A Search for Jovian Planets Around Hot White Dwarfs

ABSTRACT

Brucan樹/guy, hawati, edn
University of Huanan, Institute for Astronomy, 3860 Wooshan Drive, Honolulu, HI 96822

Volkingg Brander

and

Chung-ful, nicu, edn, carltsunfg, nicu, edn, Emedt, Eadst, nicu, edn
68201
Department of Astronomy, University of Illinois, 1000 West Green Street, Urbana, IL

You-Hua, Chia, Byn, C,等, Dune, B, Byn, and A, C, onal
1. Introduction

Searches for extrasolar planets have employed four techniques: direct imaging of the star and planet, photometric monitoring for transits, and astrometric and Doppler measurements of the reflex motion of the star due to planets. The imaging technique is difficult because a Jupiter-like planet is $\sim 10^9$ and $\sim 10^4$ times fainter than a solar-type host star at the visible and thermal IR wavelengths, respectively. The photometric method searches for occultations, but can only detect systems with the orbital plane seen edge-on, which is an exceedingly rare circumstance. For example, a Jupiter-sized planet orbiting a solar-type star at 1 AU has only $\lesssim 0.5\%$ chance of being in the proper alignment for photometric detection. The reflex motion of a star due to planets is typically small. To date, only the Doppler measurements have been successful in discovering planets around a pulsar (Wolszczan & Frail 1992) and solar-type stars (e.g., Mayor & Queloz 1995; Marcy & Butler 1996; Butler & Marcy 1996; Cochran et al. 1997). With the exception of the planets around the pulsar PSR1257+12, all other known extrasolar planets are Jupiter-sized, 0.2–11 Jupiter masses $(M_J)$, with orbital semi-major axis ranging from 0.04 AU to 3 AU.

Current searches for extrasolar planets do not explore whether intermediate-mass $(2 - 7 \, M_\odot)$ stars also possess planetary systems, because these stars, of MK spectral types A and B, have fewer stellar absorption lines available for accurate velocity measurement. Furthermore, because they are more massive than solar-type stars, the stellar reflex motion is even smaller. These difficulties can be circumvented, if one searches for planets around the descendants of these intermediate-mass stars: hot white dwarfs with $T_{\text{eff}} > 50,000$ K. A hot white dwarf’s UV radiation will photoionize the planetary atmosphere and recombination lines will be emitted by the planet. The contrast between the planet’s recombination line emission and the stellar spectrum will be the limiting factor for detecting the planet. The strength of the planet’s recombination line emission is proportional to the UV flux where the stellar emission peaks, but the recombination line is emitted at a longer wavelength where the stellar emission is lower; therefore, the contrast between the planet’s recombination line emission and the stellar spectrum is not as extreme as the contrast between the planet and star both in continuum.

Thus, it may be possible to find planets around hot white dwarfs by searching for a periodically Doppler-shifted recombination line emission superposed on the stellar spectrum. We have carried out calculations to demonstrate the feasibility of this search, taking into account the stellar evolutionary effects. In this letter we report the results of our calculations, discuss practical considerations, and present observations of a white dwarf to illustrate observational considerations.
2. Detectability of Planets around Hot White Dwarfs

Our proposed method to search for planets around hot white dwarfs utilizes recombination lines emitted by the ionized atmosphere of orbiting planets. In order to detect the planetary emission, the planet’s atmosphere needs to contain an abundant element that has recombination lines in easily observable wavelength ranges. Given currently available facilities, hydrogen provides the most observable recombination lines. Therefore, we will consider searching for only Jupiter-like gas giants around hot white dwarfs.

The progenitor of a hot white dwarf with $T_{\text{eff}} > 50,000$ K has gone through various evolutionary stages, among which the asymptotic giant branch (AGB) phase is the stage at which the star has the most pronounced effects on its planetary system, because the star swells up to a few hundred $R_\odot$, and goes through episodes of copious mass loss (Iben & Renzini 1983). At least four competing factors may affect the planetary system: (1) Planets engulfed in the stellar envelope will experience a drag force and migrate inward. (2) The decreasing central star mass will cause the planets to migrate outward. (3) Tidal interaction between a planet and the stellar envelope will slow down the planet’s orbital motion and cause it to migrate inward. (4) Planets orbiting an AGB star can experience accretion and/or evaporation. These factors have been taken into account by Livio & Soker (1984) in their calculation of the evolution of a star-planet system. They found that Jovian planets engulfed in the AGB envelope will either evaporate or accrete mass to become a close companion, depending on the mass of the stellar envelope, the initial mass of the planet, and the initial separation between the planet and the star. The calculations of Livio & Soker (1984) are admittedly qualitative, and there are no theoretical predictions which preclude the existence of Jovian planets within a few AU of a post-AGB star, or a hot white dwarf. Furthermore, a Jovian planet has been suggested to be a companion to the hot white dwarf PG 0950+139 (Dopita & Liebert 1989).

Hot white dwarfs with $T_{\text{eff}} > 50,000$ K are powerful sources for H-ionizing UV radiation. In this environment, the hydrogen-rich outer envelopes of any Jovian planets present will be photoionized. The resulting recombinations will cause the planet to emit hydrogen recombination lines. To calculate the recombination line strengths we have made a number of assumptions and approximations. For the stellar radiation, we use a blackbody radiation model to approximate the stellar spectrum and use $1 R_\odot$ as the stellar radius to determine the ionizing photon flux emitted by the star. We approximate the planetary atmosphere as a plane-parallel slab with physical dimension equivalent to the cross section of the planet. Within the slab, the UV flux from the white dwarf will ionize the outer layer of the atmosphere, to the point where the number of incident ionizing photons balances the number of recombinations. In other words, we treat the atmosphere as a “Strömgren slab.” Assuming
the ionized atmosphere is at a temperature of 10,000 K, the expected Hα luminosity is then given by:

\[ L_{\text{H} \alpha} = 7.7 \times 10^{-20} Q \left( \frac{r_p}{a} \right)^2 \text{ ergs s}^{-1}, \]

where \( Q \) is the ionizing flux of the white dwarf in number of ionizing photons per second, \( r_p \) is the radius of the planet in Jupiter radii (\( R_J \)), and \( a \) is the planet’s orbital semi-major axis in AU.

We have estimated the expected brightness contrast between a Jovian planet and the host star at the Hα line using the model described above. The calculations were performed for planets with radii of 0.5, 1.0, 2.0, and 5.0 \( R_J \) and orbital semi-major axes of 0.5, 1.0, 2.0, and 5.0 AU over a range of white dwarf temperatures, 20,000–200,000 K. The ratio of the Jovian planet’s Hα line flux to the underlying stellar flux (within a comparable bandwidth, \( \sim 0.5 \text{ Å} \), the expected thermal width of the Hα line) is shown in Figure 1.

From this simplistic model, it can be seen in Figure 1 that the ratio between the planet’s Hα line emission and the stellar continuum emission can be as high as \( \sim 1/20 \) for a Jupiter-sized planet at 1 AU from a \( \sim 200,000 \text{ K} \) star. This model, however, ignores many effects which will lower the contrast between the planet and star. For instance, in a dense, molecule-rich planetary atmosphere, H\(^+\) can react with atoms or molecules rather than recombine with a free electron; thus, the planetary Hα emission will be reduced. Furthermore, many hot white dwarfs show narrow Hα and He II \( \lambda 6560 \) line emission superposed on broad Hα and He II absorption (Reid & Wegner 1989) because of non-LTE (non-Local Thermal Equilibrium) effects in the stellar atmosphere (Lanz & Hubeny 1995; Hubeny et al. 1999). This will complicate the search for planetary Hα emission. Therefore, the results in Figure 1 portray an overly optimistic view of the detectability of Jovian planets around a hot white dwarf. On the other hand, the photoionization-driven ablation of a planetary atmosphere may produce an extended low-density (\( \sim 10^6 \text{ H-atom cm}^{-3} \)) nebula, and the forbidden lines emitted form this nebula can be easily detected (Dopita & Liebert 1989).

3. Observational Considerations

To detect the Hα emission from a Jovian planet around a hot white dwarf, multi-epoch, high-dispersion, high-S/N spectroscopic observations of a large sample of hot white dwarfs are needed. Below are some of the observational considerations for such a search.

- Velocity resolution: The orbital velocity of a planet within 5 AU of the host star
will be \( \geq 10 \text{ km s}^{-1} \). To be able to detect this motion, the precision of the velocity measurements should be \( \sim 1\text{-}2 \text{ km s}^{-1} \). This can be easily achieved with a high-dispersion spectrograph with \( R = 30,000 \).

- **Large telescope:** A sensitive search for recombination line emission from a planet requires a high signal to noise ratio \( (S/N) \). To achieve a \( S/N \) ratio of 100 for a 13.5 mag star with a reasonable exposure time \( (\lesssim 1.5 \text{ hours}) \), the telescope must be at least \( \geq 4 \text{ m} \) in diameter.

- **Long slit:** Due to the possible faintness of the planetary recombination line emission, telluric and interstellar line emission can interfere with the detection of the planetary lines. To facilitate the removal of telluric and interstellar line emission, a long slit is required for the observations.

- **Multi-epoch observations:** Given the range of semi-major axes over which this method is likely to detect H\( \alpha \) emission from a planet (a few AU), multiple epoch observations separated by 4–6 months are required to detect any change in the H\( \alpha \) emission line due to the orbital motion of the planet. Planetary H\( \alpha \) emission may be distinguished from stellar H\( \alpha \)+He II emission by the periodic velocity change of the planetary emission. Monitoring observations over a period of 2–3 years will be needed to determine the planetary orbital elements.

- **Planetary mass measurements:** Unlike reflex motion planet searches, the velocity shift observed is that of the planet rather than that of the host star. The mass of the planet cannot be accurately determined from this motion. Therefore, astrometric measurements of the reflex motions of the host white dwarfs are needed to determine the masses of discovered planets.

### 4. Example Observation of a Hot White Dwarf

The hot white dwarf Feige 34 was observed on 2000 April 23 (UT) with the echelle spectrograph on the 4-m telescope at Kitt Peak National Observatory. The high-dispersion spectra were obtained using the 79 l mm\(^{-1}\) echelle grating in combination with a 226 l mm\(^{-1}\) cross disperser and the long focus red camera. A reciprocal dispersion of 3.5 \( \text{ Å mm}^{-1} \) at H\( \alpha \) was achieved with this setup. The spectra were imaged with the T2KB CCD detector. The pixel size is 24 \( \mu \text{m} \), corresponding to 0\('\)24 pixel\(^{-1} \) along the slit and \( \sim 3.7 \text{ km s}^{-1} \) pixel\(^{-1} \) along the dispersion axis. Two 1800 s exposures were taken of Feige 34 with an east–west oriented 20\('\)-long slit of width 1\('\)5. The H\( \alpha \) region of the echellogram is presented in Figure 2.
All of the data were reduced using standard routines in IRAF\textsuperscript{1}.

The echellogram of Feige 34 shows broad Hα+He II absorption from the white dwarf superposed with a narrow Hα emission component and a faint He II emission component (marked in Figure 2). The Hα emission component has a FWHM of \(\sim 70\ \text{km}\ \text{s}^{-1}\); it appears offset blueward from the center of the absorption because the absorption is a blend of a strong Hα line and a weak He II line. Using the observations of Massey et al. (1988) for a flux calibration, we determine the Hα flux of the emission component to be \(1.4 \times 10^{-14}\ \text{erg}\ \text{cm}^{-2}\ \text{s}^{-1}\). This large flux and the lack of interstellar emission features on the Palomar Sky Survey plates rules out an interstellar origin for this emission component. Furthermore, the lack of forbidden line emission excludes the possibility that the Hα emission arises from a typical circumstellar nebula. It is possible that this Hα emission is dominated by the stellar Hα emission due to a non-LTE atmosphere (Werner 2000). This does not, however, exclude the possibility that the non-LTE stellar emission is superposed with weak Hα emission from an orbiting planet or low-mass dwarf companion.

A low-mass red dwarf companion to Feige 34 has been suggested by Thejll, MacDonald, & Saffer (1991) based on an infrared excess in JHK bands. Alternatively, a large planet close to the star, heated by the UV flux, may also produce the observed infrared excess. To distinguish between these two possibilities, further theoretical and observational work is required. Detailed modeling of a non-LTE white dwarf atmosphere for Feige 34 is needed to quantitatively assess whether all or part of the Hα emission feature in the spectrum of Feige 34 arises from the star. Follow-up spectroscopic observations are necessary to determine whether the Hα emission line profile shows temporal variations suggesting the existence of a companion. If temporal variations are detected, further monitoring observations would allow the orbital parameters and nature of the companion to Feige 34 to be determined.

5. Summary

We suggest that high-dispersion spectroscopic observations of hot white dwarfs can be used to search for Hα emission from Jovian planets within a few AU of the star. Hα emission from the ionized outer envelope of a Jovian planet as weak as 1/100 the stellar emission can be detected with modern large (\(\geq 4\)-m) telescopes. Non-LTE effects in the hot white dwarf atmosphere may produce stellar Hα emission. Stellar and planetary Hα

\textsuperscript{1}Image Analysis and Reduction Facility - IRAF 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.
emission can be disentangled by multi-epoch observations if changes in the Hα emission line profile due to the orbital motion of the planet are detected. Monitoring observations to establish the orbital parameters are required to distinguish between Jovian planets and a low-mass dwarf companion. High-dispersion spectroscopic observations of Feige 34 demonstrate the complexity and feasibility of this method to search for these planets. Such a search will provide targets for future high-precision astrometric observations (e.g., SIM, adaptive optics, etc.), and valuable insight can be obtained on the development and evolution of planetary systems around stars more massive than the Sun.

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Fig. 1.— Prediction of the contrast between the Hα line emission from a planet (L_{planet}) and the continuum emission from the host white dwarf (L_{WD}) as a function of T_{eff} of the white dwarf. The upper panel shows the variation in contrast for a 1 R_J sized Jovian planet at four different orbital semi-major axes. The lower panel shows the variation in contrast with respect to the planetary radius for an orbit with semi-major axis of 1 AU. See text for uncertainties in the model.
Fig. 2.— Continuum-normalized Hα+He II line profile of Feige 34.