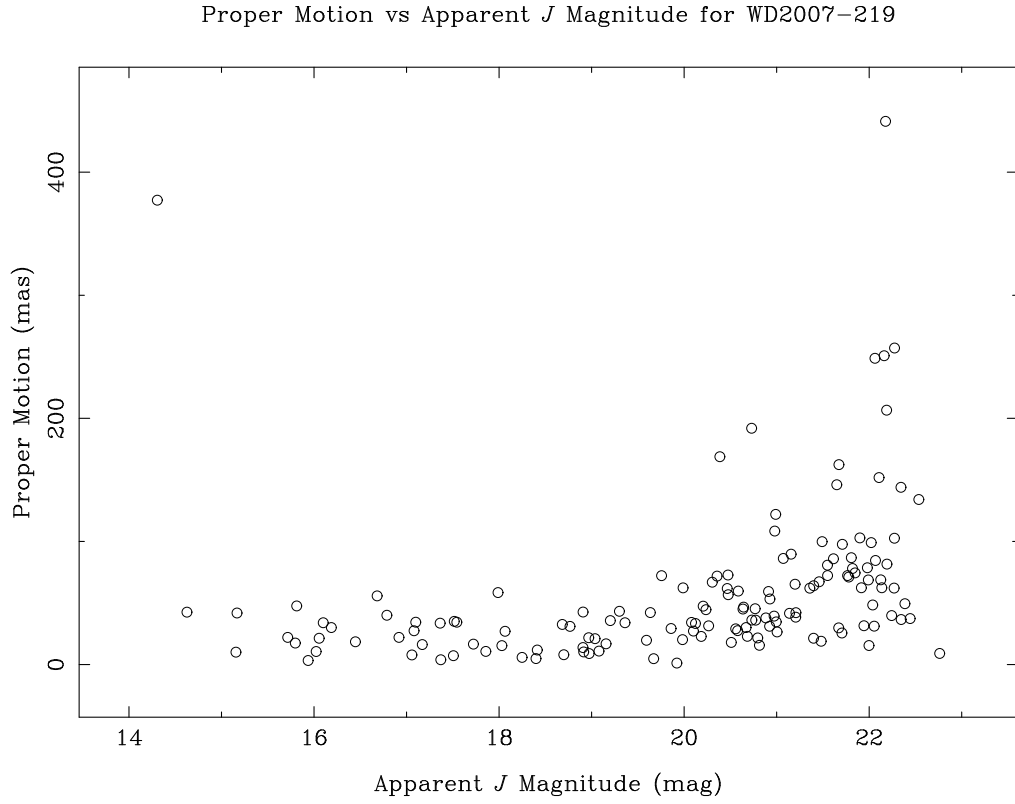


FIGURE 5.7. The motion of the objects between the 2002 first epoch and 2003 second epoch images of WD 2007 – 219. The white dwarf has a magnitude of $J \sim 14.2$ mag.

objects between $21.5 < J < 22.5$ mag is ~ 130 mas. Therefore, this candidate has a motion that is > 3 times larger than the rms, clearly separating it from the motion of the other faint objects in the field (Figure 5.7). However, the ellipticity of the candidate in the *NIRI* 2003 second epoch image is ~ 0.4 , compared to an ellipticity of ~ 0.1 in the *FLAMINGOS* 2002 first epoch image. Even though the *NIRI* second epoch image was acquired in marginally poorer observing conditions (Table 2.2), it is unlikely that this fact explains the larger ellipticity measurement. Two objects with magnitudes of $J \sim 22$ in the same quadrant as the candidate have similar ellipticities in both the 2002 first

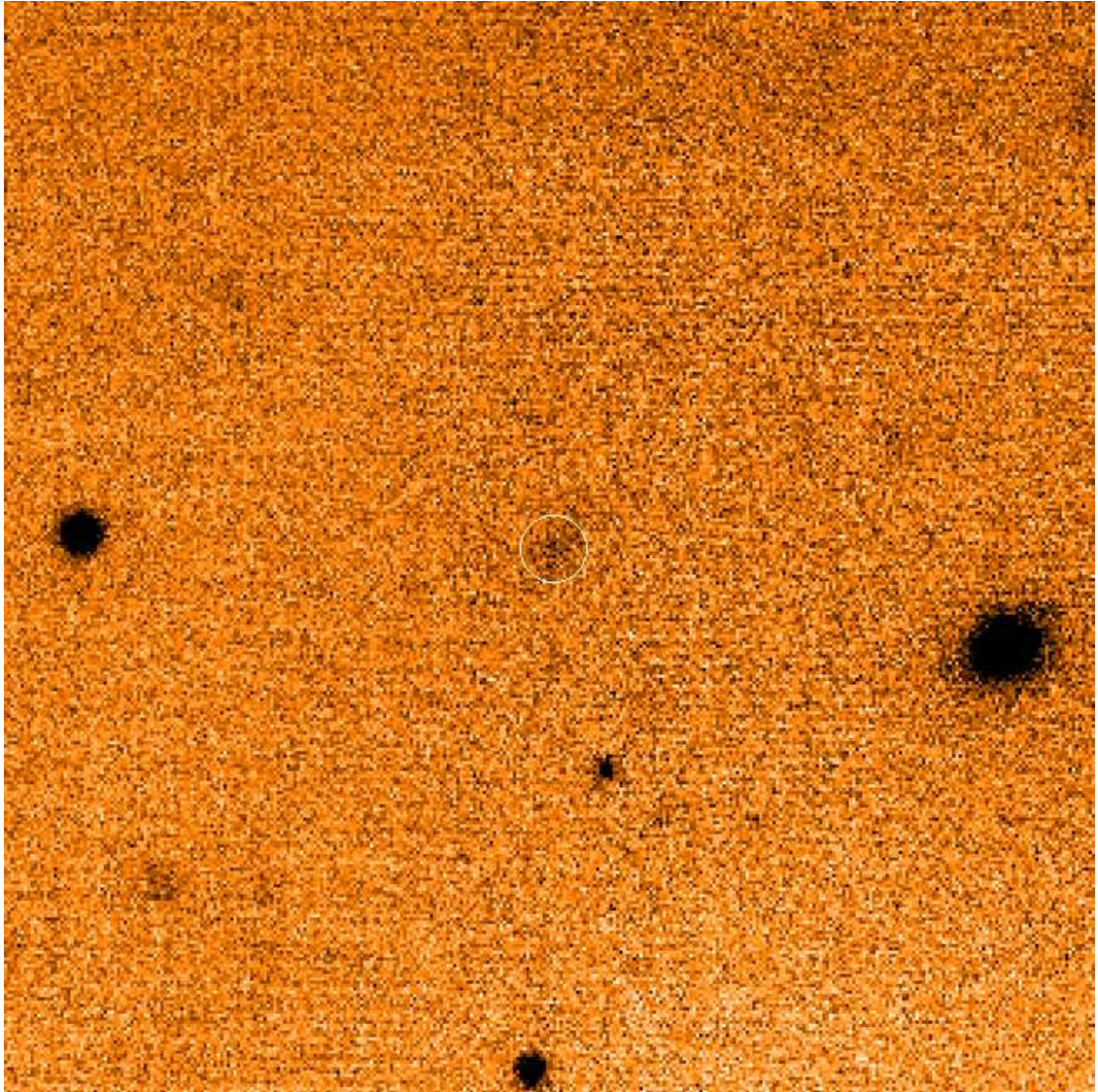


FIGURE 5.8. A close up of the candidate common proper motion companion to WD 2007 – 219, taken from the 2002 first epoch image. The image is $\sim 26'' \times 26''$. The white dwarf is $\sim 54''$ away, equivalent to a separation of ~ 980 AU.

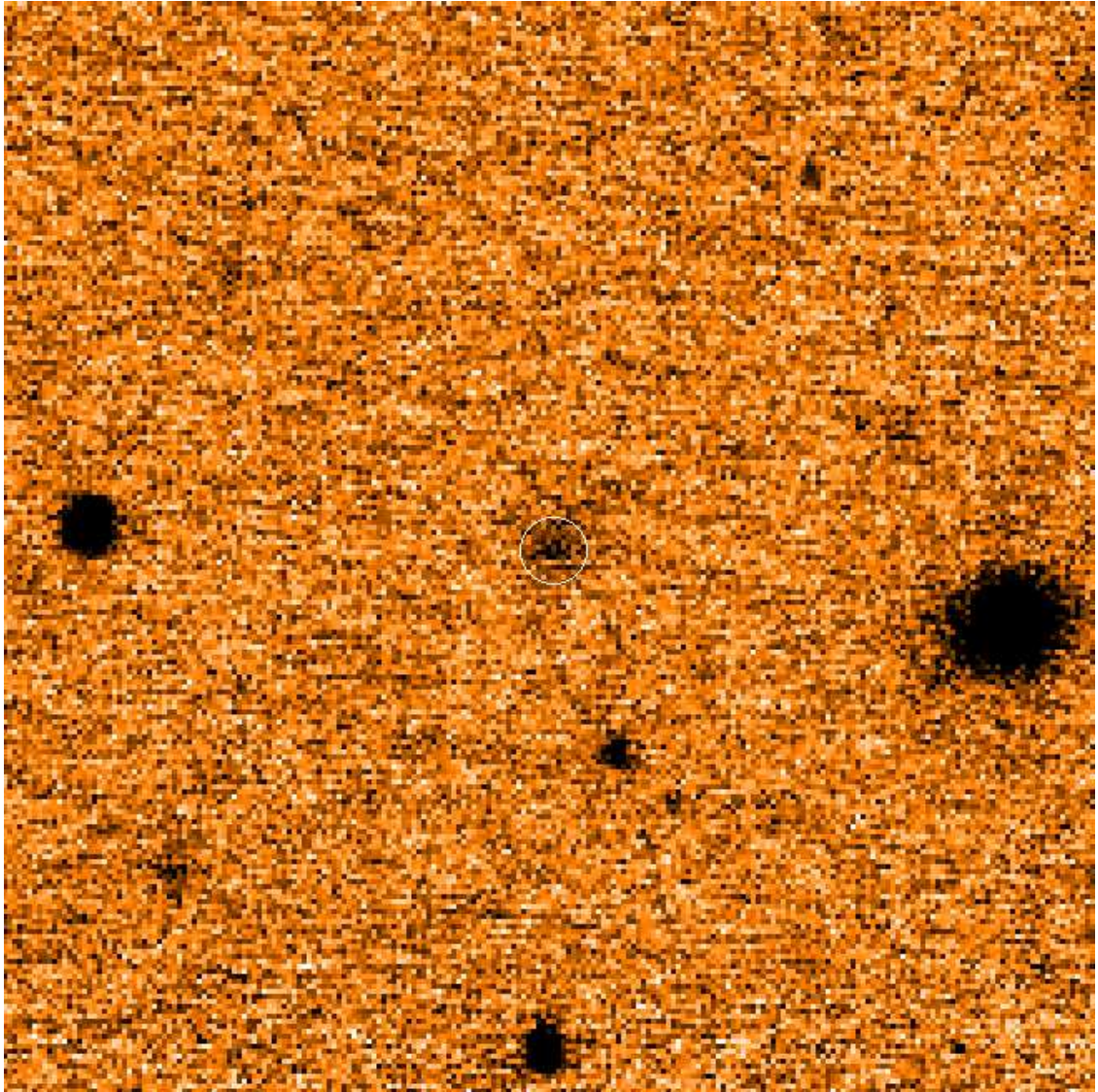


FIGURE 5.9. A close up of the candidate common proper motion companion to WD 2007–219, taken from the 2003 second epoch image. The image is $\sim 26'' \times 26''$. The white dwarf is $\sim 54''$ away, equivalent to a separation of ~ 980 AU.

epoch and 2003 second epoch images. However, these objects have very small motions (< 85 mas), suggesting that the motion of the candidate is not related to the unusually high ellipticity in the *NIRI* second epoch image. A third epoch image is required, which would determine if the candidate is a genuine common proper motion companion to WD 2007 – 219.

5.24 WD 2047 + 372

WD 2047 + 372 is a $0.69 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 14630 \pm 180$ K and a $\log g = 8.13 \pm 0.07$ (Giovannini et al., 1998). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.26 Gyr (Fontaine et al., 2001). An object with a magnitude of $J = 21.8$ mag can be detected with a 50% probability in both the 2002 first epoch and the 2004 third epoch images of WD 2047 + 372 (Figure 4.45). If such an object was determined to be a companion to WD 2047 + 372, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 0.89 ± 0.223 Gyr. Therefore, it would be possible to detect a companion with a mass of $6_{-0}^{+1} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 390 K (Baraffe et al., 2003), in orbit around WD 2047 + 372 between a projected physical separation of $54 - 202$ AU with a 50% probability (Table 4.1). The overall decrease in the completeness limit, compared to the other white dwarfs, of the images acquired of WD 2047 + 372 is due to the higher proportion of artificial stars inserted within the PSF of the large number of real stars in this extremely crowded

field. The motion of this white dwarf between the first epoch and second epoch images (Figure 4.46) is large enough to confidently state that there are no common proper motion companions to WD 2047 + 372 within these limits.

5.25 WD 2140 + 207

WD 2140 + 207 is a $0.49 \pm 0.04 M_{\odot}$ DQ white dwarf with an effective temperature, $T_{\text{eff}} = 8200 \pm 250$ K and a $\log g = 7.84 \pm 0.06$ (Dufour et al., 2005). Using the T_{eff} and $\log g$ values, the white dwarf cooling age, t_{WD} , is estimated to be 0.82 Gyr (Fontaine et al., 2001). A previous imaging search in the NIR using the CFHT suggests that no substellar companions with a mass $> 10 M_{\text{Jup}}$ exist around WD 2140 + 207 between $1 - 7''$ (Debes et al., 2006). At a distance of 12.52 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 13 – 88 AU.

An object with a magnitude of $J = 21.6$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 2140 + 207 (Figure 4.47). If such an object was determined to be a companion to WD 2140 + 207, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 4.4 ± 1.1 Gyr. Therefore, it would be possible to detect a companion with a mass of $13_{-0}^{+3} M_{\text{Jup}}$, corresponding to an effective temperature of ~ 370 K (Baraffe et al., 2003), in orbit around WD 2140 + 207 between a projected physical separation of 38 – 542 AU with a 50% probability (Table 4.1). The motion

of this white dwarf between the first epoch and second epoch images (Figure 4.48) is large enough to confidently state that there are no common proper motion companions to WD 2140 + 207 within these limits. These results give a limit on the mass of any possible companion in orbit around WD 2140 + 207 that is more massive than the limit estimated by Debes et al. (2006). However, the mass of $0.49 \pm 0.04 M_{\odot}$ used throughout this thesis was determined by accounting for the carbon present in the atmosphere of this DQ white dwarf, while Debes et al. (2006) use a white dwarf mass of $0.62 M_{\odot}$ (Bergeron et al., 2001), which was derived using a pure helium model. In contrast, it would be possible to detect a companion with a mass of $9_{-2}^{+1} M_{\text{Jup}}$ if a white dwarf mass of $0.62 M_{\odot}$ (Bergeron et al., 2001) is used to determine the total age of the white dwarf. This would lead to an upper limit less massive than the upper limit determined by Debes et al. (2006). This survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.26 WD 2246 + 223

WD 2246 + 223 is a $0.97 \pm 0.06 M_{\odot}$ DA white dwarf with an effective temperature, $T_{\text{eff}} = 10330 \pm 300$ K, a $\log g = 8.57 \pm 0.09$ and a white dwarf cooling age, $t_{\text{WD}} = 1.56 \pm 0.33$ Gyr (Bergeron et al., 2001). A previous imaging search in the NIR using the CFHT suggests that no substellar companions with a mass $> 9 M_{\text{Jup}}$ exist around WD 2140+207 between $1-7''$ (Debes et al., 2006). At a distance of 19.05 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 19 – 133 AU.

An object with a magnitude of $J = 22.0$ mag can be detected with a 50% probability in both the 2003 first epoch and the 2004 second epoch images of WD 2246 + 223 (Figure 4.49). If such an object was determined to be a companion to WD 2246 + 223 the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 1.7 ± 0.43 Gyr. Therefore, it would be possible to detect a companion with a mass of $9 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 400 K (Baraffe et al., 2003), in orbit around WD 2246 + 223 between a projected physical separation of $57 - 835$ AU with a 50% probability (Table 4.1). These results provide the same upper limit of $9 \pm 1 M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 2246 + 223 as Debes et al. (2006). However, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

The 2003 first epoch image of WD 2246+223 was degraded by severe 60 Hz interference (Table 2.2; Section 3.1.5). It is likely that this interference has introduced the large scatter in the motions of objects with magnitudes $J > 20$ mag between the 2003 first epoch and 2004 second epoch images (Figure 5.10). This suggests that the error on the motion of these faint objects is comparable to the motion of WD 2246 + 223 (Table 2.1). As a result, a single object appears to have a motion similar to the motion of the white dwarf (Figure 4.50). The candidate common proper motion companion is detected with a SNR of ~ 5 in both epoch images. However, due to the presence of 60 Hz interference, the measurement of the motion of the candidate between the first epoch and second epoch images may be inaccurate. In addition, there are two other objects which appear to

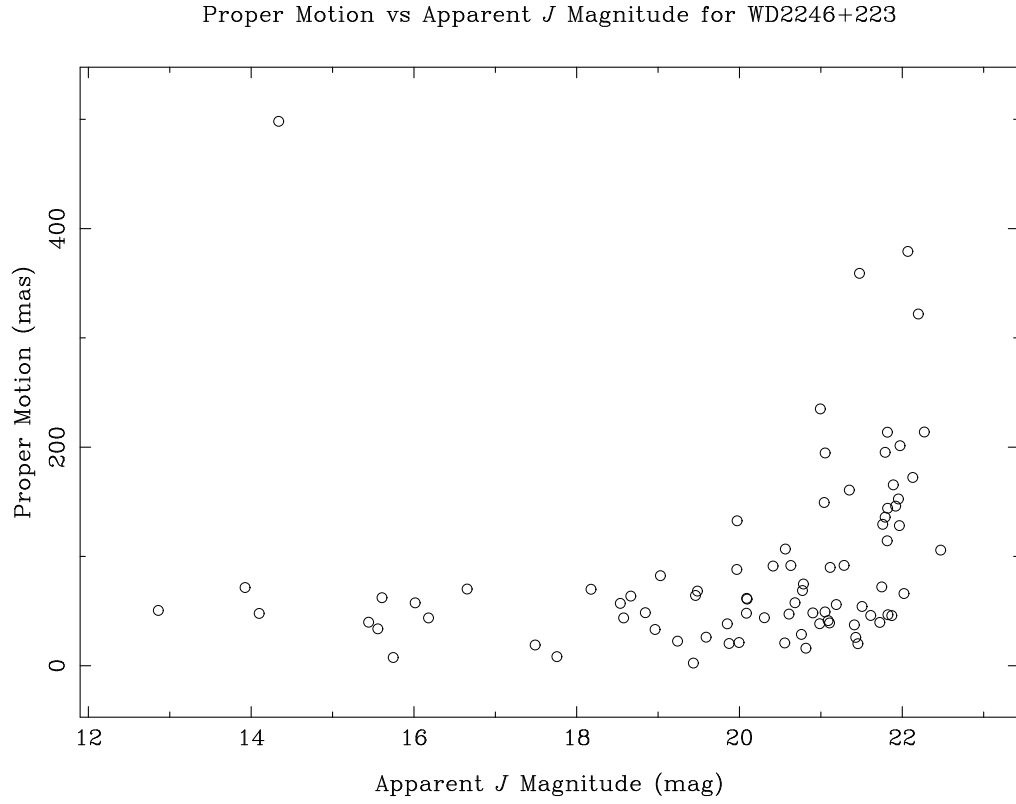


FIGURE 5.10. The motion of the objects between the 2003 first epoch and 2004 second epoch images of WD 2246 + 223. The white dwarf has a magnitude of $J \sim 14.3$ mag.

have the same magnitude of motion as the candidate, reducing the probability that the candidate is a genuine common proper motion companion. This indicates that a third epoch image is required. If this candidate is confirmed to be a common proper motion companion to WD 2246 + 223, the candidate would have a mass of $9 \pm 1 M_{\text{Jup}}$ and a projected physical separation of ~ 840 AU.

5.27 WD 2326 + 049

WD 2326 + 049 is a $0.70 \pm 0.03 M_{\odot}$ pulsating ZZ ceti DAZ white dwarf with an effective temperature, $T_{\text{eff}} = 11820 \pm 175$ K, a $\log g = 8.15 \pm 0.05$ and a white dwarf cooling age, $t_{\text{WD}} = 0.55$ Gyr (Liebert et al., 2005). This white dwarf is one of the few DAZ white dwarf known to harbour a dust disk, which may indicate the existence of an old planetary system (Section 2.2.2). A previous imaging search in the NIR using the HST and Gemini North suggests that no substellar companions with a mass $> 6 M_{\text{Jup}}$ exist around WD 2326 + 049 between $1 - 5''$ (Debes, Sigurdsson and Woodgate, 2005a). At a distance of 13.62 pc (van Altena et al., 1995), this corresponds to a projected physical separation between 14 – 68 AU.

An object with a magnitude of $J = 21.8$ mag can be detected with a 50% probability in both the 2002 first epoch and the 2003 second epoch images of WD 2326 + 049 (Figure 4.51). If such an object was determined to be a companion to WD 2326 + 049, the object would have an age, equal to the sum of the main sequence progenitor lifetime and the white dwarf cooling age, of 1.1 ± 0.28 Gyr. Therefore, it would be possible to detect a companion with a mass of $6 \pm 1 M_{\text{Jup}}$, corresponding to an effective temperature of ~ 370 K (Baraffe et al., 2003), in orbit around WD 2326 + 049 between a projected physical separation of 41 – 396 AU with a 50% probability (Table 4.1). The motion of this white dwarf between the first epoch and second epoch images (Figure 4.52) is large enough to confidently state that there are no common proper motion companions to WD 2326 + 049 within these limits. These results provide the same upper limit of

$6 \pm 1 M_{\text{Jup}}$ on the mass of any possible companion in orbit around WD 2326 + 049 as Debes et al. (2005a). However, this survey extends out to a much larger projected physical separation, around both the white dwarf and the main sequence progenitor, than previous searches.

5.28 Summary

No common proper motion companions within the limits given in Table 4.1 were discovered around 18 of the 26 equatorial and northern hemisphere white dwarfs in the DODO survey. However, multiple objects appear to have motions similar to the motions of the remaining 8 white dwarfs.

The white dwarfs WD 0148 + 467, WD 0346 – 011, WD 0438 + 108 and WD 1134 + 300 all move $< 350\text{mas}$ between their 2003 first epoch and 2005 second epoch images. In addition, the first epoch images of WD 0148 + 467 and WD 1134 + 300 were degraded by 60 Hz interference. Due to the combination of the very low proper motions of these white dwarfs and the presence of 60 Hz interference, a third epoch image is required to clearly distinguish the proper motion of the white dwarfs from the background objects in the field.

The white dwarfs WD 1633 + 433, WD 1900 + 705 and WD 2246 + 223 all move $> 450\text{mas}$ between their 2003 first epoch and 2004 second epoch images. However, the

first epoch images of the three white dwarfs were all degraded by 60 Hz interference. In addition, the presence of a streak in the first epoch image of WD 1633 + 433 has likely decreased the accuracy of the measurement of the motion of the faintest objects between the first epoch and second epoch images. Again, a third epoch image, without the presence of any interference, is now required.

The white dwarf WD 2007 – 219 has a single promising $7 \pm 1 M_{\text{Jup}}$ common proper motion candidate companion. However, due to the relatively high ellipticity of the candidate in the 2003 second epoch image, a third epoch image is required. This will help to determine whether this candidate is a genuine common proper motion companion.

The cumulative completeness limits, in terms of mass and effective temperature, and the corresponding range of projected physical separations over which these limits apply have been determined for the 26 equatorial and northern hemisphere white dwarfs in the DODO survey (Figures 5.11, 5.12, 5.13, 5.13).

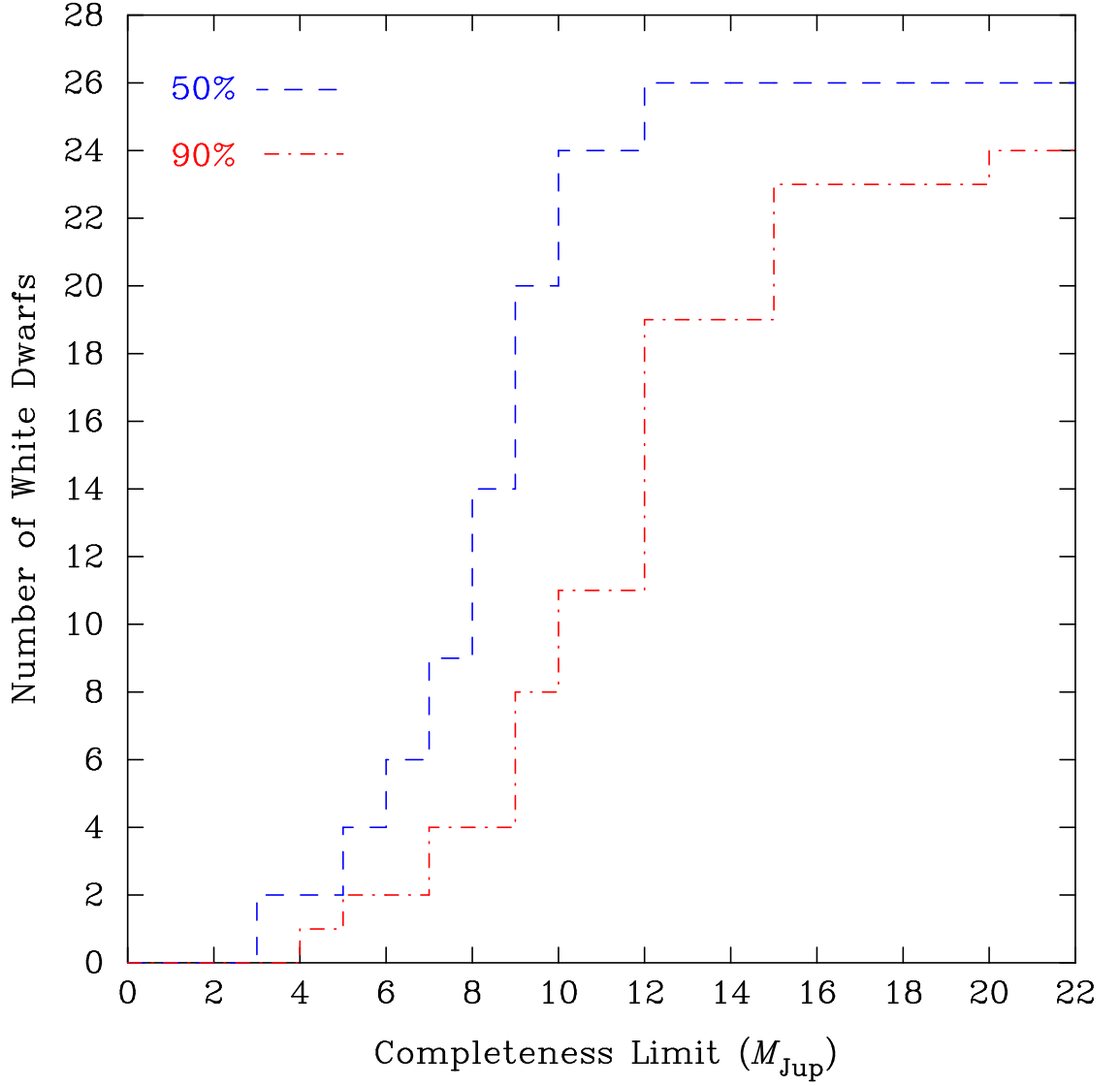


FIGURE 5.11. The cumulative completeness limit, in terms of companion mass, for the 26 equatorial and northern hemisphere white dwarfs in the DODO survey. The red dotted-dashed line indicates the frequency of the completeness limit in M_{Jup} at which 90% of companions with that mass could be detected, while the blue dashed line indicates the completeness limit in M_{Jup} at which 50% of companions with that mass could be detected.

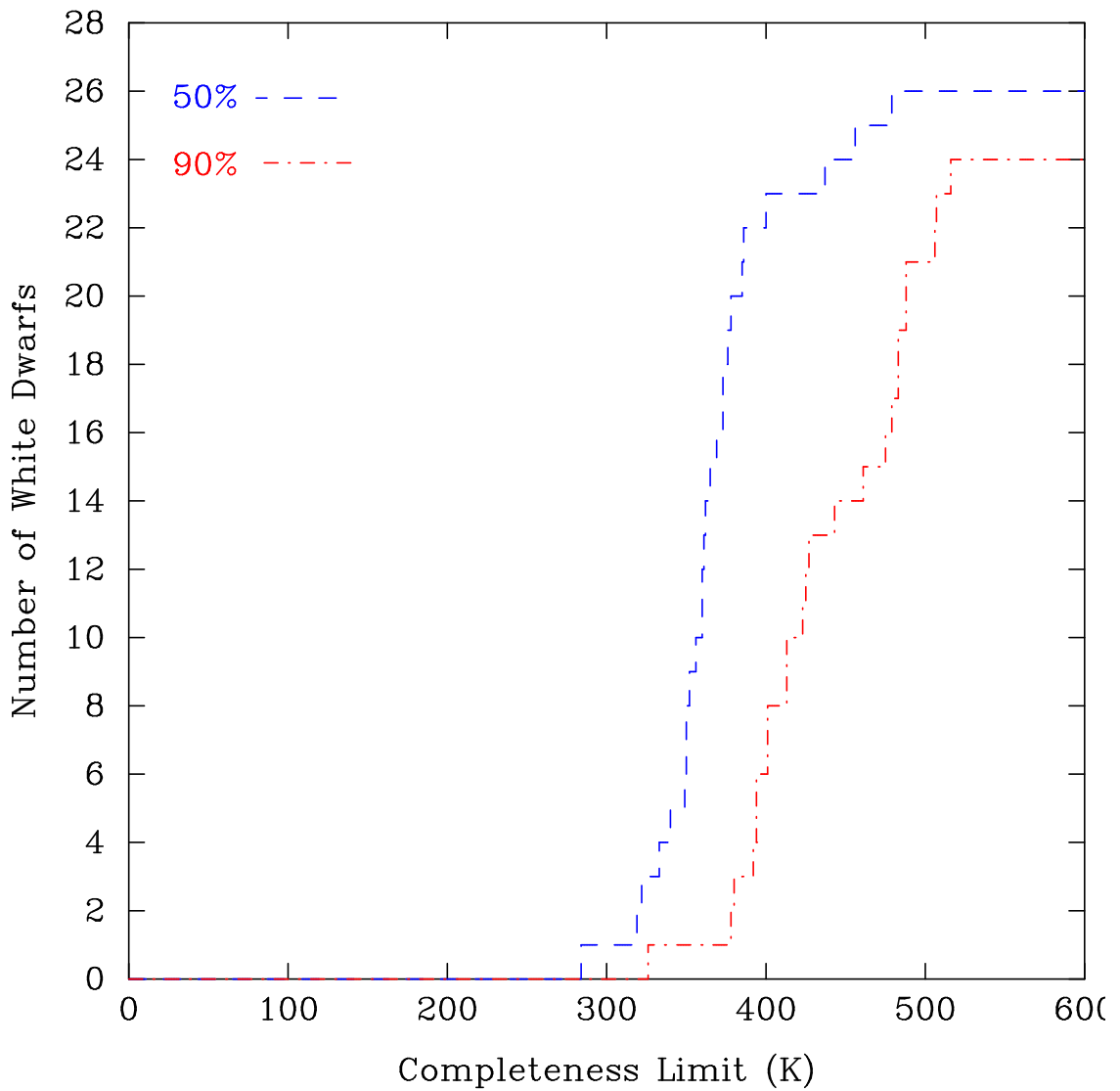


FIGURE 5.12. The cumulative completeness limit, in terms of companion temperature, for the 26 equatorial and northern hemisphere white dwarfs in the DODO survey. The red dotted-dashed line indicates the frequency of the completeness limit in Kelvin at which 90% of companions with that temperature could be detected, while the blue dashed line indicates the completeness limit in Kelvin at which 50% of companions with that temperature could be detected.

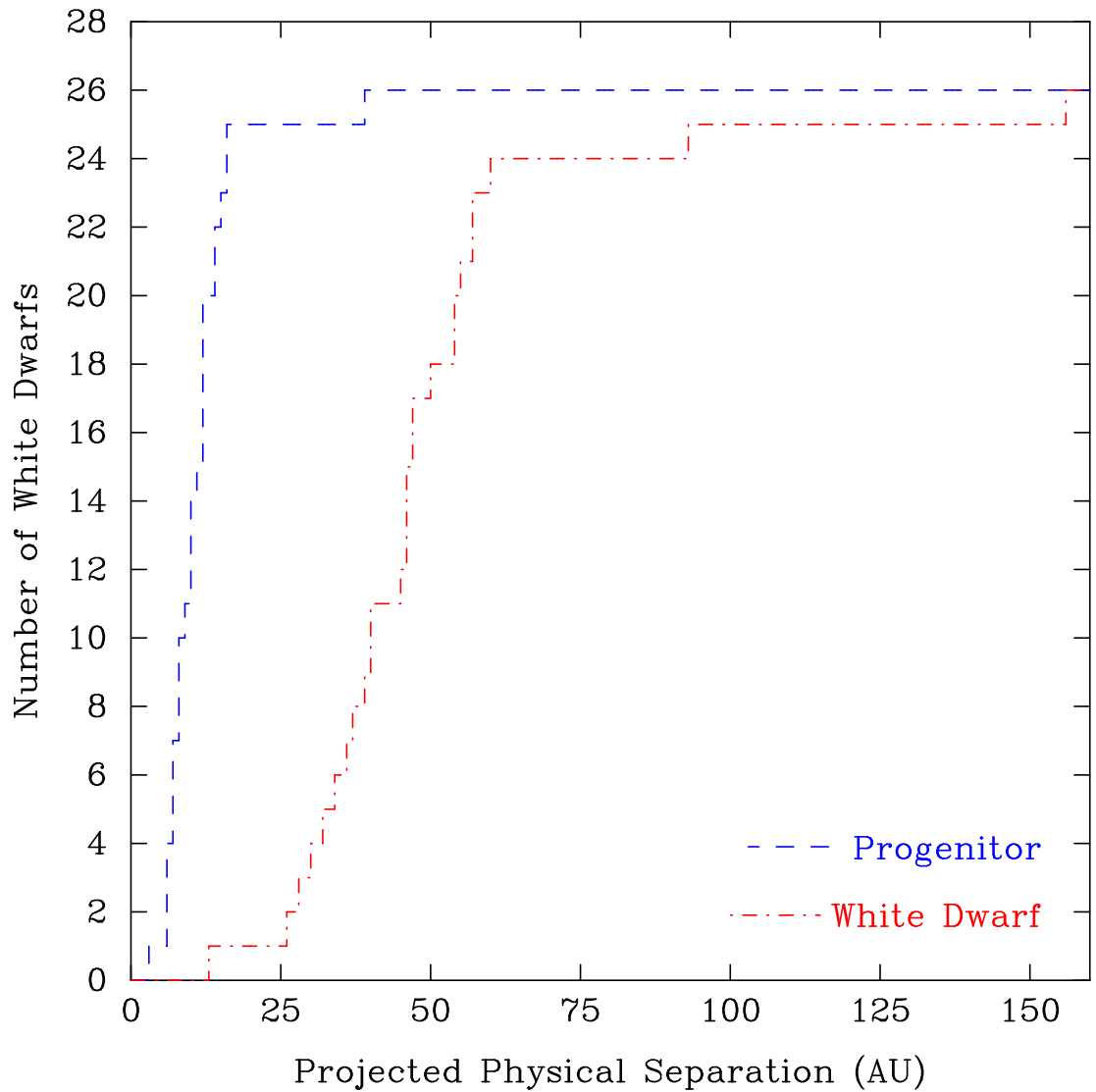


FIGURE 5.13. The cumulative minimum projected physical separations for the 26 equatorial and northern hemisphere white dwarfs in the DODO survey. The red dotted-dashed line indicates the minimum projected physical separations in AU at which a companion could be found around each white dwarf. The blue dashed line indicates the minimum projected physical separations in AU at which a companion could be found around the main sequence progenitor.

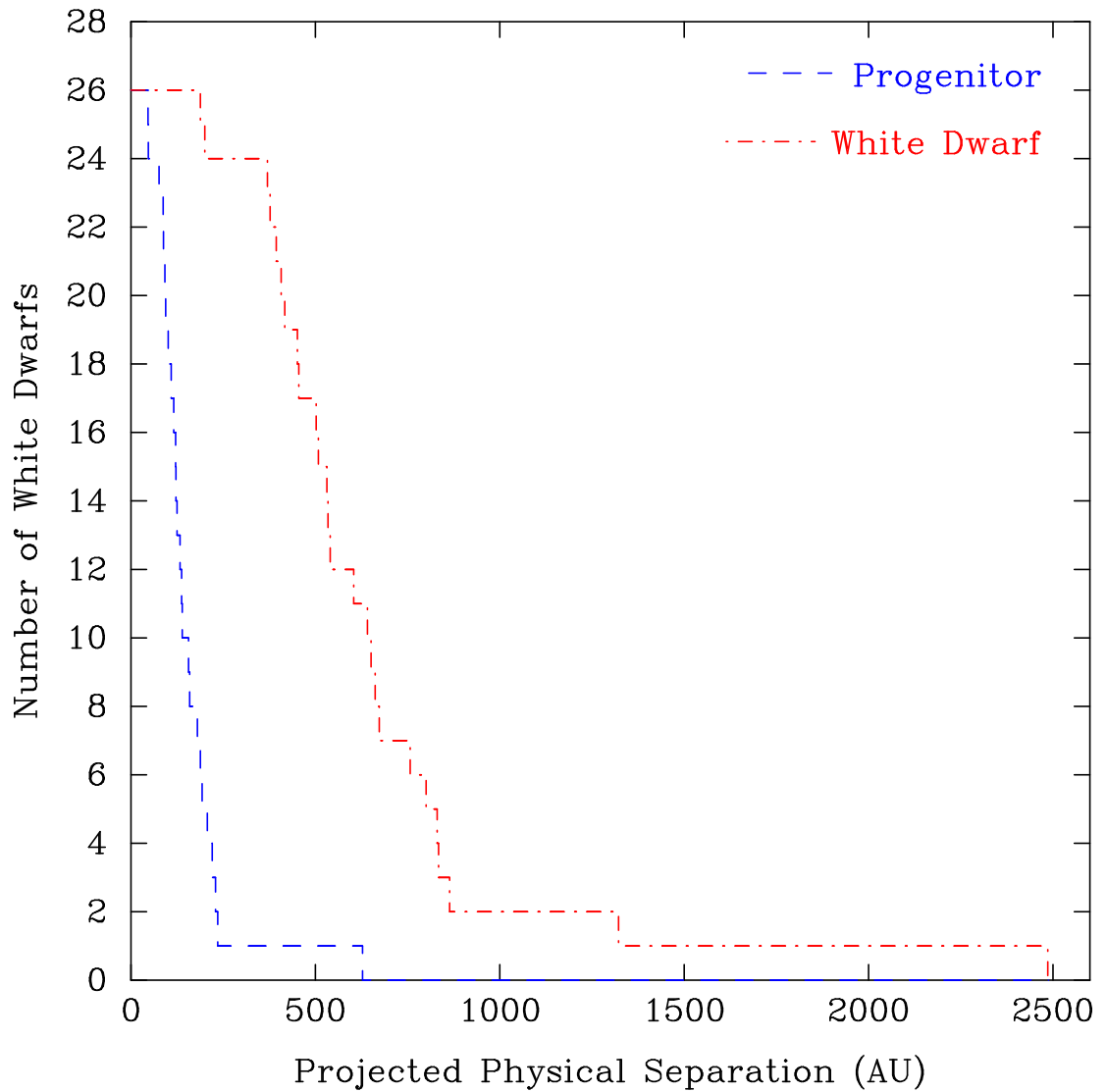


FIGURE 5.14. The cumulative maximum projected physical separations for the 26 equatorial and northern hemisphere white dwarfs in the DODO survey. The red line indicates the maximum projected physical separations in AU at which a companion could be found around each white dwarf. The blue line indicates the maximum projected physical separations in AU at which a companion could be found around the main sequence progenitor.

Chapter 6

Spectroscopy of an Unresolved Substellar Companion to a White Dwarf

6.1 Introduction

To date, only three substellar objects have been detected in orbit around a white dwarf (Section 2.3.1). The most recent of these was discovered in orbit around the white dwarf WD 0137 – 349 (Maxted et al., 2006) using the radial velocity technique (Section 1.5.3). An $H\alpha$ absorption feature, due to absorption by hydrogen in the atmosphere of the white dwarf, was found to oscillate in anti-phase to an $H\alpha$ emission feature, which arises from the atmosphere of the companion (Figure 6.1). The variation in the strength and width of this $H\alpha$ emission feature indicates that one hemisphere of the companion is undergoing irradiation by the white dwarf (Maxted et al., 2006). From the radial velocity curves of the white dwarf and the companion, $M_1 \sin^3 i = 0.097 M_\odot$ and $M_2 \sin^3 i = 0.013 M_\odot$

were calculated, where M_1 and M_2 are the mass of the white dwarf and the companion, respectively, and i is the inclination of the orbit of the companion with respect to the line of sight of the observer. Since the mass of the white dwarf is known to be $0.39 M_\odot$, the inclination was estimated to be $i \sim 35^\circ$. This led to a companion mass of $0.053 \pm 0.006 M_\odot$, which is well below the lower mass limit used to distinguish stars from brown dwarfs ($0.07 M_\odot$; Equation 1.6). The orbital period and orbital radius of this companion are ~ 116 minutes and $\sim 0.65 R_\odot$, respectively (Maxted et al., 2006).

The nature of the $0.053 M_\odot$ companion, WD 0137 – 349 B, is unclear. One scenario assumes the companion is a brown dwarf that has survived common envelope evolution. During this phase, the brown dwarf would have had an orbital radius within the red giant envelope. Frictional drag due to interactions of the brown dwarf with the red giant envelope would have caused the orbital radius of the brown dwarf to decrease due to loss of angular momentum (Section 2.2). This would result in the close, detached white dwarf–brown dwarf binary system currently observed. Alternatively, WD 0137 – 349 B may have originally been a planet that accreted a substantial amount of mass during common envelope evolution. This newly formed $0.053 M_\odot$ companion would therefore have an age approximately equal to the cooling age of the white dwarf (0.25 ± 0.08 Gyr; Maxted et al., 2006), leading to companion with an effective temperature, $T_{\text{eff}} > 2000$ K. Accurate spectral classification of the companion would allow its effective temperature to be determined, providing evidence which could distinguish between these two scenarios. An infrared (IR) spectrum of the white dwarf WD 0137 – 349 was obtained in November 2005 (Burleigh et al., 2006).

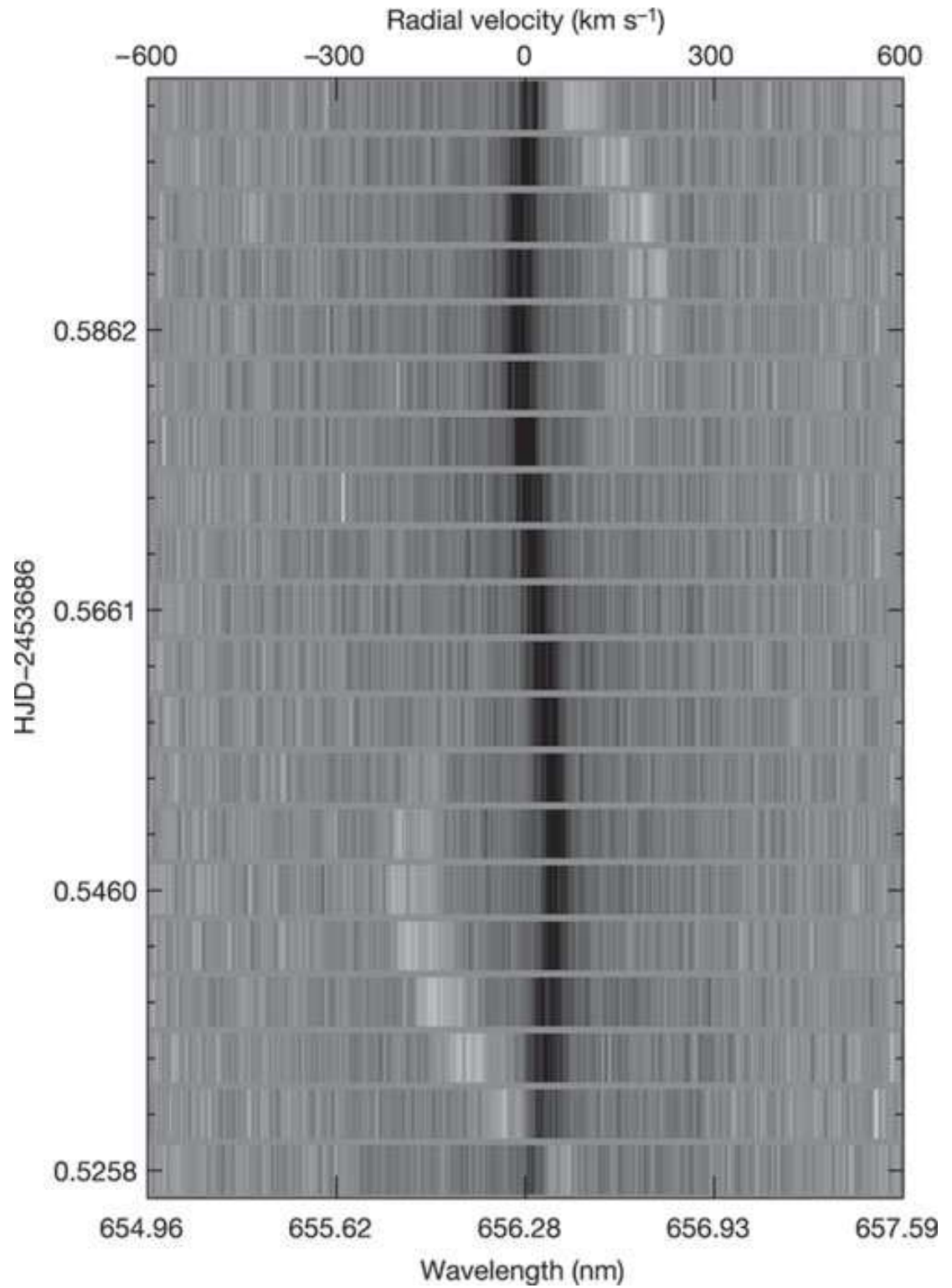


FIGURE 6.1. The H α absorption feature, due to absorption by hydrogen in the atmosphere of the white dwarf, is shown in black, while the H α emission feature arising from the atmosphere of the companion is shown in white (Maxted et al., 2006).

6.2 Observations

Observations of WD 0137 – 349 were acquired using Gemini South (GS) and the Gemini Near InfraRed Spectrograph (*GNIRS*; Elias et al., 2006). GS is an 8.1 meter altitude–azimuth telescope situated at an elevation of 8,895 feet on Cerro Pachón in Chile. *GNIRS* consists of a 1024×1024 pixel Indium Antimonide (InSb) HAWAII–III array, which has a spectral response of $0.9 - 5.5\mu\text{m}$. The cross–dispersed mode was selected for the acquisition of the data, allowing coverage of the wavelength range $0.9 - 2.5\mu\text{m}$ in a single observation. Combining the short camera, which supplies a pixel scale of $0.15'' \text{ pixel}^{-1}$, with the $31.7 \text{ lines mm}^{-1}$ grating centred on $1.65\mu\text{m}$, along with the $0.3''$ (2 pixel) slit provides a spectral resolution of $R = \lambda/\Delta\lambda \sim 1700$.

The science data were acquired using a dither pattern, which involved systematically offsetting the telescope along the length of the cross–dispersed slit, to allow the effective removal of the sky background. However, since the cross–dispersed slit is only $6''$ in length, a 2 point dither pattern, positioned at $\pm 1.5''$ from the central position of the slit, was used during the acquisition of the science data. These two dither points, or nod positions, have the names “A” and “B”. The total exposure time given in Table 6.1 was achieved by obtaining 120 second individual exposures per nod position. Dome flats were acquired by imaging a uniformly illuminated screen within the dome. However, using the standard IR lamp in combination with cross–dispersed mode did not effectively illuminate the array at the shorter wavelengths without heavily saturating the array at the longer ones. Therefore, three sets of flat field images were acquired with different

Table 6.1. Details of the observation of the white dwarf WD 0137 – 349

White Dwarf Number	Date Observed	ET [min]	IQ [%-ile]	CC [%-ile]	WV [%-ile]	SB [%-ile]
0137 – 349	2005–11–22	40	70	50	Any	Any

Columns: ET is the total exposure time, measured in minutes; IQ is the image quality percentile; CC is the cloud cover percentile; WV is the water vapour percentile; SB is the sky background percentile.

exposure times using two different lamps. The first set of flat field images were acquired using the IR lamp and an exposure time of 3.6 seconds per individual image. The second and third sets were acquired using a quartz–halogen (QH) lamp and exposure times of 4.8 and 6.6 seconds per individual image. An arc image was acquired by observing a screen within the dome, which was uniformly illuminated using an argon lamp, to wavelength calibrate the science data. A telluric standard with a spectral class of A1V (HD 10538) was also acquired before and after the science observations to correct for absorption features present in the science data, due to the atmosphere of the Earth. Finally, a pinhole image was acquired to help identify the curved aperture of the science data.

6.3 Data Reduction

The *GNIRS* data were reduced using the Image Reduction and Analysis Facility (IRAF; Tody, 1986) and the *GEMINI* package, versions 2.12.2a and 1.9, respectively. Raw *GNIRS* images are in the form of multi–extension fits (MEF) files with most of the header information in the Primary Header Unit (PHU), “[0]” extension and the raw image data in the second, “[1]” extension. The *NSHEADERS* and *NSPREPARE* tasks in the *GEMINI*

package were applied in turn to all raw data acquired with *GNIRS*. The *NSHEADERS* task adds certain essential *GNIRS* keywords to the header of each data file, while the *NSPREPARE* task prepares the *GNIRS* data for further processing, allowing the subsequent data reduction tasks to be applied.

6.3.1 *GNIRS* Cross-Dispersed Data

In cross-dispersed mode, the $0.9 - 2.5\mu\text{m}$ wavelength range is split up into 6 separate orders, which lie approximately parallel to each other on the array (Figure 6.2), but slightly slanted with respect to the dispersion axis, which lies along the columns of the array. The orders, which are numbered 3 through to 8, are positioned decreasing in wavelength from left to right and from bottom to top. Orders 3 ($1.88 - 2.52\mu\text{m}$), 4 ($1.13 - 1.90\mu\text{m}$) and 5 ($0.95 - 1.25\mu\text{m}$) are approximately equivalent to the *J*, *H* and *K* bands, respectively. One common reduction step for the *GNIRS* data was the application of the *NSREDUCE* task in the GEMINI package. This task calls the *NSCUT* task, which was used to place each order of each individual image into a separate extension. The result of this task is a single MEF file with 6 separate extensions containing orders 3 through to 8.

GNIRS has a “flip in” acquisition (pick-off) mirror to allow the precise positioning of objects on the slit without moving the grating, prism or camera. This pick-off mirror consists of a $10 \times 100''$ strip with a superposed half circular field, $15''$ in radius, cen-

tered on the optical axis (Figure 6.2). A persistence effect present in the science data (Section 3.1.4), due to acquisition images taken of the white dwarf before the cross-dispersed science data were obtained, caused the pick-off mirror region to contain a large unwanted signal compared to the rest of the array. This signal was removed by scaling an acquisition image so that the signal in the pick-off mirror region was equal to the mean value of the signal in the pick-off mirror region in the science data. The IMARITH task in the IMAGES package was then used to subtract this scaled image from the science images to remove this persistence effect.

6.3.2 Flat Division

Effects due to illumination variations in the optical system, anomalies in the optical path and sensitivity variations between pixels in the array can be removed by dividing the individual science images by an image known as a flat field. The three sets of individual flat field images were combined according to their exposure times to create three separate combined flat field images. These images were then normalised independently for each order by dividing the combined flat field images by the spectral signature of the appropriate lamp along the length of each order. The final normalised flat field image was created by combining the extensions containing orders 3, 4–5 and 6–8 from the normalised flat field images comprising of the individual flat field images with exposure times of 3.6, 4.8 and 6.6 seconds, respectively. The NSFLAT task in the GEMINI package was used to create the normalised flat field images. The tasks FXCOPY and FXINSERT



FIGURE 6.2. An individual exposure of the white dwarf WD 0137 – 349 acquired using *GNIRS* in cross-dispersed mode. The orders are positioned decreasing in wavelength from left to right and from bottom to top, and are numbered 3 through to 8. Persistence in the region of the pick-off mirror can be clearly seen.

in the FITSUTIL package was used to create the final normalised flat field image. The NSREDUCE task in the GEMINI package was used to divide the individual science and telluric standard images by this final normalised flat field image.

6.3.3 Sky Background Subtraction

The near infrared (NIR; $1 - 2.5\mu\text{m}$) sky background is dominated by emission from hydroxyl radicals (OH^-) in the upper atmosphere of the Earth. Since the individual science and telluric standard images were acquired using nod positions in the order ABBA, the first nod position A image supplied a measure of the sky background for the second nod position B image, and vice versa. This allowed the effective removal of the short term variation in the intensity of the OH^- emission lines (Section 3.1.3). The NSREDUCE task was used to subtract the correct sky background image from the individual science and telluric standard images. The NSCOMBINE task in the GEMINI package was then used to align and combine the reduced individual science and telluric standard images.

6.3.4 S-Distortion Correction

In addition to the fact that the cross-dispersed orders of the *GNIRS* data are not parallel to the dispersion axis (Figure 6.2), each order also exhibits a varying amount of curvature along the spatial axis, which lies along the rows of the array. This spatial distortion is a function of wavelength and is more commonly known as S-distortion. The pinhole

image acquired to help identify this curved aperture is composed of 5 bright parallel features positioned along the length of each order. The NSSDIST task was used to trace the curved aperture, after the bright features had been manually identified, and to calculate the transformation required to straighten each order. The NSTRANSFORM task in the GEMINI package was then used to apply this S-distortion correction to both the final stacked science and telluric standard images.

6.3.5 Wavelength Calibration

The wavelength calibration for the *GNIRS* data was established independently for each cross-dispersed order. The NSWAVELENGTH task was used to identify and match emission lines in the observed argon arc lamp spectrum with a list of low resolution argon lines, tailored to lines seen at a resolution $R \sim 1700$. This step was done interactively to ensure that the emission lines were correctly matched. The NSTRANSFORM task was then used to apply this wavelength correction to both the final stacked science and telluric standard images.

6.3.6 Extraction

The NSEXTRACT task in the GEMINI package was used to extract the spectra from the final stacked science and telluric standard images by manually choosing the correct aperture.

6.3.7 Removing Telluric Features

The GEMINI tasks used to remove telluric features from the science data were not fully functional at the time this *GNIRS* data were reduced. As a result, tasks from the STAR-LINK package FIGARO were utilised. The ISEDIT task was used to linearly interpolate over detectable intrinsic hydrogen absorption features present in the telluric standard spectrum, leaving only telluric absorption features in the remaining spectrum. The SCROSS and ISHIFT tasks were used to calculate and apply the shift between the telluric standard spectrum and the white dwarf spectrum, by cross-correlating telluric absorption features. The IRFLUX task was then used to divide the white dwarf spectrum by the telluric standard spectrum to remove the telluric absorption features in the white dwarf spectrum. Since the white dwarf spectrum was divided by the continuum of the telluric standard, the resulting white dwarf spectrum was multiplied by a blackbody with the effective temperature of the telluric standard. The A1V telluric standard, HD 10538, was assumed to have a temperature of 9145 K (Cox, 2000). The final white dwarf spectrum was created by combining the individual orders of the corrected white dwarf spectrum (Figure 6.3; Burleigh et al., 2006).

6.3.8 Flux Calibration

To flux calibrate the final white dwarf spectrum, the spectrum was shifted to match the Two Micron All Sky Survey (2MASS; Skrutskie et al., 2006) *J* band flux measurement.

6.4 Data Analysis

The following data analysis performed on the final spectrum of WD 0137 – 349 was completed by Dr. Matthew Burleigh. Firstly, the spectrum of WD 0137 – 349 was compared to a pure hydrogen synthetic white dwarf spectrum, which was created using plane-parallel, hydrostatic, non-local thermodynamic equilibrium (non-LTE) atmosphere and spectral synthesis codes TLUSTY and SYNSPEC. This revealed an excess of flux at wavelengths longer than $\sim 1.95\mu\text{m}$ in the spectrum of WD 0137 – 349 when compared to the synthetic white dwarf spectrum. This IR excess confirms the existence of a spatially unresolved substellar companion. To determine the spectral type of this companion, the spectrum of WD 0137 – 349 was compared to the combination of the synthetic white dwarf spectrum with empirical models for substellar objects, constructed using the NIR spectra of L and T dwarfs (McLean et al., 2003). The best match to the data is provided by a model which combines a white dwarf and an L8 brown dwarf (Figure 6.3).

6.5 Discussion

The effective temperature of the L8 brown dwarf companion in orbit around the white dwarf WD 0137 – 349 can be estimated from its spectral class. The mean effective temperature of an L8 brown dwarf is 1390 K (Vrba et al., 2004). Evolutionary models for very low mass (VLM) stars and brown dwarfs, which include the presence of atmospheric dust, can be used to describe the evolution, photometric and spectroscopic prop-

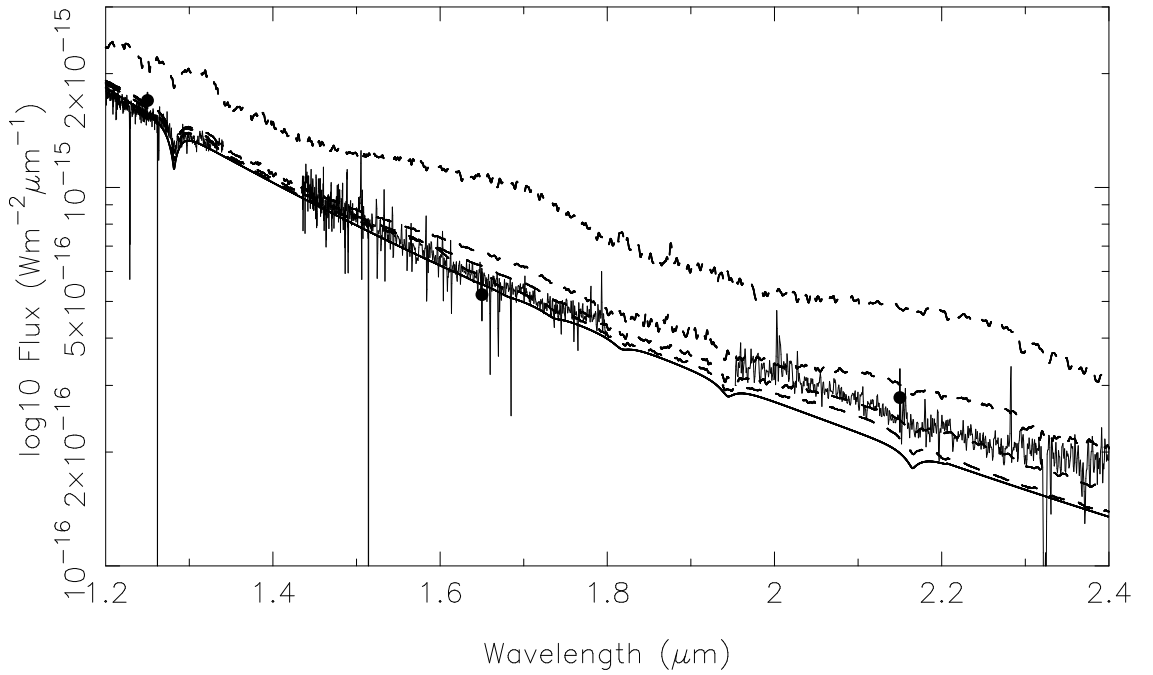


FIGURE 6.3. The *GNIRS* spectrum of WD 0137 – 349 from 1.2 – 2.4 μm . The solid line indicates the synthetic white dwarf spectrum using a pure hydrogen atmosphere model. The dashed lines, from the top to the bottom, show the synthetic white dwarf spectrum combined with an L0, L6, L8 and T5 brown dwarf spectrum, respectively. The best match to the spectrum of WD 0137 – 349 is provided by the model combining a white dwarf and an L8 brown dwarf. The remains of the telluric water features present between 1.35 and 1.42 μm , and 1.8 and 1.95 μm have been omitted from this spectrum.

erties of early L dwarfs with effective temperatures between $1300 \text{ K} \lesssim T_{\text{eff}} \lesssim 2800 \text{ K}$ (Chabrier et al., 2000). These “DUSTY” models suggest that the age of WD 0137 – 349 B, which has a mass, $M = 0.053 M_{\odot}$, determined from radial velocity measurements and an effective temperature, $T_{\text{eff}} = 1390 \text{ K}$, determined from its spectral class, is of the order of $\sim 1 \text{ Gyr}$. This relatively old age supports the scenario that WD 0137 – 349 B is a brown dwarf that has survived common envelope evolution. In contrast, a lower mass brown dwarf or planet that accreted mass during the common envelope phase to become a newly formed $0.053 M_{\odot}$ companion would have an age similar to the cooling age of the white dwarf, which is determined to be $0.25 \pm 0.08 \text{ Gyr}$ (Maxted et al., 2006). The “DUSTY” models suggest that an object with a mass $0.053 M_{\odot}$ and an age of $\sim 0.25 \text{ Gyr}$ would have an effective temperature, $T_{\text{eff}} \sim 2000 \text{ K}$, which is inconsistent with the spectral class of WD 0137 – 349 B.

Since WD 0137 – 349 B orbits the white dwarf at a radius of only $\sim 0.65 R_{\odot}$, it is expected that the brown dwarf is tidally locked with WD 0137 – 349, resulting in permanent day and night sides. The variation in the strength and width of the $\text{H}\alpha$ emission feature (Figure 6.1), produced by irradiation of one hemisphere of the companion by the white dwarf (Maxted et al., 2006), certainly indicates that WD 0137 – 349 B has a day and a night side. Detecting a similar asymmetric heating of an extrasolar planet is extremely difficult, since these objects are considerably fainter. Therefore, WD 0137 – 349 B is an ideal candidate to study the effects of irradiation of the atmospheres of very cool, low mass objects. To attempt to detect the difference in temperature between the day and night sides of WD 0137 – 349 B, the *GNIRS* data were combined into 5 separate spectra

in the hope of determining variations in the flux levels of the spectra. Unfortunately, the signal to noise ratio (SNR) of these combined spectra, which consisted of only four individual images, giving a total exposure time of 8 minutes, was too poor to observe any variations. Accurate K band photometry over the entire orbital period should reveal variability due to temperature differences between the day and night sides, allowing the characterisation of the photometric properties of the brown dwarf WD 0137 – 349 B.

Chapter 7

Conclusions

7.1 Conclusions

The Degenerate Objects around Degenerate Objects (DODO) survey aims to obtain a direct image of an extrasolar planet in a wide orbit around a white dwarf. By acquiring images of 26 equatorial and northern hemisphere white dwarfs a year or two apart (Table 2.2), the motions of all objects in the field of view of each white dwarf between the first epoch and second (or third) epoch images have been determined. Multiple objects appear to have motions similar to the motions of 8 of these white dwarfs. The very low proper motions of the white dwarfs WD 0148+467, WD 0346−011, WD 0438+108 and WD 1134+300 have made the identification of genuine common proper motion companions difficult, since the motions of these white dwarfs are not clearly distinguished from the motions of the background objects in these fields. The presence of 60 Hz interference in the first epoch images of the white dwarfs WD 1633 + 433, WD 1900 + 705 and

WD 2246 + 223 has likely caused inaccuracies in the measurement of the motions of the faint objects in these fields between the first epoch and second epoch images. The white dwarf WD 2007 – 219 has a single promising common proper motion candidate. This white dwarf has an adequate proper motion and both epoch images are free from 60 Hz interference. For these 8 white dwarfs, a third epoch image is required to determine if any of these candidates are genuine common proper motion companions.

Assuming that no common proper motion companions are confirmed around the 8 white dwarfs requiring a third epoch image and recognising that the DODO survey contains a relatively small number of targets, tentative conclusions regarding the frequency of substellar and planetary mass companions to white dwarfs and their main sequence progenitors at wide separations can be made. Firstly, objects with effective temperatures $\gtrsim 500$ K could have been detected in the images of all 26 white dwarfs in the DODO survey with a 90% probability. This temperature is significantly below the temperature of the coolest T dwarf found to date (T8.5; $600 < T_{\text{eff}} < 700$ K; Section 1.4.2). Using the 24 white dwarfs in the DODO survey within ~ 20 pc, the frequency of low mass substellar companions with spectral classes of L, T and sub-T8.5 with effective temperatures $\gtrsim 500$ K and projected physical separations from the white dwarf between 60 – 200 AU is estimated to be $\lesssim 5\%$. For the same range of projected physical separations, the frequency of low mass substellar companions with masses $\gtrsim 13 M_{\text{Jup}}$ is estimated to be $\lesssim 8\%$, while the frequency of low mass substellar companions with masses $\gtrsim 10 M_{\text{Jup}}$ is estimated to be $\lesssim 9\%$. However, for many of the white dwarfs in the DODO survey, these limits apply to a wider range of projected physical separations (Table 4.1). These

frequencies are based on the assumption that the sample of white dwarfs in the DODO survey are indicative of white dwarfs as a whole. The projected physical separations from the white dwarf of 60 – 200 AU correspond to projected physical separations around the main sequence progenitor of 20 – 45 AU.

7.2 Future Work

The discovery of an extrasolar planet around a white dwarf could supply new information on the frequency and mass distribution of extrasolar planets around intermediate mass main sequence stars and confirm whether these companions can survive the final stages of stellar evolution. In addition, if the DODO survey accomplishes its aim of obtaining a direct image of an extrasolar planet in orbit around a white dwarf, it would allow the spectroscopic investigation of planets much older than any previously found. Therefore, the DODO survey should utilise larger telescopes in an attempt to obtain deeper images, which would allow lower mass companions to be detected.

The James Webb Space Telescope (JWST) is a large, infrared (IR) space based telescope, which is scheduled for launch in 2013. JWST will have a large 6.5 meter mirror and instruments that include a near infrared (NIR) camera (*NIRCam*), a NIR multi object spectrograph (*NIRSpec*) and a mid infrared (MIR) instrument (*MIRI*). *MIRI* has a similar pixel scale and field of view as *NIRI*. However, the contrast between a planet and its parent star is optimised when such a system is observed in the MIR, since the peak of

the thermal emission of a planet occurs at these wavelengths (Section 1.5.3). Therefore, *MIRI* has the ability to more easily obtain a direct image of an extrasolar planet around a white dwarf.

Targeting massive white dwarfs may increase the probability of obtaining a direct image of an extrasolar planet in orbit around a white dwarf. It is thought that massive extrasolar planets are formed from massive circumstellar disks, which are most likely to be found around the massive main sequence progenitors of massive white dwarfs. However, the most massive white dwarfs are too distant to have measureable proper motions within a reasonable timescale, requiring larger baselines between the observations of the two epoch images.

Spectroscopic observations of the white dwarf WD 0137 – 349 has allowed the determination of the spectral class of the brown dwarf companion. The variation in the strength and width of the $H\alpha$ emission feature, produced by irradiation of one hemisphere of the companion by the white dwarf, indicates that WD 0137 – 349 B has a day side and a night side. Follow up spectroscopic observations of this system will allow the investigation of the asymmetric heating of the L8 brown dwarf companion. This information could be used to improve theoretical models that predict the effects of irradiation on extrasolar planets.

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