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Letter to the Editor

The closest extrasolar planet

A giant planet around the M4 dwarf Gl 876[⋆,⋆⋆]

X. Delfosse[1,2]**, T. Forveille**[2]**, M. Mayor**[1]**, C. Perrier**[2]**, D. Naef**[1]**, and D. Queloz**[3,1]

[1] Observatoire de Genève, 51 Ch des Maillettes, CH-1290 Sauverny, Switzerland
[2] Observatoire de Grenoble, 414 rue de la Piscine, Domaine Universitaire de S^{t} Martin d'Hères, F-38041 Grenoble, France
[3] Jet Propulsion Laboratory, Mail Stop 306-473, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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Abstract. Precise radial velocity observations of the nearby M4 dwarf Gl 876 with the Observatoire de Haute Provence 1.93 m telescope and the new 1.20 m swiss telescope at la Silla indicate the presence of a jovian mass companion to this star. The orbital fit to the data gives a period of 60.8 days, a velocity amplitude of 246m.s^{-1} and an eccentricity of 0.34. Assuming that Gl 876 has a mass of 0.3 $M_{\odot}$, the mass function implies a mass for the companion of 2/$\sin i$ Jupiter masses.

Key words: giant planet formation – extrasolar planets – giant planets – M dwarf stars

1. Introduction

The still recent discovery of the first extrasolar planet, around 51 Peg (Mayor & Queloz, 1995), has since been followed by many more. The count currently runs to 11 very low mass companions (Marcy & Butler, 1998; Queloz, 1999), with minimum masses (M $\sin i$) which range between 0.5 and 10 times the mass of Jupiter. Asides from their Jupiter-like masses, which largely reflect the sensitivity threshold of current radial velocity programs, the known extra-solar planets are a very diverse class. Some of them have large eccentricities when others have nearly circular orbits, and their periods range between 3.3 days and 4.4 years. Giant planets can thus have very much shorter periods than in our solar system, which clearly does not represent the only possible outcome of planetary system formation and evolution.

To date on the other hand, planets have mostly been looked for around solar type stars, and, pulsar companions asides, they have only been found orbiting such stars. This reflects to some extent an understandable desire to identify close analogs to our own solar system, which could perhaps contain life sustaining planets. Also, the selection function of the radial velocity planet searches has a relatively sharp optimum around spectral class G. Essentially all stars hotter than approximately F5 have fast rotation (Wolf et al., 1982), so that it is impossible to measure their radial velocity to the $\sim$ 10m.s^{-1} accuracy needed to detect planets. At the other end of the mass spectrum, most M dwarfs have slow rotation (Delfosse et al., 1998a) and their velocity can be measured accurately, as we discuss below. Their luminosities however are much lower than those of solar type stars. At a given distance a much longer integration time is thus needed to obtain a given radial velocity precision on an M dwarf than on a G dwarf. All planet search programs have thus understandably concentrated on solar type stars.

G dwarfs however only represent a small fraction of the disk stellar population, with the lower mass M dwarfs outnumbering them by about an order of magnitude (Gliese & Jahreiss, 1991). It is thus likely that most planets in our galaxy orbit stars whose mass and luminosity are significantly lower than the Sun's (Boss, 1995), unless some as yet unidentified physical process restricts planet formation to the environment of sufficiently massive stars. It is clearly important to establish whether such a mechanism exists.

For the last three years, we have been monitoring the radial velocities of a nominally volume limited sample of 125 nearby M dwarfs. The two main goals of this large observing program ($\sim$ 30 nights/year) are to establish the controversial (e.g. Kroupa, 1995, and Reid & Gizis, 1997, for two contrasted views) multiplicity statistics of field M dwarf systems, and to pin down the still uncertain mass-luminosity relation at the bottom of the main sequence. Delfosse et al (1998b) present preliminary results for the stellar companion search, with 12 new components found in these nearby M dwarf systems, including the third detached M dwarf eclipsing binary (Delfosse et al., 1998c). A byproduct of this program, related to the angular momentum dissipation of very low-mass stars, is described in Delfosse et al (1998a).

Send offprint requests to: Xavier Delfosse
(e-mail: Xavier.Delfosse@obs.unige.ch)

[⋆] Partly based on observations made at the Observatoire de Haute Provence (CNRS)

[⋆⋆] Partly based on observations obtained with the swiss 1.2m telescope at the European Southern Observatory

Even though this was not the main focus of the program, we also realised from the start that for most of these stars we obtain radial velocity precisions which are sufficient to detect giant planets, if any exists around them. We present in this letter the first such detection, around Gl 876 (BD-15°6290, LHS 530, Ross 780, HIP 113020), a V=10.2 M4 dwarf (Reid et al., 1995) at d = 4.702±0.046 pc (ESA, 1997).

Delfosse et al. (1998a) present in detail the observed sample, while Delfosse et al. (1998b) discuss the observing and analysis technique at length. We therefore only briefly summarize this information in Sect. 2. We then proceed to discuss in Sect. 3 the radial velocity detection of the planetary companion of GL 876. In Sect. 4 we consider the implications of this detection and suggest some possible follow-up observations.

Table 1. Orbital elements of GL 876.

Element	Value	St. Err.	Unit
P	60.97	.19	Days
T	2450661.7	1.5	Julian Days
e	.336	0.019	
ω	5.2	4.8	deg
K_1	248.0	6.6	m.s^{-1}
V_0	-1.902	0.006	km.s^{-1}
$a_1 \sin i$	0.00131		AU
f(m)	7.810^{-8}		$M_\odot$
O-C(CORALIE)	23	(rms)	m.s^{-1}
O-C(ELODIE)	16	(rms)	m.s^{-1}

2. Observing program

The sample contains the 127 M dwarfs listed in the third edition of the nearby star catalog (CNS3 preliminary version, Gliese & Jahreiss, 1991) with a distance closer than 9 pc, a B1950.0 declination above -16 degrees, brighter than V=15, and without a close much brighter primary. Observations have been carried out since September 1995 with the ELODIE fiber-fed spectrograph (Baranne et al., 1996) on the 1.93m telescope at Observatoire de Haute Provence (OHP). The R=42000 spectra are wavelength calibrated through simultaneous observations of a thorium lamp. Since June 1998 some southern stars have also been observed with the nearly identical CORALIE spectrograph on the recently commissioned swiss 1.2m telescope at la Silla (Chile). CORALIE mostly differs from the older ELODIE instrument by its spectral resolution of R=50000, better sampling of the spectrograph PSF by the CCD camera pixels, and significantly better temperature control. The first indications are that these modifications together result in a substantially improved intrinsic stability (Queloz et al., in preparation).

The extracted M dwarf spectra are analysed through cross-correlation with a binary (0/1) template constructed from an observed ELODIE spectrum of Barnard's star, Gl699 (Delfosse et al., 1998b). For slowly rotating stars the resulting velocities have internal standard errors (photon noise plus low level uncalibrated instrumental instabilities) which typically range from 10-15 m.s^{-1} for bright M dwarfs (V $\lesssim$ 10) to $\sim$ 75 m.s^{-1} at the magnitude limit of the sample. For Gl 876 (V=10.2) typical standard errors are 10 to 20 m.s^{-1}, depending on airmass and seeing conditions. Magnetic activity is common in M type dwarfs, and may further degrade the measurement accuracy (Saar et al., 1998). This potential error source is still uncompletely characterised for M dwarfs, but for slowly rotating stars ($V\ sini < 3km.s^{-1}$) we can already bound it to $\sigma_{\mathrm{V}r} \lesssim$ 20m.s^{-1} for our cross-correlation analysis with the M4 binary template. Within the brighter two thirds of the sample, a conservative assumption at the present time is that we will detect all variables with semi-amplitudes larger than 40m.s^{-1}. Assuming for illustration a 5 years period, this corresponds to a 1 Jupiter mass (M$_J$) planet orbiting a 0.25 $M_\odot$ M4V primary (at 1.8 AU), or to a 2 M$_J$ planet orbiting a 0.6 $M_\odot$ M0V primary (at 2.5 AU).

3. A planet around Gl 876

Since planet detection was not initially emphasized in the observing program, its sampling strategy is not optimal for detection of low amplitude variations on timescales shorter than a few years. Gl 876 was observed once at each observing seasons in 1995 and 1996 and its velocity variations became apparent from the three observations obtained in late 1997. It was then marked in our program lists as a variable. This low declination source however became unobservable from OHP before we could gather more data and determine its orbit. The commissioning of the swiss 1.2 m telescope at la Silla and its CORALIE spectrograph in June 1998 provided the first opportunity to obtain 3 additional measurements of this southerly source, which allowed to finally determine its orbit. These observations were obtained within two weeks of the first light of this telescope, providing an encouraging indication on its potential for planet discovery. An end of night measurement from OHP at a large airmass provided a confirmation on June 22, just in time to confidently announce the discovery at the IAU “Precise Stellar Radial Velocities” conference (Victoria, Canada, June 21st to 26th). At this conference we learned from G. Marcy that his group independently identified the orbit of Gl 876, with orbital elements compatible with our own determination. Weather permitting, we have since then attempted to observe Gl 876 at most every three nights, and often every night. The 1998 data therefore dominate the orbital solution.

The orbital solution is given in Table 1. Preliminary solutions included a velocity zero point offset between the northern (ELODIE) and southern (CORALIE) datasets as a free parameter. The two systems were found to be entirely consistent, and this parameter was thus held fixed to zero for the final solution. Fig. 1 shows the individual radial velocity measurements as a function of orbital phase (the 16 orbital periods elapsed since the first measurement make unpractical a display as a function of time; we however have essentially continuous coverage of one period in June and July 1998, excluding any possible spectral alias). The orbital period is two months and the velocity semi-amplitude is $\sim$250 m.s^{-1}, over 10 times the standard error of one radial velocity measurement. The radial velocity curve implies a moderate but highly significant eccentricity of e=0.34.

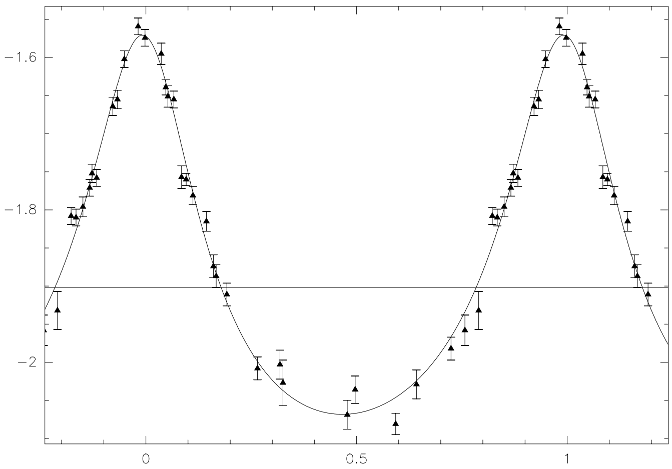

Fig. 1. Combined ELODIE and CORALIE radial velocities for Gl 876. The solid line is the radial velocity curve for the orbital solution.

The large amplitude and moderate period of the radial velocity variation argue strongly for orbital motion as its cause. An integration of the radial velocity curve implies a minimum physical motion of $\sim 0.5\ R_\odot$. This variation is about twice the radius of an M4 dwarf (Baraffe & Chabrier, 1996; Chabrier & Baraffe, 1997), excluding pulsation as a possible explanation. Gl 876 in addition only has low level photometric variability, and indeed happens to be one of the standard stars of the original UBV system (Johnson & Harris, 1954). It is actually variable, but with low rms amplitudes of 13 mmag at V, 9 mmag at R and 6 mmag at I (Weis, 1994). The photometric variations don't phase well at 61 days and appear consistent with a BY Dra type variability (Sasselov and Cody, private communication). Since Gl 876 is a very slow rotator (V$\sin i$ $<$2km.s^{-1}, Delfosse et al., 1998a), rotational modulation of such low level surface inhomogeneities cannot explain its large radial velocity variations. Densely sampled photometry would on the other hand be of considerable interest to establish the stellar rotation period.

The mass of Gl 876 unfortunately contributes some uncertainty to the minimum mass of its companion. As a consequence of H_2 recombination in the photosphere and the deepening convection for lower mass stars (Kroupa et al. 1990), the luminosity does not drop nearly as quickly per unit mass for mid-M dwarfs as it does for both higher and lower mass stars (Henry & Mc Carthy, 1993), and it has a stronger metallicity dependence. Between $\sim 0.50\,M_\odot$ and $\sim 0.18\,M_\odot$, Mass-Luminosity relations therefore have both shallow slopes and large intrinsic dispersions (Henry & Mc Carthy, 1993). Gl 876 thus belongs to a spectral type range where the mass of a single star is poorly constrained by its observable characteristics. Taking at face value either the solar neighborhood observational mass-luminosity relation of Henry & Mc Carthy (1993) or the solar metallicity models of Baraffe et al. (1998), the absolute magnitudes of Gl 876 (M_V=11.81, M_J=7.56, M_H=6.96, M_K=6.70, Leggett (1992) and ESA (1997)) imply a mass of 0.30±0.05 $M_\odot$ for Gl 876. As an illustration of possible uncertainties however, Delfosse et al (1998c) measure M = 0.432 ±0.001 $M_\odot$ and M_V = 11.7±0.2 (M_V=11.81 for Gl 876) for the brighter star in GJ 2069A, an M3.5V eclipsing binary which is probably super-metal-rich ([M/H]∼+0.5). From its position in colour-colour diagrams (Leggett, 1992), and from the relative depth of its cross-correlation dips with several binary templates (Delfosse et al., in preparation), Gl 876 is probably more metallic than the sun, though not as much as GJ 2069A. We adopt a mass of 0.3 $M_\odot$ for the rest of the discussion but warn that it is uncertain by perhaps 30%. The minimum semi-major axis and planetary mass which result from the orbital solution are then $a\sin i$ = 0.20 AU and $M_2 \sin i$ = 2.0M_J. They respectively scale as $M^{\frac{1}{3}}$ and $M^{\frac{2}{3}}$.

4. Discussion

The orbital elements of Gliese 876b are worth noting. In spite of the low mass of Gl 876, the ice-condensation radius at the time of planet formation around this star is $\sim$4 AU, only 20% lower than around a solar type star (Boss 1995). Once again the orbital semi-major axis (a = 0.20 AU) is thus much smaller than the expected minimum radius for giant planet formation, and some orbital migration must have occcured. However the observed orbital separation is also 4 times larger than the measured semi-major axes of 51 Peg, τ Boo and υ And (0.04-0.05 AU). The excess of planets with such small semi-major axes is believed to result from outward torques which counteract at short distances the inward torque induced by the interaction of the planet and the protoplanetary disk (Lin et al. 1996, Trilling et al. 1998). These torques only become effective at separations significantly smaller than 0.20 AU, and cannot have played a signficant role for the Gl 876 system. It is also interesting to note that the orbit of GL 876b is eccentric (e=0.35), while interaction with an accretion disk is expected to damp any significant orbital eccentricity of a planet (Goldreich and Tremaine, 1980). Several mechanisms may be called in to explain the large orbital eccentricities of giant extrasolar planets, but in the present case the most interesting possibility is probably the chaotic interaction of several giant planets (Weidenschilling & Marzari, 1996; Rasio & Ford, 1996; Lin & Ida, 1997). A frequent final result of such a strong gravitational interaction is a planetary system with a single giant planet at a moderate semi-major axis, in an eccentric orbit. This could thus simultaneously explain the semi-major axis and the eccentricity.

Contrary to all previously confirmed planets around main sequence stars, Gl 876b orbits a star which is very different from our Sun, showing that planetary systems form around stars of widely different types. Gl 876 is much less massive than the Sun, $\sim 0.3\,M_\odot$, and at most only $\sim$150 times more massive than its planet. Its radius is only three times as large: the radius of Gl 876 is $\sim 0.3\,R_\odot$(Chabrier & Baraffe, 1997), while that of Jupiter is 0.10 solar radii. Gl 876 is also much cooler than the Sun, and much less luminous. From the observed I-K and V-I colours (Leggett, 1992) its effective temperature is 3100 to 3250 K (Leggett et al., 1996), compared with 6000 K for the solar surface. From its absolute V magnitude and the bolometric correction of Delfosse et al. (1998a) it bolometric magnitude is

9.42, corresponding to 1.35 $10^{-2}\ L_\odot$. Even though the planet of Gl 876 is twice closer to its star than Mercury is to the Sun, the stellar flux at Gl 876b is only ten times the solar flux at Jupiter, and lower than the solar flux at Mars. The apropriate albedo for Gl 876b is unclear, and, by analogy with Jupiter (e.g. Podolak et al., 1993), its thermal balance of Gl 876b may also include a substantial contribution from an internal heat source. A detailed evaluation of its effective temperature is thus beyond the scope of the present letter, but Gl 876b is clearly much too cold to possibly sustain liquid water above the 1 bar level.

Gl 876 is closer to us than all other stars orbited by known extra-solar planets, by at least a factor of 3. At d=4.7 pc, Gl 876 is the 40^{th} closest stellar system to our Sun, and the 53^{rd} closest star. Since M dwarfs make up $\sim$ 80% of the solar neighbourhood population (Gliese & Jahreiss, 1991), it is only natural that the first member of this numerous class found orbited by a planet is a very nearby one, unless planetary formation would have selected against low mass stars. This discovery weakens such an hypothesis but improved statistics would obviously be needed for a reliable conclusion.

This detection represents an opportunity to confirm a radial velocity detected planet through astrometry and determine its actual mass, or at the very least to set a lower limit which is firmly planetary. Gl 876 is both at least 3 times closer to us than any other star with a detected planetary companion, and about 4 times less massive (only 0.3 $M_\odot$ instead of about $\sim 1\ M_\odot$ for all previous detections). Despite its relatively short orbital period of 61 days, the astrometric reflex motion induced by its $\sim 2M_J$ companion is therefore unusually large by extrasolar planet standards, with a minimum semi-major axis of 0.27 milliarcsecond for an edge-on orbit, and larger by 1/sin(i) for more face-on geometries. The best single measurement precision of an astrometric observations is at present 1 milliarcsecond, with the FGS instrument on HST. A detection is clearly an ambitious measurement at this time if the orbit is seen edge-on, and it would need a very determined effort. A lower limit on the inclination of $|\sin i| > 0.25$ on the other hand will be easily obtained, and would already imply $M_2 < 8\ M_J$. In addition, these observations can be accomplished over the short timescale of one orbital period, only 2 months.

Finally, it is interesting to note that the measurements of Gl 876 obtained with the new CORALIE spectrometer on the 1.2 m telescope have residual O-Cs as small as 22 m/s, for a V magnitude of 10.2. This discovery of a giant planet around a rather faint M4 dwarf illustrates that this small telescope will powerfully contribute to the search for extrasolar planets. The application of the cross-correlation technique to the full wavelength domain (300 nm) of CORALIE compensates to some extent the disadvantage of the small telescope aperture (Baranne et al. 1996), and the nearly full-time availability of the telescope for planet searches will make future period identifications much easier.

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