In Search of Terrestrial Planets in the Habitable Zone of M Dwarfs

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After the availability of UVES at the VLT in 2000, we began a survey of M dwarf stars in order to find low-mass planetary companions. This ongoing survey, which currently enjoys ESO Large Programme status, provides a time baseline of up to six years. It is thus capable of finding planets of just a few Earth masses in close-in orbits that correspond to the habitable zones around these stars.

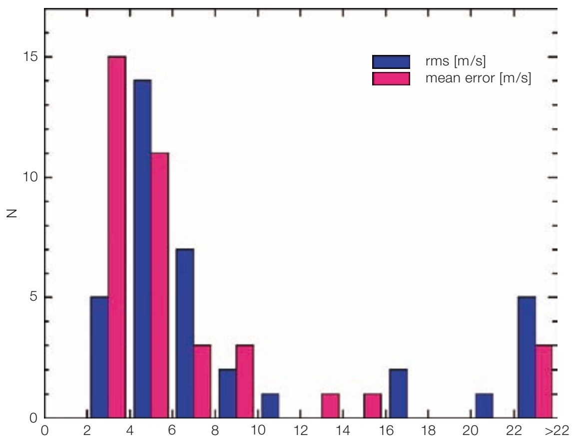


Figure 1: Comparison of the observed rms scatter and the mean error of the RV measurements for our 37 programme stars. In most cases we reach errors in the 2–4 ms^{-1} bin; larger errors either correspond to fainter stars with lower signal-to-noise level or indicate (previously unknown) double-lined spectroscopic binaries such as those in the right-most bin that contains all values exceeding 22 ms^{-1}. The rms peaks around 5 ms^{-1} indicating the presence of variability either by the star itself or due to possible planets; rms values in the > 22 ms^{-1} bin belong to binaries.

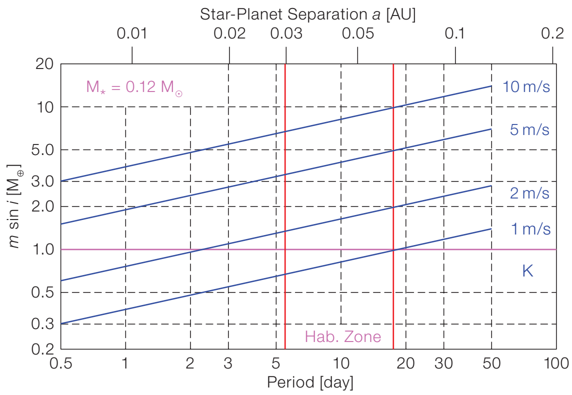


Figure 2: Minimum planet masses *m* sin *i* for RV signals with different semi-amplitudes *K* as a function of orbital period or star-planet separation *a* (scale at top). This example is for a star with 0.12 $M_\odot$, e.g. Proxima Centauri. Circular orbits were assumed. The habitable zone is located between the red vertical lines.

Measurements of stellar radial velocities at very high precision (a few ms^{-1}) have so far produced the majority of the discoveries of the more than 170 extrasolar planets found during the last ten years. Most of these planets are gas giants comparable to Jupiter, but with increasing measurement precision lower-mass planets have become accessible over time. The current record holder among the low-mass planets discovered by RVs (radial velocities) is the third planet in the GI876 system found by Rivera et al. (2005). The discoverers estimate its most likely mass to be 7.5 $M_\oplus$ (Earth masses) with a minimum mass of 6 $M_\oplus$. This record has been rivalled by a very recent announcement of a planet discovered with the microlensing technique (Beaulieu et al. 2006). The most likely mass of this object is 5.5 $M_\oplus$, but this value has a large uncertainty since the mass of the host star is not known.

Reaching this regime of low-mass planets with RV measurements is possible for close-in planets around low-mass stars due to the stronger associated radial-velocity signal. The low-mass planet in the Gl876 system fulfills both requirements: it is in a short-period orbit with a period of just 1.9 day and it orbits a low-mass star with an estimated mass of 0.32 $M_\odot$. This leads to a semi-amplitude (half of the peak-to-valley variation) of the radial-velocity signal of 6.5 ms^{-1}, detectable with state-of-the-art measurement precision.

Studying low-mass planets near the limit of current detection thresholds is the goal of our RV search programme for planets around M dwarf stars using the UVES spectrograph at the VLT-UT2 *Kueyen*. This survey was begun in 2000, when UVES became available, and has recently received ESO Large Programme status for two years, of which the last semester of observations is currently underway. Still the amount of allocated observing time permitted only a moderate sample size, which we have recently increased from originally 20 stars to 37 stars. We selected our stars for moderate levels of stellar activity which could otherwise complicate the measurements.

Using UVES in the self-calibration mode provided by its iodine gas absorption cell we achieve a routine RV measurement precision of about 2.5 ms^{-1} for the brighter stars (see Figure 1). This corresponds to spectral displacements of only about 1/500 of a CCD pixel in UVES, or about 30 nm, reliably recorded over several years. UVES therefore provides us with sufficient precision to find planets of a few Earth masses in close-in orbits around M dwarfs or, in the absence of a detectable RV signal, to exclude the presence of such planets. This can be seen from Figure 2 which, for the example of our nearest neighbour, Proxima Centauri, relates the strength of the observable RV signal (its RV semi-amplitude) to the minimum mass of the planet as a function of orbital period or star-planet separation.

Apart from the better chance of finding low-mass planets with RVs, M dwarfs are interesting for two more reasons. First, they are the most numerous type of star – probably more than 70 % of all stars fall into this category. Therefore, any attempt to determine the frequency of planets in the galaxy must include M dwarfs in extrasolar planet searches. A few years ago this was difficult to do with RVs because of the absence of spectrograph/telescope combinations of sufficient efficiency. So early RV surveys concentrated on spectral types F7V through K7V, i.e. stars with masses greater than 0.5 $M_{\odot}$. Still today, the bulge of the M dwarfs is still basically out of reach as with decreasing mass this type of star becomes very faint. All stars in our survey are brighter than V = 11.7, and are on the relatively massive side of the M dwarfs with masses ranging between 0.2 and 0.5 $M_{\odot}$. Exceptions are the two M dwarfs nearest to us, Proxima Centauri and Barnard's star, with masses of just 0.12 $M_{\odot}$ and 0.16 $M_{\odot}$, respectively.

The second interesting characteristic of M dwarfs is the fact that, due to their small luminosity, the so-called habitable zone is located quite near the star where orbital periods are short and RV signals of terrestrial planets are sufficiently high to be detected (see Figure 2). At this point the terms 'terrestrial planet' and 'habitable zone' should be defined.

Terrestrial planets and the habitable zone

Terrestrial planets are rocky objects that are not dominated by the vast gasous envelopes that giant planets such as Jupiter, Saturn, Uranus or Neptune possess. Masses of terrestrial planets must be below 8–10 $M_{\oplus}$, because more massive planets experience a phase of runaway gas accretion in their formation process. The minimum mass of a terrestrial planet has not yet been well defined.

The *habitable zone* is that region around a star where surface water (a prerequisite for life as we know it) can exist in liquid form on a rocky planet. For this to be really possible, the planetary atmosphere must possess quite a number of suitable properties (Kasting et al. 1991). The location of the thus defined habitable zone depends on the luminosity of the star and therefore on its mass. In a star with 0.5 $M_{\odot}$ the habitable zone is the region separated by about 0.2–0.5 AU from the star, while for a stellar mass of 0.1 $M_{\odot}$ it ranges from only 0.02–0.05 AU. For circular orbits these separation ranges correspond to periods of 50–180 days for the 0.5 $M_{\odot}$ star and 3–13 days for the 0.1 $M_{\odot}$ star.

The true 'habitability' (i.e. suitability for life) of these zones around M dwarfs has been questioned. One reason is that extreme temperature gradients must exist on most planets in this region where the proximity of the star forces their rotation to synchronise with the orbit via tidal interaction. This means that they always have the same side facing the star, like the Moon to the Earth; see Joshi et al. 1997 for arguments who argue that these planets can still be habitable. Another concern is the high level of X-ray radiation that a close-in planet will receive from its active host star. These issues are still under discussion.

Known planets around M dwarfs – are Jupiters rare?

The known planets around M dwarf stars are summarised in Table 1. At the time of writing five planets orbiting three different M dwarfs have been found with RV searches. Not included is the recent microlensing announcement with its uncertain mass.

When compared with the total number of more than 165 extrasolar planets discovered by RV searches the number of planets around M dwarfs is quite small. Partially, this can be explained as a selection effect as surveys of faint M dwarfs had to await the advent of efficient instrumentation and therefore do not go as far back in time as surveys of solar-type stars. So the collected data sets are not as rich and have shorter time baselines.

However, some evidence is emerging that this is not the whole story, and that Jupiter-type planets around M dwarfs are relatively rare, at least for semi-major axes < 1 AU (Endl et al. 2006). Due to small-number statistics this conclusion is not yet 100 % secure, however, and needs to be investigated further.

Towards Earth-mass planets

Figures 3 and 4 show the time series of our UVES RV data for two of our stars, Barnard's star and GJ1, respectively. Barnard's star is the star with the largest proper motion in the sky (10″/yr), and the motion of GJ1 is also large (6″/yr). This motion changes the direction of the line of sight to the star. Since the radial velocity is the component of the stellar space velocity along the line of sight, its observed value must also change with time. This effect is called the secular acceleration of the RV, and its amount can be predicted using the astrometric data base of the Hipparcos satellite. For Barnard's star and GJ1 the expected RV change is 4.5 $ms^{-1}yr^{-1}$ and 3.7 $ms^{-1}yr^{-1}$, respectively, in full agreement with our RV measurements and demonstrating the excellent performance of UVES.

In the following we use our particularly rich data set for Barnard's star (data from 70 nights) as an example to illustrate how the data are analysed for the presence of periodic signals that could reveal an orbiting planet. Figure 5 shows our data of Barnard's star, after subtraction of the secular RV change, and displayed together with the best-fit planetary orbit. If interpreted as an orbiting companion, this variation would indicate a terrestrial planet with an orbital period of 44.9 d and an RV semi-amplitude of 3.0 ms^{-1}, corresponding to an orbital radius of 0.13 AU and a minimum mass of 4.9 $M_{\oplus}$. This would be the lowest-mass planet found so far; it would orbit somewhat outside of the habitable zone. The orbital eccentricity would be small and most likely zero.

Star	Spectral type	Mass [$M_{\odot}$]	V [mag]	$m \sin i$ [M_{Jup}]	a [AU]	P [d]	e	Discovered by
GJ876	M4V	0.32	10.17	1.94	0.21	60.94	0.02	Marcy et al. 1998
				0.56	0.13	30.1	0.27	Marcy et al. 2001
				0.02	0.02	1.94	0	Rivera et al. 2005
GJ436	M2.5	0.41	10.68	0.07	0.03	2.64	0.12	Butler et al. 2004
GJ581	M3	0.31	10.33	0.056	0.041	5.366	0	Bonfils et al. 2005

Table 1: The five RV-discovered planets around M dwarfs. The columns list name of the star, spectral type, stellar mass, visual magnitude V, minimum mass $m \sin i$, orbital semi-major axis a, period P, eccentricity e, and the discovery paper.

Figure 3: RV time series of UVES data for Barnard's star. 'BJD' is the barycentrically corrected Julian date; both the RV and time values are referenced to the barycentre of the solar system in order to take out the movement of the Earth. The red line depicts the expected secular change of the RV of 4.5 $ms^{-1}yr^{-1}$ which agrees well with our measurements.

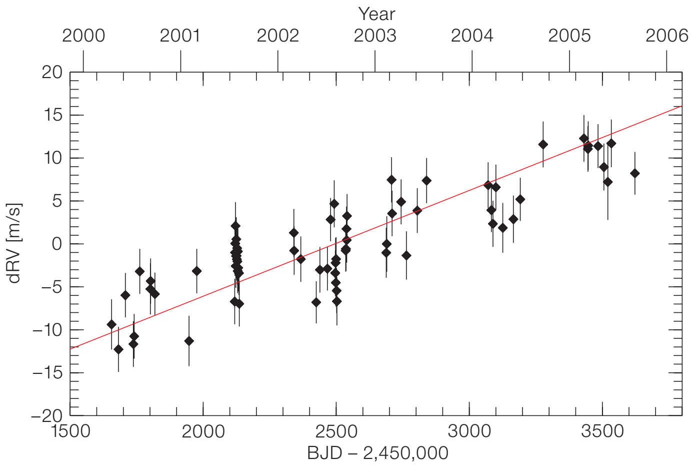
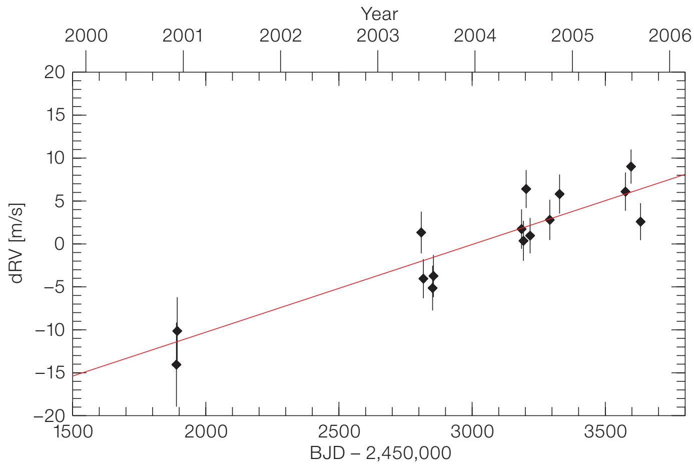


Figure 4: RV time series of UVES data for GJ1. The red line represents the expected secular acceleration of 3.7 $ms^{-1}yr^{-1}$.



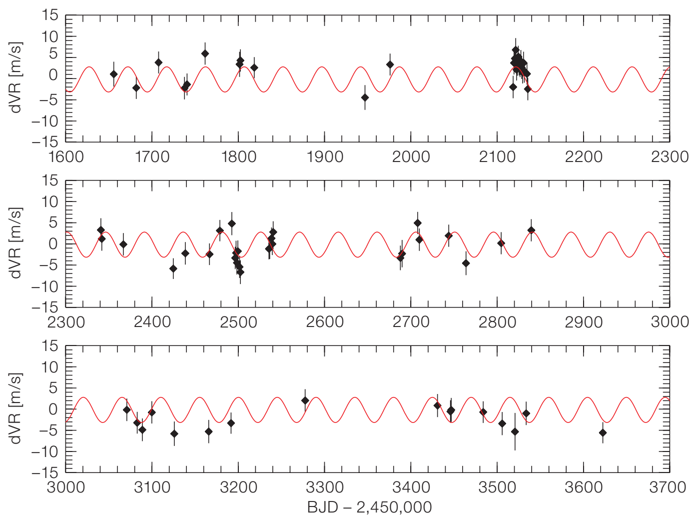


Figure 5: RV data for Barnard's star together with the best-fit sinusoidal orbit (red line). For display purposes the time series has been broken into three panels. This variability appears to be largely related to stellar activity rather than a planet.

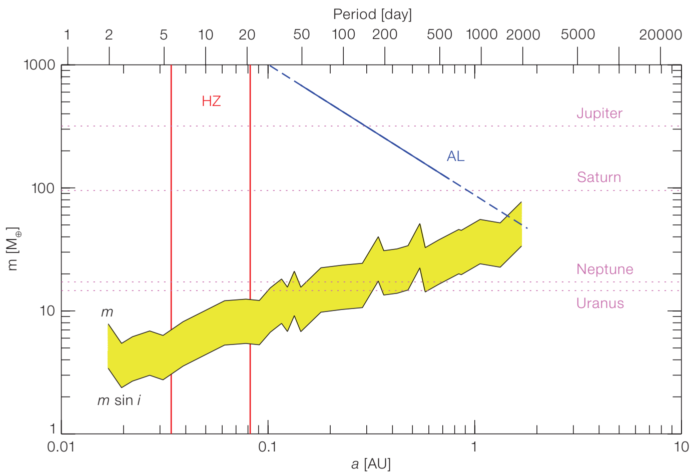


Figure 6: Upper limits to companion masses for Barnard's star. The line labelled '*m* sin *i*' corresponds to the minimum mass, the line labelled '*m*' is for masses greater by a factor of 2.3, higher true masses are excluded with 90 % confidence. The blue line shows astrometric limits from Benedict et al. (1999). Red vertical lines delimit the habitable zone. For comparison, the masses of the Solar System giant planets are indicated.

However, even though this model is formally significant, passes the usual statistical tests, and thus confirms that genuine variability is present, the data appear to show a few systematic deviations from the model, e.g. near BJD 2,452,430 and 2,453,510. It turns out that a two-planet model does not improve the quality of the fit by much. And in fact there is reason to believe that the discovered signal is by itself variable and therefore not due to an orbiting planet.

Further analysis shows the signal to be correlated with the strength of the Hα absorption line (Kürster et al. 2003). This line is an indicator for active regions in the upper stellar atmosphere, the so-called chromosphere. Active region spectra show Hα in emission which combines to reduce the strength of the photospheric Hα absorption line when active regions come into view. Photospheric star spots associated with these active regions affect the shapes of those absorption lines that are used for RV measurements which become erroneous. Since active regions come and go and reconfigure themselves their influence can be quite irregular, but will to some degree also show periodic behaviour because of the regular visibility changes caused by stellar rotation.

No clear planetary signal having been found, we can exclude the presence of planets with quite low masses within 1.8 AU around Barnard's star. This is shown as the lower edge of the yellow region in Figure 6 which represents the statistical upper limits for the minimum companion mass as a function of star-planet separation and period (scale on top). Planets with minimum masses larger than this limit would have produced such a strong RV signal that we would have discovered it, planets below this limit could have gone undetected. The employed statistical method is called bootstrap simulation (details in Kürster et al. 2003). Note that all results relate to the minimum mass of the planet, $m \sin i$ rather than the true mass, since the inclination i of the orbit with respect to the plane of the sky is not known. However, one can show that there is a 90 % chance that the true mass is no more than a factor of 2.3 larger (corresponding to the upper edge of the yellow region), and that the minimum mass is the most probable value.

Also shown in Figure 6 are astrometric mass limits (blue line) for Barnard's star from Benedict et al. (1999) based on data from the Fine Guidance Sensor of the Hubble Space Telescope. As astrometry is more sensitive for larger orbital radii, these limits are complementary to our RV-derived limits. Combining both types of limits we can exclude the presence of any Saturn-mass planet with high confidence.

In short-period (few days) orbits planets of just a few Earth masses would have been discovered. In the habitable zone planets with minimum masses greater than about 5 $M_\oplus$ are excluded and the true mass of any undiscovered planet should be below the mass of Uranus. Continued monitoring of Barnard's star will lower these limits over time enabling us to search for planets of increasingly lower mass.

Acknowledgements

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Low-Mass Exoplanet Found Using Microlensing

Using a network of telescopes scattered across the globe, including the Danish 1.54-m telescope at ESO La Silla, astronomers have discovered a new extrasolar planet which is only about five times as massive as the Earth, and circles its parent star in about 10 years. It is the least massive exoplanet around an ordinary star detected so far and also the coolest. The planet most likely has a rocky/icy surface. Its discovery marks a ground-breaking result in the search for planets that may support life.

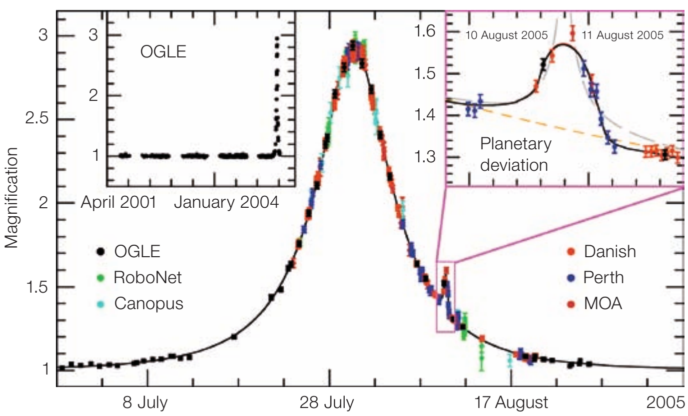
The microlensing technique is based on the temporary apparent brightening of a background star by the gravity of an intervening massive object (star or planet) passing in front. An intervening star causes a characteristic brightening that lasts about a month. Any planets orbiting this star can produce an additional signal, lasting days for giant planets down to hours for Earth-mass planets.

In order to be able to catch and characterise these planets, nearly-continuous round-the-clock high-precision monitoring of ongoing microlensing events is required, once the beginning of an event has been reported. The present case was discovered on 11 July 2005, and observed until well into August, when the planetary deviation was noticed.

The new planet orbits a red star five times less massive than the Sun, located at a distance of about 20 000 light years, not far from the centre of our Milky Way Galaxy. Its relatively cool parent star and large orbit implies that the likely surface temperature of the planet is –220° C, too cold for liquid water. It is likely to have a thin atmosphere, like the Earth, but its rocky surface is probably deeply buried beneath frozen oceans. It may therefore more closely resemble a more massive version of Pluto, rather than the rocky inner planets like Earth and Venus.

A full report has been published by Jean Philippe Beaulieu et al. in Nature 439, 437 (2006). This result is a joint effort of three independent microlensing campaigns: PLANET/RoboNet, OGLE, and MOA, involving a total of 73 collaborators affiliated with 32 institutions in 12 countries (France, United Kingdom, Poland, Denmark, Germany, Austria, Chile, Australia, New Zealand, United States of America, South Africa, and Japan).

(Based on ESO Press Release 03/06)



Light Curve of OGLE-2005-BLG-390.