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Regular eccentricity oscillations of terrestrial exoplanets in habitable zones

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Abstract. For several known extrasolar planetary systems we consider the orbital characteristics of low-mass planets sited in the system's habitable zone, deriving limits on the range of planetary eccentricity oscillation.

1. Introduction

The discovery of planetary systems around other stars represents an outstanding scientific achievement. As of November, 2005, the tally stands at 170 exoplanets in 146 exoplanetary systems, and 18 systems with more than one planet (Schneider, 2005). These data allow one to address major issues such as planetary formation scenarios, but also to address many dynamical problems, such as exoplanetary motion and the evolution of orbits (Laughlin and Adams, 1999, Sokolov, 2002, Sokolov and Pitjev, 2004, Malhotra, 2002, Menou and Tabachnik, 2003, Ferraz-Mello et.al., 2005, Zhou and Sun, 2005); the stability of exoplanetary systems (Laughlin and Adams, 1999, Ferraz-Mello et.al., 2005, Zhou and Sun, 2005), resonances in such systems, (Ferraz-Mello et.al., 2005, Zhou, and Sun, 2005); regular and chaotic motion (Laughlin and Adams, 1999, Sokolov, 2002, Sokolov and Pitjev, 2004, Ferraz-Mello et.al., 2005, Zhou and Sun, 2005) among many others.

Many of massive planets found to date, have, unlike Jupiter, large orbital eccentricity, while low mass like the Earth are not yet observable. In this paper we investigate the possible stable orbits of such low mass planets (without considering resonances) but including quasi-circular orbits and orbits in habitable zones.

Menou and Tabachnik (2003) have made an extensive numerical investigation of possible motions of low-mass planets in “habitable zones”. Here we discuss some peculiarities of these motions, using not only numerical but also an analytical approach.

2. On an exoplanet's orbital evolution

We investigate the motion of low-mass planets within the framework of the restricted elliptical three-body problem. The initial eccentricity of the low-mass planet's orbit is small or equal to zero.

If the initial distance between orbits is sufficiently large then the motion is regular (non-chaotic) with the following properties (Sokolov and Pitjev, 2004):

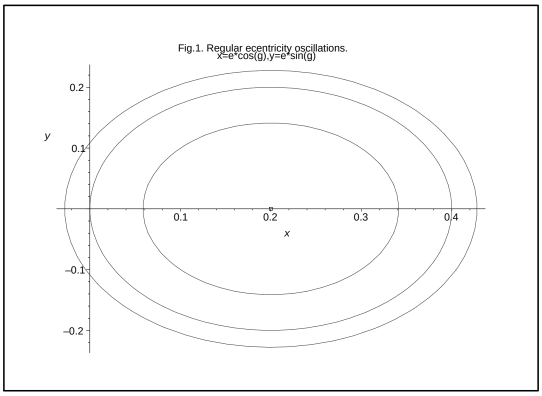

Figure 1. Regular eccentricity oscillations. $x = e\cos(g)$, $y = e\sin(g)$.

- in the planes (a, e) and $(e\cos\pi, e\sin\pi)$ there is an invariant curve for each trajectory, where a is the semimajor axis, e is the eccentricity, π is the pericenter argument,
- the orbital evolution does not depend on initial planetary positions in their orbits; the same invariant curve exists for different initial positions. Here we explicitly ignore possible narrow resonance zones.

The invariant curves have been derived numerically, and are: the segment $a = \text{const}, 0 \leq \text{e} \leq \text{e}_{\text{max}}$ in the plane (a, e) and the circle $(e\cos\pi - \text{e}_{\text{max}}/2)^2 + (e\sin\pi)^2 = e^2_{\text{max}}/4$ in Lagrangian variables $(e\cos\pi, e\sin\pi)$.

To investigate and verify these properties, we use the classical analytical solution — the theory of secular perturbations developed by Laplace and Lagrange (Charlier, 1927). After averaging over two fast variables and some simplifications, we have $a = const$ and

$$y^2 + (x - e_c)^2 = const.$$

Here x, y — Lagrangian variables, $e_c \approx 9\alpha e_p/8, \alpha = a_p/a < 1$, and the index p corresponds to the massive planet (Sokolov, 2002).

Figure 1 shows the orbital evolution in Lagrangian variables $(e\cos\pi, e\sin\pi)$.

If the eccentricity of the massive planet's orbit is large and the motion is regular, then we find that the eccentricity of the low-mass planet's orbit is usually large too. Similar results have been found by Malhotra (2002).

In the region between regularity and chaos (Sokolov and Pitjev, 2004) we have:

- regular trajectories, described above
- nonchaotic trajectories, with the characteristic property $a = const$ and

- chaotic trajectories.

These conditions depend of course on the initial conditions of the planets. We note that some of the nonchaotic trajectories are stable quasicircular (Sokolov and Pitjev, 2004).

3. Regions of regular orbits in habitability zones

Habitability may be defined by the requirement that a terrestrial planet's atmosphere sustain liquid water. The habitabilty condition leads to restrictions on the maximum a_+ and minimum a_- distance between the low-mass planet and the central star, giving us the "habitable zone" condition: $a_- < r < a_+$. We will also make use of habitability zones (a_-, a_+) of known extrasolar planetary systems, as presented in Menou and Tabachnik (2003).

For regular motion of an "Earth" in the habitable zone, we have restrictions on the eccentricity $(q = 1/a)$:

$$e < qa_+ - 1, \tag{1}$$

$$e < 1 - qa_-. \tag{2}$$

On the other hand,

$$e > e_c = 9qa_je_j/8. \tag{3}$$

Conditions (1) to (3) and $a_- < 1/q < a_+$ describe orbits in the habitable zone.

4. Application to several exoplanetary systems

Figure 2 shows Eqs. 1, 2 and 3 (lines 1, 2 and 3) and the function $e = 2e_c(q)$ (line 4) for the extrasolar planetary system HD 89774. The region of planar orbits in the habitable zone lies below lines 1 and 2 and above line 3. The region is triangular. The semimajor axis lies between 2.09 AU and 2.31 AU. Similar regions are constructed for HD 52265, HD 16141, HD 169830. To verify the existence of such motions we have derived trajectories in these regions using numerical integration. The eccentricity oscillations, derived numerically, were found to agree closely with the analytical values.

For the extrasolar planetary system HD 40979 we have derived stable quasicircular orbits in the region "between Regularity and Chaos" in the habitable zone, $a \approx 1.5 a.u., v_0 \approx 85°$.

5. Conclusions

Using analytical tools, we have described possible regular motions of low-mass planets in exoplanetary systems. For some extrasolar planetary systems we have derived families of regular orbits in the habitable zones. The analytical results obtained have been verified numerically.

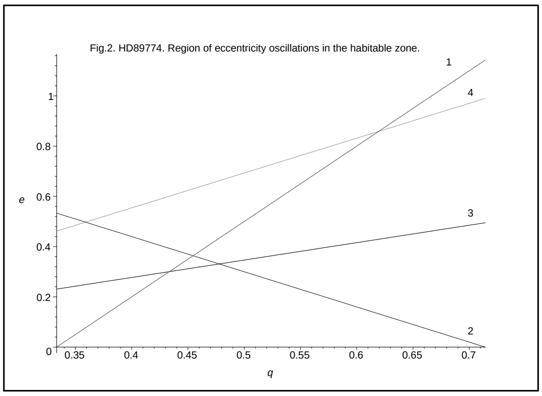

Figure 2. HD 89774. Region of eccentricity oscillations in the habitable zone.

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References

Schneider, J. 2005, Extra-solar Planets Catalog. http://www.obspm.fr/encycl/cat1.html.

Laughlin, G., Adams, F.C., 1999, ApJ, 526, 881

Sokolov, L.L., 2002, Solar System Research, 36, 5, 403.

Sokolov, L.L., Pitjev, N.P., 2004, Motions in Extrasolar Planetary Systems: between Regularity and Chaos. ASP Conf. Ser., Vol.316, p145

Charlier, C.L., 1927, Die Mechanik des Himmels, Berlin and Leipzig. Walter de Gruyter and Co.

Malhotra, R., 2002, ApJLetters, 575, L33

Menou, K., Tabachnik, S., 2003, ApJ, 583, 473

Ferraz-Mello, S., Michtchenko, T. A., Beauge, C., Callegar, N. Jr., 2005, Lectures on Extrasolar Planetary Systems (preprints). http://www.astro.iag.usp.br/ dinamica/exopl.htm

Zhou, J. L., Sun, Y. S., 2005, in Dynamics of Populations of Planetary Systems. Proceedings IAU Colloquium No 197, 2005, Z. Kuezevivic and A. Milani, eds., p29