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Orbital Motion and Magnetic Activity in Close Binaries and Planetary Systems

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Abstract. The connection between orbital period variation and magnetic activity cyclic behaviour in close binaries with late-type components is addressed by discussing recent observational studies of Algols, RS CVn's, W UMa's and CVs. A theoretical model based on the Applegate's mechanism seems capable of explaining the observed orbital period modulation in terms of cyclic changes of a gravitational quadrupole moment induced by a magnetic activity cycle affecting one of the binary components. In such a case, the study of orbital period modulations offers a promising tool to investigate hydromagnetic dynamos operating in the interior of active stars, in particular, to address the fundamental question of the interaction between rotation and magnetic fields in nonlinear dynamo regimes. Moreover, interesting applications to planetary systems with a magnetically active central star are discussed.

1. Introduction

The long-term timing of eclipses in several classes of close binary systems shows cyclic changes of their orbital periods. In Algols and in RS CVn's the relative amplitude of such changes is of the order of $\Delta P/P \sim 10^{-5}$ with typical time scales ranging from ~ 30 yr to more than a century. In W UMa-type contact binaries, $\Delta P/P \sim 10^{-6}$ with cycles of $10 - 100$ yr, whereas in cataclysmic variables (CV) $\Delta P/P \sim 10^{-6}$ with time scales of decades. In the systems with the longest timing records, such as Algol (Söderhjelm 1980), both short-term cycles with time scales of a few decades and long-term cycles with time scales longer than 100 years have been identified. We shall be concerned with the cyclic changes over time scales of decades for which a sufficiently extended database is presently available (e.g., Kreiner, Kim, & Nha 2001). Our considerations may possibly be extended also to cycles with longer time scales.

Hall (1989, 1990) analysed orbital period changes in Algol binaries and found that cyclic changes are observed only among those with a late-type secondary, i.e., of spectral type later than F5, whereas systems with early-type components show only monotone period variations (see also Simon 1999; Zavala et al. 2002). The components of Algols with spectral type later than F5 have extended convective envelopes and are fast rotators thanks to the strong tidal interaction that effectively synchronizes their spin and orbital motions. Therefore, they satisfy the sufficient conditions for the excitation of a hydromagnetic dynamo, as indicated by the observations of several proxies of atmospheric magnetic fields, in particular X-ray stellar coronae and strong flares (Schmitt & Favata 1999; Ness et al. 2002). Moreover, the other classes of close binaries in which cyclic orbital period changes have been detected are characterized by one or both components with convective envelopes. In consideration of such phenomenological evidence, Hall (1989, 1990) suggested that cyclic orbital period variations are related with cyclic magnetic activity in the late-type components of binary systems.

It is interesting to note that a light-time effect can not be invoked to explain the observed period changes, except for about 10% of the systems. Actually, there is no evidence for a third light, while the predicted minimum mass of a third body should generally be of a few solar masses that should not have escaped detection. Moreover, the observed modulation of the orbital period is usually not strictly periodic, as expected on the basis of the third-body hypothesis. In some cases, the third-body hypothesis can be rejected on the basis of radial velocity measurements, which do not confirm the expected acceleration of the system barycentre (e.g., Donati 1999 for HR 1099).

Several physical mechanisms have been proposed to account for the association between orbital period modulation and magnetic activity. DeCampli & Baliunas (1979) considered the role of flares and of a time-varying magnetized stellar wind that modulate the angular momentum loss from the active component along an activity cycle. The tidal interaction may couple the spin and orbital angular momentum variations inducing alternate orbital period changes. However, the amount of mass loss that is required to explain the amplitude of the observed changes in RS CVn's is at least of the order of $10^{-8} - 10^{-7}$ $M_{\odot}$/yr, i.e., about 2-4 orders of magnitude larger than the maximum mass loss rate observed in such systems. Another difficulty is that the tidal time scales to couple the variation of the spin angular momentum of the magnetically active component to the orbital motion are of the order of $(2 - 10) \times 10^{3}$ yr in RS CVn's, i.e., about two orders of magnitude larger than the time scales of the orbital period cycles (cf. Zahn 1989).

The hypothesis of a mass transfer among the components is ruled out in detached systems such as RS CVn's and it is not viable for Algols and CVs because the mass flow goes from the less massive secondary to the more massive primary. This mass flow would induce a monotonic rather than cyclic variation of the orbital period. Moreover, the required mass exchange rate should be of the order of $10^{-7} - 10^{-5}$ $M_{\odot}$/yr, at least one or two orders of magnitude larger than the observed mass loss or exchange rates in Algols (cf. Richards & Albright 1999).

In consideration of such difficulties, Applegate & Patterson (1987) and Warner (1988) reconsidered a suggestion by Matese & Whitmire (1983) by proposing that the gravitational quadrupole moment of magnetically active components in close binaries may vary along the activity cycle in response to the change of the magnetic pressure at the base of their convective envelopes. The model can account for the time scales of the orbital period changes because a variation of the quadrupole moment of one of the components implies a variation of its outer gravitational potential, which immediately affects the orbital motion of the system without requiring a tidal coupling. Specifically, when the quadrupole moment of the active component increases, the companion star will experience a stronger gravitational pull, which forces it to move a little bit closer and faster around the companion in order to conserve the system angular momentum. Conversely, when the quadrupole moment decreases, the orbital period will increase. A relative variation of the stellar radius of $\Delta R/R \sim 10^{-5}$, that is induced by the variation of the magnetic pressure gradient, would produce a variation of the quadrupole moment that can account for orbital period changes of the order of $\Delta P/P \sim 10^{-5}$ in RS CVn's and Algols.

The model proposed by Applegate & Patterson (1987) and Warner (1988) was criticized by Marsh & Pringle (1990), who showed that the energy required to produce the isotropic expansion of the convective envelope is larger than the energy radiated by the active star during an activity cycle. However, Applegate (1992) reconsidered the model and showed that the energy constraint can be satisfied by assuming a variation of the internal angular velocity instead of the radius of the active component. In this model some angular momentum is cyclically exchanged between different shells inside the convection zone due to the torque exerted by the Lorentz force that is variable along the activity cycle. As the angular momentum of the outer shell increases, also the centrifugal force increases. Hence, when the star oblateness and its quadrupole moment reach maximum values the orbital period reaches a minimum. Conversely, when the angular momentum is transferred into the inner shell, the quadrupole moment attains a minimum and the orbital period attains its maximum length.

2. Applegate's mechanism and the observations of magnetically active close binaries

The model proposed by Applegate (1992) leads to three remarkable predictions that can be tested observationally: a) the length of the orbital period cycle is the same of the stellar activity cycle; b) the rotation rate of the active component varies versus time and the amplitude of its change is correlated with the amplitude of the orbital period change; specifically, in Algols and RS CVn's an angular velocity variation of the order of $\Delta\Omega/\Omega \sim 2\%-3\%$ is required in order to account for the observed period changes, whereas in short-period binaries ($P < 1$ d), such as short-period RS CVn's, CVs and W UMa, a variation of $\Delta\Omega/\Omega \sim 0.1\%-0.3\%$ is enough to account for the period variation; c) the stellar luminosity should vary cyclically to provide the energy required to transfer angular momentum back and forth between internal shells.

A first test of Applegate's predictions was made by Hall (1991) who considered the short-period RS CVn binary CG Cyg. The available observations were sparse, but apparently confirm prediction a) and, possibly, prediction c), whereas prediction b) could not be tested. More detailed tests were presented by Rodonò, Lanza, & Catalano (1995) for the prototype active binary RS CVn, Lanza et al. (1998a) for AR Lac, Anders et al. (1999) for CF Tuc, Donati (1999) for HR 1099, Lanza et al. (2001) for SZ Psc and Lanza et al. (2002) for RT Lac. They have shown that the length of the orbital period cycle is twice the period of the short-term spot activity cycle in RS CVn, AR Lac and RT Lac, while they are comparable in CF Tuc and, possibly, in HR 1099. For SZ Psc, no evident correlation was found from the available data. The determination of orbital period and spot cycles is usually made by means of the Lomb-Scargle periodogram, which is capable of detecting the presence of a cyclic variation in a noisy time series. In the case of the orbital period, some noise may come from actual errors in the determination of the O-C's (cf. Hall & Kreiner 1980), as well as from real changes of the orbital period on time-scales of a few years. Indeed, short-term variations of the orbital period are sometimes seen to be superposed on longer-term cycles (see the case of RT Lac discussed by Lanza et al. 2002 and Cakirli et al. 2003).

The variation of the rotation rate can be measured by using photospheric starspots as rotation tracers and it is about 5-10 times smaller than predicted by Applegate's model for RS CVn, HR 1099, CF Tuc and RT Lac, whereas no significant changes were detected in AR Lac and SZ Psc. However, the presence of active longitudes, probably locked to the tidal deformation, may introduce systematic errors in the measurement of the rotation rate of the active components in close binaries (cf. Eaton, Henry, & Fekel 1996; Holzwarth & Schüssler 2003a, 2003b). It is therefore of interest to consider the behaviour of a single active star. Specifically, the rapidly-rotating K-dwarf AB Dor is a good proxy for the late-type secondaries of short-period RS CVn's, i.e., those systems with an orbital period shorter than about 1 d. Collier Cameron & Donati (2002) found that its equatorial angular velocity did change by $\sim 0.4\%$ over a time scale of $8-10$ yr. Moreover, the difference in the angular velocity between the pole and the equator did also vary over the same time scale. Their results were based on the measurements of surface differential rotation obtained by cross-correlating maps of cool spots obtained by means of the Doppler imaging technique. Given the absence of tidal effects, AB Dor represents a good test for the Applegate's mechanism and indeed the amplitude of its rotation changes are in agreement with the prediction of the model. However, the length of the spot activity cycle differs from that of the rotation change cycle. Amado et al. (2001) found a short-term spot cycle of ~ 5.3 yr superposed upon a longer-term variation over a time scale of ≈ 20 yr, comparable with the overall extension of their photometric database. Therefore, AB Dor provides us with further evidence for a 2:1 ratio between the length of the orbital period cycle and the spot activity cycle.

In principle, the change of the internal rotation assumed in the Applegate's model may be tested by means of asteroseismic measurements. However, a high level of activity may significantly perturb the eigenfrequency variations, making such a test difficult to be performed (Lanza & Rodonò 2002a).

The luminosity variations predicted by Applegate's model are of the order of 10% - 20% along a cycle of the rotational modulation and should affect the effective temperature of the active star inducing changes of its optical color indexes. The available evidence indicates that the variation of the stellar luminosity can be entirely attributed to the variation of the spot coverage along an activity cycle without any global change due to a variation of the stellar effective temperature outside spots (cf. also Henry et al. 1995).

3. Improvements to Applegate's model

In consideration of the above limitations of the Applegate's model, Lanza, Rodonò & Rosner (1998b) and Lanza & Rodonò (1999) proposed a new model which can account for the observations. It assumes that, in addition to the variation of the internal centrifugal force, also the variation of the Lorentz force may induce changes of the gravitational quadrupole moment along an activity cycle. If a toroidal magnetic field with a mean strength of $\approx 10^5$ G is present in the deep layers of the convective envelope of the active component, it may significantly affect its quadrupole moment. It is possible to relate the variation of Q, the principal component of the quadrupole moment along the axis joining the barycentres of the two components, with the variations of the internal magnetic energy and of the rotational energy of the active star (see Lanza & Rodonò 1999 for details):

$$\Delta Q = \left(\frac{5}{6\xi}\right)\left[\frac{R^3(\Delta T - \Delta E_m)}{GM}\right], \tag{1}$$

where G is the constant of gravitation, ΔQ is the variation of the gravitational quadrupole moment of the active star, R and M are its radius and mass, ΔT is the variation of its kinetic energy of rotation, ΔE_m is the variation of its total magnetic energy and $\xi \approx 4$ is an adimensional parameter depending on the density stratification inside tha star and on the spatial distribution of the centrifugal and Lorentz forces.

The variation of the orbital period is given by:

$$\frac{\Delta P}{P} = -9\,\frac{\Delta Q}{Ma^2}, \tag{2}$$

where M is the mass of the active component and a the semi-major axis of the relative orbit.

The observation that in several RS CVn's the length of the orbital period cycle is twice the spot cycle may be explained by assuming that a torsional oscillation is responsible for both the quadrupole moment change and the spot cycle, as suggested by Lanza et al. (1998b). Such an oscillation is an Alfven wave for which the restoring force is the azimuthal component of the Lorentz force. It periodically converts a fraction of the stellar kinetic energy of rotation into magnetic energy, and viceversa, and may be excited by an $\alpha^2\Omega$ dynamo operating in the convective envelope (see Moffatt 1978 and Lanza et al. 1998b for more details). In those component stars where an $\alpha\Omega$ dynamo is activated, we expect that the orbital period cycle and the spot cycle have the same length. In the Sun, where the dynamo is supposed to be operating in the $\alpha\Omega$ regime, the perturbation of the surface rotation is indeed closely associated with the dynamo waves, as traced by the migration of the activity belts along the solar cycle (e.g., Rüdiger 1989).

The variation of the photospheric angular velocity is reduced in the Lanza et al. (1998b) model by at least a factor of 2 in comparison to Applegate's

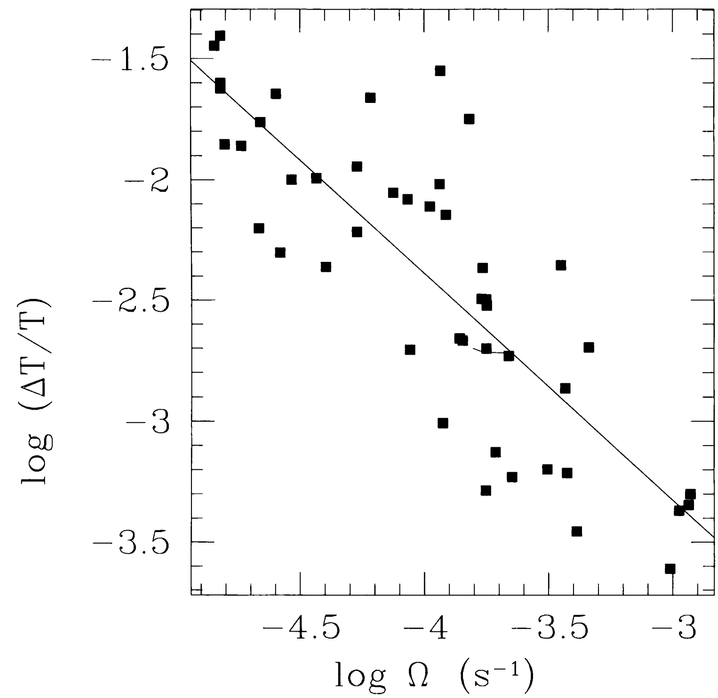

Figure 1. The relative amplitude of the variation of the kinetic energy of rotation versus the angular velocity of the active component for a sample of 46 close binaries (after Lanza & Rodonò 1999).

prediction because the Lorentz force takes part in the variation of the quadrupole moment as well.

The variable quadrupole moment model proposed by Lanza & Rodonò (1999) can be applied to investigate the amplitude of kinetic and magnetic energy exchanges that accompany the orbital period variation. They statistically analysed the period changes in 46 close binaries and derived the following regression relation between the relative amplitude of the kinetic energy change $\Delta T/T$ and the angular velocity Ω of the active component:

$$\log \frac{\Delta T}{T} = -0.93(\pm 0.10) \log \Omega - 6.13 \tag{3}$$

The correlation coefficient is $|r| = 0.83$ (see Fig. 1). The variation of the magnetic energy can be immediately derived by assuming that the sum $T + E_m$ is constant all along the operation of the stellar dynamo (cf. Lanza & Rodonò 1999).

In Fig. 2 the length of the observed orbital period cycle P_{mod} is plotted versus the angular velocity of the active component for the same sample. The

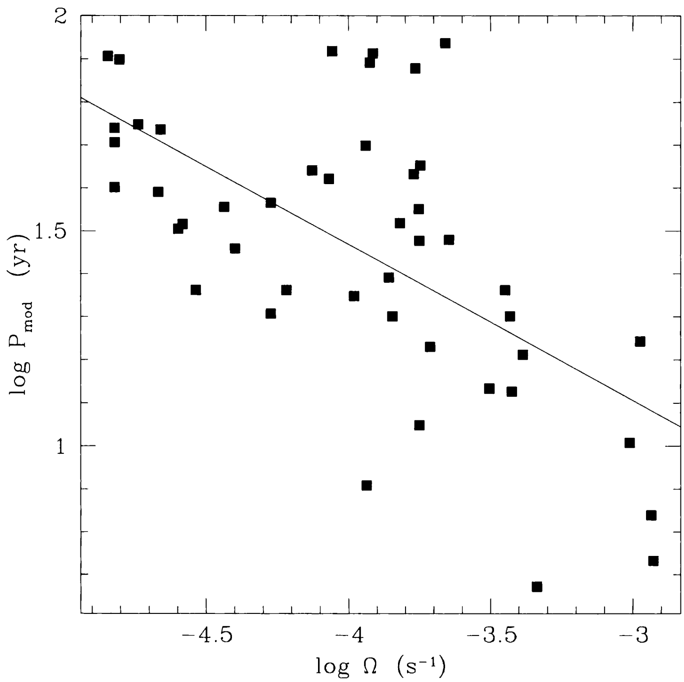

Figure 2. The length of the orbital period cycle versus the angular velocity of the active component in a sample of 46 close binary systems (after Lanza & Rodonò 1999).

regression relation is:

$$\log P_{mod} = -0.36(\pm 0.10) \log \Omega + 0.018, \qquad (4)$$

which agrees with the correlation relation obtained for the length of activity cycles in late-type dwarfs by Baliunas et al. (1996), thus supporting the connection between orbital period changes and magnetic cycles.

In our approach (Lanza & Rodonò 1999), the energy requirements are significantly reduced in comparison to Applegate's predictions. Only a fraction of the energy needed to maintain the time-invariant stellar differential rotation is required to support the quadrupole moment variation. Moreover, the luminosity variations associated with the operation of a non-linear hydromagnetic dynamo are predicted to be of the order of $\Delta L/L \sim 10^{-6} - 10^{-5}$, as discussed by Brandenburg, Moss, & Tuominen (1992). Any variation of the internal energy of the convective envelope is indeed smoothed out by its large thermal capacity and only changes occurring on time scales comparable with its Kelvin-Helmoltz time can produce significant perturbation of the effective temperature outside spots (cf. Spruit 1982, Spruit & Weiss 1986).

Episodes of orbital period changes over time scales of a few years are difficult to be interpreted in the framework of Applegate's model, but they may be understood by invoking instabilities of the strong internal magnetic fields (cf. Lanza & Rodonò 2002b). As a matter of fact, the stability of fields of the order of 10^5 G in the deep layers of an active component convective envelope is still an unsolved issue. A stable storage might be possible in the case of a deep convective envelope, where the magnetic tension force may overcome the destabilizing magnetic buoyancy, but a detailed model has not been proposed so far for the storage of the field and for dynamos operating in nearly completely convective stars (cf. Lanza, Rodonò, & Rosner 2000).

4. Orbital period changes in star-planet systems

The recent discovery of single Jupiter-sized planets and of planetary systems consisting of two or three giant planets orbiting around a late-type star offers the interesting possibility to look for orbital period changes related to magnetic activity cycles in the central star of such systems.

The radial velocity method for planetary detection can be applied only to stars with a low-level magnetic activity, ruling out the possibility of finding systems with a central star as active as the components of magnetically active close binaries. Consequently, we do not expect to observe magnetically-induced orbital period modulation in spectroscopically detected planetary systems because its predicted amplitude would be $\Delta P/P \ll 10^{-6}$, too small to be measurable with presently available spectroscopic techniques (see below).

The situation is different for planetary systems for which a precise timing is allowed by transit detections. Presently, only the planet around HD 209458 (e.g., Brown et al. 2001) and the supposed planetary companion of OGLE-TR-56 (Konacki et al. 2003) show transits, but in the near future a much larger number of transiting planets is expected to become available from dedicated ground-based and space-borne surveys, such as those to be performed by the space missions COROT, Kepler and Eddington. From space it will become possible to detect transits by Earth-sized planets, extending the detection of extra-solar planets towards smaller sizes.

The eclipse timing of the HD 209458 system can be made with an accuracy of ~ 1 s by means of a space-borne telescope thanks to the low level of activity of the star (relative optical flux variations $\Delta F/F \approx 10^{-4}$), an amplitude of the light variation at the central time of the transit of $\approx 1\%$ and a ratio of the planet's radius to the orbit semi-major axis of ~ 0.0133. Therefore, it may be possible to achieve a relative accuracy of the order of 10^{-8} in the determination of the orbital period over a time baseline of 1 yr.

The amplitude of the expected period changes in presently known planetary systems is smaller than in close binaries, because the ratio of the stellar radius to the semi-major axis of the planetary orbit is correspondingly smaller (cf. Eq. (2)). In Fig. 3 the expected relative amplitude of the period changes is plotted versus the orbital period of the planet orbiting around a typical lower main sequence star. Three different rotation periods (3, 10, 30 d) are assumed for the central star; these periods refer to high, moderate and low activity level, respectively. The amplitude of the quadrupole moment variation can be esti-

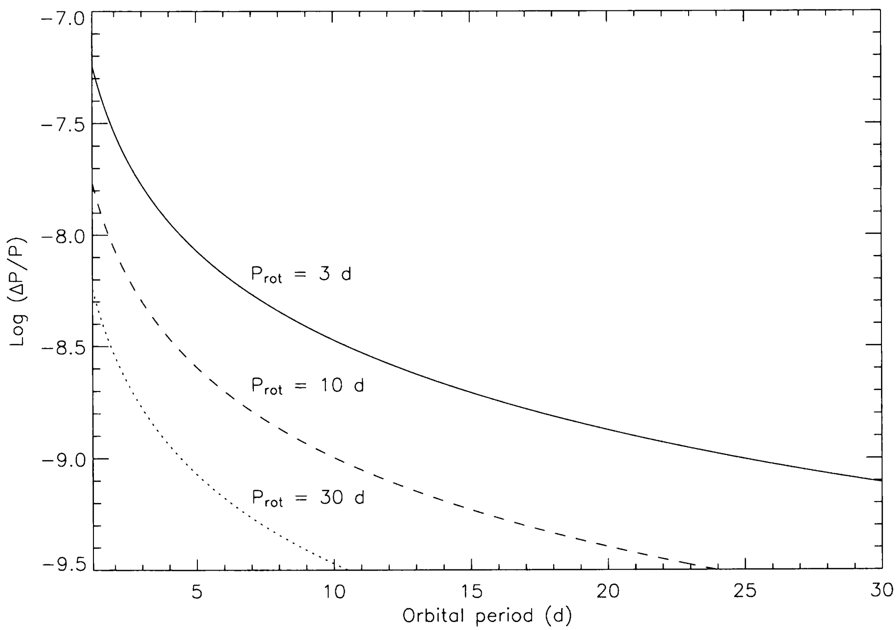

Figure 3. The expected relative orbital period variation of a star-planet system versus the orbital period of the planet according to an extrapolation of the model by Lanza & Rodonò (1999). The central star is assumed to be a late-type dwarf of mass $M = 0.7\,M_{\odot}$ and radius $R = 0.86\,R_{\odot}$. The plots are labeled by the rotation period P_{rot} of the central star, respectively – $P_{rot} = 3$ days: solid line; $P_{rot} = 10$ days: dashed line; $P_{rot} = 30$ days: dotted line.

mated according to Eq. (1) by assuming $\Delta T = -\Delta E_m$ and that ΔT varies with Ω according to Eq. (3).

The high timing precision attainable by means of planetary transits will compensate for the reduced amplitudes allowing us to detect a variation of the order of $\Delta P/P \sim 10^{-8}$ in a few years, or $\Delta P/P \sim 10^{-9}$ in a few decades. The duration of the transit Θ will change as well according to: $\Delta\Theta/\Theta \sim (1/3)(\Delta P/P)$, which is valid provided that the semi-major axis of the orbit is much larger than the star and planet radii.

The length of the modulation cycle, predicted according to Eq. (4), should range from ≈ 40 yr for $P_{rot} = 3$ days to ≈ 100 yr for $P_{rot} = 30$ days. However, the large dispersion of the points around the regression line in Fig. 2 implies that such values are purely indicative.

A high level of activity in the central star may limit the timing accuracy because the presence of photospheric spots and faculae may severely distort the shape of the transit light curve. However, it is encouraging that in the case of the Sun at the activity maximum it is possible to fit the bolometric flux variations produced by spots and faculae, thus reducing the distortion of simulated transit light curves (see Lanza et al. 2003).

In addition to stellar activity, a variation of the period between transits and of the transit duration may be produced by the perturbations due to other unseen planets. Miralda-Escudé (2002) showed that the perturbation due to another planet with a mass as small as that of the Earth can be detected in a system like HD 209458 by performing a timing of the transits over a time scale of a few decades by means of space-borne photometry. A discrimination between magnetic activity and perturbations by other planets requires a monitoring of the activity level of the central star by means of high-precision optical photometry or CaII H&K flux observations. In fact, from their variations it would be possible to check the presence of an activity cycle with length comparable to the observed orbital changes or in a 2:1 ratio, according to the torsional oscillation model proposed by Lanza et al. (1998b).

The amplitude of the orbital period changes due to the Applegate's mechanism scales as a^{-2}, where a is the semi-major axis of the planet orbit. Therefore, the effect is predicted to be the larger the closer the planet is to its parent star (cf. Fig. 3). For instance, in the case of the supposed planet around OGLE-TR-56, the effect is expected to be about 5 times larger than in the case of HD 209458, if the central star experiences the same quadrupole moment variation. Such a dependence may be relevant for the stability of planetary systems in a 2:1 resonance that may exist around some stars, notably around the M dwarf GJ 876 (Marcy et al. 2001).

In order to minimize the gravitational interaction among the two planets, they move along their orbits in such a way that when the outer planet is at the apastron, the inner planet is at the periastron with a longitude difference of 180°. If the orbital period variation of the inner planet is larger than that of the outer planet, the difference among their longitudes will oscillate around 180° with an amplitude depending on the length of the orbital period cycle and the amplitude of the period variations. Such an effect may increase the gravitational interaction among the two planets and perhaps lead to an unstable situation if their longitude difference approaches zero (cf. Murray & Dermott 1999).

5. Conclusions

The orbital period modulation in magnetically active close binaries is a very interesting phenomenon that may couple the operation of highly non-linear stellar dynamos to the orbital dynamics of such systems. In the case of classic RS CVn binaries, extended photometric databases are available and it will be possible to test the proposed models. The model developed by Lanza et al. (1998b) and Lanza & Rodonò (1999), starting from the original hypothesis by Applegate (1992), appears to be the most promising to explain the observations and it allows us to derive interesting information on the energetics of non-linear dynamo processes in close binaries. However, several aspects still need to be investigated in detail, in particular, the mechanism driving the torsional oscillations that are supposed to take place in the active components of some systems and the stable storage of super-equipartition magnetic fields in the deep super-adiabatic stellar convective envelopes.

The Applegate's model predicts that orbital period changes should occur also in planetary systems with a magnetically active central star. Their detection would represent a strong support for such a model and would provide us with information on the dynamo operating inside the central star. Moreover, the orbital period changes induced by magnetic activity may play a significant role in the dynamics and the evolution of those young planetary systems where the central star is a late-type dwarf with a high level of magnetic activity. We intend to discuss such effects in more detail in forthcoming works.

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