Imaging planets around nearby white dwarfs

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ABSTRACT

We suggest that Jovian planets will survive the late stages of stellar evolution, and that white dwarfs will retain planetary systems in wide orbits (≥5 au). Utilizing evolutionary models for Jovian planets, we show that infrared imaging with 8-m class telescopes of suitable nearby white dwarfs should allow us to resolve and detect companions ≥3 MJup. Detection of massive planetary companions to nearby white dwarfs would prove that such objects can survive the final stages of stellar evolution, place constraints on the frequency of main-sequence stars with planetary systems dynamically similar to our own and allow direct spectroscopic investigation of their composition and structure.

Key words: planetary systems – white dwarfs.

1 INTRODUCTION

Over 70 extra-solar planets have now been detected since the discovery of a companion to the solar-type star 51 Peg in 1995 (Mayor & Queloz 1995). All of these planets have been discovered via the radial velocity technique, in which the presence of a planet is inferred by the motion of the central star around the barycentre of the system. Instrumental and intrinsic noise limit the sensitivity of these studies to Saturn-mass companions in short-period orbits, with more massive companions detectable in more distant orbits. The duration of current programmes limits this to ~3.5 au (Fischer et al. 2002), although some systems do display interesting trends indicative of more distant companions. Therefore, we have little information on systems with massive companions at large radii, such as our own Solar system. The only constraint on Jovian-like systems comes from micro-lensing statistics, which suggest less than 1/3 of M stars have Jupiter-mass planets orbiting at 1.5–4 au (Gaudi et al. 2002).

The planets discovered by the radial velocity technique are not open to further direct study, owing to their close proximity to the much brighter parent star. The only exception to this is the transiting companion to HD 209458 (Porb = 3.5 d). Transit photometry shows this planet is a gas giant, and Charbonneau et al. (2002) have recently detected sodium in its atmosphere. Still, the planet itself cannot be directly imaged.

Several groups have conducted imaging surveys of nearby main-sequence stars to search for low-mass companions, including the use of adaptive optics, coronographs and space-based observations with the Hubble Space Telescope (e.g. Turner et al. 2001; Neuhäuser et al. 2001; Oppenheimer et al. 2001; Kuchner & Brown 2000; Schroeder et al. 2000). However, the extreme contrast (≥20 mag) and small separations (5 au = 1 arcsec at 5 pc) between main-sequence stars and Jovian planets makes sensitive surveys very difficult. To date, no planetary mass companions to nearby stars have been imaged, although several brown dwarf companions have been detected via direct imaging (e.g. Nakajima et al. 1995).

The end state of main-sequence stars with M ≲ 8 M⊙, white dwarfs, are typically 105–107 times less luminous than their progenitors. Thus, there is potentially a strong gain in the brightness contrast between a planet and a white dwarf when compared to a main-sequence star, assuming that planets can survive the late stages of stellar evolution. The gain in contrast is strongest in the mid-infrared, where the thermal emission of the planet peaks well into the Rayleigh–Jeans tail of the white dwarf. Indeed, Ignace (2001) has suggested that excess infrared emission could be detectable from a hot Jupiter orbiting a 10 000 K white dwarf at a distance of ~103 white dwarf radii and with an orbital period of ~10 d. Chu et al. (2001) have also suggested that, near a hot UV-bright white dwarf, the atmosphere of a Jovian planet would be photoionized and emit variable hydrogen recombination lines, which may be detected by high-dispersion spectroscopic observations. However, both these methods rely on the planet being in a close (0.01–2 au) proximity to the white dwarf, where it would be difficult to resolve.

In this letter, we discuss the potential for imaging planetary companions in wide (≥5 au) orbits around nearby white dwarfs. In Section 2 we investigate the probability of a planetary system surviving the late stages of stellar evolution. We discuss the detectability of any surviving planets in Section 3, suggest suitable target white dwarfs in Section 4, and discuss the expected frequency of wide planetary companions to white dwarfs in Section 5.

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2 PLANETARY SYSTEMS IN THE POST-MAIN-SEQUENCE PHASE

Any planetary companion to a white dwarf must have survived the red giant branch (RGB) and asymptotic giant branch (AGB) phases of stellar evolution. During these stages, the white dwarf progenitor swells up to a few hundred solar radii in size and undergoes significant mass loss. What happens to a planet during this time depends on the initial orbital separation, the stellar mass-loss rate, the total mass lost, tidal forces and interaction with the ejected material.

Any planet in an initial orbit within the final extent of the red giant’s envelope will be engulfed and migrate inwards. Livio & Soker (1984) showed that these planets will either completely evaporate or accrete mass and become a close companion to the eventual white dwarf.

Planets in wider orbits that avoid direct contact with the expanding red giant envelope (such as the Jovian planets of our own solar system) will have a greater chance of survival, migrating outward as mass is lost from the central star. However, stars more massive than the Sun lose more than half of their original mass in evolving to the white dwarf stage (Weidemann 1987; Wood 1992). If over half the mass of the central star is lost instantaneously then any accompanying planets will likely escape, since their orbital velocity will suddenly exceed the escape velocity of the system. Thus, we might naively expect no white dwarfs to retain planetary systems.

Of course, in reality, main-sequence stars of $M \lesssim 8.0 \, M_\odot$ do not evolve into white dwarfs instantaneously. Mass loss on the RGB and AGB, and final ejection of the planetary nebula is a relatively slow process. The Sun, for example, will lose around $0.2 \, M_\odot$ on the RGB in $\sim 10^5 \, yr$, and up to another $0.2 \, M_\odot$ on the AGB on a time-scale of up to $\sim 10^7 \, yr$. The final thermal pulse, in which the cool red giant develops a super-wind and finally ejects the remainder of its envelope, exposing the core, is poorly understood but probably occurs on a time-scale of a few $\times 10^6 \, yr$ (Soker 1994).

The dynamical time-scale for a planet to react to the change in the mass of the central star, and thus the gravitational force between the star and planet, is given by

$$ t_{dyn} = \frac{a}{v_{orb}} , $$

where $a$ is the semi-major axis of the orbit and $v_{orb}$ is the orbital velocity, and

$$ v_{orb} = \sqrt{G(M_1 + M_2)/a} , $$

where $M_1$ is the mass of the central star and $M_2$ is the mass of the planet. Assuming $M_1 \gg M_2$,

$$ t_{dyn} = 14 \, yr \left(\frac{a}{20 \, au}\right)^{3/2} \left(\frac{M_1}{M_\odot}\right)^{-1/2} . $$

This is much less than the mass-loss time-scales mentioned above. Even if a 2-$M_\odot$ star lost its entire envelope (1.4 $M_\odot$) during a short PN phase of $10^3 \, yr$ (which it does not, only the last few tenths of a solar mass), the orbit would not become unbound. Thus, to a first approximation, the orbits of planets which do not interact directly with the red giant will simply expand adiabatically by a maximum factor $M_{MS}/M_{WD}$ (Jeans 1924; Zuckermand & Becklin 1987). For example, for a main-sequence star $\sim 2 \, M_\odot$ and a white dwarf $\sim 0.6 \, M_\odot$, the orbit would expand by a maximum factor $\sim 3$.

For planets in orbits $\lesssim 10 \, au$, tidal forces between the planet and red giant are important in slowing orbital migration by transferring angular momentum from the orbit to stellar rotation. For example, Soker (1994) shows that, neglecting tidal forces, as the Sun evolves to a white dwarf Jupiter’s orbital radius will expand from its present value of $a = 1118 \, R_\odot$ to $a = 1860 \, R_\odot$. However, tidal forces on the RGB will counteract this expansion, reducing this final orbital radius by $\sim 3$ per cent, and by a further $\sim 14$ per cent on the upper AGB. For planets within 5 $au$, Livio & Soker (1983) showed that tidal interactions will actually cause them to migrate inwards. Soker (1996) suggests that tidal interactions between evolving red giants and low-mass companions could be responsible for producing the large fraction of elliptical PN observed, indicating low-mass companions may be common among PN progenitors.

The orbits of distant planets will also be subjected to drag resulting from their interaction with the material ejected by the central star. Duncan & Lissauer (1998) define the total amount of material impacting a planet during post-main-sequence evolution as

$$ M_{int}(M_\odot) = \frac{R_p^2}{12 a^2} \left[ 1 - \frac{M_{WD}}{M_\odot} \right]^3 \times \left( \frac{v_{sw}^2 + v_{orb}^2}{v_{sw}^2 + v_{orb}^2} \right)^{1/2} \left( 1 + \frac{v_{esc}^2}{v_{sw}^2 + v_{orb}^2} \right) , $$

where $v_{sw}$, $v_{orb}$ and $v_{esc}$ are the velocities of the stellar wind, the planet and the escape velocity of the planet respectively, and $R_p$ is the radius of the planet’s magnetosphere. Evaluation of this equation, however, shows that gas giants will collide with significantly less than 1 per cent of their own mass over the entire red giant phase. The orbits will decay inwards only slightly as a result.

Duncan & Lissauer (1998) have made detailed simulations of the effects of post-main-sequence mass loss on the stability of the Solar system and for planetary systems around more massive stars. They show that the orbits of the giant planets will probably be stable for tens of billions of years subsequent to the Sun’s death. However, planetary systems dynamically similar to our own around somewhat more massive stars may eventually be de-stabilized. Duncan & Lissauer’s calculations show that giant planets around, for instance, an initially 4-$M_\odot$ star, will be liberated by large-scale chaos in less than a Hubble time.

Finally, Soker (1999) points out that the newborn planetary nebula central star is hot ($T_{eff} \gtrsim 100 000 \, K$) and a strong source of ionizing soft X-ray and UV radiation. The interaction of this radiation with a planet may lead to ablation of the planetary atmosphere, but this will only be effective for planets having an escape velocity $v_{esc} \lesssim c_s$, where $c_s = 15 \, km \, s^{-1}$ is the sound speed of the ionized planetary material. For a Jupiter-mass planet $v_{esc} = 61 \, km \, s^{-1}$ and thus there will be negligible ablation.

It seems likely, then, that giant planets in initially distant ($a > 5 \, au$) orbits around main-sequence stars 1–8 $M_\odot$ will survive the late stages of stellar evolution, and remain in orbit around the remnant white dwarfs at increased orbital radii for at least several billion years.

3 DETECTING PLANETS AROUND NEARBY WHITE DWARFS

Our ability to detect an extra-solar planet around a nearby white dwarf will depend on its intrinsic luminosity, which in turn depends on its age, its distance from us, and its separation from the parent star.

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3.1 Luminosities of extra-solar planets

Burrows et al. (1997) have made non-grey calculations of the expected spectra, colours and evolution of solar-metallicity massive planets. We have used these models to predict the infrared magnitudes of planets around nearby white dwarfs. The Burrows et al. models describe the evolution of a planet in isolation and do not include the effects of thermal insolation by, or reflected light from, a parent star. In reality, gas–giant planets will have been kept warm throughout their lives by the white dwarf progenitors. They will also have accreted matter during the RGB/AGB/PN phases.

Both effects would act to increase their temperatures and luminosities, although the unsharp phase reflected light makes a negligible contribution to the brightness of the planet. Our predicted luminosities are, therefore, lower limits.

White dwarf cooling ages are dependent on a number of parameters including: effective temperature, mass (usually derived from the surface gravity), composition of the core and the thickness of the surface H- (or He-) dominated atmosphere. Temperature, surface gravity and atmospheric composition are usually determined through fitting model atmospheres to optical and UV spectra (e.g. Bergeron, Saffer & Liebert 1992; Marsh et al. 1997; Finley, Koester & Basri 1997). The mass is then inferred from the surface gravity measurement using evolutionary models (e.g. Wood 1992, 1995). These same models also give the cooling age. The cooling ages and masses of many nearby white dwarfs have been calculated in this manner by Bergeron, Leggett & Ruiz (2001, BLR). For nearby white dwarfs not included in the BLR sample (generally, those hotter than \( \sim 10000 \) K), we have estimated cooling ages from published temperature and mass measurements.

The relationship between the mass of a white dwarf and its main-sequence progenitor, the initial–final mass relation, has been investigated by a variety of authors. We have adopted model A from Wood (1992)

\[
M_{\text{MS}} = 10.4 \ln \left( \frac{M_{\text{WD}}}{M_\odot} \right) \frac{M_\odot}{0.49} \tag{4}
\]

Wood (1992) also gives a simple formula for estimating main-sequence lifetimes

\[
\tau_{\text{MS}} = 10 \left( \frac{M_{\text{MS}}}{M_\odot} \right)^{-2.5} \text{Gyr.} \tag{5}
\]

The white dwarf cooling age and the main-sequence lifetime can then be combined to give the system age of local white dwarfs. We use this age, combined with the distance to the white dwarf, to estimate the magnitude of planets.

4 SUITABLE TARGETS AMONG NEARBY WHITE DWARFS

There are 118 white dwarfs currently catalogued within 20 pc of the Sun (Holberg, Oswalt & Sion 2002). All of these systems are close enough to allow us to resolve planetary companions in \( \sim 5–100 \) au from the ground. For example, at 10 pc an orbit of 10 au is equivalent to a maximum separation of 1 arcsec on the sky. Planets in wider orbits will be easier to resolve. Adaptive optics, coronographs and techniques such as nulling interferometry will increase the chances of resolving closer companions.

However, only those white dwarfs young enough for Jovian companions to still be detectable will make suitable targets for extra-solar planet searches. We are most likely to be able to detect an extra-solar planet around a relatively warm and young (\(<a \sim 0.6\)
few $\times 10^8$ yr), massive ($>0.6M_\odot$) white dwarf descended from a relatively massive progenitor ($>2M_\odot$), since its main-sequence lifetime is short ($<1.8$ Gyr). For $M_{\text{WD}} < 0.6M_\odot$, the main-sequence lifetime is very sensitive to errors in the $M_{\text{WD}}$ estimate (see Fig. 1). Therefore, we would be unwise to rule out white dwarfs with mass estimates below 0.6 $M_\odot$, as they may be descended from more massive stars than we expect.

Table 1 lists the top 10 candidates among nearby white dwarfs for a search for planetary companions, considering the main-sequence lifetime $t_{\text{MS}}$, the white dwarf cooling age $t_{\text{COOL}}$, and the distance. Also included in the table are the estimated $J$-band magnitude of 3, 5 and 10 $M_{\text{JUP}}$ planets in each system.

In Fig. 2 we plot the magnitude of a $5M_{\text{JUP}}$ planet around these white dwarfs in several near-IR bands ($J$, $H$, $K$, $L'$ and $M$). Also plotted are the nominal sensitivity limits for current near-infrared imaging instruments (from on-line exposure time estimates): Gemini-North + NIRI (solid lines) and VLT + ISAAC (dashed lines). We can see that although the planets are brighter in the $M$ band (5 $\mu$m), the instruments are only sensitive enough in the $J$ and $H$ bands (1.1 and 1.6 $\mu$m).

## 5 THE EXPECTED FREQUENCY OF PLANETS IN WIDE ORBITS AROUND WHITE DWARFS

Assuming that massive planets born in initially wide ($>5$ au) orbits remain bound to white dwarfs, then the expected frequency of massive planets around nearby white dwarfs is simply a function of the frequency of solar-like and more massive main-sequence stars with Jovian-like planetary systems. Unfortunately, we currently have little observational information on these systems, although it is possible to extrapolate from existing data to make some estimate of what we might expect. Lineweaver & Grether (2002, LG) have analysed the statistics of planets detected via radial velocity techniques, and estimated the number of Jovian-like systems we might expect to find. They have produced a fit to the completeness-correct period distribution of planets so far detected, in the mass range $0.84M_{\text{JUP}} < M \sin i < 13M_{\text{JUP}}$:

\[
\frac{dN}{d\log P} = a \log P + b,
\]

where $a = 12 \pm 3$ and $b = -9 \pm 2$. The initial orbital periods of interest range from $\sim 10$ yr, to avoid direct interaction with the expanding red giant envelope, to $\sim 200$ yr, where we might expect Jovian planet formation to end. Integrating equation (6) over this range, we estimate there to be $\sim 55 \pm 16$ Jovian planets per $\sim 1000$ white dwarf systems. However, for a significant sample of nearby white dwarfs we can only detect planets $\geq 5M_{\text{JUP}}$ with current technology. LG fit the observed planetary mass function as

\[
\frac{dN}{d\log(M \sin i)} = a \log(M \sin i) + b,
\]

where $a = -24 \pm 4$. To produce $55 \pm 16$ planets over the mass range $0.84M_{\text{JUP}} < M \sin i < 13M_{\text{JUP}}$ we need to set $b = -58.4 \pm 19.7$. Therefore, from equation (7), we expect $\sim 15 \pm 6$ planets $\geq 5M_{\text{JUP}}$ per 1000 white dwarfs. Hence, we may expect $1\% - 2\%$ of white dwarfs to possess one or more planets $\geq 5M_{\text{JUP}}$. Note that we treat $M \sin i$ as equivalent to $M$, so this predicted number density is a lower limit.

This analysis is, however, based on statistics for planets in orbits $\leq 3.5$ au. It is quite possible that laws derived for planets in this area of orbital parameter space around $\sim 1M_\odot$ stars do not apply to Jovian planets at large radii ($>5$ au) around more massive stars ($2\sim 8M_\odot$).

## 6 DISCUSSION

We have suggested that Jovian planets will survive the late stages of stellar evolution, and that some nearby white dwarfs possess planetary systems in wide orbits. Utilizing evolutionary models for Jovian planets, we have shown that infrared imaging of suitable nearby white dwarfs should allow us to resolve and detect companions $M \geq 3M_{\text{JUP}}$ with 8-m class telescopes. The best candidates for an observational search are relatively hot (young), massive ($>0.6M_\odot$) white dwarfs, as they have the shortest overall system age. However, given that we have neglected potential heating mechanisms such as thermal insolation and accretion from the red giant’s wind, Jovian planets around nearby white dwarfs are likely to be brighter than we have suggested in Fig. 2, and may be detectable around $\sim 0.55M_\odot$ white dwarfs descended from progenitors as low in mass as $1.2M_\odot$.

Our ‘top ten’ list of targets among nearby white dwarfs (Table 1) includes degenerates descended from main-sequence progenitors from $2.6\sim 7.4M_\odot$, corresponding to spectral types early A and B. The existence of a dust disc around Vega (A0V) strongly suggests that planetary systems may exist around such early-type stars, although they are not the subject of current radial velocity searches.

Detection of massive planetary companions to nearby white dwarfs would prove that such objects can survive the final stages of stellar evolution, place constraints on the frequency of main-sequence stars with planetary systems dynamically similar to our own, and allow direct spectroscopic investigation of their composition and structure.

An unsuccessful search would suggest one of, or a combination of, a number of scenarios, including: (a) that planets $\geq 3M_{\text{JUP}}$ are rarer than expected from the evolutionary models we have used; (b) that, at least for a sub-sample of targets, any accompanying planets have too small a projected separation from the white dwarf to be resolved; (c) that massive Jupiters in wide orbits around $1\sim 8M_\odot$ main-sequence stars are not common; (d) that these planets do not remain bound to white dwarfs. This last scenario would raise the possibility that the Galaxy contains a population of
isolated Jovian-mass planets ejected by white dwarfs during the final stages of their evolution.

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