SED Signatures of Jovian Planets Around White Dwarf Stars

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ABSTRACT

The problem of detecting Jovian-sized planets orbiting White Dwarf stars is considered. Significant IR excesses result from warm Jupiters orbiting a White Dwarf of $T_{\text{eff}} = 10000$ K at a distance of $\sim 10^3$ White Dwarf radii (corresponding to $\sim 10^2$ Jupiter radii or a few tenths of an AU) with an orbital period of $\sim 100$ days. Such a planet will have a 10 micron flux density at its Wien peak that is comparable to the emission of the White Dwarf at that wavelength. Although the White Dwarf is much hotter than the planet, the planet will have peak brightness at the IR, well into the Rayleigh-Jeans tail of the White Dwarf, plus Jovians are about 10 times larger than White Dwarfs, so there is a substantial gain in the planet to star brightness contrast as compared to planets around Main Sequence stars. In the solar neighborhood, there are 51 White Dwarf stars within 13 pc of the Sun. At 10 pc, the IR flux density of “warm” Jupiters (a few hundred Kelvin) will fall in the range 10–100 micro-Jansky which should be observable with SIRTF.

Subject headings: Stars: Planetary Systems — Stars: White Dwarfs

1. Introduction

There is tremendous excitement in the astronomical community regarding recent discoveries of extrasolar planets and future projects for accelerating detection rates and expanding the range of planetary types that can be observed (e.g., see reviews by Marcy & Butler 1998; Woolf & Angel 1998). The method which has been so successful in the ongoing discovery of extra-solar planets is based on Doppler shift observations of stellar photospheric lines, an indirect method for inferring the presence of an orbiting companion (e.g., Mayor & Queloz 1995; Marcy & Butler 1996; Butler & Marcy 1996). Other methods have been used in the search for extra-solar planets but without as much success as the Doppler technique. For example, direct detection through imaging is hampered both by the faintness of planets and the brightness of the central stars. Transit events are similarly difficult to detect owing to the small brightness variations of the star and the requirement for a special viewing orientation; however, the transit of HD 209458 by its planetary companion demonstrates the tremendous potential for gleaning important information about a planet during such occurrences (Charbonneau et al. 2000; Henry et al. 2000; Brown et al. 2001).

Some have considered the possibility of detecting planets around White Dwarf stars. The problem has been approached from several different directions. For example, Provencal (1997) has discussed the possibility of phase analysis techniques for pulsating White Dwarfs. Li, Ferrario, & Wickramasinghe (1998) consider methods based on the interaction of Jovian planets with the magnetosphere of the White Dwarf (in analogy to the Jupiter-Io system). Chu et al. (2001) discuss a technique based on hydrogen recombination lines formed in the Jovian atmosphere for planets around UV-bright White Dwarfs. Livio, Pringle, & Saffer (1992) comment that an Earth-like planet with a temperature of 300 K would produce an IR excess of about 1% of the White Dwarf continuum emission. The contribution of this paper is to consider the

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IR excess for Jovian-type planets at a range of orbital radii, and to make quantitative estimates on the expected continuum emission and the number of nearby targets that could reasonably be expected to yield possible detections.

Observationally, the major advantage of searching for giant planets around White Dwarfs is that they are much smaller in diameter than solar-type Main Sequence stars. They also tend to be somewhat hotter than G dwarfs. Using the 4th edition of the Catalog of Spectroscopically Identified White Dwarfs (McCook & Sion 1999), Holberg, Oswalt, & Sion (2001) have identified the known White Dwarf stars within 20 pcs. Using the type designation provided in their Table 1 to estimate effective surface temperatures, I find an average value of about 8700 K for 103 stars (approximately one-fourth of the stars have temperatures in excess of 10000 K, up to about 25000 K). In the net, White Dwarfs tend to have luminosities of about a thousand times smaller than solar-type stars. So there is potentially a strong gain in the brightness contrast of a planet around a White Dwarf star when compared to a late-type Main Sequence star.

However, it is not quite so straightforward. Consider the elementary expression for the temperature $T_P$ of a planet with an albedo, $A_P$, in a circular orbit of radius $d_P$ about a White Dwarf of radius $R_{WD}$ and temperature $T_{WD}$:

$$T_P = T_{WD} (1 - A_P)^{1/4} \left( \frac{R_{WD}}{2d_P} \right)^{1/2}.$$  

(1)

The ratio of Bolometric luminosities between the planet and the White Dwarf will be

$$\frac{L_P}{L_{WD}} = \frac{R_P^4 T_P^4}{R_{WD}^4 T_{WD}^4} = \left( \frac{R_P}{2d_P} \right)^2 (1 - A_P).$$  

(2)

so that the Bolometric brightness contrast between the planet and star does not actually depend on the star at all, only the radius of the planet, its distance from the star, and the albedo. (Of course, cooler stars will be fainter, and all things being equal, their planets will be cooler and fainter too, so that longer integration times will be needed to reach a given detection threshold.) On the other hand, the orbits of planets can drastically change during a star’s post-Main Sequence evolution, such as might occur during a common envelope phase (e.g., Livio & Soker 1984). It may be possible that $d_P$ could degrade to small values. In some cases a low-mass companion will spiral into the star during its bloated AGB phase; in other cases a companion may drift to orbits of larger size. Given that the discovery of large planets orbiting solar-type stars with periods of a few days came as a great surprise to the astronomical community, nature may have a way of placing Jovian planets in orbits of small or modest size ($\lesssim 1$ AU) around White Dwarf stars. Taking the purely empirical approach, what are the observational signatures that should be considered to determine in fact whether planets around low-mass stellar remnants are common or rare?

The approach adopted here will be to consider spectroscopic signatures in terms of the continuum energy distribution from a White Dwarf + Jovian Planet system. These results should also be applicable to binary systems involving a White Dwarf and a Brown Dwarf (e.g., as discussed by Stringfellow, Black, & Bodenheimer 1990). If the system is a close binary, the Brown Dwarf companion might not be resolvable as a secondary source but could betray its presence through an IR excess.

The following section details the flux density estimates for such a planet orbiting a White Dwarf in terms of the central star’s temperature and the planet’s orbital proximity. The paper concludes with a discussion of the observational prospects.
2. The Combined Spectrum of a White Dwarf and Jovian Planet

To compute the spectral energy distribution (SED) of a White Dwarf and a planetary companion, it shall be assumed that both objects emit a blackbody spectrum. Specifying the temperature and radius of the White Dwarf allows one to calculate the planet’s temperature assuming radiative equilibrium and provided values for the albedo, planet radius, and orbital distance. However, in considering a planet that orbits quite close to the White Dwarf, one cannot use the elementary form for computing the planet temperature. Also, one must realize that a Jovian planet is an order of magnitude larger than the White Dwarf. This means that the shortest orbital distance between the two is

\[ d_P = R_{WD} + R_P \approx R_P. \]

Actually, this is a geometric limit. A more fundamental physical barrier is the Roche limit. For a typical White Dwarf and a Jupiter-like planet, the classical Roche limit (in this case \( r_{\text{clas}} = 2.44 R_{WD} (\rho_{WD}/\rho_P)^{1/3} \) for a liquid spherical planet) yields a value of 270 \( R_{WD} \), or 24 \( R_J \). However, continuing with an exact derivation of the planet temperature yields

\[ T_P = T_{WD} (1 - A_P)^{1/4} \left( \frac{R_{WD}}{R_P} \right)^{1/2} [W(R_P, d_P)]^{1/4}, \]

(3)

where the dilution factor \( W \) is given by

\[ W(R_P, d_P) = \frac{1}{2} \left( 1 - \sqrt{1 - \frac{R_P^2}{d_P^2}} \right). \]

(4)

In the limit that \( (R_P/d_P)^2 \ll 1 \), the dilution factor approximates to \( W \approx 0.25 (R_P/d_P)^2 \), and equation (3) reduces to the standard elementary form.

Figure 1 plots curves of \( T_P \) against the orbital distance \( d_P \). The lower scale is for \( d_P/R_{WD} \), and the upper scale is for the orbital period \( P \) in days, assuming that \( R_{WD} = R_\oplus \). Each curve is for a different temperature parameter \( T_0 \) associated with the White Dwarf. This parameter is defined by

\[ T_0 = 2^{-1/2} (1 - A_P)^{1/4} T_{WD}, \]

(5)

which is essentially the constant coefficient for the elementary form of \( T_P \) if only \( d_P/R_{WD} \) is allowed to vary. From lower left to upper right, the curves are for \( T_0 = 2000, 4000, 8000, 16000, 28000, \) and 56000 K. For comparison, Chu et al. (2001) considered models with \( T_{WD} \) in the range of 20000–200000 K for \( d_P \) between 0.5 and 5 AU \( (10^4 - 10^5 R_{WD}) \) for gas giants of \( R_P \) between 0.5 and 5.0 \( R_J \). Assuming \( A_P \ll 0.5 \), the curves in Figure 1 have some overlap with the temperature range considered by Chu et al., but are generally for cooler stars as appropriate for the sample of nearby White Dwarfs; however, those authors targeted hot White Dwarfs, which although fairly rare, provide the requisite UV flux for the planetary recombination line analysis that they were investigating.

Assuming that the planet has a radius like that of Jupiter, the Figure shows an excluded region at left corresponding to \( d_P < (R_J + R_{WD}) \). The arrow at bottom indicates the classical Roche limit. There is also a forbidden region at top, where the planet becomes so hot that hydrogen gas can readily escape the planet’s atmosphere. This is set by the condition that \( v_{th}(H) \gg 1/6 v_{\text{esc}} \), corresponding to \( T_P \gg 4100 \) K.

For a particular set of values for the White Dwarf and planet parameters, the specific fluxes are given respectively by

\[ F_\nu^{WD} = \frac{\pi R_{WD}^2}{4 D^2} B_\nu(T_{WD}) \quad \text{and} \quad F_\nu = (3.4 \times 10^6 \text{ mJy}) \times \frac{R_{WD}^2}{D_{\text{pc}}^2} B_\nu(T_{WD}), \]

(6)
and

\[ F_\nu^P = \frac{\pi R_P^2}{4 D^2} B_\nu(T_P) = (4.2 \times 10^8 \text{ mJy}) \times \frac{R_P^2}{D_{\text{pc}}^2} B_\nu(T_P), \]  

(7)

where \( R_\oplus \) signifies the White Dwarf radius in Earth radii, \( R_J \) signifies the planet radius in Jupiter radii, \( D_{\text{pc}} \) indicates the distance to the system in parsecs, and \( B_\nu \) must be given in cgs units. Figure 2 shows SEDs for a White Dwarf at \( D = 1 \text{ pc} \) with fixed values of \( T_{WD} = 10000 \text{ K} \) and \( R_{WD} = R_\oplus \) but Jovian sized planets of various temperatures. The frequency range spans from the UV out to the sub-mm. The dotted line is for the White Dwarf, the dashed lines for the planet, and the solid lines represent the combined spectra. The three planetary curves are for \( T_P = 150, 225, \) and \( 450 \text{ K} \) (this latter value is the approximately maximum possible based on the Jovian being at the classical Roche limit). The SEDs can be significantly modified from a Planckian for hot Jupiters in the IR (even the NIR for planets around hotter White Dwarfs). For cool Jupiters, the long wavelength spectral slope deviates from the power law of \( \nu^2 \) for the Rayleigh-Jeans tail in the vicinity of the Wien peak for the planet. For warm Jupiters of several hundred Kelvin, the IR excess occurs at the level of tens of milli-Jansky. At sufficiently long wavelengths, both the planet and the White Dwarf SED will vary as \( \nu^2 \); however, the presence of the planet can still be inferred (for a sufficiently sensitive instrument) from the excess emission. In the Rayleigh-Jeans portion for the combined spectrum, the ratio of total emission to that of just the White Dwarf will be given by

\[ 1 + \left( \frac{R_P^2 T_P}{R_{WD}^2 T_{WD}} \right) \approx 1 + 100 T_P / T_{WD}, \]

with values ranging typically from 1 (planet not detectable) to 10 (long wavelength emission dominated by the planet). It has been assumed that for the analysis of an observed spectrum, the value of \( T_{WD} \) is already known, and that other sources of long wavelength emission are incommensurate with the continuum slope or amount of emission.

3. Discussion

White Dwarfs are interesting as candidates for harboring planets because (a) planets are thought to be a common occurrence around solar-type stars, and White Dwarfs are the endstates of low-mass stellar evolution, (b) it is possible for planets to suffer orbital degradation during evolved stages of evolution, and (c) White Dwarfs are fairly common (\( \sim 10^{-2} \text{ pc}^{-3} \)) and thus there are a significant number of them to be found in the locale of the Sun. This paper reports on the possibility of detecting extra-solar planets around White Dwarf stars through an analysis of SEDs. The Roche limit is found to be an important limiting factor on the temperature and hence brightness of planets. Using the classical limit, the planet cannot orbit any closer than about 24 \( R_J \), and so its temperature is limited to \( T_P \lesssim 0.043 T_{WD} \). This means that the typical nearby White Dwarfs could have warm Jupiters, but not hot ones. The primary observational diagnostics arise from (a) an IR “bump”, or softening of the power law spectral index, in the SED around the vicinity of the Wien peak for the planet but well into the Rayleigh-Jeans tail of the White Dwarf, or (b) significant excess emission in the Rayleigh-Jeans tail of the combined emission.

In the tabulation of nearby White Dwarf stars, Holberg et al. (2001) determine that the catalog is complete to 13 pcs, and that there are 51 White Dwarfs within a spherical volume of that radius (from their Tab. 1). Of these, 17 are binary systems (two are double-degenerate systems), leaving 32 single star candidates to target for a search of planetary companions. The SEDs in Figure 2 were computed for a White Dwarf at 1 pc. A “warm” Jupiter of a few hundred Kelvin orbiting a White Dwarf at a distance of 10 pc should have a flux density at its Wien peak (10–30 microns) that is comparable to that of a 10000 K White Dwarf with a value in the range of 10–100 micro-Janskys. Such faint signals should be detectable, for example, with SIRTF. The IRAC camera conducts IR photometry at 3.6, 4.5, 5.8, and 8.0 microns (with bandpasses of 1–2 microns in width). At 8.0 microns, the IRAC can detect an 18 micro-Jansky source at \( 5\sigma \) in about 8 minutes (less time is required at the shorter wavelengths). This would be sufficient to determine
whether or not a White Dwarf exhibited an IR excess. For the same time and S/N, the low resolution short
wavelength spectrograph on the IRS could build up a spectrum for a 550 micro-Jansky source in the range
5–14 microns. (Observing time estimates for both IRAC and IRS are based on information provided by the
SIRTF Science Center at the web site http://sirtf.caltech.edu/SciUser/.)

One consideration that has been neglected is the possibility that the planet might show brightness
variations with orbital phase. If a planet is relatively close to the star, it might be in synchronous orbit
(however the timescale for spin locking the secondary depends sensitively on $d_P/R_{WD}$ with the 6th power;
e.g., see Trilling 2000). If so, then one would generally expect variable brightness of the planet as the “day”
and “night” sides alternately face the Earth during the planet’s orbit. At just a few hundred $R_{WD}$ distant
(or tens of $R_J$), the orbital period would be only a few hours. However, it is not clear how discrepant
the day-night temperatures will be to yield IR variations. Changes in the brightness at UV and optical
wavelengths could vary by as much as $\approx 1 \pm A_P(\lambda)R_J^2/4d_P^2$ for a suitable viewing perspective, with $A_P(\lambda)$
the wavelength dependent reflectivity of the Jovian atmosphere. For the classical Roche limit, the minimum
orbital radius will be about $d_P \approx 24R_J$, so that even if $A_P$ were unity, the maximum brightness variation
in reflected light would be 0.04%.

It is worth noting that the reflex motion of the star from the presence of the orbiting planet might be
measurable. Observed Balmer lines tend to have broad sloping wings but a relatively narrow absorption
core. For example, the core widths in the Hα profiles of Heber, Napiwotzki, & Reid (1997) and Koester
et al. (1998) are around 1 Å, corresponding to velocity widths of 40–50 km s$^{-1}$. Although the typical critical
speed of rotation for a White Dwarf is quite high ($v_{\text{crit}} \approx 4600$ km/s$^{-1}$), the observations are consistent
with little or no rotation (e.g., upper limits of tens of km s$^{-1}$ from Heber et al. 1997 and Koester et al.
1998). For purposes of a quantitative estimate, consider a White Dwarf of 1$M_\odot$ with a core line width of
about 40 km s$^{-1}$, and a planet of 1$M_J$ orbiting at 1000$R_{WD}$ with a period of about 3.2 days. Assuming a
circular orbit, as has been the case throughout this paper, the reflex motion imparted to the star will be
$\approx 150$ m s$^{-1}$. However, the problem with White Dwarfs is that they are generally faint. Of the local sample,
the brightest star is about $m_V = 10.5$, and most are fainter than 12th magnitude. To detect the reflex
motion of such a speed with 10% accuracy would require a spectral resolution $\lambda/\Delta\lambda = 2 \times 10^6$ (or at least
a centroiding algorithm to that accuracy), which demands long integration times on large telescopes for
such faint targets. Note that Jovians at smaller $d_P$ would produce larger reflex motions in the central star
as $d_P^{-1/2}$; however, the orbital period decreases as $d_P^{3/2}$, placing an additional constraint on the integration
time.

Finally in closing, the SEDs have been derived under the simplifying assumption of blackbody source
functions. The gas giant would be expected to show absorption features by molecules, for example, and
these would modify the quantitative predictions of the run of flux density with frequency for the combined
SEDs. Modification of the planet temperature by internal heat has also been ignored. Three of the gas
giants in our solar system show excess IR emission by about 50% above what is absorbed in sunlight. Even
so, the results presented in this paper provide quantitative flux density values that are likely adequate for
motivating a search of planets around the nearest single White Dwarf stars.

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Fig. 1.— A plot of the expected planetary temperature $T_P$ for Jupiter-sized gas giant in a circular orbit of radius $d_P$ from a White Dwarf star of radius $R_{WD} = R_\odot$ and mass $M_{WD} = 1 M_\odot$. The upper axis indicates the orbital period $P$ in days. The five curves are distinguished by the temperature parameter $T_0 = 2^{-1/2} T_{WD} (1 - A_P)^{1/4}$ as indicated. (For $A_P = 0.5$, the curves correspond to $T_{WD} \approx 3400, 6700, 13500, 27000, 47000, \text{and} 94000 \text{ K}$. ) The shaded region at top is a “forbidden zone” where a Jovian would obtain to such a high value of $T_P$ that hydrogen would readily escape from the planet. At left is a forbidden region corresponding to $d_P = R_{WD} + R_J$, although in reality a Jovian would never get this close since the Roche limit falls at around $d_P \approx 270 R_{WD}$. 
Fig. 2.— Spectral energy distributions in milli-Janskys for a 10000 K White Dwarf (dotted line), four different planetary temperatures (dashed), and the combined flux densities (solid). The planetary SEDs are calculated for $T_P = 150, 225, \text{ and } 450 \text{ K}$. Although asymptotically, the low frequency slope of the SEDs is that of the Rayleigh-Jeans tail, the presence of a planet can produce a strong IR/sub-mm excess above the White Dwarf spectrum, and in the vicinity of the Wien peak for each planet, the merged SED significantly deviates from Planckian. Note that the flux density scale as shown applies for a White Dwarf + Jupiter system at $D = 1 \text{ pc}$.