The CORALIE survey for southern extra-solar planets

I. A planet orbiting the star Gliese 86[*]

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Abstract. A $4\,M_J$ planet with a 15.8 day orbital period has been detected from very precise radial velocity measurements with the CORALIE echelle spectrograph. A second remote and more massive companion has also been detected.

All the planetary companions so far detected in orbit closer than 0.08 AU have a parent star with a statistically higher metal content compared to the metallicity distribution of other stars with planets. Different processes occuring during their formation may provide a possible explanation for this observation.

Key words: stars: planetary systems – stars: individual: GJ 86 – stars: low-mass, brown dwarfs – stars: binaries: spectroscopic

1. Introduction

Almost 20 planetary companions with minimum masses ($m_2 \sin i$) less than $10\,M_J$ have so far been detected by very high-precision radial velocity surveys (Butler et al. 1999; Marcy et al. 1999a; Fischer et al. 1999 and Marcy et al. 1999b for a review of older detections). The semi-major axes of their orbits range from very small (0.05 AU) to 3 AU. Some have eccentric orbits, others have secondary more massive companions, some have both. The large observed spread in orbital characteristics of all known planetary candidates causes some difficulties in understanding their formation process in comparison with our own solar system. It also raises the issue of the real nature of these objects, particularly the more massive ones.

In June 1998 we initiated a systematic and large scale exoplanet search survey (1600 nearby G and K stars) in the southern hemisphere with the new 1.2 m alt-azimuth Euler Swiss telescope at La Silla, ESO Chile. The technique we are using to detect planets is to look for a stellar reflex motion due to an orbiting planet by very precise radial velocity measurements. The CORALIE echelle spectrograph is used to measure star spectra from which the Doppler effect is then computed.

CORALIE is an improved version of the ELODIE spectrograph (Baranne et al. 1996) with which, 4 years ago, the first extra-solar planet orbiting a star (51 Peg) was discovered (Mayor & Queloz 1995). The CORALIE front-end adaptator is located at the Nasmyth focus of the Euler telescope. Two sets of two fibers can alternatively feed the spectrograph which is located in an isolated and temperature controled room. The set of fibers used for high precision radial velocity measurements includes a double scrambler device designed by Dominique Kohler (see Queloz et al. (1999) for references) to improve the stability of the input illumination of the spectrograph. Thanks to a slightly different optical combination at the entrance of the spectrograph and the use of a 2k by 2k CCD camera with smaller pixels (15μm), CORALIE has a larger resolution than ELODIE. A resolving power of 50,000 ($\lambda/\Delta\lambda$) is observed with a 3 pixel sampling. As with the ELODIE spectrograph, CORALIE makes use of on-line reduction software that computes the radial velocity of stars several minutes after their observation. (See Baranne et al. (1996) for details about the reduction process). The simultaneous thorium technique is used to correct any instrumental drifts occuring during the star exposure (see Queloz (1999) for details). The many improvements carried out in the thermal control and the resolution of the instrument, as well as in the reduction software, yield a factor two improvement in the instrument precision compared with ELODIE.

2. A planet orbiting Gliese 86

Gliese 86 (HD13445, HIC 10138) is a bright ($m_V = 6.12$) early K dwarf ($B - V = 0.81$, $T_{\mathrm{eff}} = 5350\,K$, $\log(g) = 4.6$, Flynn & Morell 1997) from the southern hemisphere, in the Eridanus (River) constellation. It is a close star, $10.9\,$pc away from our Sun ($\pi = 91.6\,$mas, measured by the Hipparcos satellite). Its absolute magnitude is 6.257, yielding (with $BC = -0.2$) a luminosity $L = 0.27\,L_\odot$. It is a high proper motion star, slightly metal poor ([Fe/H] = -0.24, Flynn & Morell 1997). It has low chromospheric activity ($\log R'_{\mathrm{HK}} = -4.74$, Saar & Osten 1997). No rotational broadening has been detected (Saar & Osten 1997) and there is only an upper limit on the Li content in its atmosphere (N(Li)< -0.24, Favata et al. 1997). From Hipparcos photom-

Table 1. Orbital elements of Gliese 86 after correction of the $0.36 \, \text{m s}^{-1} \, \text{d}^{-1}$ linear drift of the γ-point.

P	15.78	± 0.04	d
T	2451146.7	± 0.2	d
e	0.046	± 0.004	
$V_r^\dagger$	56.57	± 0.01	km s^{-1}
ω	270	± 4	$^\circ$
K_1	380	± 1	m s^{-1}
$f_1(m)$	$8.9 \cdot 10^{-8}$	$\pm 0.1 \cdot 10^{-8}$	$M_\odot$
$(O-C)^\ddagger$	7		m s^{-1}
N	61		

(†) At $T_0 = 2451150 \, \text{d}$
(‡) Without the drift correction the O-C of the fit would be $13 \, \text{m s}^{-1}$

Fig. 2. *Filled dots*: radial velocity drift observed with CORAVEL. A mean $0.5 \, \text{m s}^{-1} \, \text{d}^{-1}$ variation of the radial velocity of Gliese 86 is measured (*dotted line*). The 15.8 day reflex motion from the planet is marginaly seen as an extra scattering in the last CORAVEL measurements. In the right lower box is displayed for comparison the γ-point drift measured with CORALIE. (Note that the time scale is artificially extended for the sake of a better display). Open dots: previous measurements found in the literature. No error bars are displayed but a typical 2–$5 \, \text{km s}^{-1}$ error may be assumed for these measurements
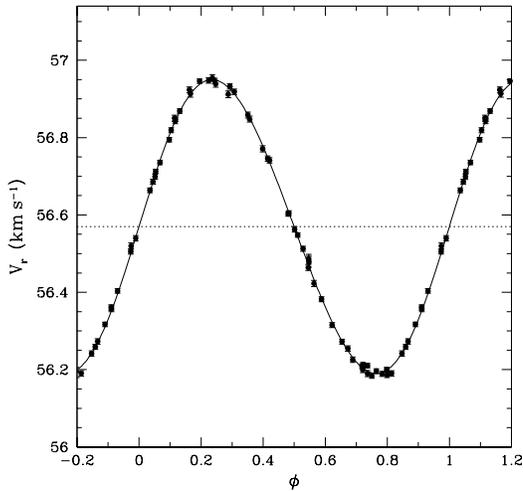

Fig. 1. Phased orbital motion of Gliese 86 corrected from the long term drift. The solid line is the best fit orbit. See orbital elements in Table 1

etry, the star is stable ($\sigma(\text{H}_p) = 0.008$). In summary, Gliese 86 bears all the characteristics of a few billion year old K dwarf from the old disk population. In the H-R diagram, Gliese 86 lies slightly below the ZAMS. However we believe that there are enough uncertainties in the temperature and bolometric correction estimates of Gliese 86 – stemming from its low metal content – to believe that its location in the HR diagram below the ZAMS is not significant.

A 15.8 day period radial velocity variation has been detected from CORALIE measurements (Fig. 1). In Table 1 are listed the orbital elements of the best fit solution (least square) for an orbital motion after correction of a $0.36 \, \text{m s}^{-1} \, \text{d}^{-1}$ linear drift (see below). Assuming a $0.8 M_\odot$ for the primary and that the radial velocity effect is caused by the orbital motion of the star, we conclude that a $4 \, \text{M}_J$ companion (minimum mass) is orbiting Gliese 86.

The planetary companion to Gliese 86 is close to its host star with a $0.11 \, \text{AU}$ semi-major orbital axis. It has a low, although 99% significant non-zero, eccentricity (Lucy & Sweeney 1971). The $7 \, \text{m s}^{-1}$ residual from the fit indicates very low intrinsic intrumental errors from night to night, taking into account that each measurement has approximately
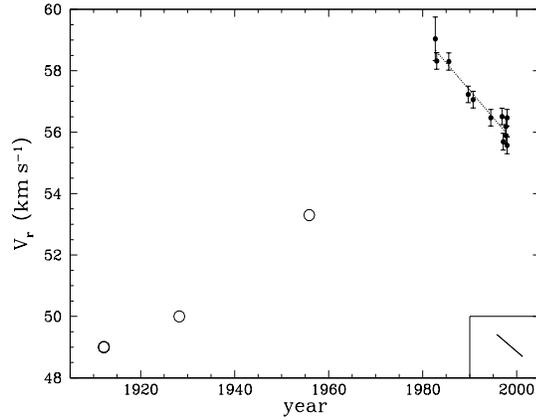
$5 \, \text{m s}^{-1}$ photon noise error and could be affected as well by some low level radial velocity variations intrinsic to the stellar atmosphere. Such low instrumental error agrees with the instrumental error measured by $P(\chi^2)$ analysis of all the stars of our sample so far observed (about 300). See Duquennoy (1991) for a detailed description of the instrument error estimate by the $P(\chi^2)$ statistic.

A long term drift of the radial velocity ($0.5 \, \text{m s}^{-1} \, \text{d}^{-1}$) is observed from 20 years of CORAVEL measurements (Fig. 2). With the $300 \, \text{m s}^{-1}$ typical precision of CORAVEL radial velocities, the short orbit is marginally detected in the last measurements. Interestingly, with the recent CORALIE measurements a smaller $0.36 \, \text{m s}^{-1} \, \text{d}^{-1}$ drift is observed (Fig. 3). A statistical analysis of the reliability of the drift correction shows that an orbital solution without drift correction has 0.0001% chance to occur ($\chi^2 \approx 210$). The probability jumps to 40% when the linear drift correction is taken into account. A conservative $7 \, \text{m s}^{-1}$ instrumental error is assumed for this calculation.

The period measurement of the short period planetary companion is still not accurate enough to correct the old CORAVEL data from their extra scattering and obtain a precise drift estimate from these measurements. Thus, the difference in drift slope between the old CORAVEL measurements and the recent CORALIE measurements is perhaps significant, but remains to be confirmed by further measurements during the course of the next season.

The long term radial velocity variation is the signature of a remote and more massive companion. The use of historical radial velocity data together with the CORAVEL and the CORALIE observed drifts suggest a stellar companion with a period longer than 100 yr (semi-major axis larger than 20 AU).
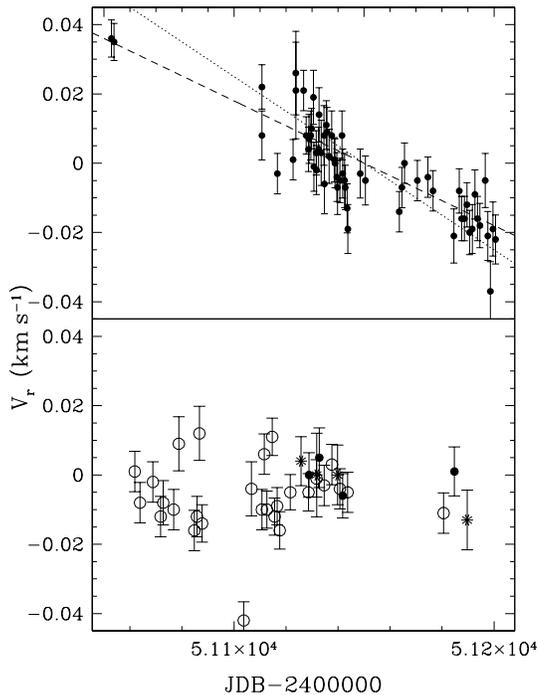
Fig. 3. *Top:* CORALIE observed γ-point drift (residuals from the short orbit fit). The dashed line is the best linear fit after correction of the short period from the planetary companion. It corresponds to a linear drift of $0.36\,\mathrm{m\,s^{-1}\,d^{-1}}$. The dotted line is the $0.5\,\mathrm{m\,s^{-1}\,d^{-1}}$ drift measured over 20 yr CORAVEL data. *Bottom:* Set of 3 non-variable stars measured at the same period of time (open dots: HD10700, stars: HD39091, filled dots: HD67199). No instrument zero point drift is observed

A direct detection would be worth attempting since the star is close to us.

Alternative explanations to a low mass companion to explain the observed 15.8 day period radial velocity change of Gliese 86 would be activity related phenomena (Saar & Donahue 1997). However Gliese 86 doesn't exhibit any of the classical activity signatures seen on young stars, as for exemple HD166435 (Queloz et al. in prep). Gliese 86 has no chromospheric activity. No rotational broadening is detected either, and its photometry is very stable. Therefore, the planetary hypothesis is most likely the correct interpretation for the observed periodic radial velocity changes.

3. Discussion

The observed orbital charateristics of planets are the direct outcome of their formation processes and of their evolutions. Therefore, these characteristics may be used to retrace their formation mechanisms and to constrain theories of planetary formation. The recent spectroscopic studies of stars where planets have been detected have shown that the host star itself may also bear marks from some processes occuring during planetary formation (Gonzalez 1997). More specifically a large number of planets with short-period orbits have surprisingly metal rich host stars. These planets, very close to their stars, are usually
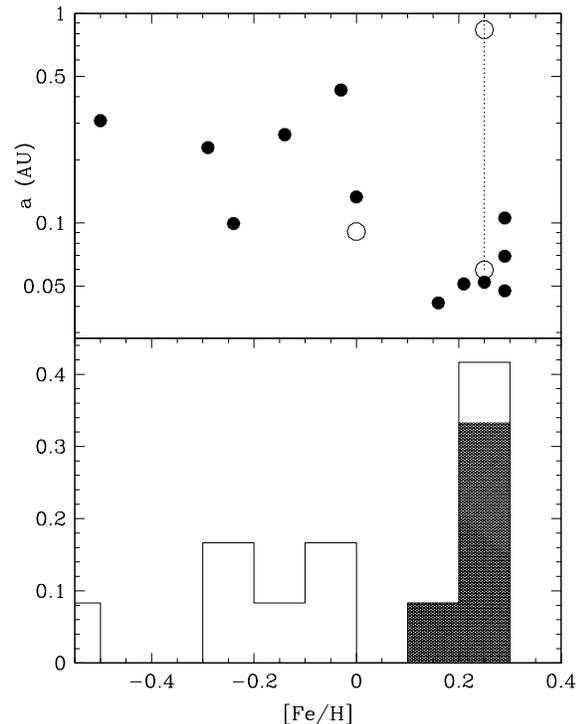

Fig. 4. *Top*: [Fe/H] content of stars versus semi-major axis of the planetary orbit for all known planetary candidates with a $m_2 \sin i < 12\,\mathrm{M}_J$ and $a \leq 1\,\mathrm{AU}$. [Fe/H] measurements are from Gonzalez 1998 and Gonzalez et al. 1999. A typical 0.06 error on [Fe/H] estimates are given by the authors. The dotted line connects the dots representatives of the two inner planets orbiting the star υ Andromedae. *Bottom*: Distribution of the metallicity of stars with a planet (solid line). The shaded area indicates stars with a planet closer than 0.08 AU. Note the υ And multiple system and the planet orbiting the late M star GJ876 are not included in the histogram (open dots on Top diagram)

referred as 51 Peg like, or "hot Jupiters". The metallicity of their host star is much higher than the "average field star" and is not the result of a selection process in the survey samples (Marcy et al. 1999b). Typical metallicities similar to field stars may be assumed for the stars from various surveys, since these star samples have not been selected from any metallicity criteria.

If we look in more detail at all the planets with semi-major axis less than 1 AU, where the number of detections is significant and not strongly high-mass biased, we observe a relation between the semi-major axes of the planetary orbits and the metal content of their host stars. All planets with semi-major axes less than 0.08 AU seem to have a star with an unusually very high metal content compared to other stars with planets (see Fig. 4). Actually, a comparison of the two distribution using the Kolmogorov-Smirnov test indicates a 99% probability that the two distributions are indeed different.

The unusual metal content of the short orbit planets had been pointed out shortly after the detection of 51 Peg (Mayor & Queloz 1995). But now, with the large number of detections of similar systems and others with slightly larger semi-major axes, we observe a typical distance (or period) for which this unusual high metal content is systematically observed. A

possible explanation may be related to some very specific processes occuring during the formation of these very close systems. However the large incertainties on the estimation of the age of these systems and the small mass range of primaries are noteworthy. Therefore it is difficult to completely rule out a stellar population effect.

The migration theory (Lin & Papaloizou 1986; Lin et al. 1996; Ward 1997; Trilling et al. 1998) is one of theories that has been called for to explain the existence of very close planets that were not described by the "classic" solar-system planetary formation model (Boss 1995; Lissauer 1995). But so far, we have a poor understanding of the way the planet stops its migration. The two different metallicity distributions pointed out in this article are perhaps a new clue to a better understanding of the migration process or the likelyhood of an in-situ formation (Bodenheimer et al. 1999).

Others scenarios involving strong gravity interactions with other planets have been proposed as a possible origin for small planetary orbits (Weidenschilling & Marzari 1996; Rasio & Ford 1996). Since these models are purely driven by dynamical interactions it seems a priori difficult to expect any metallicity enhancement effect. Moreover such scenarios do not really explain the very small orbit planets like 51 Peg. However, if one believes that the high metal content of the star is the end-result of a planet swallowed by the star (Sandquist et al. 1998), the gravity interaction is a possible means to send planets into their stars.

The precision of surveys from which the planets have been found so far has been limited to the detection of systems with a V_r-amplitude (K) larger than $25\,\mathrm{m\,s}^{-1}$. Therefore it is still premature to compare the mass of the two sets of planets because there is a direct relationship between the amplitude of the radial velocity curve, the semi-major axis, and the minimum mass of the planet that can be detected. However if we limit our comparison to a sample free of such bias, including planets only having semi-major axes smaller than 0.3 AU, we may be inclined to believe that metal rich stars tend to host on average less massive planets than solar stars or metal poor stars.

The distribution of mass of all planets that have been detected can also be studied with a restricted sample of planetary systems in order to avoid a biased selection towards small orbits and massive systems. We see that with a sample restricted to minimum masses greater than $1\,\mathrm{M}_J$ and semi-major axes smaller than 1.3 AU, the number of planets per mass bin is almost constant from 1 to $5\,\mathrm{M}_J$ and then drops suddenly for more massive companions. This reinforces the idea that a maximum planet mass may lie somewhere close to 5-$7\,\mathrm{M}_J$ as pointed out earlier by Mayor et al. 1998.

New discoveries and improved detection precision will allow us to get a better picture of the relation between the mass and certain orbital characteritics of planets and some peculiarities seen in the atmosphere of their host stars. This will perhaps enhance our understanding of the mechanisms of planetary formation.

References

Baranne A., Queloz D., Mayor M., et al., 1996, A&AS 119, 1
Bodenheimer P., Hubickyj O. Lissauer J.J., 1999, In: Mannings V., Boss A., Russell S. (eds.) Protostars and Planets IV, in press
Boss A.P., 1995, Sci 267, 360
Butler R.P., Marcy G.W., Fischer D., et al, 1999, ApJ, in press
Duquennoy A., Mayor M., Halbwachs J.-L., 1991, A&AS 88, 281
Favata F., Micela G., Sciortino S., 1997, A&A 322, 131
Fischer D., Marcy G.W., Butler R.P., Vogt S.S., Apps K., 1999, PASP 111, 50
Flynn C., Morell O., 1997, MNRAS 286, 617
Gonzalez G., 1997, MNRAS 285, 403
Gonzalez G., 1998, A&A 334, 221
Gonzalez G., Wallerstein G., Saar S.H., 1999, ApJ 511, L111
Lin D.N.C, Papaloizou J., 1986, ApJ 309, 846
Lin D.N.C., Bodenheimer P., Richardson D.C., 1996, Nat 380, 606
Lissauer J.J., 1995, Icarus 114, 217
Lucy L.B., Sweeney M.A., 1971, AJ 76, 544
Marcy G.W., Butler R.P., Vogt S.S., Fischer D., Liu M.C., 1999a, ApJ 520, 239
Marcy G.W., Cochran W.D., Mayor M., 1999b, In: Mannings V., Boss A., Russell S. (eds.) Protostars and Planets IV, in press
Mayor M., Queloz D., 1995, Nat 378, 355
Mayor M., Queloz D., Udry S., 1998, In: Brown Dwrafs and Extrasolar Planets. ASP Conf. Ser. Vol. 134
Queloz D., Casse M., Mayor M., 1999, In: Hearnshaw J.B., Scarfe C.D. (eds.) IAU Colloquium 170, Precise stellar radial velocities. Victoria BC Canada, ASP Conference Series, in press
Rasio F.A., Ford E.B., 1996, Sci 274, 954
Saar S.H., Osten R.A., 1997, MNRAS 284, 803
Saar S.H., Donahue R.A., 1997, ApJ 485, 319
Sandquist E., Taam R.E., Lin D.N.C., Burkert A., 1998, ApJ 506, L65
Trilling D.E., Benz W., Guillot T. et al., 1998, ApJ 500, 428
Ward W.R., 1997 ApJ 347, 490
Weidenschilling S.J., Marzari F., 1996, Nat 384, 619