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Eccentricity Evolution of Multiple Planetary Systems due to the Depletion of Protostellar Disks

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Abstract. We investigate the eccentricity evolution of non-resonant multiple extrasolar planets during the epoch in which the protostellar disk outside the planets is gradually cleared. We calculate the initial eccentricities of planets around Upsilon Andromeda, HD168443, HD74156, and 47 UMa and analyze their evolution during depletion of the disk. We find that the disk depletion could cause a change in the eccentricities.

1. Introduction

We study the evolution of eccentricities of planets around Upsilon Andromeda (c & d), HD168443, HD74156, 47 UMa, and Jupiter and Saturn during depletion of the protostellar disk. These systems are not in a mean motion resonance from their orbital elements (http://exoplanets.org/almanacframe.html). Figure 1 (c) shows current orbits of these planets and equi-Hamiltonian contours. Eccentricities (e) and a value of Γ for the outer two planets around Ups And are $e_{\rm i}$=0.23, $e_{\rm o}$=0.35, and Γ=1.87, where, $\Gamma \equiv (a_{\rm o}/a_{\rm i})^{1/4}(M_{\rm o}/M_{\rm i})^{1/2}$, a is a semi-major axis, M is planet mass, and the subscripts i and o are the values for the inner and the outer planets, respectively. The longitudes of periastrons of this system are always close to each other (Figure 1 (c)-1). Current orbital elements of the planets around HD168443 are $e_{\rm i}$=0.53, $e_{\rm o}$=0.20, and Γ=2.63. The planets are circulating, i.e., a relative longitude of periastrons between planets, η, evolves from $-\pi$ to π (Figure 1 (c)-2). The planets around HD74156 have $e_{\rm i}$=0.65, $e_{\rm o}$=0.40, and Γ=4.12. Current orbits are circulating (Figure 1 (c)-3). The orbits of planets around 47 UMa are not well determined. Their most probable values are $e_{\rm i}$=0.06, $e_{\rm o}$=0.1, Γ=0.65, and η= 0.78 (radian). For these values of e and η, the orbits of planets marginally librate (Figure 1 (c)-4) but it is equally likely that they circulate. The system of Jupiter and Saturn (Γ=0.64) has a circulating orbit (Figure 1 (c)-5).

2. Model

We neglect mutual inclinations between the two planets and between the planet and the disk. We also neglect the influence of the planets on the disk. We consider the thin and axisymmetric disk whose region inside 1.58 $a_{\rm o}$ is depleted well before the outer region. For illustration purposes, we take the surface density (Σ) of the disk to be 5 times as much as the minimum mass solar nebula model (Hayashi 1981) for all of the systems. The surface density is assumed to decline with time (t) such that $\Sigma \propto \exp(-t/t_{\Delta N})$. We assume that the disk depletion time scale ($t_{\Delta N}$) is much longer than the time scale of libration (or circulation) of the planets. Although the exact initial eccentricities of planets before the disk depletion depend on the disk models, the properties of their evolution do not depend on these models. To study the essence of the evolution, we used the first order equations of motion that are averaged over an orbital period (eqs. [8] and [9] of Nagasawa, Lin & Ida 2003) for the calculations of x and η during the disk depletion. The results are almost the same as the results solved from the full equations of motion.

3. Results

The orbits of planets prior to the disk depletion obtained from direct orbital integration are shown in Figure 1 (a). In the systems where the outer planets are more massive than the inner planet (more precisely, where $\Gamma < 1$) such as the planetary system around Ups And, HD168443, HD74156, the geometry of the (x-η) diagram is inverse at the line of $x = \Gamma$ before and after the disk depletion, where $x \equiv e_{\rm i}/e_{\rm o}$. This is because the perturbation on the massive outer planet is greater than on the inner planet before the disk depletion because of the dominance of the disk potential. In the case of Ups And (Figure 1 (a)-1), the initial eccentricities that are averaged over a period of the secular interaction are $e_{\rm i}$=0.69 and $e_{\rm o}$=0.046. The initial orbits before the disk depletion are librating around η=0. The initial eccentricity ratio of the HD168443 system is only slightly smaller than the current one, since the geometry of the (x-η) diagram hardly changes near $x = \Gamma$. The mean eccentricities are $e_{\rm i}$=0.52 and $e_{\rm o}$=0.21. The orbits are circulating (Figure 1(a)-2). The current eccentricity ratio of planets around HD74156 is $x \ll \Gamma$ if we assume the mass of outer planet as $7.5 M_{\rm J}$. Therefore initial $x \sim 11 \gg \Gamma$. This means, however, that the initial $e_{\rm i}$ is larger than unity provided the total angular momentum is conserved between the planets.

In the system where the inner planets are more massive (more precisely, where $\Gamma > 1$) such as the planets around 47 UMa and the Jupiter-Saturn system, the inversion of the (x-η) diagram does not occur because the perturbations on the lighter outer planet always surpass those on the inner planet. The planets initially in the region of $x > \Gamma$ stay there after the disk depletion and the reverse is also true. The initial eccentricities of planets around 47 UMa are $e_{\rm i}$=0.081 and $e_{\rm o}$=0.056 in average (Figure 1 (a)-4). Similarly, the initial eccentricities of Jupiter and Saturn are close to the current ones and their orbits are circulating (Figure 1 (a)-5).

Figure 1(b) shows the evolution of the eccentricities during the epoch of protostellar disk depletion. The planets around Ups And maintain the near alignment of their periastron despite the large changes in x during the disk depletion (Figure 1(b)-1). The planets around HD168443 evolve in the circulating orbit except for the temporary libration near the secular resonance (Figure

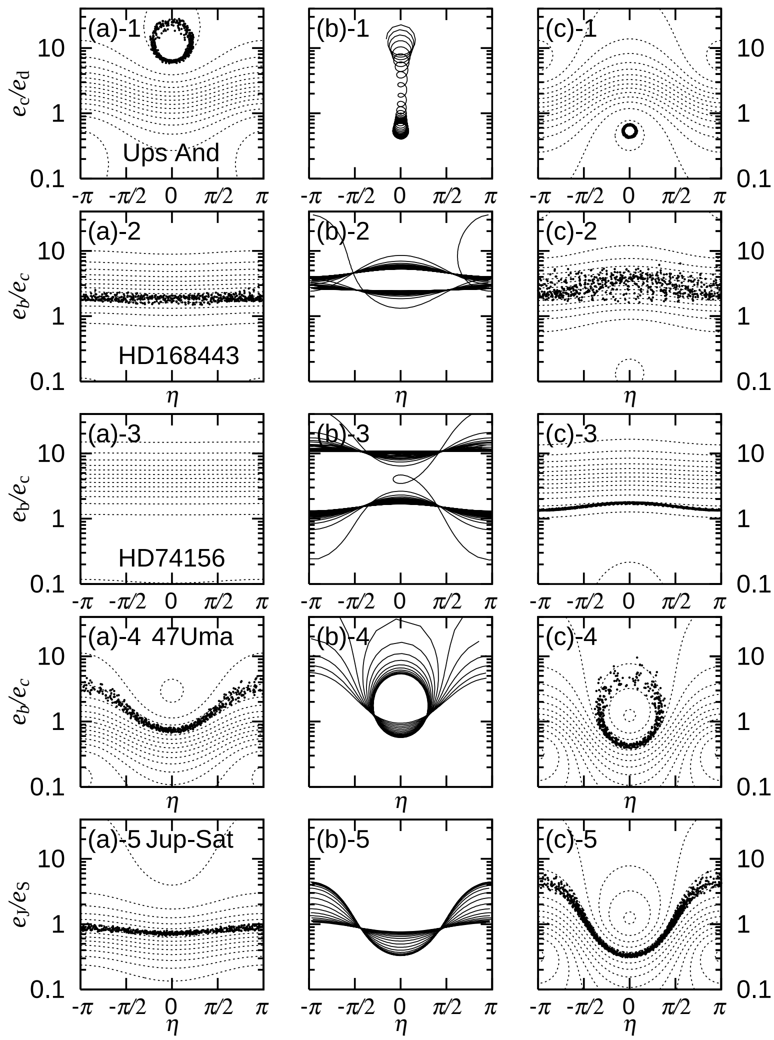

Figure 1. The evolution of the eccentricity ratio and the relative longitude of periastrons (η). (a) The orbits of planets before the disk depletion. (b) The evolution of the planets during the disk depletion. (c) The numerically integrated orbits from current orbital elements. To the order from the top, they are the orbits of planets around Ups And (c & d), HD168443, HD74156, and 47 UMa and Jupiter-Saturn. The dotted lines are equi-Hamiltonian contours. The points are orbits of planets computed from the full equations of the motion for over several circulation/libration periods.

1(b)-2). Figure 1(b)-3 is the case of the planets around HD74156. However, this evolution cannot be real, since the initial value of $x \sim 11$ requires $e_{\rm i} > 1$. The current eccentricities should be reached by a small change of x, as in the case of HD168443. The mean eccentricities of planets around 47 UMa do not significantly change, while the orbits change from circulating to librating (Figure 1(b)-4). The librating orbits occupy a large region in (x-η) diagram when the stationary points at $\eta = 0$ and π are close to each other. Since the distance of current stationary points of this system is smaller than the distance before the disk depletion, the circulating orbit next to librating orbit ends in the librating orbit. There is no large change in the property of orbits of Jupiter-Saturn system (Figure 1(b)-5) except for a small change in the amplitude of oscillation.

4. Conclusion

We calculated the evolution of eccentricities of multiple planets during the depletion of the protostellar disk. In the system where $\Gamma > 1$, the geometry of the (x-η) diagram is inverse before and after the disk depletion. Consequently, in the system where $x \gg \Gamma$ or $x \ll \Gamma$ such as Ups And and HD74156, the large changes of the eccentricities occur during the disk depletion while in the system where current $x \sim \Gamma$ such as HD168443, the change of eccentricities is limited. On the other hand, in the system where $\Gamma < 1$ (planets around 47 UMa and Jupiter-Saturn), there is no large change in the geometry of the (x-η) diagrams. The initial eccentricities are expected to be almost conserved.

The change of the eccentricities of the planets around HD74156 is too large so that the orbits with initial $e_{\rm i}$ less than unity cannot be current orbits in the limit of our model. To avoid being $e_{\rm i} > 1$, we need some conditions such that 1) the outer planet is more massive or the disk mass is less massive than our model, 2) there is a ring disk between the planets which is depleted more slowly than the outside disk, or 3) the disk is depleted faster than the period of η evolution ($\sim 10^6$year) and the change is no longer adiabatic. The third condition would be difficult in the case of HD74156, since the lifetime of the protostellar disk is inferred as at least 10^6–10^7 years from observations of T-Tauri stars (Strom, Edwards, & Skrutskie 1993; Zuckerman, Forveille, & Kastner 1995). When we have more samples of the multiple planets, we will find some constraints on the disk depletion time scale and the initial disk mass from this point of view.

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