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Kozai effect on planetesimal accretion in highly inclined binaries

G. Zhao[1,a], D.N.C. Lin[2,3] and J.-L. Zhou[1]

[1] *Department of Astronomy, Nanjing University, Nanjing 210093, China*
[2] *UCO/Lick Observatory, University of California*
[3] *KIAA, Peking University*

Abstract. Planet formation in highly inclined binaries is a complex issue. The Kozai mechanism plays an important role in this situation, since it will lead to high eccentricity and high relative impact velocity of planetesimals, thus hinder the planetesimal accretion. However, as we will show here, the presence of gas disk in some circumstance will suppress the Kozai effect by increasing the apsidal precession rate of the planetesimals, which increases the critical inclination. A criterion of the disk mass above which Kozai effect will not occur is given.

1. INTRODUCTION

Current survey indicates that approximately 25% of extrasolar planetary systems are in binary environments. Planet formation in binary system is a complex problem, because the perturbation of companion can increase the relative impact velocities of Kilometer-sized planetesimals which will halt the accretion process. The cases in which the orbit planes of planetesimals are coplanar, or with small inclinations, to the binary plane have been well studied by Xie & Zhou [1, 2]. However, planet formation process isn't clear in highly inclined binaries which are common if the separations of the stars is greater than 40 AU [3]. Marzari et al. [4] shows that if the inclination of the companion respect to the disk plane is large enough, Kozai mechanism [5] will strongly increase the relative impact velocity and hinder the planet formation process. However, we will show in this paper that, Kozai mechanism will be suppressed if the apsidal precession of the planetesimals induced by the disk is at a fast enough rate.

2. MODEL AND RESULTS

In our model, we consider two stars moving around their mass of center in circle orbits. The disk is assumed to have constant profile, with its surface density profile $\Sigma = \Sigma_0 \times 10^3 (r/1\,\mathrm{AU})^k$ where $\Sigma_0 = 1.7 \times 10^3\,\mathrm{gcm}^{-2}$ and $k = -3/2$ as the minimum mass solar nebula (MMSN). Gaseous disk dissipates with a timescale of $\sim 10^5$–10^6 yr which is at least one order of magnitude greater than the timescale of planetesimal accretion. Thus the dissipation of disk affects little for the studied topic, and will be neglected in this scenario. The planetesimals are initially put in circle orbits of the disk plane around the prime star, and the inclination of companion is i_b respected to the disk plane. If $i_b \neq 0$, the orbital plane of planetesimals will also be misaligned with the disk plane due to the secular perturbation of the companion, and the planetesimals affected by gas drag only when they cross the gaseous disk

[a] e-mail: zhaog@nju.edu.cn

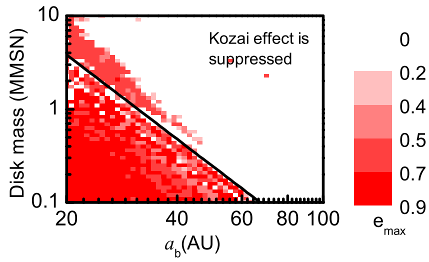

Figure 1. Critical disk mass versus companion's separation. The solid curve shows the critical mass according to Equation 2. Background shows the maximum eccentricity of planetesimal by numerical simulation. In the white area, the Kozai effect will not occur. The semi-major axis of planetesimal is 4AU, companion's mass is $0.5M_\odot$ and it's inclination $i_b = 60°$, the range of disk is [0.1 AU, 9 AU].

plane. If the disk is a thin one and i_b is high enough, the effect of the gas friction is small and can by neglected as a first approximation [4].

The potential of the disk will cause an additional apsidal precession of planetesimal which has the same direction with that induced by the companion. According to Fabrycky & Tremaine [6], if the direction of additional apsidal precession is same as that caused by companion, Kozai effect will be suppressed. Following the deductions in Innanen et al. [8], but with an additional apsidal precession, we obtain the critical inclination for the occurrence of Kozai effect:

$$\sin i_c = \sqrt{\frac{2}{5} + \frac{4\pi\sigma\Sigma_0}{15a}\frac{a_b^3}{m_b}\left(\frac{a}{1\,\mathrm{AU}}\right)^{-3/2}} \tag{1}$$

where a is the semi-major axis of the planetesimal, the coefficient σ is decided by the range of disk $[r_{\mathrm{in}}, r_{\mathrm{out}}]$. But as long as $r_{in} < a < r_{out}$, $\sigma \approx 1 + \sum_{n=1}[(2n)!/2^{(2n)}(n!)^2]^2/(4n+1) \approx 1.094$ is a constant [7], thus i_c is independent with the range of the disk. So the critical values for the onset of Kozai mechanism is increased for the presence of a disk. For a give inclination (i_b) of the companion orbit, the minimum mass of the disk above which the Kozai resonance will not occur for the planetesimals initially coplanar with the disk ($i_c > i_b$) is given as,

$$\Sigma_{\mathrm{crit}} = \frac{15a}{4\pi\sigma}\frac{m_b}{a_b^3}\left(\frac{a}{1\,\mathrm{AU}}\right)^{3/2}\left(\sin^2 i_b - \frac{2}{5}\right). \tag{2}$$

Figure 1 shows the critical disk masses for an example system.

3. SUMMARY AND DISCUSSION

In this paper, we show if the mass of disk is large enough, bf the Kozai effect will not occur in a given inclined binary system for the planetesmials initially embedded in the disk, which is helpful to the planetesimal accretion and planet formation in these systems. Notice that semi-major axis of the planetesmial appears in the right hand side of Equation 2, Kozai effect is easy to be suppressed for the planetesimals having small semi-major axis. Thus planet formation in highly inclined systems will mostly occur in the inner part of the disk.

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