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Imaging extra-solar planets around nearby white dwarfs

Matt Burleigh

Dept. of Physics and Astronomy, University of Leicester, Leicester, UK

Fraser Clarke, Simon Hodgkin

Institute of Astronomy, Madingley Road, Cambridge, UK

Abstract. White dwarfs should retain planetary systems in wide orbits ($\gtrsim$ 5 AU). Evolutionary models for Jovian planets show that infra-red imaging of suitable nearby white dwarfs should allow us to resolve and detect companions $\gtrsim 5\,\mathrm{M_{JUP}}$. We have instigated programmes with both the 8m Gemini North (using NIRI), Gemini South (using Flamingos) and with the NAOMI Adaptive Optics system on the 4.2m William Herschel Telescope to search for such objects, which will share the large proper motions of their white dwarf hosts.

1. Introduction

To date, no planetary mass companions to nearby stars have been directly imaged, although several brown dwarf companions have been detected (e.g. Gl229B, Nakajima et al. 1995). Of course, the extreme contrast ($\gtrsim$ 20 magnitudes) and small separations (10AU $= 1''$ at 10 pc) between main sequence stars and Jovian planets makes sensitive surveys very difficult. One solution to these problems is to target low luminosity stars.

White dwarfs, the end state of main sequence stars with $\mathrm{M} \lesssim 8\mathrm{M}_{\odot}$, are typically $10^2 - 10^4$ times less luminous than their progenitors. Thus, there is potentially a strong gain in the brightness contrast between a planet and white dwarf when compared to a main sequence star. The gain is strongest in the mid-infra-red, where the planet's thermal emission peaks well into the white dwarf's Rayleigh-Jeans tail.

The idea of looking for low mass companions to white dwarfs is not new. Indeed, the first L dwarf discovered is a companion to the white dwarf GD165 (Becklin & Zuckerman, 1988). The photometric surveys of Probst (1983a,b), and Zuckerman & Becklin (1992) looked for near IR excess from white dwarfs. More recently, Farihi, Becklin & Zuckerman (2002) have surveyed nearby white dwarfs for wider proper motion companions as faint as $J = 19$. These surveys did not, however, have the sensitivity to detect planetary mass objects.

Burleigh, Clarke & Hodgkin (2002) discuss in detail the possibilities for detecting massive Jovian planets around nearby white dwarfs, including a consideration of the evolution of extra-solar planetary systems in the post- main sequence phase. Here, we summarize and update that discussion, and present the first results of the observing programmes that we are currently conducting.

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. 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 (conservatively, 5 AU) will be engulfed and migrate inwards, either completely evaporating or becoming 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 in our own Solar System) will have a greater chance of survival, migrating outwards as mass is slowly lost from the central star. The orbits remain bound to the central star since the dynamical timescale for the planet to react to a change the central star's mass is much less than the typical mass loss timescales. To a first approximation, the orbits of planets which do not interact directly with the red giant will expand adiabatically by a maximum factor M_{MS}/M_{WD}. For example, for a main sequence star $\sim 2M_{\odot}$ forming a $\sim 0.6M_{\odot}$ white dwarf, the orbit will expand by a maximum factor ~ 3. A planet in a Neptune-like orbit would be relocated to ~ 90 AU. At 10 pc this is equivalent to a separation of $9''$ on the sky - easily resolvable, even if the difference in brightness between white dwarf and planet is > 10 magnitudes.

Duncan & Lissauer (1998) have made detailed calculations of the effects of post- main sequence mass loss on the stability of our Solar System and for planetary systems around more massive stars. They show that the orbits of the giant planets will remain stable for tens of billions of years subsequent to the Sun's death, although planetary systems dynamically similar to our own around more massive stars may become de-stabalised in less than a Hubble time.

3. The luminosities of 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, and also on its distance from us. We (Burleigh et al. 2002) have used Burrows et al.'s (1997) models for planets evolving in isolation, together with estimates of the *total* ages (i.e. main sequence lifetime + cooling age) of catalogued white dwarfs within 20 pc (Holberg, Oswalt & Sion 2002), to predict the infra-red magnitudes of accompanying planets of a variety of masses. Note that Burrows et al.'s models do not include the effects of thermal insolation by, or reflected light from, the parent star. In reality, the planets would have been warmed throughout their lives by the white dwarf progenitors, as well as accreted matter during the RGB/AGB and planetary nebula phases. Therefore, our predicted luminosities are likely lower limits.

Table 1 and Figure 2 of Burleigh et al. (2002) detail the predicted infrared magnitudes of 3, 5 and 10 M_{JUP} planets around the "top ten" white dwarf targets within 20 pc, and compare these predictions with the 1 hr, 5σ limiting sensitivities for the 8m Gemini North telescope + NIRI ($J_{\mathrm{limit}} \sim 23.5$). Massive Jovian planets should be detectable around all these nearby white dwarfs in the near infra-red, especially in the J band. The planets themselves are brightest at M (5 microns), but no ground-based telescope is sensitive enough yet to detect these objects in the thermal IR.

The "top ten" list include degenerates descended from main sequence progenitors from 2.6–7.4$M_\odot$, corresponding to spectral types early A and B. Main sequence stars this massive are not the subject of current radial velocity searches, although the existence of a dust disk around Vega (A0 V) strongly suggests that planetary systems exist around such early type stars.

Since the publication of our original MNRAS paper, Adam Burrows has kindly supplied us with more recent calculations of the evolution and expected luminosities of massive Jovian planets. These new models show little change in the expected infra-red magnitudes of 10 M_{JUP} planets; indeed, at an age of $\sim$ 1 Gyr the planets are slightly brighter. However, at $\sim$ 1 Gyr we now expect the J band luminosity of 5 M_{JUP} planets to decline steeply, causing them to fade beyond detectability. This change is due to the inclusion of H_2O condensation clouds below $T_{\mathrm{eff}} \simeq$400K. Therefore, we now only expect to be able to detect planets ($\lesssim 5\,M_{\mathrm{JUP}}$) around a few of the most favourable targets, although $\sim$ 10 M_{JUP} remains a realistic goal for a significant sample of nearby white dwarfs.

Of course, more massive substellar companions, brown dwarfs, will be easily detected. Therefore, we can place limits on the fraction of B–F stars with substellar companions between 10–1000 AU. This region is of particular interest, as current surveys show a discrepancy between the brown dwarf companion fraction at small radii (<10AU; 0.5%; Marcy and Butler, 2000) and large radii (>1000AU; 10–30%; Gizis et al, 2001). The change between these two regimes presumably occurs between 10–1000 AU.

4. Observing programs and first results

We have active observing programmes to search for substellar and planetary mass companions to nearby white dwarfs with the 8m Gemini North telescope on Hawaii, Gemini South in Chile, and with the 4.2m William Herschel Telescope on La Palma. At Gemini North we are using NIRI, at Gemini South Flamingos-I, and at the WHT we are using the new NAOMI adaptive optics system together with the INGRID near-IR detector. All observations are initially made in the J band. Typical total exposure times are ≈1 hour. With NIRI this gives us a 5σ sensitivity of J $\sim$ 23.5, nearly 5 magnitudes deeper than Farihi et al. (2002).

Initial results are promising, and a number of candidate faint companions have already been identified. For example, Figure 1 (on the accompanying CD-ROM) shows a WHT+NAOMI/INGRID observation of the bright (V $\sim$ 11.5) white dwarf Wolf 1346 (d ≈ 15 pc). A number of faint sources are visible at interesting separations from the target, including a J $\sim$ 20.6 object that would lie at a true separation of $\sim$ 50 AU if it is physically associated with the white dwarf. Wolf 1346 is too old (> 5 Gyr) for even massive planets to be detectable, but this faint source could be a sub-stellar object. Figure 2 (also on the CD-

ROM) gives an estimate (to a factor ~ 2) of the minimum mass we are sensitive to (10σ) in this observation, as a function of separation from the white dwarf.

Of course, we cannot claim that any of our candidate faint companions are physically associated with a white dwarf until follow-up observations are made to check their proper motions. Nearby white dwarfs have high proper motions ($\gtrsim 0.1''$/yr), and any true companions must of course share this motion.

5. Summary

Jovian planets in wide orbits ($\gtrsim 5\,$AU) should survive the late stages of stellar evolution, and any $\gtrsim 5\,\mathrm{M_{JUP}}$ should be directly detectable around suitable nearby white dwarfs. We are conducting searches with both 8m Gemini telescopes and the 4.2m WHT on La Palma. Initial results have revealed a number of candidate faint companions; follow-up observations will show whether those objects share the white dwarfs' high proper motion.

Direct detection of planetary companions to white dwarfs would allow spectroscopic investigation of their composition and structure, place constraints on the frequency of main sequence stars with planetary systems dynamically similar to our own, and place constraints on the frequency of main sequence stars more massive than the Sun with planetary systems. Non-detection might suggest that massive planets are not common around early-type main sequence stars, or that planets do not remain bound to white dwarfs.

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