Part 6

Searches for Substellar Companions

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Brown Dwarfs
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Searching for Planets of Brown Dwarfs [1]

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Abstract. Up to now, most planet search projects have concentrated on G and K stars. In order to considerably widen the view, we have stated a survey for planets of old, nearby brown dwarfs and very low-mass stars. Using UVES, we have observed 26 brown dwarfs and very low-mass stars. As it turned out these objects are very inactive and thus highly suitable for such a project. For 19 objects, we can exclude a planet with the mass of 3 M_J, and a period of 100 days or less with a probability of more than 60%. For these objects, we can also exclude Pegasi-planets with a high probability. For another 4 objects, we can exclude at least a brown dwarf companion. One object is a double line spectroscopic binary, and one object shows significant radial-velocity variations that can not be caused by a normal stellar-spot. This object either has a planetary-mass companion, or the variations are caused by surface structures that are quite different from normal star-spots.

1. Introduction

Up to now, most efforts for detecting extra-solar planets have concentrated on old solar-like G and K stars. Stars much earlier, or much later than that have usually been excluded from the surveys. With the currently available data it is thus very hard to tackle the question what the influence of the central mass on the planet formation is. In here, we present the first results of a survey for planets of brown dwarfs (BDs) and very low-mass star (VLMSs). By searching for planets of these objects, we hope to gain more insight of how the mass of the central object influences the formation of planets. As shown by Comerón et al. (2000), Persi et al. (2000), Muench et al. (2001), Testi et al. (2002) and Apai et al. (2002a) even the lowest mass young objects can show an infrared excess which is characteristic for a circum-stellar disk. Like for solar-like stars one can thus envision that planets are also formed in orbit around these objects. However, in standard models it is generally assumed that the disk has about 3%

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of the mass of the central object only (Natta & Testi 2001). This would imply that the disk of a BD would have the mass of only a few times that of Jupiter, which would make it rather difficult to form massive planets. On the other hand, the true masses of the disks of these objects have not been determined yet, and standard disk models are apparently in conflict with mid IR observations (Apai et al. 2002a, Apai et al. 2002b). Additionally, the smaller mass of the central object will results in relatively larger Roche-Lobes and larger feeding zones at typical planetary masses which might then lead to relatively large masses of the planets that are being formed.

Although outward orbital migration may play a role, it is reasonable to assume that most of massive planets might be found at orbital radii corresponding *to* the snow-line (Hayashi 1981) or *less*. For a passive, none-accreting disk of an 0.08 $M_\odot$ object the snow-line corresponds to orbital periods in the range between 20 to 40 days. For an accretion disk, the orbital period would be slightly longer (Sasselov & Lecar 2000).

2. Observations and data reduction

In order to maximise the sensitivity for the detection of planets with periods of less than 100 days, we took three spectra of each of the targets with a time-lag of about a month. All observations were taken with UVES on the VLT UT2 (KUEYEN) in service mode. Because these BDs and VLMSs are very red, we had to use the wavelength region between 6670 Å to 10400 Å to get a good S/N-ratio. Thus, the iodine cell could not be used as secondary wavelength reference. For the wavelength calibration we thus used the ThAr-lamp to perform the global wavelength solution, and then applied a shift determined by comparing the measured position of telluric lines with the true position of the lines. This shift occurs because the light-path of the ThAr-lamp is different from that of an object, amongst other reasons. In order to measure the shift, we used the telluric bands in the vicinity of 6900 Å and 7600 Å which are located different Echelle-orders. Tests confirmed that this procedure yields an accuracy of about the order of 20 to 50 m/s. However, most of the radial-velocity (RV) measurements are limited by the S/N-ratio and large v sin i to 200 to 300 m/s.

3. The spectroscopic binary 2MWJ2113-1009

We took three spectra of the M6V-star 2MWJ2113-1009 at MJD 52106.317, 52115.107, and 52134.091. The first spectrum shows a nice Gaussian cross-correlation function. In the second spectrum the cross-correlation function is about 4 km/s broader than in the first. The third spectrum then shows two peaks of about the same height and separated by about 13 km/s. We thus conclude that 2MWJ2113-1009 is a double-line spectroscopic binary. Assuming an age of the order of 5 Gyrs and using the evolutionary tracks from Chabrier et al. (2000) the mass of both components is between 0.08 and 0.09 $M_\odot$. The distance is about 10 to 15 pc. From the separation of the peaks in the third spectrum we conclude that the orbital period has to be less than 3 years if the eccentricity is 0.4 or less. If the period is longer than 140 days, it would be possible to resolved the system with CONICA on the VLT. While three spectra

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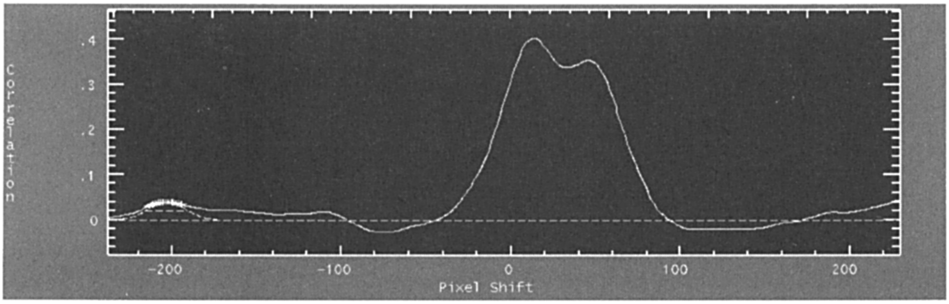

Figure 1. Cross-correlation function of 2MWJ2113-1009, demonstrating that it is a double-lined spectroscopic binary.

are certainly not enough to determine the orbit, the chances are quite good that this object can be resolved with CONICA. Thus, it might be possible to determine the true masses of the two very low mass stars in the near future.

4. Limits of the masses of companions

From the 26 objects observed, 20 objects were observed three or more times. Two spectra where taken of five objects, and one object was observed only once. For 4 objects the RV-variation where found to be ≤ 0.2 km/s, for 13 the variations where between 0.2 and 0.5 km/s and one object shows RV-variations between 0.5 and 1.0 km/s. In all these cases the RV-variation where consistent with the errors which depend on the S/N-ratio and the $v \sin i$ of the object. That means for 13 objects, the probability is higher than 70% that they are not orbited by a planet with a mass of 3 M_J (or more), and with a period of 100 days (or less). For the other five objects we can exclude such a companion with a probability of 60%. While these limits do not sound very impressive, a planet of the same mass, and with the same orbital period as that of 51 Peg but orbiting a 0.08 $M_\odot$ BD would have RV-variations with a semi-amplitude of more than 300 m/s. Thus, for most of our objects, we can exclude also 51 Pegasi-planet. For four of the remaining eight objects we can at least exclude a BD companion with more than 13 M_J and a period of 100 days or less. In all these cases, the v sin i is larger than 40 km/s, making precise RV-measurements rather difficult. As mentioned before, one object is a double-line spectroscopic binary, and for the remaining two the S/N-ratio is insufficient to draw any conclusion. Thus, there is only one remaining object on our list: LP 944-20.

5. LP 944-20

LP 944-20 (=BRI 0337-3535) is an isolated, none-accreting, brown dwarf identified through its Li abundance and low luminosity. Its parallactic distance is 5.0 ± 0.1 pc. The mass of LP 944-20 is estimated to be between 0.056 and 0.064 $M_\odot$. With an age between 475 and 650 Myrs, the object is quite young (Tinney 1998). Recent flux-measurements at 5, 9.8 and 11.9 $m\mu$ do not show

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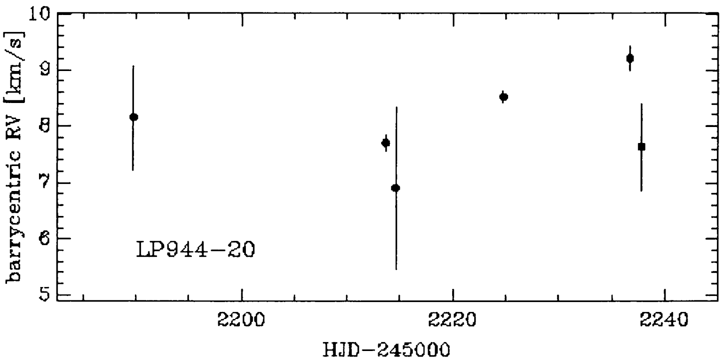

Figure 2. RV-measurements of LP 944-20. The object clearly shows significant RV-variations.

any excess emission (Apai et al. 2002b), this object thus does not have a disc. As pointed out by Tinney & Reid (1998), LP 944-20 is one of those very late type objects that are very inactive despite rapid rotation. These authors find a $log(L_{H\alpha}/L_{bol})$ of -5.6 despite a v sin i of 28 km/s. The same conclusion can be drawn from our spectra, as we measure a v sin i of 32 ± 4 km/s but do not detect any CaII emission lines. The X-ray emission in quiescence is so small that it has not been detected yet. Rutledge et al. (2000) give an upper limit of $L_X/L_{bol} < 2\,10^{-6}$. This value should be compared with the X-ray flux at the saturation level of stars of $L_X/L_{bol} = 10^{-3}$, or the emission at the solar maximum of $L_X/L_{bol} = 10^{-7}$. Tinney & Tolley (1999) have detected brightness variations of 0.04 mag. These are equivalent to $T_{\rm eff}$-variations of 20 K over the entire visible disc, or 80 K over 25% of the disc, or 400 K over 5% of the disc. Judging from the light-curves, it seems more likely that the brightness variations are caused by large, extended structures rather than small spots. As pointed out by Reid et al. (1995), the ratio of the fluxes in the 7042 to 7046 Å-band versus the flux in the 7126 to 7135 Å-band can also be used for determining the temperatures of very late-type objects. We derived this ratio for all our spectra of LP 944-20, and find that the variations are 20 ± 10 K peak-to-peak. All these results cited so far thus are in good agreement: LP 944-20 is a non-accreting, in principle inactive but rapidly rotating BD. This is however contradicted by the fact that the object is a relatively bright none-thermal radio source (Berger et al. 2001), and that a large X-ray flare has been observed (Rutledge et al. 2000).

Fig. 2. shows the RV-values derived for LP 944-20. Significant RV-variations were detected. Even if we take only those measurements, where the errors are 200 m/s or less, the rms-scatter is about 600 m/s. For stars in the Hyades, which have the same age as LP 944-20, Paulson (2002) derived a relation between v sin i and the rms-scatter of the RV. For a $v\,sin\,i$ of 30 km/s, the rms-scatter of the RV of a star would be 80 m/s. We thus conclude that the RV-variations found are much larger than those of stars of the same v sin i. This result is especially interesting, because the rms-scatter of the RVs usually decreases, and not increases for cooler objects.

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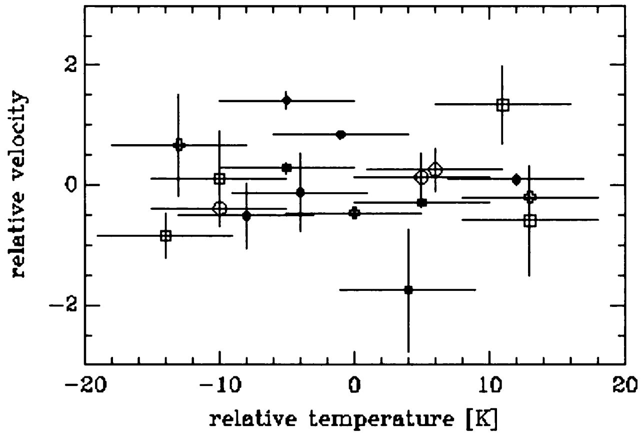

Figure 3. Shown are the temperature and RV-variations of all objects with a spectral type of M8 or later. Each of the symbols represents a different object. If there were spots like star-spots on these objects, we would see a correlation between RV and temperature. Since we do not find such a correlation, we believe that these objects do not have big star-spots. In the same direction points the small amplitude of the temperature variations.

There are of course two possible explanations for the large RV-variations of LP 944-20. One is that this brown dwarf is in fact orbited by a planetary mass object. With our data it is of course entirely impossible to derive an orbit. However, if we assume a circular orbit and furthermore assume that the period longer than 60 days is unlikely, we find $m\,sin\,i < 2.5 M_J$. The other explanation is that the RV-variations are caused by surface features. If we take the relation between filling factor and rms-scatter of the RV-variations for stars from Saar & Donahue (1997), we derive a filling factor of about 3% , similar to an active star. As pointed out before, such a filling factor is in conflict with the observed small variations of the brightness and temperature. On the other hand the none-thermal radio emission, and observation of a huge flare may imply that LP 944-20 is an active object. It may thus be possible that the RV-variations are caused by a magnetic field that changes the convection pattern but that does not show up as brightness variations, or maybe there are extremely strong winds in the atmospheres of these objects.

Another interesting object in our sample is LHS 2065. With a distance of 8.5 pc (Monet et al. 1992), this object belongs to the nearest very low mass stars. The age seems to be larger than 0.5 Gyr. A giant X-ray flare with an energy release which exceeds that of the largest solar flares by an order of magnitude has been detected on it (Schmitt & Liefke 2002). A giant flare has also been observed in the optical (Martín & Ardila 2001). Despite the large activity, we do not find any significant RV-variations ($< 0.48\,km/s$ rms). The temperature fluctuations of 26 K peak-to-peak are also small.

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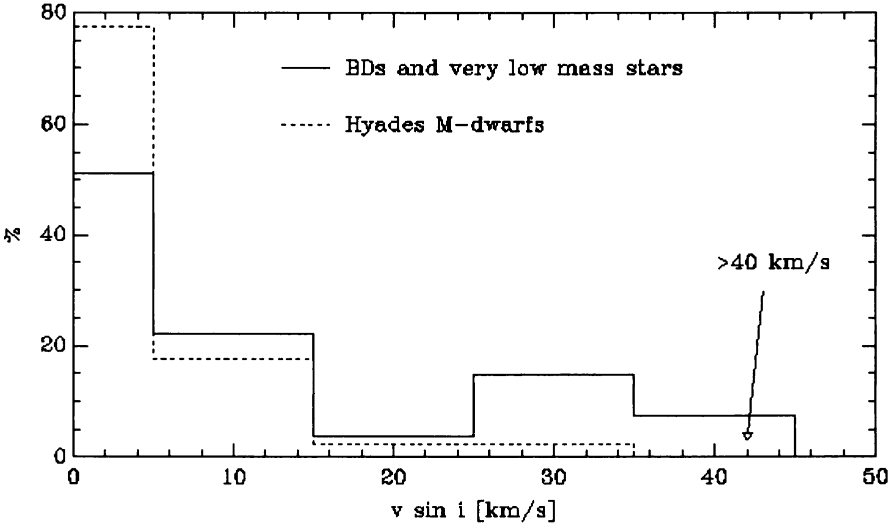

Figure 4. Rotational velocities derived for the BDs and VLMSs of our sample. Also shown is the distribution of v sin i for M-dwarfs in the Hyades (Stauffer et al. 1997). As can clearly be seen, the low mass objects rotate more rapidly than the normal M-stars.

6. Temperature fluctuations

In the previous section, we have given an example for an object that shows large RV-variations, and is also known to be active but where we did not find any evidence that the RV-variations are caused by spots. The other object that we discussed was LHS 2065. This object is also known to be active but again we do not find large temperature fluctuations. In here we try to answer the question whether RV-variations might be caused by star-spots or not in a statistical approach. If there is a spot on a star, the spectral lines are red-shifted, because of the lack of convectional-blue-shift. At the same time the star get slightly darker, and cooler. Thus, on a spotted star, the temperature-variations and the RV-variations are correlated. Although the quality of the data is insufficient to do this experiment with an individual object, we tried to carry it out by using all objects with a spectral type later than M8. The result is shown in Fig. 4. We do not find a trend that cooler temperatures corresponds to a redshift of the lines. What was said above for LP 944-20 may also apply for all other objects with a spectra type later than M8: If there are spots on theses objects there physical nature has to be different from normal star-spots.

7. The v sin i story

As a byproduct of our survey, we also measured the v sin i for all objects. For stars it is well known that they rotate slower when becoming older. At the age

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of the Hyades, almost all stars are slow rotators. Fig. 3. shows the distribution of the v sin i derived for our sample of BDs and VLMSs. Since our objects are all located in the field, we expect them to be at least as old as the Hyades. In contrast normal old stars, we find that the old BDs and VLMSs rotate significantly faster than the stars in the Hyades.

As pointed out by Basri & Marcy (1995) very low-mass objects have only very little H_α-emission, even if they rotate fast. Up to now, only in one case the X-ray emission from an old brown dwarf in quiescence has been detected (Mokler & Stelzer 2002). Both results seem to indicate that old brown dwarfs do not have large chromospheres, or coronae, despite the fact that they have flares. It is henceforth possible that they are also lacking a stellar wind, and thus keep their fast rotation rate from the earlier phase of evolution. BDs would actually spin up when they are getting older, because they are contracting.

8. Conclusions

We have observed a 26 brown dwarfs and very low-mass stars in order to search for companions with orbital periods of 100 days or less. In one case we found an object to be a double-line spectroscopic binary. For most of the other objects, we can exclude a companion with a mass of more than 3 M_J, with an orbital period of 100 days or less. The data for LP 944-20 is not yet conclusive. We have detected significant RV-variation but it is not yet clear, whether there is a planetary-mass companion, or whether the RV-variations are caused by surface features. If the RV-variations are caused by surface features, their properties have to be quite different from normal star-spots.

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