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A New Look at the Dynamical Properties of Systems With Multiple Planets

Ludmila Kiseleva-Eggleton

Dept. of Math and Computer Science, St. Mary's College of California, Moraga, CA 94575, USA; e-mail: lkissele@stmarys-ca.edu

Eric Bois, Bertrand Dauphole & Nicolas Rambaux

Observatoire de Bordeaux, 2 rue d'Observatoire, B.P.89, F-33270, Floirac, France

Krysztof Goździewski

Torun Center for Astronomy, N. Copernicus University, Gagarina 11, 87-100 Torun, Poland

Andrzej Maciejewski

Institute of AStronomy, University of Zielona Góra, PL-65-265 Zielona Góra, Poland

Bruno Guiderdoni

Institute d'Astrophisique, 98bis Bld Arago, 75014 Paris, France

Abstract. We show that a new technique called MEGNO may efficiently distinguish between regular and chaotic orbits in systems with multiple planets. We present the results of the application of this technique in a wide neighborhood of orbital parameters determined using standard Keplerian fits for υ And and Gliese 876. Some preliminary results of MEGNO application to the new planetary systems HD 12661, HD 38529, HD 37124 and HD 160691 with not yet very well determined orbital parameters are also discussed.

1. Introduction

The recent discoveries of a number of multiple extrasolar planetary systems with dynamical properties very different from those of our solar system provide us with a natural test bed for detailed study of the their long-term dynamical stability. Most members of these systems have relatively large masses, eccentric orbits and small semi-major axes. These may lead to dynamical instability due to significant mutual gravitational, and possibly also non-gravitational, interactions. Non-linear effects dominate the dynamics of such systems, and most of them display signs of chaotic behavior. In most of these systems the strong dynamical interaction between planets makes planetary orbital parameters, found using standard two-body Keplerian fits, unreliable (Laughlin & Chambers 2001, 2002). There is also a great uncertainty in the determination of planetary masses. All those leave us a substantial available parameter space to be explored in order to identify the the zones in the orbital parameter space which lead to chaotic behavior. Note that *chaotic* in the Poincaré sense means that the dynamical behavior is not quasi-periodic, but does not necessarily mean that the system will disintegrate during any given period of time.

A classical method that allows one to distinguish between regular and chaotic dynamical states is the method of Lyapunov Characteristic Numbers (LCN). The estimation of LCN usually requires computations over long evolutionary time, sometimes much longer than the lifetime of the system studied. In ths paper we apply a new method developed by Cincotta & Simó (2000) and called **MEGNO** (the acronym of *Mean Exponential Growth factor of Nearby Orbits*) to the study of dynamical stability of extrasolar planetary systems. This method is based on the same ideas as LCN but converges about 100 times faster, and is more sensitive. For details related to the application of MEGNO technique to extrasolar planetary systems see Goździewski et al. (2001a, 2001b).

2. Results for Different Planetary Systems

2.1. υ Andromedae

υ And was the first discovered system with multiple planets orbiting a solar-type star. It consists of three Jupiter-type planets orbiting the central star in orbits with semi-major axes smaller than 2.8 AU (a size similar to the main asteroid belt of our solar system). Strong interactions among planets lead to non-Keplerian orbits. In this study we used the orbital parameters of the system from the best Keplerian fit to the Lick and AFOE (Advanced Fiber-Optic Echelelle Spectrograph) radial velocity data by Stepinski, Malhotra & Black (2000) (hereafter SMB).

The first interesting result of the MEGNO application to the υ And system came from a comparative study of 2-planet (i.e., the dynamical influence of the innermost planet is neglected) and 3-planet models based on the LICK and AFOE nominal sets of parameters from the SMB paper. While 2-planet models for both sets of parameters display the MEGNO signature of regular dynamical regimes, for the AFOE 3-planet model we found clear signs of chaotic behavior after $\approx 10^4$ yrs. However the time evolution of the orbital elements appears to be quasiperiodic (see SMB, also our own computations in Goździewski et al. 2001a), even over a long period of time. In order to explain this paradox we followed the evolution of the system defined by two sets of very similar initial conditions. One of them was defined by the nominal AFOE elements. As the second set we used the nominal data modified by changing the x heliocentric coordinate of the planet C in the 14th digit (see Gozdziewski et al. 2001a for details). After less than 4×10^4 yrs the eccentricities as well as other elements began to differ. In a similar experiment performed on Lick data we did not find any notable change in the elements. Estimation of the Lyapunov time, which is very short, just of the order 10^3 yr is consistent with estimations quoted by Laughlin & Adams (1999). Our results are in good agreement with Laughlin & Adams (1999) and SMB who found that the innermost planet has a rather destabilizing effect on the system. One may conclude that the 2-planet models can only provide necessary but not sufficient conditions constraints on the system stability.

We also used MEGNO for an extensive search of stability zones in the space of the parameters which cannot be directly defined from radial velocity measurements: the planetary inclinations to the light-of-sight i_C and i_D and the relative inclination between planetary orbits i_r. Our results are in a good agreement with SMB: for instance there are very few initial conditions leading to regular behavior for $\sin i < 0.23$, which was identified as a border of stability by SMB for the Lick parameters. But MEGNO allows us to determine the ranges of the parameters corresponding to regular dynamical systems more precisely and in much shorter integration times — of the order of 3×10^4 yrs for one set of initial conditions compared to 10^6 yr integrations by SMB. Our experiments also showed the possibility of changing the mass hierarchy in υ And. Fixing M_D at the minimal value we can select M_C up to almost $2M_D$, and the system still remains in the quasiperiodic regime. This result is not in contradiction with the stability limits found by SMB (and confirmed by us), because they used $i_C = i_D$ in their analyses, and therefore did not switch the mass hierarchy. Let us note, however, that if one simply interchanges masses M_C and M_D without changing any other parameters, the Lick 2-planet υ And system becomes unstable, at least in a point-mass approximation (small perturbations to Newtonian gravity due to tidal friction and quadrupolar distortion of the planets may stabilize this system, see Kiseleva-Eggleton & Bois 2001). So, the absolute masses of planets can in some cases be more important for the dynamical stability than the mass hierarchy.

2.2. Gliese 876

We used MEGNO to conduct a detailed analysis of two sets of the GJ 876 orbital parameters found by Laughlin & Chambers (2001)(Lick-Keck fit and Keck fit hereafter). Lee & Peale (2002) claim that the Lick-Keck fit almost certainly represents the real state of GJ 876 system. Using the MEGNO stability maps, we determined the regions of stable initial conditions. Both sets of orbital parameters are located in wide stability regions.

We found that the 2:1 mean motion resonance and its width are very robust to changes of the planetary semi-major axes and determined the resonance width which reaches 0.01 AU for both semi-major axes. We also found that the stability of orbital configurations defined by both the Lick and Lick-Keck fits is very robust to the changes of orbital eccentricities. Fixing the other orbital parameters we found on the (e_b, e_c)-maps a few islands of stability in regions of extremely high eccentricities - up to 0.95 for the inner planet and up to 0.6 for the outer planet. Surprisingly, the area of low eccentricities is very irregular and divided by a net of secular resonances (Goździewski et al. 2001b).

We also found dynamical limitations on the relative inclinations i_r and masses of the planetary companions. Rivera & Lissauer (2001) indicated that non-coplanar as well as coplanar configurations can provide a good fit to the observations. In order to find dynamical constraints on the relative inclination we examined a special case (similar to one we studied for the υ And system) when both planets have the same inclinations i to the line of sight. MEGNO showed that stable systems can be found in a very wide range of masses, and that, depending on i, the initial relative inclination of the planetary orbits can vary: for $\sin i = 0.5$ the range of stable i_r is $\pm 15°$, for $\sin i = 0.78$ it is $\pm 45°$, and for $\sin i = 1$ we found stable configurations with perpendicular orbital planes.

2.3. New Multiple-Planet Systems: HD 12661, HD 38529, HD 37124, HD 160691

In order to distinguish between regular and chaotic planetary orbits we apply MEGNO in a wide neighbourhood of orbital parameters determined using standard two-body Keplerian fits for these recently discovered 2-planet systems. Our tests showed that the currently announced orbital parameters (see *www.exoplanets.org*) place these systems in very different situations from the point of view of dynamical stability. While HD 38529 and HD 37124 are located within large stability zones in the phase space around their determined orbits, the preliminary orbits in HD 160691 are highly unstable. However, using MEGNO we found stability regions in the neighourhood of annonced orbits. The planetary orbits for this system are poorly determined (even the presence of the second planet has not yet been fully confirmed) due to insufficient observational data (Jones et al. 2002). The stability of this system appears to be very sensitive to angular orbital parameters such as ω, Ω, $\overset{\circ}{M}$ (not unusual for systems locked in 2:1 mean motion resonance) but surprisingly it is more likely to be stable when both orbital eccenticities are very large.

The orbital parameters of the HD 12661 planets are located in a border region between stable and unstable dynamical regimes, so while its currently determined orbital parameters produce stable regular orbits, a minor change within the margin of error of just one parameter may result in a chaotic dynamical system (see Kiseleva-Eggleton et al. 2002 for details).

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