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Searching for Companions to Late Type M Stars

Brian Oetiker, Nebojsa Duric, John McGraw, Tom Williams, Dale Jackson

University of New Mexico, Dept. of Physics and Astronomy, 800 Yale Blvd. NE, Albuquerque, NM 87131

Hans-Jörg Deeg

Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain

Michael Scheibner

Univerität Würzburg, Physikalisches Institut, Am Hubland 97074, Würzburg, Germany

Michael Tepper

Albuquerque High School, Albuquerque, NM 87102

Derek Garcia, Eric Wilcox

El Dorado High School, Albuquerque, NM 87111

Abstract. We describe a spectro-photometric method for detecting companions to M4 and later stars. Stars are imaged with 22 Angstrom FWHM optical filters tuned to the edge of the TiO molecular feature near 8400 Angstroms. This feature is found in the spectra of main sequence stars of spectral type M4 and later. A CCD camera is used to detect very small variations in flux caused by companion induced doppler oscillations of the TiO feature. This high photon efficiency technique allows for 1.5 km/s radial velocity precision on M stars as faint as 21st magnitude in V (on a 3 m class telescope). The current aim of the survey is the detection of non-stellar companions to M4 and later stars with orbital periods of days to months.

1. Introduction

Since the landmark discovery of an extrasolar planet by Mayor and Queloz in 1995, more than 25 additional planets have been observed. Similarly, the 1995 detection of Gl 229B by Nakajima et al, 1995 represented the discovery of the first of more than 50 presently known brown dwarfs. A consensus has yet to be reached on how to observationally distinguish between these two types of substellar object. Spectroscopic observations (Marley et al, 1999) may reveal differences in the reflected spectra of extrasolar giant planets compared to the combination of emission and reflected spectra of brown dwarf companions. The orbital elements (Black, 1997) of a substellar companion may also provide clues for distinguishing between these two objects. Both of these ideas are inherently connected with two distinct models (Boss, 1997) for the formation of massive substellar companions. One model proposes that extrasolar giant planets form by accretion of material in a disk orbiting a newly formed star. The other model suggests that the substellar companion forms as a result of a fragmentation of a protostellar cloud. By studying the composition and orbital characteristics of extrasolar giant planets and brown dwarfs, insights will be gained into these formation models.

Mazeh et al (1998) presents evidence of a gap, or transition region, in the mass distribution of 9 extrasolar companions which may represent two distinct populations. This gap falls in the mass region $\sim 30M_J$. Such a finding has serious implications on models for the formation of both brown dwarfs and extrasolar giant planets (Mazeh et al 1998). Certainly, more observational evidence is needed to substantiate this.

Because of experimental constraints, virtually all search projects have focussed on stars of spectral type G and K. Surveys of M stars have been done (Marcy and Benitz 1989, Marcy et al 1998) which include stars as late as M4, and as late as M6 (Delfosse et al 1998), but none have focussed exclusively on stars with spectral type M5 and later. As a result, companions have been found for stars with spectral type only as late as M4.

In this paper, we describe a spectro-photometric method whose aim is to survey nearby M5 and later stars for giant planetary and brown dwarf companions. The results of this survey aims to investigate these key issues regarding the nature of giant planets, brown dwarfs, and very cool stars.

2. Brief Description of Selected Search Methods

Nearly all contemporary extrasolar planet search techniques can be placed into three major categories: Spectroscopic, photometric, and astrometric. Each method has merits that make it suitable for searching for companions to various stellar types. We will briefly discuss the first two techniques because of their relevance to the spectro-photometric method described later in this paper.

2.1. Spectroscopic Technique

The spectroscopic method relies on the precise measurement of the radial velocity of a star. This measurement is made successively over an extended period of time with the goal of detecting slight companion-induced periodic doppler motion. The radial velocity is usually measured using a spectrograph mounted on a large (3m or larger) telescope. Usually thousands of atomic absorption lines are required (Cochrane and Hatzes, 1996). The light from the star is passed through a calibration medium (a chamber containing a gas with many known atomic features) before entering the spectrograph. If the star is relatively bright, that is $V \gtrsim 10$, then the spectroscopic method is capable of achieving radial velocity measurements as fine as 10 m/s (Mayor and Queloz 1995; Marcy et al 1998; Delfosse et al 1998).

Such astoundingly precise measurements are responsible for the detection of virtually all extrasolar planets today (with the exception of companions to pulsars). Thus, it is no surprise that radial velocity measurements using a spectrograph is the most popular method for searching for extrasolar planets.

Although the spectrograph is currently the most sensitive tool for searching for planets around stars other than our sun, it does have limitations (Baranne et al 1996). Primarily, this instrument requires large numbers of photons to achieve its optimal precision. Typically, this method is limited to stars brighter than V=10 for obtaining radial velocity measurements with precision of 10-20 m/s. For fainter sources, down to V=14, the precision of the radial velocity measurement drops to 0.5 km/s (Delfosse et al 1998). When translated to spectral type, magnitudes of V=10 and V=14 correspond to M4 and M6 respectively, at a distance of 9 pc. Thus, because of the relative lack of precision for fainter stars, extrasolar planet search projects using a spectrograph have not included stars of spectral type M6 and later.

2.2. Photometric Technique

A method more suited to searching for extrasolar planets around low mass stars is the photometric method. This method is conceptually much simpler than the spectroscopic method. Essentially, the observer monitors the star photometrically over a long time period hoping to observe a transit event; that is, small periodic drops in brightness corresponding to a planet passing in front of the star. (See Deeg et. al. 1998 for an good description of the transit method)

Because of their small surface areas and luminosities, late type stars are the most attractive candidates for extrasolar planet transit survey projects. Any planet or companion passing in front of the star will block a larger proportion of the star's flux, and will thus produce a larger signal. In fact, a body with a radius of $\sim 3R_{\oplus}$ passing in front of a late M star would produce 0.01 magnitude drop. This is readily detectable in a light curve produced using differential photometry (Deeg et al 1998).

Perhaps the biggest advantage of the photometric method is its high photon efficiency. That is, it relies on traditional photometric measurements of the star; using a CCD camera mounted on a telescope. Photometry has the added benefit of simple and quick data reductions. This increases the feasibility of surveys containing large numbers of stars. Thus, the transit search method is well suited to observing large numbers of faint, late M type stars for non-stellar companions.

A major limitation of the transit method is the fact that it can only detect companions with very specific orbital orientations. That is, only planetary systems with orbits very close to edge-on will produce observable transit events. As a consequence, hundreds of stars must be included in a survey in order for it to have a reasonable chance of detecting a companion (Heacox 1996).

Clearly, each of these two methods plays an important role in searching for and discovering companions to stars other than our sun. Equally important, these methods have historically neglected a significant portion of the stellar spectral sequence. That is, searching for non transiting extrasolar companions to stars of spectral type later than M6. We propose a method whose aim is to survey such stars for companions.

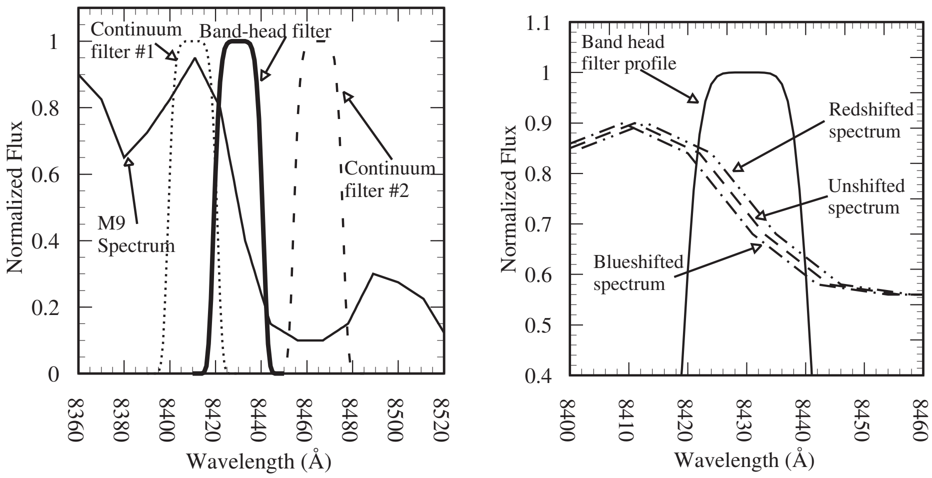

Figure 1. a) Continuum and band-head filter profiles superimposed with TiO band-head feature. b) Band-head filter superimposed with red and blue shifted spectrum.

3. Spectro-Photometric Method

3.1. Design

The spectro-photometric technique combines the versatility of the spectroscopic method and the simplicity of the photometric method. It utilizes a set of three very narrow band optical filters along with a CCD camera. The optical filters are placed on and around a molecular band-head feature in the spectrum of the star (figure 1). As the star and companion orbit their common center of mass, the band-head feature periodically doppler shifts within the range of the middle filter. The shifting of the band-head produces a periodic variation in the flux of starlight passing through the middle filter (figure 2). The photometric variation of the star is monitored over an extended time period to produce a light curve.

The optical filters surrounding the band-head are chosen such that any doppler shifting of the stars spectrum produces a minimal amount of change in flux through these filters. Essentially, these "continuum" filters serve as experimental controls. Any photometric variations which are present in all three filters can be attributed to an intrinsic change in the brightness of the star. Any photometric variations which are present only in the middle (band-head) filter must be attributed to doppler shifting of the band-head feature. Therefore, by imaging the star successively through each of the three filters, we are able to distinguish between intrinsic and doppler variations in the light curve.

The TiO band head feature near 8430 Angstroms was chosen for a number of reasons. This feature is very weak in spectral types as early as M3, and becomes dominant and steep in spectral types later than M5 (Kirkpatrick et al 1991). This particular feature is not near any telluric lines, and it is near the optimal wavelength in terms of quantum efficiency for most CCD cameras.

3.2. Capabilities of this Method

The ultimate measure of sensitivity for a doppler-based extrasolar planet search is how precisely radial velocity can be determined. Since the spectro-photometric method measures differences in magnitude (via a light curve), it is necessary to determine a relationship between magnitude or flux variations and radial velocity variations. The flux of starlight passing through the filter, F_λ can be calculated by equation 1. Where $s(\lambda)$ is the spectral line profile based on spectra from Kirkpatrick et al (1991), $f(\lambda)$ is the filter profile provided by the manufacturer, and λ_1 and λ_2 are minimum and maximum wavelengths over which the filter

$$F_\lambda = \int_{\lambda_1}^{\lambda_2} s(\lambda) f(\lambda) d\lambda \tag{1}$$

allows light to pass. Since the degree of red or blue shifting is determined by the radial velocity of the source, the above equation can be used to calculate corresponding changes in flux or magnitude. The results of such numerical calculations are summarized in table 1.

Table 1. Magnitude variations corresponding to radial velocity

$\Delta\lambda$ (Angstroms)	v(km/s)	Δ mag(mmag)
0.05	1.8	1.53
0.1	3.5	3.05
0.2	7.0	6.10
0.3	10.6	9.15
0.5	17.6	15.2
0.7	24.7	21.3
0.9	31.8	27.4
1.0	35.3	30.5
2.0	70.6	61.0
3.0	105.9	91.5

Current observational methods utilizing differential photometry limit photometric measurements to at best 1 mmag (Robinson et al 1995). In practice, we were able to achieve photometric accuracy of less than 2 mmag at Capilla Peak Observatory. If we adopt 1 mmag precision as an optimistic photometric precision, then a radial velocity of 3.5 km/s would correspond to a 3σ signal over the noise in the light curve. If we adopt a more conservative 3 mmag as a typical value for photometric precision, a radial velocity of 3.5 km/s will correspond to a 1σ signal above the noise. In either case, we consider 3.5 km/s a reasonable limiting value for measuring radial velocity using the spectro photometric method.

Now that the sensitivity of the spectro photometric method has been established in terms of radial velocity, it is relatively straight forward to examine the sensitivity of the method in terms of minimum detectable mass. For an extrasolar planetary system, the radial velocity of the parent star is given by equation 2. P is the period of the system, m is the mass of the planet, M is the

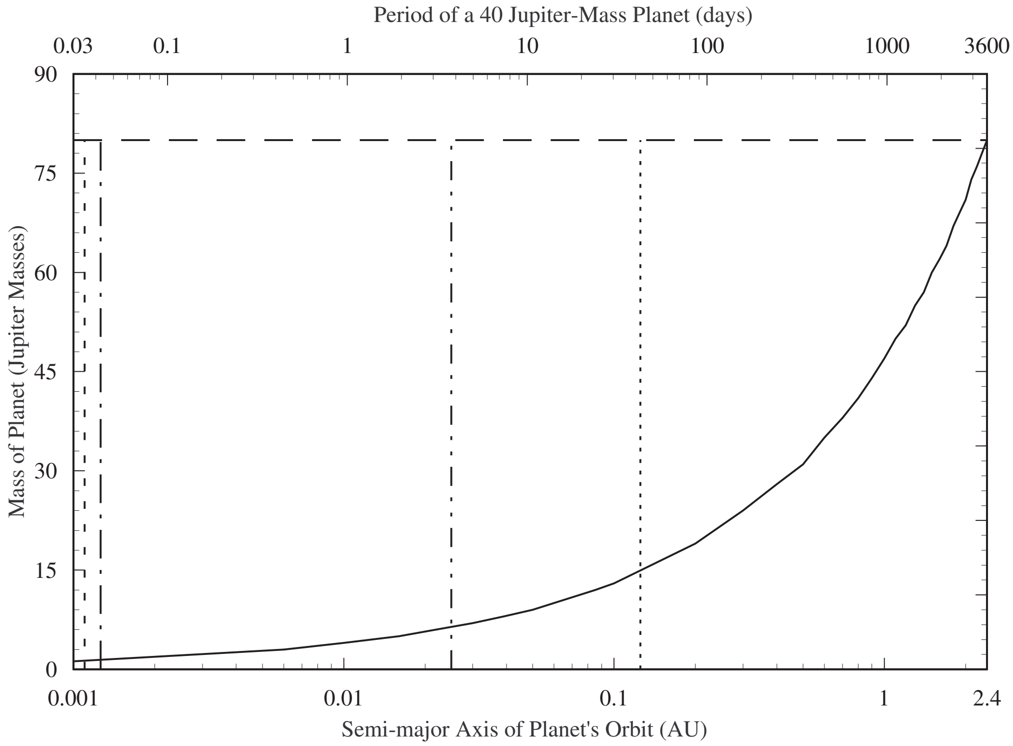

Figure 2. Experimental limits for a $0.1M_{\odot}$ star. Upper dashed line represents mass cutoff for brown dwarf - star transition. Dashed line at left is Roche limit. Dot-dash, dot-dot-dash, and dotted lines represent orbital distances to receive same flux as 51 Peg companion, Earth, and Jupiter. Solid line is limit for sensitivity of the method. Although the spectro-photometric method is not, in principle, limited by the apparent brightness of the source, a number of practical constraints exist. Namely, integration times must be short enough to avoid cosmic ray saturation and undersampling of short period signals. Adopting a maximum of one hour integration time, this method is magnitude limited to V=17 using a 0.6 m and V=21 on a 3.5 m telescope.

$$v_r = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m}{M^{2/3}} sini \tag{2}$$

sum of the mass of the planet and the mass of the star, and i is the inclination angle of the system.

The observable parameter space of the spectro photometric method is summarized in figure 2. The mass of the star was taken to be $0.1M_{\odot}$. The radial velocity lower limit is represented by the thick solid line. Any mass above this line is detectable by this method. The maximum allowable mass for a non- luminous companion (Allard et al 1997) is represented by the dashed horizontal line. The Roche limit for tidal disruption sets a lower bound for the minimum allowable separation represented by the small dash vertical line. Included on the figure are the orbital distances Earth, Jupiter, and the 51 Peg companion would be at (orbiting a $0.1M_{\odot}$ star), if they were to receive the same flux in their current systems. These distances are represented by the dot-dot-dashed, dotted, and dot- dashed lines respectively.

4. Preliminary Observations

Prototype observations were done in the summer of 1998, and the winter of 1999. All observing took place at Capilla Peak Observatory on a 0.6 m telescope using a Photometrics S 300 CCD camera. Three 1"x1" narrow band optical filters manufactured by Barr and Associates were used. These filters allowed for a 8 arcmin field of view on the CCD frame.

Ten different program stars were included in this study, with spectral types ranging from M3.5 to M9, and V magnitude as faint as 16.7. A total of 399 images were taken over the course of the observing program. Two stars in particular, WX Uma and DX Cnc, were chosen as the focus of the study. A sample light curve from one night's observation of each star is shown in figure 3. These light curves present three key pieces of information: First, the band-head feature at 8420 Angstroms is, in fact, present, and our filters are at the proper wavelength. Second, it is possible to achieve photometric accuracies close to the ideal values we adopted in section 3.2. Finally, we are able to attain this photometric precision for stars as faint as V=16.7.

5. Current Observations

Current observations are underway which include a number of improvements over the prototype study. A larger, 2" x 2" set of optical filters is being used to take advantage of the full field of view of the telescope. This increases the number of reference stars, improving the precision of the photometric measurements. Both surfaces of the optical filters are anti-reflection coated, improving the quality of the star images and thus, the photometric accuracy. Finally, the exposure times for each star have been optimized to obtain the best photometric measurements, while keeping the time resolution as fine as possible.

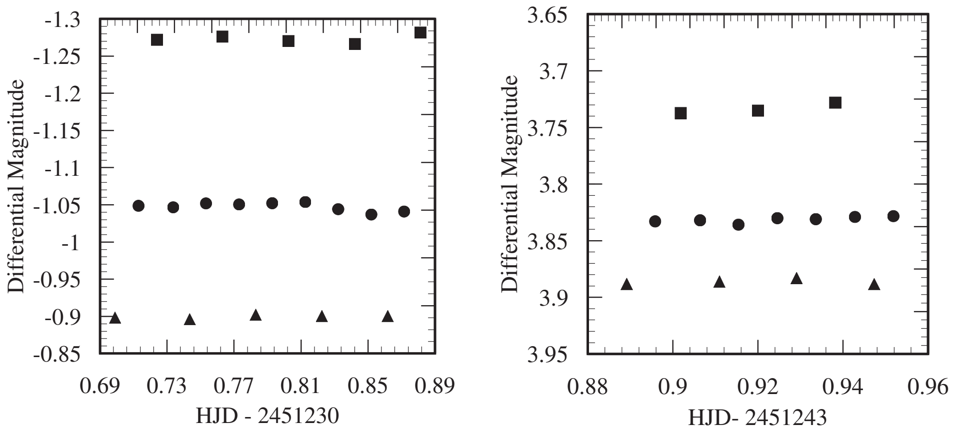

Figure 3. Light curves of (left) DX Cnc and (right) Wx Uma. The standard deviation about the mean ranges from 2 mmag to 5 mmag. The standard deviation about a best fit line ranges from less than 1 mmag to 3 mmag.

6. Concluding Remarks

A gap exists in current knowledge about companions to very low mass stars of spectral type M4 and later. This gap exists because these stars are very faint, and not of much interest in most spectroscopic search programs. Our spectro-photometric method aims at filling this gap. This method is capable of radial velocity precision of 3.5 km/s on stars as faint as V=17 on small sub-meter class telescopes with a CCD camera. On larger, 3 m class telescopes, stars as faint as V=20 may be surveyed.

Because of the high photon efficiency of the spectro-photometric method, it is particularly well suited to surveying large numbers of stars for companions with periods from fractions of a day to a few years. By searching this parameter space, we hope to address key issues in the study of brown dwarfs as companions to cool stars as well as extrasolar giant planets.

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