CAN THE PERTURBATION OF A STELLAR MOTION IN A TRIPLE SYSTEM MIMIC A PLANET ?

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ABSTRACT

The first extra-solar planets have been detected by the measurement of the wobble of the parent star. This wobble leads to the periodic modulation of three observables: radial velocity, position on the sky and time of arrival of periodic signals. I show that the same wobble, and therefore the same modulation of the three observables, can be due to the presence of a distant binary stellar companion. Thus, the observation of the wobble does not, by itself, constitute a proof of a planet detection; in particular, astrometric confirmation of a wobble does not necessarily provide a sufficient proof of the existence of a planet candidate detected by radial velocity; additional conditions must be fulfilled. I investigate the observed wobble for the planet candidates detected up to now by radial velocity and find that, for each case, a wobble due to a binary stellar companion can be excluded.

Key words: Planetary systems; Dynamical systems; Perturbations.

1. INTRODUCTION

The detection of the first extra-solar planets rests on an indirect method, namely the measurement of the reflex motion of the parent star. In cases where only the wobble is detected, one can ask whether the detection of radial velocity (RV) variations (1) are indeed due to a stellar wobble and not to other effects (such as stellar rotation or variable stellar activity) (2) are indeed due to a planet and not to other dynamical effects (3) that the companion is indeed a planet.

Here I consider the case where the wobble is real but due to the perturbation by non-planetary bodies. I essentially consider the case of a distant binary star. In a few cases, the planet detection is confirmed by (or was preceded by) the detection of a transit of a planet. But one may wonder if other stellar wobbles are due to a planet and not to a distant binary star.

2. PERTURBATION OF STELLAR MOTION BY A BINARY STAR

Consider a triple hierachical system consisting of a single star of mass M_* and a distant binary star of equal mass components M_B with a separation $2\Delta r = 2a_B$, located at a distance $r = a_C$. See Figure 1 for definition of the notations.

Assuming $a_B \ll a_C$, the equation of motion of the star of mass M_* in the gravitational potential of the distant binary reads:

$$\vec{\gamma} = \ddot{\vec{r}} = -GM_B \left(\frac{\vec{r} + \vec{\Delta r}}{\|\vec{r} + \vec{\Delta r}\|^3} + \frac{\vec{r} - \vec{\Delta r}}{\|\vec{r} - \vec{\Delta r}\|^3} \right) \quad (1)$$

where $\vec{\Delta r} = \Delta r \vec{v}$ is the the position vector of one of the components of the binary with respect to the binary centre of mass (Figure 1). Let $\vec{u}$ be the unit vector along the line joining the primary and the binary star (directed toward the third star): $\vec{r} = r\vec{u}$.

After some elementary algebra Equation 1 leads to (in the first order of $(\Delta r/r)^2$):

$$\ddot{\vec{r}} = -\frac{2GM_B}{r^2} \left[\vec{u} + \left(\frac{\Delta r}{r}\right)^2 \left[(-\frac{3}{2} + \frac{15}{2}\cos^2\theta)\vec{u} - 3\cos\theta\vec{v}\right]\right] \quad (2)$$

where $\cos\theta = \vec{u}.\vec{v}$. Let $(\vec{i}, \vec{j})$ be an inertial orthogonal reference frame and $\vec{r}_o = r_o(\vec{i}\cos\Omega t + \vec{i}\sin\Omega t)$ be a solution of Equation 2 for $a_B = 0$ (with $\Omega = \sqrt{2GM_B/r^3}$). Let us consider $\vec{r} = \vec{r}_o + \vec{\epsilon}$ as a perturbation of $\vec{r}_o$ and search for solutions for $\vec{\epsilon}(t)$ under the form

$$\vec{\epsilon}(t) = a_*\vec{u}\cos 2\omega t + b_*\vec{v}\sin 2\omega t \quad (3)$$

Using

$$\cos^2\omega t = \frac{1+\cos 2\omega t}{2} \quad \text{and}$$
$$\sin\omega t\cos\omega t = \frac{1}{2}\sin 2\omega t \quad (4)$$

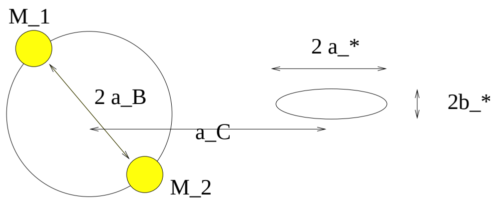

Figure 1. Schematic representation of a binary star generating a wobble in the motion of a distant single star.

the insertion of expression (3) into Equation 2 then leads to

$$\frac{3GM}{r_o^2}[\vec{i} + \left(\frac{\Delta r}{r}\right)^2 [(-1 + 5/2(1+\cos 2\omega t))\vec{i} \\ -(\vec{i}(1+\cos 2\omega t) - \vec{j}\sin 2\omega t)]] \\ = -r_o\Omega^2\vec{i} - 4a_*\vec{i}\omega^2\cos 2\omega t \\ -4b_*\vec{j}\omega^2\sin 2\omega t \quad (5)$$

Identifying the $\cos 2\omega t$ and $\sin 2\omega t$ modes in the left and righthand sides of Equation 5 finally gives:

$$a_* = \frac{9}{2}a_B\left(\frac{a_B}{a_C}\right)^4 \\ b_* = 3a_B\left(\frac{a_B}{a_C}\right)^4 \quad (6)$$

3. MIMICKING OF A PLANET

The motion of the primary star C can mimic the wobble by a planet. The derived apparent parameters of the pseudo-planet are:

$$P_{\rm pl} = P_* \quad (7)$$

$$a_{\rm pl} = \left(\frac{P^2{}_{\rm pl}GM_*}{4\pi^2}\right)^{1/3} \quad (8)$$

$$e = \sqrt{1-(b_*/a_*)^2} \quad (9)$$

$$M_{\rm pl} = M_*\frac{a_*}{a_{\rm pl}} \quad (10)$$

From these expressions, one can derive the mass M_B required to lead to the observed values for a pseudo-planet:

$$M_B = (9/8)^{-3/5}M_{\rm pl}^{3/5}M_*^{2/5}a_C^{12/5}a_{\rm pl}^{-12/5} \quad (11)$$

4. APPLICATION TO EXOPLANETS DETECTED BY RADIAL VELOCITY

One may wonder if the low amplitude wobble detected in more than 100 stars (see www.obspm.fr/planets for a permanent update) is due to a planet or to a more distant binary star. I will discuss two different cases, namely stars considered as simple and stars known as components of a binary system.

4.1. Planets Around Single Stars

From the point of view of radial velocity measurements, a star is considered as single if there is no long term drift in its velocity curve. The absence of velocity drift imposes a minimum value for the distance of an hypothetical companion. $\gamma = GM/a_C^2$ being the acceleration of the target star due to a companion at a distance a_C, the velocity drift acquired over a time span ΔT is $\Delta V = \gamma\Delta T = GM/a_C^2\Delta T$. The star is single if ΔV is smaller than the the observational limit. Taking from the last years of radial velocity surveys $\Delta V < 10$ m s^{-1} and ΔT = 5 yrs, one gets, for $M = 1M_\odot$, $a_C >$ 300 pc. From Equation 11 one derives the following relation between the possible pseudo-planet mass and orbital period for $M_* = m_B = 1M_\odot$:

$$\left(\frac{M_{`pl'}}{M_J}\right)^{1/4} = 3 \times 10^3\left(\frac{P_{`pl'}}{1\ yr}\right)^{12/3}\left(\frac{1\mathrm{AU}}{a_C}\right)^{-1} \quad (12)$$

Figure 2 represents the known planets around single stars with orbital periods larger than 1 yr and the pseudo-planet mass-period relation derived from Equation 12 for a_C = 200 pc and 300 pc. It clearly shows that the known planets do not follow Equation 12 and therefore that they cannot be explained as a stellar wobble generated by an hypothetical binary distant companion.

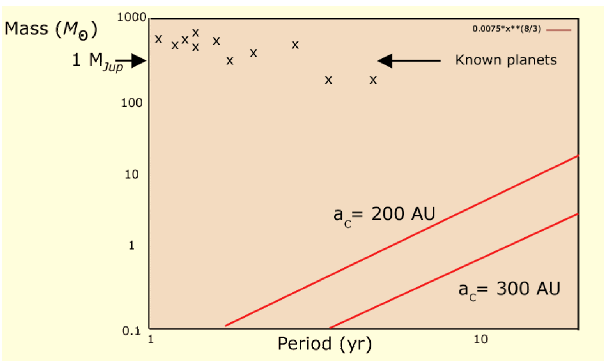

Figure 2. Comparison of known planets around single stars with the mass-period relation of a pseudo-planet corresponding to the wobble induced by a binary star located at 300 AU.

4.2. Planets in Binary Star Systems

There are presently (October 2004), 14 planets detected in binary star systems (Eggenberger et al. 2003). One may wonder to what extent the second companion is in fact not a binary star inducing a stellar wobble on the target star, mimicking a planet. Since the separation a_C is then known, the mass of the binary is then given by Equation 11.

From the data of Eggenberger et al. for a_C, M_{pl} and a_{pl}, Table 1 shows in each case the value for M_B derived from Equation 11:

Table 1. Values of M_B derived from Equation 11 using data from Eggenberger et al.

Name	a_C	a_{pl}	M_{pl}	M_B
HD 40979	6400	0.8	3.3	4×10^{11}
GL 777 A	3000	3.65	1.15	1.0×10^{9}
HD 80606	1200	0.469	3.9	2.7×10^{10}
55 Cnc	106	0.038	0.045	1.3×10^{12}
		0.115	0.84	3.2×10^{11}
		0.241	0.21	3.2×10^{10}
		5.9	4.05	4.7×10^{7}
16 Cyg B	850	1.66	1.64	3.8×10^{7}
υ And	750	0.059	0.69	6.4×10^{11}
		0.828	1.96	1.7×10^{9}
		2.56	3.98	1.5×10^{8}
HD 178911 B	640	0.32	6.92	1.9×10^{10}
HD 75289	621	0.046	0.42	1.5×10^{9}
τ Boo	240	0.05	4.09	1.0×10^{10}
HD 195019	150	0.136	3.55	3×10^{9}
HD 114762	130	0.351	10.96	4×10^{8}
HD 19994	100	1.3	2.0	4.7×10^{6}
Gl 86	20	0.11	4	6×10^{7}
γ Ceph	18	2.03	1.6	2.5×10^{4}

The values found for M_B are aberrant; thus the corresponding stellar wobble cannot be explained as due to the binary nature of the companion star.

5. FUTURE PERSPECTIVE FOR GAIA

Figure 3 represents the apparent mass of a pseudo-planet generated by a binary companion as a function of its orbital period for different separations a_C. The detection space of Gaia in the same (M_{pl}, P_{pl}) plane is represented for a star distance of 5 pc (Sozzetti et al. 2003). It shows that for $a_C <$ 50 AU Gaia has a sufficient sensitivity to detect such pseudo-planets.

6. CONCLUSION

By itself a stellar wobble is not a proof that a planet is detected. It is necessary to verify that no distant binary star

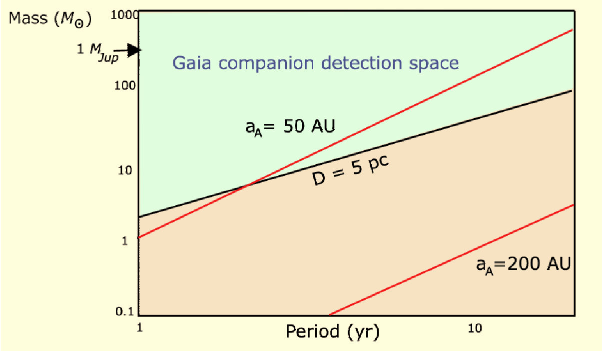

Figure 3. For a binary distant by less than 50 AU, there may be an ambiguity between a planet detected by Gaia and a stellar wobble induced by the binary.

generates the wobble or to confirm the planet by transit or direct imaging observations. For the presently known planets, the explanation by a perturbing binary star can nevertheless be ruled out. But the sensitivity of Gaia is such that for some regions of the (M_{pl}, P_{pl}) plane there can be an ambiguity between a true planet detected by astrometry and a wobble induced by a binary star. Further details are given in Schneider et al. (2005).

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