

Extra-solar massive planets with small semi-major axes?

S. Fernández, D. Giuliodori and M. A. Nicotra

Observatorio Astronómico.
Universidad Nacional de Córdoba.
5000 Córdoba, Argentina.

Abstract

In this paper we explore the perturbing forces between two giant planets as a possible mechanism for the observed depletion of massive planets with small semi-major axis and high eccentricities in recently detected extra solar systems. The orbital evolution of simulated systems composed by a solar like central star and two massive planets is performed by the numerical integration of the classical equations of motion using a Bulirsch-Stoer integrator. Our results show strong dependence on initial conditions and the adopted mass for planetary companions.

Key words and expressions: Exoplanets, numerical simulations, orbital evolution.

MSC: 37M05, 70F15, 70M20, 85A99.

1 Introduction

The detection of extrasolar planets during the last years is one of the greatest discoveries in the history of Astronomy. In fact, the possibility of existence of other worlds beyond our solar system has attracted the human mind since ancient epochs. For astronomers interested on celestial mechanics problems, these indirectly detected objects show unexpected dynamical features and open a rich field for exploration with a new series of challenges. More than one-third of the detected exoplanets have significantly elliptical orbits, with eccentricity $e > 0.3$ and about two-third seem to be orbiting their host star much than the Mercury-Sun mean distance.

The progress in the understanding on formation and properties of the extrasolar planets is in evolution but it is far from being considered as a complete theory.

Detection methods are very indirect because the available instrumentation and techniques do not easily permit the direct observation of such members of extrasolar systems, principally due to the distance ranges from the terrestrial observer. In the following paragraphs, we describe briefly these methods.

2 Detection Methods

Basically, the detection methods rely on the possibility of a precise determination of the very minor variations in the flux or in the spectra that is received from the central star.

The motion of a single planet around a star causes the star to undergo a reflex periodic motion about the star-planet barycentre. This fact results in periodic perturbations of two observable parameters:

- radial velocity,
- angular position.

Radial velocity measurements are today possible by very precise spectra determinations based on the Doppler effect. Very accurate measurements of angular position variations by astrometric techniques are also suitable for extrasolar systems near the Sun.

Another detection technique, which depends on the determination of variations in the flux received from the central star due to periodic transits of the companion between the star and the observer, is known as the transit method. Each one of the detection techniques is complementary to the others.

The Doppler method, by the way of which it is possible to estimate the lower mass limit of the exoplanet, introduces biasing towards low orbital periods, and high values for the planet mass and eccentricity. It is also limited to solar like stars.

The astrometric technique is sensitive for higher orbital periods ($P > 1$ yr) and is applicable to hot quick rotator stars.

The transit technique, by which the orbital inclination is known, is complementary to the radial velocity method, where the inclination is unknown. If it is possible to apply both techniques, then it is also possible the mass determination of the exoplanet.

Practically all detections of extrasolar planets obtained up to date have resulted from Doppler method, although there are a few candidates for direct imaging, and one detected transit of a planet HD209458 [2] whose existence was previously derived by Doppler method [3].

By the means of the aforementioned methods, 102 planets and 10 multiple systems have been detected to date (June 2003) [7]. The mass range for these star companions is extended onto the range between 0.16 and 17 times the Jupiter mass M_J .

Multiple systems have also been discovered. These are systems composed by several planets around the same host star as in the case of our planetary system.

3 Dynamical Behaviour of Exoplanets

One of the most surprising features in the observed parameters resides in the eccentricity (e) vs. semi-major axis (a) distribution. As it was early established by Butler *et al.* [1] the detected extrasolar planets move around their host stars in eccentric orbits, with very low semi-major axis (see Figure 1). Nothing like this is observed in our solar system.

It is remarkable the lack of massive planets ($M_p > 3.5M_J$) for $a < 0.1$ AU, and the concentration of them in the range $0.2 < e < 0.6$ and $0.1 \text{ AU} < a < 3.0 \text{ AU}$.

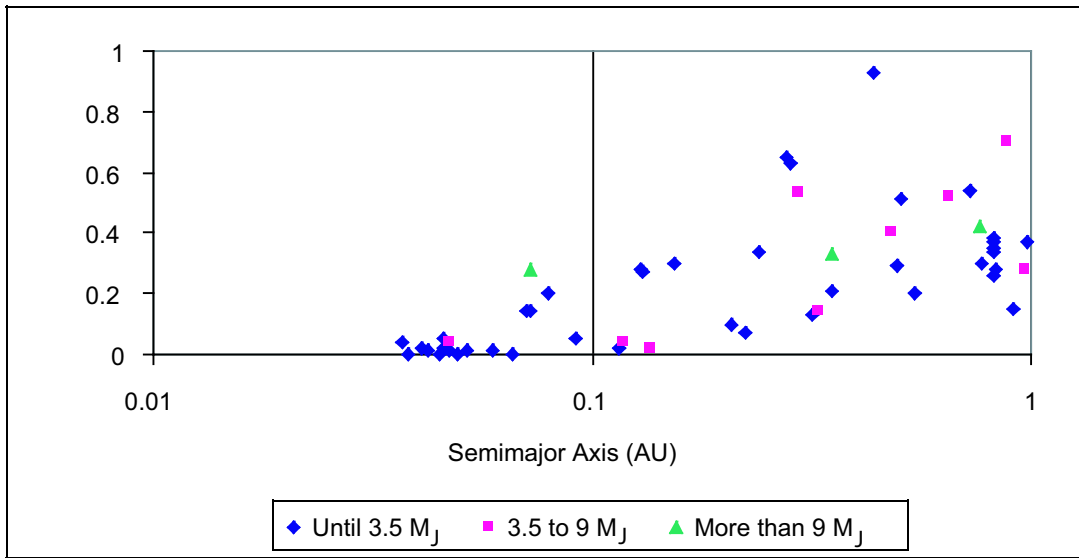


Figure 1: Eccentricity vs. semi-major axis for detected extra-solar planets with $a < 1$ AU. Triangles: planets with $M_p > 9M_J$. Squares: $9M_J > M_p > 3.5M_J$. Diamonds: $M_p < 3.5M_J$.

The orbital evolution of giant planets at small heliocentric distances from the host star has been discussed by Trilling *et al.* [6], showing that these giant companions may persist in close orbits possibly due to a migration process induced by protoplanetary disk-planetary torque interactions. The mentioned authors conclude that a wide range of distances for giant planets could be confirmed by new detection methods. The observational evidence however points towards a lack of giant exoplanets with small semi-major axis, low eccentricities and large masses. Trilling *et al.* [6] have also proposed mass loss processes at small distances, because the planet radius can be greater than its Roche radius. Such a mechanism could be the responsible one accounting for the observed results.

In our work, we explore a very different explanation for these observational evidences, based on the dynamical evolution under the perturbing forces by another planetary com-

ponent of the extrasolar system. By carrying out numerical integrations, we follow the changes in the orbital elements for 106 years for two planets with masses greater than Jupiter mass M_J , around a solar like mass central star, taking into account the gravitational interaction among the three components. The perturbing forces arising among the planetary components of such systems could provide suitable mechanisms in order to derive the observed depletion of giant planets in the inner region ($a < 0.1$ AU) of the extrasolar systems.

If a two-body model is considered composed by the host star and a companion planet, orbital elements do not vary against dynamical time. If there is another component in the planetary system, each planet undergoes the gravitational perturbation of the other planet. This results in time dependence for the planetary orbital elements. One can write the equations of motion introducing the disturbing function R :

$$\frac{d^2\mathbf{r}}{dt^2} + \frac{\mu\mathbf{r}}{r} = \nabla R,$$

$$r = |\mathbf{r}|.$$

As it is clearly established, there are no other first integrals to be added to those arisen from the two-body problem integration. The three body problem must be then solved by means of numerical integration techniques.

We adopt the equations of motion of a Newtonian dynamical model, which are numerically solved using a Bulirsch-Stoer integrator [4]. Nor relativistic or tidal effects are taken into account in our equations. The energy system and momenta conservation are used as test conditions during the integration procedures. A wide set of 100 different initial conditions is obtained varying semi-major axis, eccentricities, relative initial positions and planetary masses.

4 Results of the Model

As a result of numerical integrations, we find three classes of behaviour for the planetary components:

1. One planet runs away from the system.
2. One planet falls down into the host star.
3. Both companions exhibit stable orbits.

We find high sensitivity to small variations in the initial values adopted for the orbital elements, as it could be expected for such non-linear systems. The mass ratio between the planetary companions plays also an important role in this sense, since little variations in its value produce very different responses in the dynamical system. If the masses of

both companions are smaller than $3.5M_J$, stability is found for the two planetary orbits. If $M_{p1} > 3.5M_J$ and $M_{p2} < M_{p1}$, the P_2 planet falls down into the central star, whereas the other planet P_1 increases its semi-major axis.

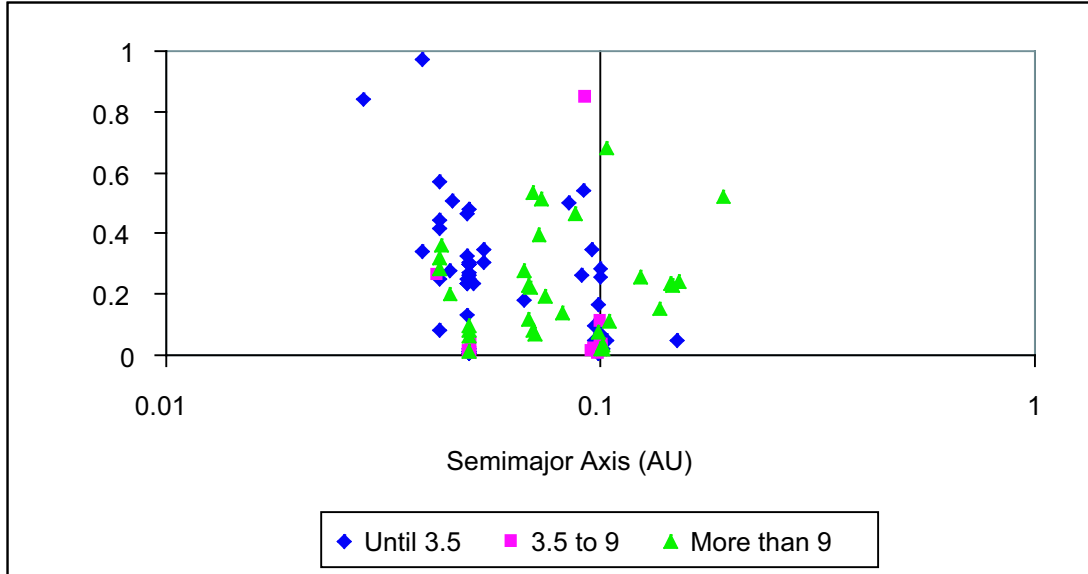


Figure 2: Eccentricity vs. semi-major axis. Obtained values from our simulations. Triangles: planets with $M_p > 9M_J$. Squares: $9M_J > M_p > 3.5M_J$. Diamonds: $M_p < 3.5M_J$.

As it can be seen in Figure 1, the detected values show that eccentricities for planets with semi-major axes lower than 0.1 AU are clearly $e < 0.3$. However, the final eccentricities obtained by numerical integration (Figure 2) show only 50 % of the sample with values lower than 0.3. This difference between both e vs. a distributions could be a consequence of discarding tidal effects. In fact, as Rasio & Ford [5] have claimed, dissipative tidal effects can be important at small heliocentric distances, leading to a reduction of the eccentricity on the planetary orbit in a scale time of 1 Gyr.

5 Discussion

The classical approach for the equations of motion in the simulated extrasolar planetary systems shows dynamical effects highly dependent on initial conditions and planetary masses. The stability for planets with semi-major axis smaller than 0.1 AU is then unpredictable. In addition, the final values for eccentricities derived from our calculations are not compatible with observations.

One important feature in the observed exoplanets resides in the high-determined masses compared to the members of our solar system. In addition, exoplanets are closer the host star than the planets around the Sun, and for this reason their orbital velocities are one order of magnitude greater. These are non negligible features because of

the possibility of some effects beyond the classic dynamics (e.g. the perihelion shift due to relativistic effects). Furthermore, tidal interactions, which are not considered in our model, can be important due to small orbital distances. As a consequence, perturbing forces between two massive companions cannot be yet discarded as a suitable mechanism for planetary depletion in the inner region of extrasolar systems, specially if these forces favour planetary captures by the central star.

We think there are several open doors for future and more refined simulations in order to include those additional effects. Therefore, further studies will be presented in a future paper.

Acknowledgments

Research supported by a grant from SeCyT (National University of Córdoba, Argentina), Projects # BFM2002-03157 of Ministerio de Ciencia y Tecnología (Spain) and Resolución 92/2002, Departamento de Educación y Cultura, Gobierno de Navarra (Spain).

References

- [1] Butler, R. P., Marcy, G. W., Fischer, D. A., Vogt, S. S., Tinney, C. G., Jones, H. R. A., Penny, A. J. and Apps, K.: 2004, ‘Statistical properties of extrasolar planets’. *Planetary Systems in the Universe: Observation, Formation and Evolution*, International Astronomical Union Symposium **202**, 1–10. Astronomical Society of the Pacific, *to appear*.
- [2] Charbonneau, D., Brown, T. M., Latham, D. W. and Mayor, M.: 2000, ‘Detection of planetary transits across a Sun-like star’, *The Astrophysical Journal* **529**, L45–L48.
- [3] Henry, G. W., Marcy, G., Butler, R. P. and Vogt, S. S.: 1999, ‘HD 209458’, *IAU Circulars* **7307**, 1.
- [4] Press, W. H., Teukolsky, S. A., Vetterling, W. T. and Flannery, B. P.: 1993, *Numerical Recipes in FORTRAN. The Art of Scientific Computing*, Cambridge University Press, New York.
- [5] Rasio, F. A. and Ford, E. B.: 1996, ‘Dynamical instabilities and the formation of extrasolar planetary systems’, *Science* **274**, 954–956.
- [6] Trilling, D., Benz, W., Guillot, T., Lunine, J. I., Hubbard, W. B. and Burrows, A.: 1998, ‘Orbital evolution of extra-solar giant planets’, *Brown Dwarfs and Extrasolar Planets*, ASP Conference Series, vol **134**, Astronomical Society of the Pacific, 280–283.
- [7] <http://exoplanets.org>