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LETTER

Letter to the Editor

Planetary systems or double stars?

M. Imbert and L. Prévot

Observatoire de Marseille, 2 Place Le Verrier, F-13248 Marseille Cedex 04, France

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Abstract. Stars showing very small amplitudes of radial velocity have been interpreted as systems having planetary companions. For some of them, we present an alternative interpretation in which the star would be a binary system seen face-on, a scheme relying mainly on the fact that the observed amplitude of radial velocity is determined from the blended lines of two stars having close parameters. This model very satisfactorily explains the observational data of 47 UMa, 70 Vir and 16 Cyg B with, however, a low probability. Such systems will certainly occur in the case of large samples. We conclude that in the limited samples available for the moment, almost all the systems with very small amplitudes of radial velocity variations must be considered as planetary systems.

Key words: binaries: spectroscopic – planetary systems

1. Introduction

In the last few years, a new generation of spectrometers (e.g. the Haute Provence ELODIE echelle spectrograph, the Lick Observatory Hamilton spectrometer, the MacDonald coudé, the Cfa Advanced Fiber Optic Echelle Spectrograph) allow measurement of radial velocity of 15 m s^{-1} (Baranne et al. 1996) and even less (Butler et al. 1996). These instruments have been mainly designed to detect low mass stars, brown dwarfs or massive planets orbiting around stars in the solar neighbourhood. This research has given spectacular results, the first of which being the discovery of faint variations in the radial motion of 51 Peg. These variations have been interpreted as the presence of a planet (Mayor & Queloz 1995). Other similar systems have been discovered subsequently by Butler & Marcy 1996, Butler et al. 1997, Cochran et al. 1997 and Noyes et al. 1997. The summary of the results obtained in the field of the planetary search is available on the Web (Schneider 1998).

Some objects among a sample of nearby solar-type stars have shown periodic motions of very low amplitude. These observations have been explained by the perturbation produced by a planet on the star's motion, the periodic variations of the stellar radial velocity being considered as the radial component of the orbital motion of a spectroscopic binary system of which only one component is visible.

The elements deduced from the observations are the period P, the eccentricity e, and the half-amplitude of the radial velocity variation K_{obs}. The mass function f(m) is derived from these elements: it depends on the mass m_1 of the main body, on the mass m_2 of the secondary and on the inclination angle between the orbital plane and the plane of the sky.

$$f(m) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = 1.0385\ 10^{-7}\ K^3\ P(1 - e^2)^{3/2}$$

(P is in days and K in km s^{-1})

A value of some tens of ms^{-1} for K_{obs} leads to f(m) of the order of 10^{-10} $M_\odot$ for a period of several days. The mass of the secondary can be estimated if one can assess the mass of the primary and the inclination of the orbit. The mass of the main component is derived from its spectral type. If one can show that the orbit's inclination is about 90°, the mass of the companion is derived with the help of the usual assumptions. In this interpretation, generally accepted, the mass of the secondary is about one Jupiter mass. A very low value of the mass function can also show that the secondary has a stellar mass if the inclination is close to zero. The question is whether **all** spectroscopic systems with low amplitudes of radial velocity variations must be considered as planetary systems. We propose an alternative interpretation of such observations which implies a classical binary system and we estimate the probability of the configuration.

2. Spectroscopic double systems with two stars of comparable mass and low values of K_{obs}

2.1. Modelling

Let us consider the case of two dwarf stars of similar mass orbiting in a plane inclined at about 0°. The amplitudes of variations of the radial velocity of the two components are:

$$K_1 = [\frac{f(m)}{\alpha\ P(1 - e^2)^{3/2}}]^{1/3},$$

$$K_2 = K_1 \frac{m_1}{m_2},\ \ (\alpha = 1.0385\ 10^{-7})$$

Send offprint requests to: M. Imbert

since i is close to 0°, f(m) is low, and K_1 and K_2, which depend on them, are small too. This means that even at the time of the maximum difference between the radial velocities of the components, the spectral lines will not be resolved and hence they will seem to show a single component. If the luminosities of the two stars are different, for a given spectral line, the position of the blend will be determined from the positions of the lines of each component weighted, to a good approximation, by the luminosities of each component. The observations of the radial velocity over an orbital cycle will provide the amplitude K_{obs} also weighted by the luminosities of the two stars:

$$K_{obs} = \frac{K_1 L_1 - K_2 L_2}{L_1 + L_2}$$

Is this pattern able to explain the characteristics of the spectroscopic systems showing very small amplitudes of radial velocity variations such as those considered to be planetary systems?

The observable parameters like the visual magnitude m_v, the colour index B-V, and the spectral type are generally known with a high accuracy for the bright stars. Since 1997, we have at our disposal the parallaxes of high precision measured by Hipparcos, which allow us to very reliably determine the absolute magnitude M_v of the system. With these data we can calculate a model involving two stars, which accounts simultaneously for the spectral type, the observed magnitude, the colour index and the orbital parameters.

As a first step, we fit the luminosities and colours of each component in such a way that their sum is equal to the observed magnitude. Starting from spectral types of main sequence stars compatible with the observed spectrum considered to be composite and from the related values of the masses, luminosities and colour indices, successive iterations allow us to find the visual absolute magnitude and the B-V colour index of the system. Once these parameters have been determined, we calculate the luminosities L_1 and L_2 which weigh the amplitudes of the velocity variations of each component. The amplitude K_{obs} depends on the one hand on L_1 and L_2 and on the other hand on K_1 and K_2 which are themselves functions of the masses m_1 and m_2, the period P, the eccentricity e and the inclination i of the orbital plane. Finally, we adjust the inclination i in order to find the value of K_{obs} again, by successive evaluations of

$$f(m) = \frac{(m_2 \sin i)^3}{(m_1+m_2)^2}, \quad K_1 = \left[\frac{f(m)}{\alpha\, P(1-e^2)^{3/2}}\right]^{1/3},$$

$$K_2 = K_1 \frac{m_1}{m_2} \; \mathit{and}\; K_{obs} = \frac{K_1 L_1 - K_2 L_2}{L_1 + L_2}$$

The values that we give to the masses, absolute magnitudes and colour indices are in agreement with the ones generally attributed to stars of the main sequence. However, it is known that, for a given spectral type, these parameters can show slight differences. So several close models can fulfill the requirements of the set of constraints. Therefore we are allowed to adjust these parameters slightly in order to obtain the best fit to the observational data. In our modelling, a star a little hotter or a little cooler remains obviously compatible with the observational data. To be valid, the model must provide values of K_1 and K_2 that do not result in the separation of the spectral lines which must remain blended at all the phases of the orbital cycle. Thus the faint amplitude of the velocity variation is fully taken into account.

An additional constraint plays a part in the model's elaboration: the apparent dimension of the orbit and the relative luminosities of the two components must be such that they lead to a photocentric orbit the dimension of which is, at most, equal to the detection limit of Hipparcos, typically 2 milliarc seconds according to the orbits published in the catalogue.

2.2. Probabilities

One of the major arguments which led to an interpretation in favour of planetary systems is the very low probability of having a stellar secondary component.

2.2.1. Constraint by the orbital inclination

The probability bound to the orbital inclination is calculated from the mass function and from the mass given to the main component. For binary systems whose orbital planes are distributed at random, the probability of having an inclination i larger than a given value i_o is equal to cos i_o. For a given value m_{02} of the mass of the secondary, we determine a value i_o calculated from m_1 and f(m). The probability of finding $m_2 \geq m_{02}$ is given by:

$$p_1 = 1 - \cos i_o$$
$$= 1 - \cos\left[\arcsin\left[\frac{[f(m)(m_1+m_{02})^2]^{1/3}}{m_{02}}\right]\right].$$

In our modelling, the true value of K_1 being much larger than the observed value, the mass function increases strongly and hence the probability too.

2.2.2. Constraint by the mass ratio

Our model imposes relatively close values on the masses of the two components. In a sufficiently large and unbiased sample of spectroscopic binaries, extracted from Duquennoy & Mayor (1991), we find that about 40 percent of the systems have mass ratios between 0.7 and 1.0 (limiting values beyond which the model is not applicable). So we adopt a probability p_2 = 0.4.

2.2.3. Constraint by the period

Our model does not impose any limits on the periods. However, among nearby stars of solar mass, systems having periods longer than 3000 days are most probably all detected as visual binaries. The analysis of the homogeneous sample of nearby stars published by Duquennoy & Mayor gives about ten percent of spectroscopic binaries having periods shorter than 3000 days. Therefore, we adopt p_3 = 0.1

These estimates of the different probabilities give an overall probability p_1 p_2 p_3. The probable number of systems similar to the one described by our model which are present in a sample of N stars can thus be estimated as n = N p_1 p_2 p_3.

Table 1. Observational data

	47 UMa	70 Vir	16 Cyg B
π_{Hip} (mas)	71.04	55.22	46.70
m_v	5.03	4.97	6.25
M_v	4.29	3.68	4.60
B-V	0.624	0.714	0.661
Sp	G0V	G5IV-V	G5V
P (days)	1095	116.7	804
e	0.05	0.4	0.67
K_{obs} ((km s^{-1})	0.0455	0.318	0.505
f_1(m) (10^{-6} $M_\odot$)	0.0106	0.300	0.0042
V sin i (km s^{-1})	1.9	0.9	2.0

π_{Hip}: parallax from the Hipparcos catalogue (1997)
m_v: visual magnitude from CDS (1998)
M_v: visual absolute magnitude
B-V: colour index from CDS (1998)
Sp: spectral type from CDS (1998)
P: period
e: eccentricity
K: radial velocity amplitude
f(m): mass function
V sin i: projected rotational velocity (Fuhrmann, K. et al. 1997, Henry, G. 1997)

Table 2. Models of two-stars systems

	47 UMa	70 Vir	16 Cyg B
Sp_1	G0V	G5IV/V	G5V
Sp_2	G5-8V	G5V	G8V
m_1 ($M_\odot$)	1.10	1.12	1.00
m_2 ($M_\odot$)	0.795	0.82	0.78
Mv_1	4.90	4.20	5.20
Mv_2	5.20	4.70	5.50
Mv_{sys}	4.29	3.67	4.59
$(B-V)_1$	0.59	0.71	0.66
$(B-V)_2$	0.67	0.72	0.66
$(B-V)_{sys}$	0.62	0.71	0.66
LB_1 ($L_\odot$)	0.929	1.585	0.661
LB_2 ($L_\odot$)	0.655	0.991	0.501
i°	16.78	8.12	11.22
f(m) (10^{-6} $M_\odot$)	3370	413	1102
K_1 (km s^{-1})	3.10	3.54	3.23
K_2 (km s^{-1})	4.29	4.83	4.14
a (UA)	2.57	0.58	2.04
a (mas)	175	32	93
a_{phot} (mas)	1.1	1.2	0.7
p_1 $\{m_2 \geq m_{02}\}$	0.043	0.010	0.019

Sp: spectral type
m: mass
Mv: visual absolute magnitude
B-V: colour index
LB: blue absolute luminosity
i: inclination in degrees
f(m): mass function
K: radial velocity amplitude
a: semi major axis of the relative orbit
a_{phot}: photocentric semi major axis of the relative orbit
p_1 $\{m_2 \geq m_{02}\}$: Probability of a mass m_2 of the secondary component being larger than a value m_{02}, determined from the elements of the model.

3. Application

To check the validity of the model described above, we have calculated the parameters of ficticious solar-type systems having all the required characteristics. They have given probabilities p_1 of the order of five percent. More realistically, we have also applied the model to the observational data of nine objects considered as planetary systems with m_2 sin i < 0.01 $M_\odot$.

Our model gives results which satisfactorily fit the data of 51 Peg, 55 Cnc, ρ CrB, υ And, τ Boo and HD 114762 (Latham et al. 1985); however, their probabilities p_1 reach 10^{-4} at most.

Three systems with longer periods, 47 UMa, 70 Vir and 16 Cyg B, are also well fitted by our model, but this time with a probability p_1 which reaches four percent. We therefore conclude that there is a non-negligible possibility that such systems could be observed. For these three stars, the model leads to almost face-on systems, the inclinations of their orbits reaching a few degrees at most. The applications made on real systems show that the probability p_1 inferred from the calculated solar-type systems is realistic.

For these three systems we have also considered the other arguments put forward in favour of a planetary interpretation: i) the values of the projected rotational velocities and ii) the X-ray luminosities of these stars.

i) The projected rotational velocities are low enough, in view of their incertainties, for them to be compatible with velocities close to zero, as they must be in systems seen nearly face-on. Moreover, it is to be noted that even in the absence of rotation, the spectral lines are never resolved, which has the effect of broadening them. When considering the system as a single star, this broadening is obviously interpreted as rotation.

ii) Pravdo et al. (1996) have shown that the X-ray luminosities allow discrimination between single stars and relatively close binaries. According to these authors, systems having periods of two to six days show, without exception, X-ray emission much stronger than that of single stars of similar spectral types. This emission is imputed to the coupling of the stellar rotational velocities with the period of revolution of the system. This is most probably not the case for these three systems, as they have much larger orbits and periods of 100 days and more.

These two additional contraints do not introduce any incompatibility between the model and the real systems.

The three objects considered as planetary systems and with non-negligible probability p_1 are all extracted from the sample of 120 stars monitored by Marcy & Butler. We derive n ≈ 0.2 for this sample. Although small, this number is not negligible. It shows that in a sample larger by at least an order of magnitude, will certainly appear one or several stellar systems of this kind.

Table 1 gives the observational data for 47 UMa, 70 Vir and 16 Cyg B; their orbital elements are respectively those of Butler & Marcy (1996), Marcy & Butler (1996) and Cochran et al.

(1997). Table 2 provides our models of binary systems which best fit the observations while respecting all the constraints.

4. Conclusion

If the orbital inclination of a system remains indeterminate, the assumption on which is based our model i.e. a system of two fairly similar stars seen face-on, must also be considered for samples of about 1000 stars or more. In the samples available today, our estimate of the overall probabilities confirms that almost all of the systems with very small amplitudes of radial velocity variations must be considered as planetary systems. It is obvious that direct observations providing the inclination and/or the distance between both components would allow removal of any remaining ambiguity concerning the nature of the companion.

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References

Baranne, A., Queloz, D., Mayor, M., et al., 1996, A&AS 119, 373
Butler, P., Marcy, G., 1996, ApJ 464, L153
Butler, P., Marcy, G., Williams, E., Doshanjh, P., Vogt, S., 1996, PASP 108, 500
Butler, P., Marcy, G., Williams, E., Hauser, H., Shirts, P., 1997, ApJ 474, L115
CDS, base SIMBAD, 1998 site Web http://simbad.u-strasbg.fr/Simbad
Cochran, W., Hatzes, A., Butler, P., Marcy, G., 1997, ApJ 483, 457
Duquennoy, A., Mayor, M., 1991, A&A 248, 485
Fuhrmann, K., Pfeiffer, M., Bernkopf, J., 1997, A&A 326, 1081
Henry, G.W., Baliunas, S., Donahue, R.A., Soon, W.H., Saar, S., 1997, ApJ 474, 503
Hipparcos & Tycho catalogues 1997, ESA publication SP-1200
Latham, D., Mazeh, T., Stefanik, R., Mayor, M., Burki, G., 1989, Nat 339, 38
Marcy, G., Butler, P., 1996, ApJ 464, L147
Mayor, M., Queloz, D., 1995, Nat 378, 355
Noyes, R., Saurabh, J., Korzennic, S., et al., 1997, ApJ 483, L111
Pravdo, S.H., Angelini, L., Drake, S.A., Stern, R.A., White, N.E., 1996, New Astronomy 1, N°2, 171
Schneider.,1998 site Web http://www.obspm.fr/departement/darc/planets/encycl.html