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Collisional Growth of Planetesimals and the Formation of Terrestrial Planets in Binary Star Systems

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Abstract

While recent simulations of the accretion of planetesimals in circumprimary disks in moderately close binary star systems point to the inefficiency of the growth of these objects to larger bodies, the detection of planets around the primaries of binary systems with stellar separation smaller than 20 AU, suggests that planet formation in such binaries may be as efficient as around single stars. We have carried out an expansive numerical study of the collision and interaction of planetesimals, and their growth to planetary embryos and terrestrial planet in such binary systems. By including non-linear gas drag, stemming from an eccentric gas disk with a finite precession rate, we have been able to show that the disk precession decreases the velocity dispersion between different-size planetesimals and facilitates their accretional collisions in particular near the outer parts of the disk. Our results also indicate that terrestrial planet formation is more efficient in binaries with perihelion distances ranging from approximately 12 to 25 AU. We will present our results and discuss their implications to the detection of terrestrial planets in binary systems such as α Cen.

1. Introduction

The detection of giant planets in moderately close binary systems has raised many questions regarding the formation of these objects. For many years simulations of the dynamical evolution of circumstellar disks suggested that planets may not form around the stars of a binary as the perturbation of the secondary star may (i) truncate the disk and remove the material that may be used in the formation of planets, (ii) increase the relative velocities of planetesimals, which may cause their collisions to result in breakage and fragmentation, and (iii) destabilize the regions where the building blocks of these objects may exist. However, the

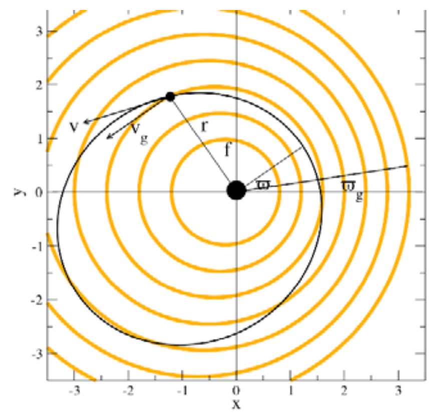

Figure 1. Astrocentric Cartesian coordinates showing the elliptic orbit of a solid planetesimal (black curve) immersed in an eccentric gas disk. The orbits of reference gas elements are shown by broad orange curves.

discovery of planets around the primaries of the binaries γ Cephei [1,2], GL 86 [3,4], HD 41004 [5,6] and HD 196885 [7], where the stellar separation is smaller than 20 AU, suggest that planet formation in such systems may be as efficient as around single stars.

Planet formation requires efficient growth of small bodies (e.g., km-sized planetesimals) to larger objects. The accretional collisions of planetesimals require low impact velocities in order to avoid disruption. In binary stellar systems, collisions are complicated especially if the pericentric distance between stellar components is lower than 20 AU. The gravitational perturbation of the secondary star in such systems, may affect the motion of small bodies by exciting their orbits and increasing their eccentricities, which may lead to encounter velocities well beyond the accretional limit.

As shown by [8], the alignment of the periastra of planetesimals due to their interactions with the nebula through gas-drag may be a possible mechanism for reducing their relative velocities. However, this mechanism is size-dependent which implies that it will stall the accretion process once collisions produce objects with different sizes [9,10]. The matter becomes more complicated as the eccentricity of the gaseous disk is taken into account. As shown by [11], an eccentric gaseous disk can force the orbits of planetesimals to become eccentric as well. In the absence of precession, and in slightly eccentric disks, this may develop a critical semimajor axis for which all planetesimals would have the same equilibrium eccentricity independent of their sizes and exhibit apsidal alignment, constituting a very favorable breeding ground for planetary embryos.

However, as we will discuss in this paper, this trend will break once the precession of the disk is taken into account. We have performed a detailed analysis of the dynamics of individual planetesimals in a precessing eccentric gaseous disk in a binary system. We present our results and discuss their implications for the accretion of planetesimlas and the formation of terrestrial-class objects.

2. Numerical Analysis and Results

We considered a binary with an eccentric gaseous and a planetesimal disk around the primary (Fig.1). We placed the origin of the coordinate system on the primary (A) and assumd that the secondary (B) has an orbit with a semimajor axis a_B and an eccentricity e_B. We also assumed that the gaseous disk precesses slowly in a retrograde motion with a frequency g_g. We integrated the orbit of planetesimals for different values of their sizes and orbital elements, and for different values of the eccentricity of the gaseous disk. Figure 2 shows the variations of relative impact velocity for six different planetesimal pairs, as a function of the semimajor axis and gas eccentriciy e_g. The horizontal line represents the critical relative velocity for a catastrophic disruption [12]. As shown here, impact velocity decreases sharply in the outer parts of the disk for small planetesimals. Although for collisions between very small bodies the impact velocity is still high, we find that for planetesimals with radii of ~2 km and semimajor axes beyond 3 AU the impact velocity is smaller than the critical value, suggesting the favorable condition for their accretional growth. Collisions between larger bodies are even more favorable (middle and lower panels). In all these cases the outcome of a collision seems to be accretion [13], at least in a significant portion of the disk. Even if the inner disk still appears hostile, it is possible to envision a scenario in which accretional collisions between small planetesimals occurs preferentially in the outer disk. Then, as these bodies grow and reach the inner regions due to orbital decay with the gas, they could continue their growth to larger bodies closer to the star.

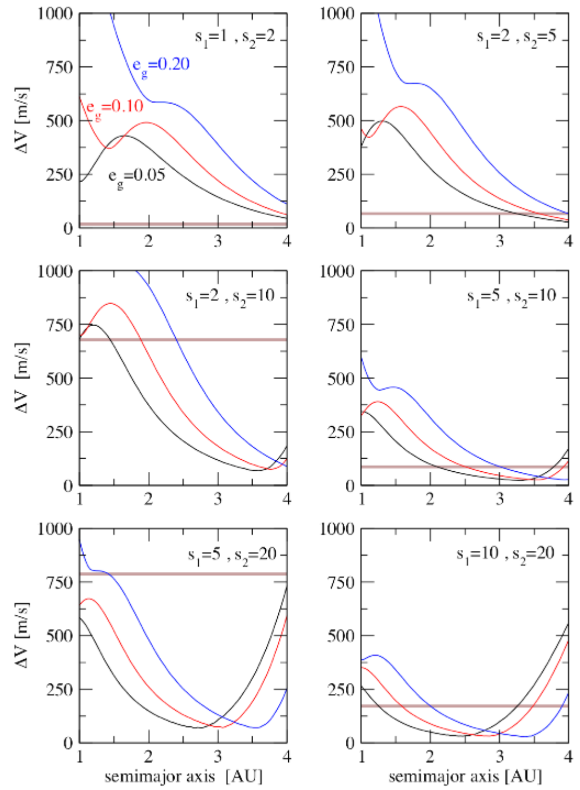

Figure 2. Relative collision velocities as function of the semimajor axis for several pairs of different sizes. Line colors correspond to different gas eccentricities. The broad horizontal brown line gives the limit for disruption collisions [12].

Acknowledgements

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