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Young Binary Star/Disk Interactions

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Abstract. Young binary star systems have associated gaseous disks that affect their evolution. Strong tidal forces of a binary give rise to gaps that separate circumstellar (CS) disks from the circumbinary (CB) disk. We discuss two important processes that involve binary/disk interactions. The first is eccentricity evolution of a binary embedded in a disk. The second is accretion of gas across the gap that separates CS and CB disks. These results may also have implications for the recently discovered planets.

1. Introduction

There is much evidence that disks are associated with young stars. Direct images of disks have been taken with HST (McCaughrean; Stapelfeldt, this volume). The standard picture of single star formation involves a central star surrounded by a (single) disk (see, e.g., review by Shu, Adams, & Lizano 1987). Such disks are a natural consequence of the fact that star formation proceeds as a collapse process. The collapse of a slowly rotating gas cloud (core) will produce a centrifugally supported disk, surrounding a central protostar, as a consequence of angular momentum conservation.

Disk sizes of roughly solar system dimensions have been determined from observations. Furthermore, observations of young stars indicate disk survival times of 10^6 to 10^7 years, comparable to the pre-main-sequence timescale. Disk masses range from about 0.001 to 0.1 $M_\odot$ (Strom, Edwards, & Skrutskie 1993; Beckwith & Sargent 1993), comparable to the minimum mass solar nebula. Since we expect all stars to undergo such a young star phase, such disks are very numerous in the Galaxy.

Most stars are found in binaries and binaries are found in high frequency among pre-mainsequence stars (see Simon et al 1995). Recent observations have determined that pre-mainsequence and main sequence binaries have typical separations of less than 30 AU (Duquennoy & Mayor 1991, Fischer & Marcy 1992, Simon et al 1995) smaller than typical disk sizes around single stars. On this basis, we expect that disks likely play an important role in the early evolution of young binaries. Observations of young binaries support the idea that binarity has an influence on observationally determined disk properties (see review by

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Mathieu 1994). Emission at mm wavelengths is expected to originate in the middle to outer parts of typical disks around young stars. There is strong observational evidence that mm emission is depressed in binaries whose separations are of this order (Beckwith et al 1990; Jensen et al 1996). On the other hand, emission is observed at wavelengths of a few microns, which originates in the innermost disk material, close to the stars. The observations then indicate that there is a depletion of disk material on scales of the binary separation.

We expect there are two types of disks in a binary environment: circumstellar (CS) disks which surround only one star and circumbinary (CB) disks which surround the entire binary. Two CS disks, one around each star, and one CB disk can be present in a binary. The CS and CB disks are separated by a tidally-produced gap (e.g., Lin & Papaloizou 1993, Artymowicz & Lubow 1994). This gap is likely responsible for the observed depletion of disk material (Jensen et al 1996).

Both pre-main-sequence and main-sequence binaries are typically eccentric, with eccentricity e of order 0.3 or more (Duquennoy & Mayor 1991; Mathieu 1994). Dynamical effects of binary eccentricity need to taken into account in understanding the properties of binary/disk systems. This situation differs from the typical circular orbit case of interacting close binaries such as CVs.

There is some observational evidence for CB disks. The circumbinary disk around GG Tau has been directly imaged and the velocity field has been spatially mapped (Dutrey, Guilloteau, & Simon 1994, Roddier et al 1996). The continuum image shows clear evidence of a disk or ring in which there is a significant central depression of emission, where the resolved binary GG Tau resides. The central depression is interpreted as being due to the tidally produced gap. At the inner edge of the CB disk, the ^{13}CO line emission data shows that the velocity arises from rotation, rather than radial collapse. This disk is quite large. The central hole is about 180 AU in radius and the disk extends to at least 800 AU.

Another line of evidence for circumbinary disks comes from the presence of mm emission in relatively close binaries whose separations are less than 1 AU. Such emission likely comes from CB disk material at considerable greater distances.

These disks can interact with young binaries to provide a rich set of dynamical phenomena. Our work to date (see reviews in Artymowicz & Lubow 1996a; Lubow & Artymowicz 1996) has shown that for cold disks ($h/r < 0.05$, $\alpha \sim 0.03$), the CB and CS disks are cleanly separated by a tidally-produced gap. For the usual case of eccentric binaries, the inner edge of the CB disk becomes eccentric and precesses. In addition, ripples or wakes can develop at this edge. We have also found that binaries gain eccentricity from tidal interactions with disks, in contrast to previous work which shows that planets can lose eccentricity (Goldreich & Tremaine 1980). For warm disks ($h/r > 0.05$), the binary develops a set of two gas streams whose mass flux is modulated in time (Artymowicz & Lubow 1996b). This mass flow can have many consequences on the observed properties of young binaries and on their evolution. This flow may be of importance in the evolution of young planets. In this paper we review two processes: eccentricity growth due to binary/disk interactions and mass flow across gaps.

2. Assumptions About Disk Properties

For the purposes of analyzing the properties of binary/disk interactions, we will make some simplifying assumptions. First, we assume the usual α disk model applies. We generally consider α values in the range of 0.01 to 0.1. The value of α is uncertain. Some effects at smaller α values have been considered by Yuan & Cassen (1994) and by Takeuchi, Miyama, & Lin (1996). We ignore here the effects of disk self-gravity and assume the binary and disk are coplanar. We have done some modeling with self-gravity and found that self-gravity does not qualitatively change our results unless the disk is gravitationally unstable. The binary might be expected to cause disks to be aligned with its orbit plane through differential precession effects. However, in some cases (warm disks) noncoplanarity might persist over fairly long timescales, because the disk could possibly precess as a rigid body (Larwood et al 1996).

3. Circumstellar and Circumbinary Disks

Properties of the CS disks are basically those of standard accretion disks, which have been extensively described in the literature. Less well known are the properties of CB disks, which act as "decretion" disks (Lin & Papaloizou 1979b, Pringle 1991).

There are two independent similarity solutions for the evolution of a viscous disk. The first corresponds to a disk with no torque at the center, but a nonzero mass flux there. The second has a nonzero torque at the center, but no mass flux there. The first corresponds to a CS disk, while the second closely corresponds to a CB disk which does not transfer mass onto the binary. In the case of a CS disk, the disk material slowly spirals inwards as it loses gravitation energy, some of which is released in the form of radiation. In the case of a CB disk, the material spirals slowly outwards, as a consequence of the central torque provided by the binary. The disk therefore *gains* gravitational energy as it evolves. Viscous CB disks must also dissipate and so radiate energy because neighboring rings of gas rotate with slightly differing angular speeds and are coupled by viscous forces that act to make them corotate. As a result of this viscous interaction, energy must always be dissipated. So a CB disk is an energy sink, due to its expansion and dissipation. The source of this energy is the orbit of the binary (see Lubow & Artymowicz 1996). In addition, the CB disk reprocesses a part of the radiation emitted from CS disks and the stars, which often dominates its total output.

4. Disk Resonances

The primary interactions between a binary and a CB disk are resonant interactions. The theory of resonances for disks has been developed as a result of work by Goldreich and Tremaine (1979). To understand how resonances arise in the theory, consider a decomposition of the binary potential Φ into a sum of rigidly rotating Fourier components:

$$\Phi(r,\theta,t) = \sum_{m,l} \phi_{m,l}(r) cos(m\theta - l\Omega_b t) \tag{1}$$

where cylindrical coordinates (r, θ) are centered on the binary center of mass in the inertial frame, and Ω_b is 2π divided by the binary orbital period.

For a circular orbit binary, only diagonal (i.e. $m = l$) terms are nonzero. Setting $m = l$ in the above, we see that the potential is static in the frame of binary where $\theta - \Omega_b t$ is a constant. In this decomposition, nondiagonal (i.e., $l \neq m$) elements arise only to the extent that the binary is eccentric, which as we said in the Introduction is typically the case. The magnitude of $\phi_{m,l}$ scales with eccentricity as $e^{|m-l|}$. At resonances, waves are launched, which exert torques on disk material as they damp.

Two types of resonances are relevant

- Lindblad resonances occur where $\Omega(r) = l\Omega_b/(m \pm 1)$. For $m = l$, their primary effect is to truncate disks. For $m \neq l$, they are called eccentric Lindblad resonances. They can truncate a disk and usually increase the binary eccentricity.
- Corotational resonances occur where $\Omega(r) = l\Omega_b/m$. They generally damp binary eccentricity.

5. Eccentricity Evolution in a Cold Disk

The eccentricity evolution of a binary depends upon the strength of the binary potential components $\phi_{m,l}$ and the disk density at resonance. The disk density distribution in turn depends on the tidal torques acting on the disk. For a given binary mass ratio, eccentricity, and disk properties (sound speed and α), the rate of change of binary eccentricity per unit disk mass can be determined. For a cold disk ($h/r < 0.05$), we can consider the binary/disk interaction to be purely gravitation and we can ignore the additional torque contributions due to advection of material across gaps (as will be discussed in section 6).

We have carried out a series of SPH simulations to determine the eccentricity evolution of a binary (Artymowicz et 1991). In addition, some results may be obtained by purely analytic considerations (Lubow & Artymowicz 1996). The rate of change of binary eccentricity $\dot{e}$ depends largely on the binary eccentricity e and mass ratio q. The qualitative results are summarized in Figure 1. For small mass ratios ($q \sim 0.001$), as is the case of star/planet systems, only a small gap (relative to the orbital semi-major axis a) is produced and several resonances may be present in the disk. Goldreich and Tremaine (1980) showed that corotational resonances can slightly overcome the effects of Lindblad resonances and cause a net eccentricity damping. For mass ratios of order unity, characteristic of binary star systems, and for eccentricity $e \sim 0.1$, the gap is quite large and is maintained by the m=2, l=1 eccentric Lindblad resonance, located at radius $r \approx 2.1a$. No other competing resonances lie within the disk, so the eccentricity grows in time (Artymowicz et al 1991). At high eccentricity ($e \gtrsim 0.5$) and order unity mass ratios, there are many strong high-order resonances present within

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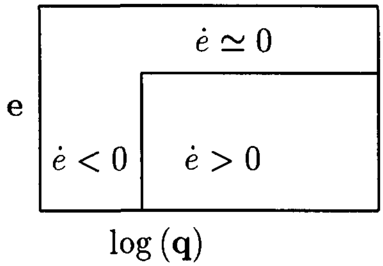

Figure 1. Regimes of $\dot{e}$ in $e - q$ plane (schematic only).

the disk that have nearly cancelling effects on eccentricity. In this case, the time-averaged eccentricity growth is considerably weakened (Lubow & Artymowicz 1993).

One important question is the critical transitional mass ratio q_{crit} between eccentricity damping (at $q < q_{crit}$) and growth. A preliminary estimate by Artymowicz (1992) suggests that $q_{crit} \simeq 0.01$ or about 10 Jupiter masses. However, this boundary may be quite fuzzy in that there is near-cancellation of $\dot{e}$ contributions of several powerful resonances. The sign of the net $\dot{e}$ produced in the neighborhood of q_{crit} appears sensitive to the details of the disk properties, such as sound speed. More work is required to better determine the properties of this transition. In the high e regime for binaries, we find a similar sensitivity to the details of the disk properties.

5.1. Observational Consequences

The general picture presented above suggests that eccentricity should generally increase with mass ratio (secondary mass divided by primary mass). We expect that few binaries should have small eccentricity, since the eccentricity growth of small eccentricity ($e \sim 0.1$), pre-main-sequence binaries surrounded by disks is rapid. This is consistent with observations (Duquennoy & Mayor 1991, Mathieu 1994).

The observations of the newly discovered planets (Mayor & Queloz 1995; Butler & Marcy 1996; Marcy & Butler 1996) support our picture that a transition in the eccentricity values from low to high occurs at several Jupiter masses (cf. Mazeh, Mayor, & Latham 1996). Because the transitional q_{crit} may depend on disk properties, e may not be a strictly increasing function of q. It is also important to keep in mind that observationally determined planet masses are often only lower limits. More detailed modeling of this transition will be required.

We have emphasized the evolutionary effects of binary eccentricity. However, initial conditions may also play a role. This point of view is plausible, provided that different mechanisms are invoked for the formation of stars and planets *and* that the newly discovered high mass planets (or superplanets) were formed like stars (see Boss 1996; Mazeh, Mayor, & Latham 1996). Stars might be expected to form by a fragmentation process which could leave a binary in an eccentric orbit, while planets are formed from within a circular disk. In contrast,

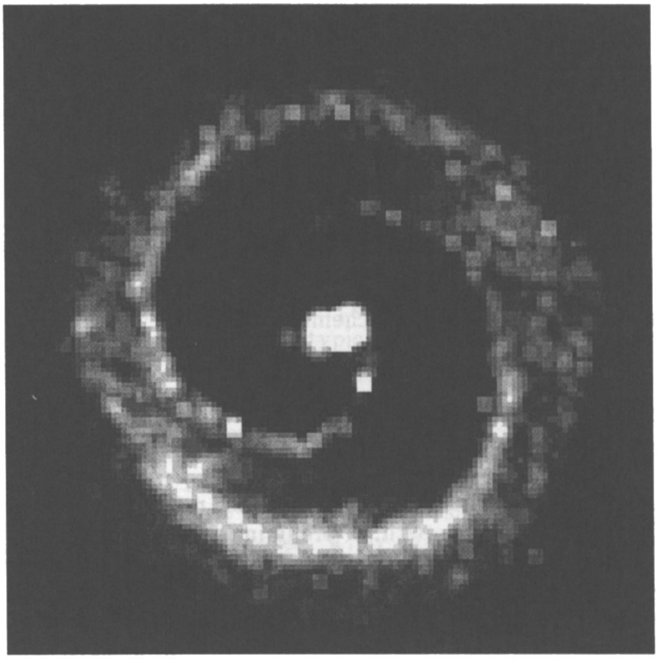

Figure 2. The appearance of the illuminated mass inflow from the circumbinary (CB) disk to the central binary at binary periastron. This is determined from an SPH simulation of an eccentric binary with $e = 0.5$ and mass ratio of 1.27, surrounded by a circumbinary disk with gas sound speed $c = 0.1\Omega R$ (see text).

the evolutionary picture with disks permits superplanets to have been formed like planets (see also discussion at end of next section).

6. Mass Flow Across Gaps

In warm disks ($h/r > 0.05$), the gaps that separate CB from CS disks are not clear of material, as has been assumed in the past. Instead, we recently found that CB disk material can penetrate the gap, generally in the form of two gas streams (Artymowicz & Lubow 1996b). In Figure 2 we plot a crude model for the appearance of such flows due to reflected light from the central stars. To account for the delocalization of the density associated with SPH particles and for the illumination of assumed optically thin gas, the SPH particles were smoothed over their kernels, projected onto grid, and then this density was divided by inverse square distances to stars. This procedure is rather simplistic, but some features in this figure bear a good resemblance to the IR image of Roddier et al (1996).

This flow has important consequences on early binary evolution. The flow would permit a young binary system to continue to gain mass from a CB disk.

Without this flow, the binary system would be cut off from this mass reservoir as soon as a gap is formed in the disk. Its mass would then be limited by the mass of the binary plus the masses of the CS disks at the point of gap formation.

For binaries whose periastron distance is comparable to the stellar radii, these gas streams might directly impact the stellar surfaces, as occurs in Algol binaries. For the typical case of more widely separated binaries, the gas streams would impact the CS disks and produce a hot spot, in analogy to the well-observed hot spots in CVs (see Horne, this volume). These gas streams can replenish CS disks. As a result, such systems could show signs of disk accretion over long timescales. The gas streams usually accrete more mass onto the secondary component of the binary than the primary and so cause the binary mass ratio to evolve toward unity. The radiation emitted as a result of the gas stream impact could cause the secondary to appear more luminous than the primary, so luminosity reversal is possible. Such effects could substantially alter observational interpretations of such systems.

For the typical case of eccentric binaries, the gas flow onto the binary is strongly modulated or pulsed in time over a binary orbit period. Similarly, the radiation produced by the gas stream impact should be strongly modulated over the binary period. The binary phase of the radiation pulse appears to depend on the binary mass ratio and eccentricity, and is less sensitive to the disk properties. The disk properties determine the overall amplitude of the accretion rate and radiation luminosity.

Some evidence for this radiation has come from observations of DQ Tau by Mathieu et al (1996). This young binary has $e = 0.55$, $q = 1.0$, and an orbital period of 15.8 days. It also has a modulation of its continuum radiation over a binary orbit period. The phase of the peak radiation is in very good agreement with the phase predicted by our simulations. The observations also show some fluctuation in the amplitude of this modulated radiation over the course of several orbit periods. This effect requires further investigation.

The origin of the flow can be understood from a model that is similar to that in mass-exchange binaries. Consider the case of a binary with $e \sim 0.2$. In this case the dominant resonance is the m=2, l=1 eccentric Lindblad resonance, which truncates the inner edge of the CB disk. Slightly inside this resonance is located the m=2, l=1 (eccentric) corotational resonance. The corotation resonance is quite important, for it serves as a saddle point in the local effective potential in the binary consisting of the m=2, l=1 perturbing potential plus the axisymmetric potential component. This corotation point plays an analogous role to the inner Lagrange (L1 point) in mass-exchange binaries (Lubow & Shu 1975). Ballistic particles, representing gas stream fluid elements, approximately follow special paths ("straight-line" solutions of the restricted three-body problem) in the neighborhood of such points that give rise to flow in the form of narrow gas streams. The gas streams are deflected from a path directly towards to accreting object(s) by Coriolis forces. The extent of this deflection can computed analytically. In the present case of accretion of CB disk material, the deflection angle is a function of the binary mass ratio and eccentricity. Since the potential in this case has m=2, there are two such saddle points, and they rotate at the pattern speed of $\Omega_b/2$. So we expect there to be two such gas streams, which rotate at half the angular speed of the binary. These properties are in

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fact found to be in good agreement in our simulations. There are also somewhat more complicated effects seen in our simulations, such as a time-varying mass flow rate and stream deflection angle, which are likely due to the presence of the other components of the binary potential that have different time dependences.

The amplitude of the mass flow through the corotation point depends on the extent to which the CB disk can penetrate inward of the eccentric Lindblad resonance to reach the corotation resonance. Such penetration is made possible due to the sound speed and viscosity of disk material that act to smooth out the disk edge. Viscosity plays a major role in establishing the disk edge location at the resonance. Based on Bernoulli's theorem, we expect that gas pentration can occur, for example, when half the square of the gas sound speed is comparable with the difference in effective potential between the disk orbit near the eccentric Lindblad resonance and the corotational resonance. Our simulations are in approximate agreement with this picture.

The mass flow can also effect the evolution of the binary's orbit. The accreted material advects energy and angular momentum to the binary. We have recently developed an analytic means of accounting for the change in binary orbital elements that result from advection in our simulations. In addition, the gas streams can cause strong tidal interactions with the binary because they come quite close to it. Preliminary indications are that mass transfer can sometimes cause the binary orbit to *expand*. The reason is that the flow carries relatively high specific angular momentum into the binary.

This flow may be the key to understanding whether young closer binaries survive orbit decay. Tidal effects alone from the CB disk cause the binary orbit to decay (Lin & Papaloizou 1979; Pringle 1991; Lubow & Artymowicz 1996), a process that is most acute for closer binaries. Gas streams may permit such binaries to survive these effects.

We have found numerically that the mass flux carried by gas streams can sometimes be comparable to the usual mass accretion rate that would occur if the binary were replaced by a point mass. Because of this effect, disks may sometimes exhibit properties of both accretion and decretion disks simultaneously. Confirmation of some of our SPH numerical results has been obtained by Różyczka and Laughlin (this volume), using a finite difference code.

In the case of extreme mass ratios, where a gas giant planet orbits a central star, the gas flow may have important consequences on the planet's evolution. In the absence of gas streams, a protoplanet orbiting in a disk would achieve a maximum mass, set by the requirement that the planet gravitationally acts to clear a gap around it at the same rate as the viscosity in the disk acts to close the gap. This condition requires a balance of gravitational torques produced by the planet with the viscous torque in the disk. For plausible disk parameters, the viscous condition predicts a maximum planet mass to be about a Jupiter mass (see Lin & Papaloizou 1993). A lower mass limit was set to stars by Boss (1988), which suggested that there may be a "mass gap" between the highest mass planets and lowest mass stars. The newly discovered superplanets (Marcy & Butler 1996) appear to partially bridge that mass gap (Boss 1996).

Ongoing accretion onto planets can occur through gas streams, even when the above-mentioned torque balance occurs and the gap is open. The continuing accretion could cause superplanets to form. It may be the case that planet masses are determined by the lifetime of the disk, rather than the torque balance condition.

7. Summary

Binary/disk interactions exhibit a dynamically rich set of phenomena. Such interactions likely play an important role in determining binary eccentricity. Current models suggest that the eccentricity of systems ranging from planets to binary stars should generally increase with secondary mass (Goldreich & Tremaine 1980; Artymowicz et al 1991; Lubow & Artymowicz 1996; see Figure 1). The transitional mass likely occurs in the range of the newly discovered high eccentricity superplanets (Artymowicz 1992), but the behavior of eccentricity in this transitional mass range appears delicate and may depend on the details of the disk. More analysis is required.

Mass flow can occur from circumbinary to circumstellar disks (Artymowicz & Lubow 1996; see Figure 2). This flow generally occurs as two gas streams that penetrate the disk gap. It has many potentially important implications for the evolution of binary stars and planets. For example, this flow may permit young close binaries to survive tidal orbit decay. The flow may permit planets to gain enough mass to become superplanets. There are clear observational signatures expected in the presence of this flow and some indications that it may have been detected (e.g., Mathieu et al 1996).

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Discussion

E. Maoz: Would the process of gap opening work also in the case of a circumbinary disk around a binary of equal-mass components on a circular orbit?

S. Lubow: Yes, gap opening would occur in that case.