Few-Body Problem: Theory and Computer Simulations
Annales Universitatis Turkuensis, Series 1A, Vol. 358, 2006
C. Flynn, ed.

Exoplanet orbital evolution under the influence of nearby stars

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Abstract.

We study extrasolar planetary systems under the influence of perturbative effects from nearby stars. If the mass of the perturbing star is sufficiently small, the velocity sufficiently large, or its distance sufficiently large, the planet's motion is integrable. Conditions for the extrasolar planet's motion without escape and exchange are derived numerically.

1. Introduction

The discovery of extrasolar planets and planetary systems has raised many research problems for astronomers. One important problem is that of orbital evolution and stability of extrasolar planetary motion (Laughlin and Adams, 1999; Kiseleva-Eggleton et al, 2002; Menou and Tabachnic, 2003).

We are presently investigating the properties of extrasolar planetary perturbations under the influence of nearby stars. If the system contains only one planet, a nearby star can be the main driver of dynamical evolution.

The problem of binary-single mass scattering has been investigated in many papers, mainly for the case of equal masses (e.g. Valtonen, 1988; Hut, 1984; Heggie, 1975).

Here we discuss the integrability of the N-body problem and stability of a planet's motion under the influence of nearby stars.

2. On the integrability of the N-body problem

It is well known that the classical N-body problem is nonintegrable, but this statement calls for refinement. Nonintegrability has been proved only in several regions of phase space and parameter space. But in addition to domains containing complicated, chaotic trajectories, there are domains with very simple trajectories. For such simple motions, integrability in the classical sense has been proved (Sokolov, 1986; Sokolov and Kholshevnikov, 1987a; Sokolov and Kholshevnikov, 1987b; Sokolov and Kholshevnikov, 1992; Sokolov, 2001; Sokolov and Kholshevnikov, 2004; Sokolov, 2005). This is termed 'regional integrability' (the notion was introduced by Prof. K. V. Kholshevnikov). Regions with integrable motions can be large in size and simple in structure.

Regional integrability refers to the existance of a complete set of smooth independent autonomous functions (integrals), which are constant along each tragectory in the region. Regional integrability implies the stability of planetary motion and other important properties.

As long ago as the work of J. Chazy, and later V. M. Alexeev arguments have been presented on behalf of integrability of the 3–body problem in the domain of these simple trajectories. As an example, Alexeev (1981) has formulated a statement about the integrability of the 3–body problem in the domain of hyperbolic, hyperbolo-elliptic and hyperbolo-parabolic motions.

Sokolov and Kholshevnikov (1987a) have shown that the following holds:

Let m_i be masses $(i = 1, 2, \ldots N)$, $\vec{r}_i(0)$ initial positions, $\vec{v}_i(0)$ initial velocities, G the gravitational constant, and the linear motions $\vec{r}_i(t) = \vec{r}_i(0) + \vec{v}_i(0)t$ permit no collisions between bodies. Then the system with masses M, m_i, initial positions $R, \vec{r}_i$, and initial velocities $V, \vec{v}_i$ is integrable, if the value of GM/RV^2 is sufficiently small.

In other words, conditions for the integrability are sufficiently small masses, or sufficiently large distances between bodies, or sufficiently large velocities of bodies.

The N-body problem is integrable not only for single fast moving masses, but for close binaries too (Sokolov and Kholshevnikov, 1987b; Sokolov, 2001; Sokolov and Kholshevnikov, 2004). For example, the system "Sun-planet-star" is integrable (Sokolov, 1986) for sufficiently small star mass, or sufficiently large star distance (at pericenter) or sufficiently large star velocity. It is interesting to compare the integrability conditions with the characteristics of Sun neighbouring stars (Mullary and Orlov, 1996). The restricted problem "Sun-planet-star" is usually integrable for known nearby stars (Sokolov, 2001).

3. Conditions for a planet's orbital stability

If the approach distance of a neighbouring star is sufficiently small, the planetary system becames unstable, and escape or capture of planet takes place. We derive this stability boundary numerically. For a fixed neighbouring star of mass m and velocity "at infinity" v, we vary the approach distance p. The planet's orbit is termed stable if elliptical motion is retained for all initial positions of the planet on the unperturbed orbit. Figure 1 shows the boundaries of stability of an initially circular planetary orbit for a star of 1 solar mass. Note that we use as mass unit the solar mass, while the unit of distance is the unperturbed radius of the planet's orbit, and the unit of velocity is the planet's unperturbed velocity.

Stable planetary motion for mass m is found to correspond to the following conditions on p:

- for $m = 1 : p > 4.58936v^{-0.58566}$,
- for $m = 2 : p > 6.01901v^{-0.602973}$,
- for $m = 3 : p > 7.16129v^{-0.618055}$,
- for $m = 10 : p > 12.7775v^{-0.629349}$.

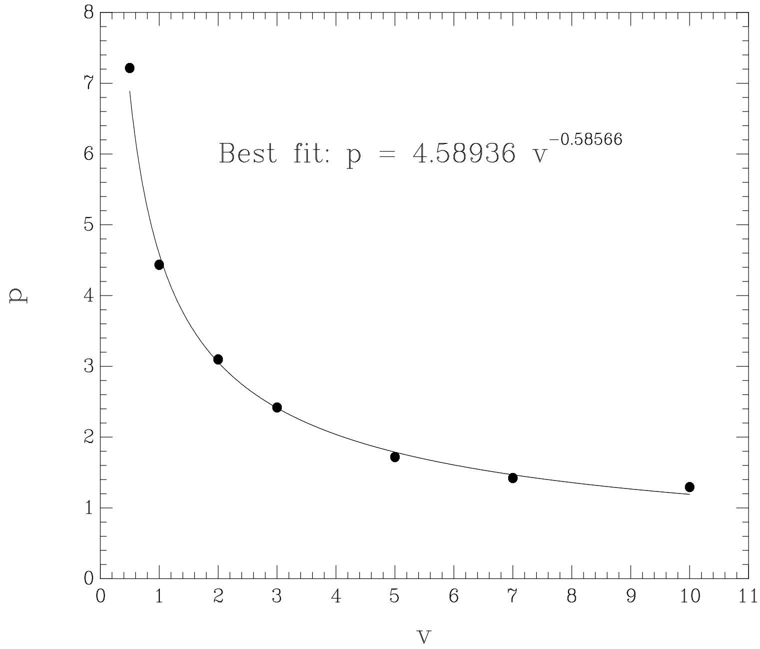

Figure 1. The boundaries of stability of an initially circular planetary orbit star for a star of 1 solar mass. Here v is the orbital velocity and p is the period, both expressed in units of the unperturbed orbital velocity and period.

If the approach distance p of the neighbouring star is large, its velocity not very large and the perturbations small, the planet's semimajor axis returns quite closely to its initial value after the interaction.

4. Conclusions

The N-body problem is almost always integrable, if the velocities of the bodies are sufficiently large. In particular, the 3-body problem consisting of a "home star, planet and fly-by star" is integrable and a planet's motion is stable for a large velocity of the fly-by star. Stability boundaries of the planet's motion under the influence of a nearby star have been derived numerically. The planetary system can break down if the approach distance and radius of planet's orbit are values of the same order.

Acknowledgments This study was supported by the Russian Foundation for Basic Research (grants 05-02-17408, 06-02-16795), by the Scientific Program "Russian Universities" (project ur.02.01.301), and by the Leading Scientific School (grants NSh-1078.2003.02, NSh-4929.2006.2).

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