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Some open questions in the dynamics of extrasolar planetary systems

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Abstract. The main concern of the dynamics of extrasolar planetary systems is the stability of the known systems and the identification of dynamical processes which may have determined their past evolution. It is expected that the systems will remain stable for times of the order of their age, but this question has to be answered for each system. These tasks are critically dependent on the access to the actual observational data. We identify immediate questions to be solved in order to determine the actual planetary masses (at least in units of the star mass), to understand the tidal evolution of close-in systems, as well as specific questions on the systems 47 UMa, 55 Cnc, HD 82943 and HD 160691, which could likely get better solutions if the modern techniques of Celestial Mechanics could be applied to the full sets of existing observations.

1. Introduction

In two recent papers (Beaugé et al. 2005a, Ferraz-Mello et al 2005a), the level of the gravitational interaction and the main resulting perturbations in the known extrasolar planetary systems was used to classify them. The known multi-planet systems were distributed into 3 classes, more or less according with the ratio of the orbital periods of planets in adjacent orbits. These ratios are directly related to the stability of the systems.

Class I includes planet pairs with small period ratio. A randomly constructed system with period ratio smaller than, say, 3 is likely to be unstable and short-lived. The observed systems with such small period ratio satisfy one of the two following conditions: (a) The planets are captured in resonant orbits; (b) The planets lie on almost circular orbits. The stability of these systems is critically dependent on the Keplerian orbital elements and a small uncertainty on their determination is enough to give rise to catastrophic events in the simulation of the systems (e.g the case of HD 82943; see Ferraz-Mello, Michtchenko & Beaugé 2005b).

The next class, class II, includes all other planet pairs in adjacent orbits with period ratio generally less than ~ 10. These planets show a significant dynamical interaction and usually present their periastra coupled in such a way that the difference of their longitudes, $\Delta\varpi$, oscillates about 0° or 180°. The stability in these cases is not so critically linked to the given Keplerian elements as in the previous case, but stability can be confirmed only if the orbits are reasonably well known. Possible instabilities can arise from the proximity to higher-order mean-motion resonances.

Finally, class III includes planets with larger period ratios (typically larger than ~ 30) and weak mutual interactions; these systems are very stable and even very inaccurate elements lead to stable solutions in numerical simulations; as a consequence, we cannot guess that the given elements of such systems are accurate or not just by looking at the results of simulations done using them.

To see updated orbital elements of the considered planetary systems see `http://www.astro.iag.usp.br/ dinamica/ exosys.htm`.

2. Class I planet pairs

Class I is formed by two sub-classes according with the characteristic responsible for the stability of the system. In Class Ia, we put planet pairs in mean-motion resonance and, in Class Ib, systems whose planets lie on orbits with small eccentricity. Class Ia includes planet pairs in which at least one of the components moves on a very eccentric orbit ($e > 0.2$). These pairs are necessarily resonant (otherwise they develop instabilities in short time). They are, currently, the planets of the stars HD 82943, HD 128311, and the planet pairs b-c of the stars GJ 876 and 55 Cnc. An odd system in this class is the pair of planets in HD 202206, which has a period ratio ~ 5. However, according with Correia et al. (2005), these planets are resonant and show the basic dynamics of the other planets in this class. The characteristic difference in this case is the mass of the innermost body, $m \sin i \sim 17.5$, much larger than all others. This means that the probability is high that the object is a subdwarf star rather than a planet. It is kept in our lists since, from the dynamical point of view, it is irrelevant if the components of a system are planets or sub-dwarfs. Class Ib is characterized by small period ratio and small eccentricities. This class includes only one known example among extrasolar planetary systems around main sequence stars, but, in addition, it includes the system of planets discovered around the pulsar PSR B 1257+12 and the Solar System. 47 UMa and PSR B 1257+12 are very important systems because they belong to the same kinematical class as the planets of our Solar System and may have a similar dynamical story. It is true that the pulsar planets formed in an environment completely different of the planets orbiting around MS stars and this may be the origin of the small eccentricities of their orbits. Its understanding may give some clues to understand why the planet orbits in our Solar System – and the putative planets of 47 UMa – are so different of the other extrasolar planetary systems.

3. Class II (and Class III) planet pairs

Class II is formed by planets in orbits not so relatively close as in the typical cases of Class I, but, nevertheless, in adjacent orbits close enough to enhance the dynamical interaction among them. The best known example is given by the two outer planets of the system υ And, which show a very rich dynamics (Michtchenko & Malhotra, 2003, Michtchenko, Ferraz-Mello & Beaugé 2005). The stability of this system is related to the conservation of the angular momentum, which is directly responsible for the e-e coupling (and the e-I coupling if the planets are not in coplanar orbits). In absence of close approaches (that is, in absence of important variations of the semi-major axes), the eccentricities of planets in adjacent orbits show an important cyclic variation and are at anti-phase in these cycles so that when the eccentricity of one of them increases, the other decreases. When the decreasing one reaches zero, the other cannot continue to grow and, therefore, remains bounded. There is also the e-ϖ coupling, which is the fact that these maxima and minima generally occur close to the positions in which the semi-major axes are aligned or anti-aligned (see Michtchenko & Malhotra, 2004). However, the most visible feature in these systems is the kinematical behavior usually (and improperly) called "secular resonance, characterized by the oscillation of the apsidal lines of the two planets around a common direction so that $\Delta\varpi$ oscillates about 0° or 180° (both cases are normal modes of oscillation of the secu;ar equation and, thus, possible). They are the planets of the stars HD 108874, υ And, HD 37124, HD 169830, the pair e-b of 55 Cnc and the pair b-c of μ Ara (= HD 160691). The inclusion of υ And b among these planets deserves a comment. The periastron of its orbit oscillates about the apastron of υ And c (see Ferraz-Mello et al. 2005a); however, this behavior may be just an artifact due to the difficulties for determination of the longitude of the periastron of this planet even when powerful techniques are used (see Ford, Lystad and Rasio, 2005).

Finally, Class III includes those planet pairs for which the gravitational interaction among the planets in each pair is relatively weak and the given orbits are very stable. One system difficult to class is HD 168443. The two planets of this star, whose current data correspond to orbits showing features characteristic of the hierarchical systems of class III, have masses (multiplied by $\sin i$) equal to 7.7 and 16.9 times the mass of Jupiter; these masses are so large that we have to consider the possibility that improved orbital elements correspond to orbits showing significant gravitational interaction.

4. Some Open Questions

The main open question concerns the origin of the systems; if it was possible to find scenarios for the migration, eccentricity enhancement and capture into resonance, in the case of the planets of Class Ia (see Papaloizou, 2003), many questions remain to be completely answered, as the marked difference between systems of the classes Ia and Ib.

Another question concerns the stability of the discovered systems. It is believed that the age of the discovered systems is not very different from the age of the stars themselves, what means some Gyrs. It is also expected that the systems will remain stable for time spans of the same order. However, this question has to be answered for each system and many of them could be solved if the observations were made soon available to theoreticians. The dynamical studies deserve to be undertaken with the same level of competence shown in the observational work and the policy of keeping observations unpublished for long times should be revised.

4.1 The mass and inclination indetermination

One of the shortcomings of the systems for which only radial velocity observations are available is the impossibility of kinematical determination of the inclination of the plane of the motion over the sky tangent plane, which leads to the impossibility of knowing the actual masses of the planets. The detection of effects due to the mutual perturbations in the observations may allow independent determination of the planet masses. This has been already done for two of the planets of the pulsar PSR B 1257+12 and two planets of GJ 876. In the case of the pulsar planets, the proximity to the 3:2 resonance is responsible for large perturbations in the longitude of the 2 planets (similar to the Great

Inequality of Jupiter-Saturn)(see Malhotra, 1993). The outer planets of GJ 876 have benefited of a long span of high quality observations allowing the differences between a pure Keplerian solution and N-body fittings to be detected (see Laughlin et al, 2005). Other planets could soon be the subject of similar results if the observational data of all sources become available. At this point, it is worth mentioning that one of the unknowns of the problem is the mass of the star. According with Allende Prieto & Lambert (1999), even in the best cases they are not known with a precision better than ~ 8 percent. In fact, the comparison of published masses obtained with different stellar models shows discrepancies up to $10-15$ percent. If N-body codes are used in a blind way, this inaccuracy will pervade the whole set of results. It is however easy to choose units such that all indeterminate elements are put together as functions of the gauge factors $\sqrt[3]{M_{star}}\sin i$ and do not impair the determination of the other elements (inclusively the mass ratio, if both planets are assumed coplanar). (Ferraz-Mello et al. 2005a).

4.2 Close-in planets

Close-in planets have a tidal interaction with the stars. As long as just one planet is considered, the classical formulas giving the bulk variation of energy and angular momentum are enough to model the evolution of one planet (see Pätzold et al., 2004). The great problem, here, is the choice of the Love numbers and the dissipation parameters of both the star and the planet. Furthermore, if the planet belongs to a system and if it has (or had) the possibility of being tied to another planet through a mean-motion resonance, bulk formulas can no longer be used because the averaged equations giving the gravitational evolution of the couple are not the same inside and outside the resonance. In such case, we need to consider the actual forces. In what concerns the tides raised by the planet on the rotating star we may use formulas corresponding to the second harmonic of the classical Darwin theory (see Mignard, 1981). However, the tides raised by the star on a close-in planet lead to its spin-orbit synchronization and the theory needs to be adapted to include the radial tides. An easy-to-work equation for these forces is not available. This question requests an urgent solution since the increasing discoveries of exoplanets by transits will soon lead to systems in which the interplay of tides and resonance will have to be taken into account to determine the evolution of the system. We remind that tidal effect on close-in planets is to drive the planet to star. In at least one case (the system HD 82943), there are evidences of the past engulfment of one planet in the star (Israelian et al 2001).

Just for illustration, we show the plots of the semi-major axes and eccentricities of two planets initially in a 2:1 apsidal corotation reso-

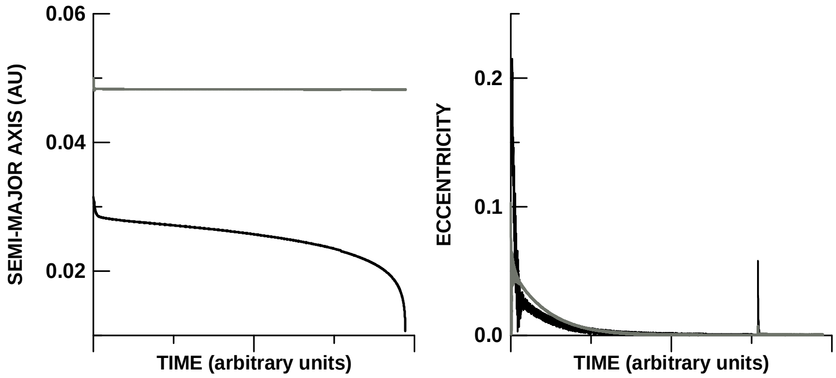

Figure 1.: *Variation of the semi-major axes and eccentricities of a pair of planets, initially in 2:1 resonance, under the action of tidal interaction with the star*

nance. The timescale is arbitrary since it depends on the values adopted for the tidal parameters of the star and the planet. It is typically of the order of 1 Gyr, but this number is inversely proportional to the dissipation factor Q and can be strongly affected by its change. (The spike seen in the eccentricity plot of the inner planet is due to the enhancement of the eccentricity when the inner planet crosses, in its fall to the star, the 3:1 resonance.)

4.3 Some specific questions (in order of priority)

47 UMa

The joint analysis of the observations from several observatories should be considered as a priority. 47 UMa is the only extrasolar system around a Main Sequence star with characteristics similar to the Solar System. However, the analysis of some series of observations cast a doubt on the existence of one of the planets in this pair (Naef et al, 2004). The joint analysis of the existing observation should help to solve this dilemma.

55 Cnc $= \rho$ *Cnc A*

The two intermediary planets of 55 Cnc are also the subject of doubts concerning the existence of one of them (55 Cnc c) (Naef, 2004). Assuming coplanar orbits, the published elements correspond to a resonant system whose motion is a large amplitude oscillation about a stationary solution (apsidal corotation resonance). The scenario of migration due to disk-planet interaction would be better compatible, in this case, with a solution closer to the stationary solution. However, the position of the stationary solution depend on the mass ratio of the two planets and a joint analysis of the existing observations should help not only to decide if 55 Cnc c indeed exists, but also, in that case, to check the small eccentricity attributed to 55 Cnc b and to provide a new estimation of the mass ratio. On the other hand, the influence of the companion star ρ Cnc B on the stability of the system remains to be considered.

HD 82943

The solutions obtained for this system range from solutions leading to catastrophic events in less than 100,000 years to solutions which remain stable forever (Mayor et al. 2004, Ferraz-Mello et al. 2005b). The contours of the stable regions is critically linked to the planet masses and a better mass determination is necessary to get a better map of them The real state of motion of this system is an open question. In addition, there is the suspicion that this system had a catastrophic event in the past, with the fall of one planet on the star (Israelian et al 2001), and we cannot rule out the consequences of such an event on the dynamics of the remaining system. In this case, the improvement of the orbital elements depends on the realization of new and more accurate observations.

HD 160691 b,c

The problems of this system are similar to those found for HD 82943: Solutions leading to catastrophic events in less than 100,000 years and solutions which remain stable forever, both fitting evenly the observations, were found (Gozdziewski, Konacki & Maciejewicz 2005). The problem of this system will not be solved soon because of the long periods of the planets involved (1.8 to 10 years). The stability maps show that even the stable solutions found are near the edge of the regular region indicating that the system is possibily being seen nearly edge-on (otherwise these orbits also would become unstable)

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