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Early Orbital Evolution of Binaries: Overview and Outlook

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Abstract. The orbital evolution of a young binary star is strongly affected by the circumstellar disks orbiting each of the stars, and/or the circumbinary disk orbiting about the entire binary. Calculation of the evolution requires the knowledge of disk structure (resonantly emitted density and bending waves, disk gap sizes, possible secular nonaxisymmetry), as well as of any gas streamers falling onto the binary. While the diagnostic signatures of the binary-disk interaction are observable (and have recently been observed), the orbital evolution cannot directly be observed so far, because of long associated time scales. Hence, theory is crucial for understanding the evolutionary stage and the future of the observed systems. We briefly review the status of the theory of orbital evolution and discuss several topics requiring further theoretical work.

1. Introduction

Observations reveal that the formation of stars (including binary stars, esp. close binary stars and planets) is always closely associated with the presence of accretion disks (e.g., McCaughrean & O'Dell 1996; Burrows et al. 1996; Stapelfeldt et al. 1998). A clear decrease with time of the fraction of optically thick disks (at <3 AU from the star) from $\sim$100% at the age $\sim$0.3 Myr down to a few percent at the age of $\sim$10 Myr has been demonstrated by Hillenbrand & Meyer (1999). The mass flow through the disk, as evidenced by the signatures of accretion onto the PMS star's surface, seems to be curtailed at (statistically speaking) the same time, equal to 1-3 Myr for T Tauri and Herbig AeBe stars, as the optically thick disks disappear. Probably the same mechanism (accretion, photoevaporation, other?) depletes the circumstellar gas in disks.

T Tauri stars, once thought to be single, are in fact mostly double/multiple, as are both the majority of young stellar objects and main-sequence stars (Mathieu, Ghez, Jensen et al. 2000). Circumbinary (CB) disks are now directly resolved (GG Tau: Dutrey, Guilloteau, & Simon 1994; Roddier et al. 1996). We cannot observe the orbital evolution of these systems directly, due to long time scales. On the other hand, short period binary systems surrounded by substantial disks, like AK Sco or RW Aur, are apparently stable (not evolving rapidly) on timescales of at least 0.1 Myr, which amounts to millions of orbits, a fact to which we draw attention in sect. 3 below. Wide PMS binaries, in contrast, are dynamically less evolved (can make thousands of orbits before disk dispersal). In each case, however, there is ample time to dynamically sculpt disk(s), and potentially sufficient time for a large modification of the orbital elements of the binary.

2. Binary → Disk Interaction

The basic picture of disk-binary interactions at the T-Tauri stage, which describes the conditions for disk gap opening and size, first emerged in the late 1970s (e.g., Lin & Papaloizou 1979) and was fully worked out in the 1980s, as reviewed by Lin & Papaloizou (1993). It has received observational support, among others, from the spectral energy distributions of the disks (Beckwith et al. 1990). New developments in the 1990s have been summarized by Lubow & Artymowicz (2000). The "new" picture differs from the "old" in several respects.

2.1. Eccentric Binaries and the Mass Transfer

Firstly, the knowledge that the typical eccentricity of a binary star (MS or PMS) is considerable ($e = 0.2 - 0.6$; cf. Duquennoy & Mayor 1991, Mathieu 1994) rather than small or zero, as has often been assumed in previous theories, has stimulated the development of the theory applicable to eccentric binaries (theory of disk gap sizes of Artymowicz & Lubow 1994, and its applications, e.g., Jensen & Mathieu 1997). The nonzero eccentricity leads to a more complicated dynamical interaction, since many more resonances are present.

Secondly, simulations showed that a circumbinary (CB) disk can transfer mass onto the central binary (Artymowicz & Lubow 1996). This resupply mechanism might explain the common presence of small circumstellar disks with nominally short viscous lifetimes in binaries (Mathieu 1994). The flow can be surprisingly efficient: for moderately warm and viscous accretion disks, the gas flux can equal or exceed the "unperturbed flow" through a disk around the primary component (without the secondary). Simulations show that only a very small gas mass resides in the CB gap, but the low density is accompanied by a large average radial flow speed that results in a substantial mass flux. The nonaxisymmetric structures (streamers) have been identified in some resolved systems (GG Tau, Guilloteau & Dutrey, this meeting; UY Aur, Duvert et al. 1998, and Close et al. 1998). At earliest phases of formation (before the T Tauri stage), an even more dramatic, dense, spiral shaped gas flow accompanies the accretion from an infalling (collapsing) cloud onto a binary protostar (Bate & Bonnell 1997, and this volume).

2.2. Time-Dependent Streaming through the Gap

The time variability in the flow forced by the binary's eccentricity e can be pronounced. It depends on the mass ratio and e, which provides a way to characterize unresolved or long-period binaries (e.g., DQ Tau observed by Mathieu et al. 1997; Basri et al. 1998). The dynamical and changing nature of the flow is

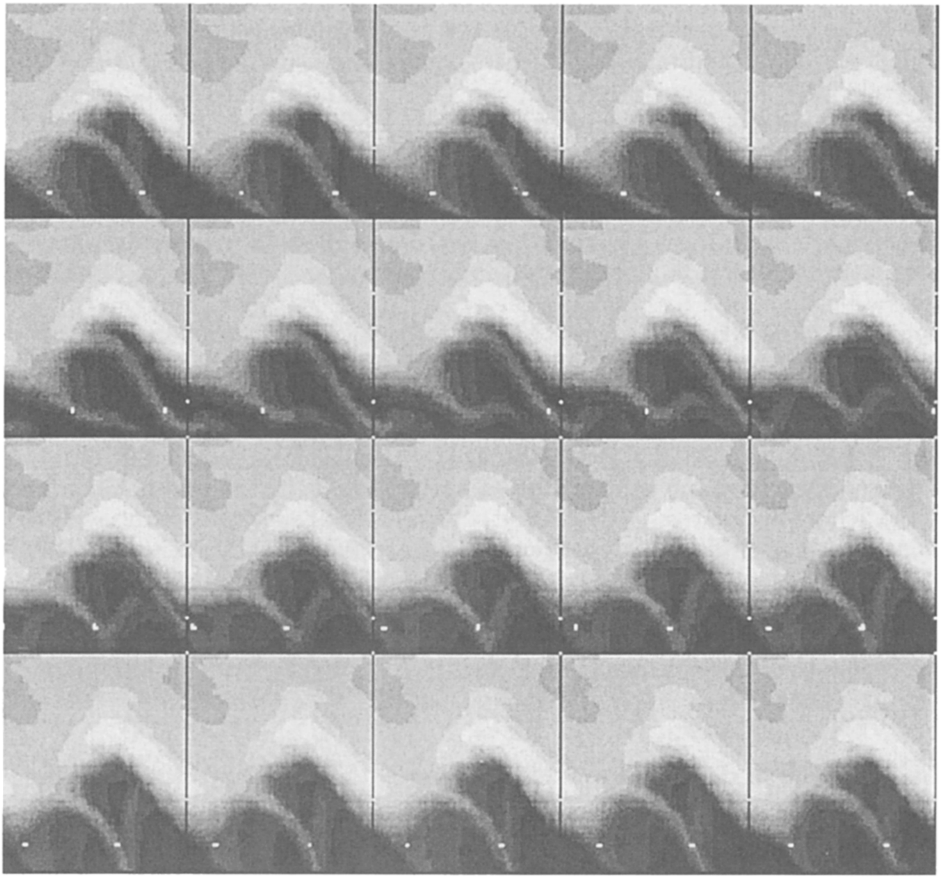

Figure 1. A movie of a circumbinary disk's grayscale-coded gas density. The central binary system has mass parameter $\mu = 0.44$, and eccentricity $e = 0.5$ (cf. Artymowicz and Lubow 1996). The movie covers its 400th orbital period, starting from the top row and ending in the bottom right corner. The disk is shown in polar coordinates: in each snapshot the horizontal axis shows the full extent (360°) of the azimuthal angle, while the vertical axis covers the distances from the center of mass from 1 to 4 times the semi-major axis. White dots are the saddle points (Lagrange points) of the effective potential Φ_{21} directing the flow of gas from the disk to the binary (cf. text). From unpubl. work by Artymowicz and Kley, using the Monotonic Transport code (cf. Kley 1999).

not fully studied yet, but may be rather important for the orbital evolution. The application of grid-based codes, as are now being applied to planet formation problems, would be desirable.

In Fig. 1 we show the preliminary results of Artymowicz & Kley (unpubl.). The sequence of panels presents a "movie" covering a single (400th) simulated orbital period of the binary with nearly equal masses and eccentricity $e = 0.5$, studied earlier by Artymowicz & Lubow (1996). The disk is standard (viscosity coeff. $\alpha = 4 \times 10^{-3}$, scale-height 0.05 times the radius). Two streams of gas constantly pass through the theoretically predicted locations (white points denoting saddle points of the effective $(m, l) = (2, 1)$ potential harmonic Φ_{21}, turning around the binary[1]). The corresponding SPH model (stopped after fewer binary orbits) was illustrated in Fig. 4 of Lubow & Artymowicz (2000). Comparing the SPH and grid-based code results, we conclude that the latter will be better suited for resolving the very low-density flows through the gap. However, in the future grid methods need to be developed to handle adequately the region between the stars (where the current use of polar coordinates is a problem).

On a secular time scale, recent simulations suggest the development of an elliptical disk/gap. Notice, for instance, how the initially circular CB disk became eccentric after 400 periods of the binary in Fig. 1 (cf. the sinusoidal outline of the dense CB disk rim). The ellipticity arises initially in response to the direct binary forcing by the "slow" harmonics of the gravitational potential, followed by the establishment of a slow 1-armed mode in the disk (cf. Lubow & Artymowicz 2000). The precession of the disk with respect to the binary can modulate any short-period variability due to the waves and/or streamers; the variations in the flow patterns have a long period equal to $10^3 - 10^4$ times the orbital period.

2.3. Non-Coplanar and 3-D Disks

The dynamics of disks that are non-coplanar with the binary orbit have been studied. Inclined circumstellar disks can precess like rigid bodies (Papaloizou & Terquem 1995; Larwood et al. 1996). Tidally truncated disks evolve towards coplanarity with the binary, as a consequence of tidal dissipation (Lubow & Ogilvie 2000). Observations of the degree of disk alignment in various young binaries potentially provides information about binary formation mechanisms, as well as the physics of disk dissipation. The timescale for achieving coplanarity is not well established. A linear, viscous disk model suggests the timescale is of order the disk viscous timescale. However, an inclined disk may be subject to a parametric instability (Gammie, Goodman, & Ogilvie 2000). The instability is a consequence an orbiting disk fluid element being subject to a time-periodic shear, resulting from the binary tidal field acting along an inclined orbit. It is plausible that this instability results in nonlinear dissipation (shocks), which may lead to a near coplanarity (within the disk thickness or about 5% to 10%) on a timescale as short as the disk precessional timescale, or about 20 binary orbits (Bate et al. 2000). Observations of noncoplanar disks may help resolve these issues (e.g., Stapelfeldt et al. 1998; Koresko 1998). Observations of misaligned

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[1] Plots are made in the inertial systems of reference. Thus, Lagrange points and the streams rotate to the right with respect to the binary at 1/2 the mean binary speed.

and precessing jets within binary systems also provide relevant information. Also desired are three dimensional simulations of inclined, warped disks that resolve well the internal structure of the disk.

The resonant interaction between a binary and a disk results in the generation of waves (Goldreich & Tremaine 1980). For disks that are vertically isothermal, these waves are adequately described by the conventional two-dimensional disk theories. However, a disk that is accreting material and is optically thick will likely possess a vertical temperature variation. For such a disk, it was expected that waves would refract to the surface on a radial scale of order the disk thickness (e.g, Lin, Papaloizou, & Savonije 1990). This is because the sound speed at midplane differs substantially from that at the surface, so the wavefront would rapidly tilt. As a result, waves would undergo shock dissipation as they propagate upwards into an ever-thinner disk atmosphere.

However, recent analytic, linear studies provide a different picture (Lubow & Ogilvie 1998). In disks with large vertical temperature variations, the excited waves act like incompressible surface gravity waves (more properly f modes) as they propagate away from the resonance. In common with refraction, the process known as “wave channeling” causes the f mode wave energy to be confined near the disk surface. Refraction does not apply because the wave cannot be regarded as propagating at its local sound speed at each height in the disk. Instead, the wave is vertically evanescent and requires a global treatment vertically. The disk acts like a waveguide. Unlike the prediction of refraction, wave channeling (vertical confinement) in a binary disk occurs on a radial length scale of order the disk radius. For a planet-disk system, wave channeling acts on a radial scale of order the disk thickness, as a consequence of the high azimuthal wave numbers that are excited. The radial scale for channeling increases as the disk becomes more isothermal or possess a deeper atmosphere (Ogilvie & Lubow 1998). With wave channeling, the launched wave does not propagate upward through the disk atmosphere. Instead, as the wave energy becomes concentrated near the upper disk layers, it remains concentrated near the base of the atmosphere (i.e., remains vertically evanescent). The wave acquires nonlinear behavior and possibly shocks only as a consequence of the vertical constriction caused by the vertical temperature variations. Nonlinearity ceases increasing once the wave energy is concentrated at the base of the disk atmosphere. Nonlinear simulations would be useful to test the predictions of wave channeling.

3. Disk → Binary Interaction

Gravity of the disturbed disk(s) transfers energy and exerts feedback torques on the perturber (binary), thus causing a coupled orbital evolution of a and e (as well as precession $\dot{\omega}$) in accordance with the Lindblad resonance theory (Goldreich & Tremaine 1980). Although some quantities, like the gravitational torque from the CB disk, are fairly insensitive to the detailed properties of the disk or the binary (except for the disk viscosity, with which the torque is in balance), others are not. The mass accreted from the disk provides extra torques and an energy transfer route, but these effects are model-dependent. Therefore, the orbital evolution is, in general, a complex matter, with some of the effects able to cancel one another.

3.1. Orbital Migration

For example, consider the evolution of the semi-major axis a. Gravitation of the circumstellar disks tends to unwind the orbit (increase a), while the CB disk has an opposite effect of tightening it (see eq. 4 of Lubow & Artymowicz 2000). Mass inflow generally opposes these trends. If the CB disk is able to transfer several times the "unperturbed disk" flux of matter onto a binary[2] (secondary component, mostly), then the orbital separation might increase. We have seen such effects in some SPH calculations of binaries, and the calculations of star+planet systems with the outer/CB disk only (Lubow, Seibert, & Artymowicz 1999). A stable equilibrium with a low-mass inner and a much more massive outer disk might be established.

In the case of very unequal binary components, it is interesting to note that the gas flow does not need to accrete onto the small secondary component to produce a significant effect. For torque production, it suffices for the gas to enter the Roche lobe of the secondary and leave at its opposite end (this produces double the effect of entering and falling on a planet in the center of the Roche lobe). A case where the gas is restricted to pass through the Roche lobe rather than accrete has recently been simulated by Masset & Snellgrove (2000), and outward migration was seen. Takeuchi & Tanaka (1999) on the other hand, claimed that sufficiently massive planets automatically migrate outward.

The orbital migration is, of course, one of the crucial processes not only in the binary evolution but also in planet formation theories (Lin, Bodenheimer, & Richardson 1996, Ward & Hahn 2000). It should be given high priority in the future work. In both contexts, we would like to understand how close binaries are produced (from wide binaries?), and once produced how they can be stable for perhaps a large fraction of the disk lifetime, i.e., ~1 Myr. Though we have suggested above that gas flow near/onto the secondary may sometimes *reverse* the normal inward migration, especially in systems with short periods of 4-14 days, where the secondary might reside in a tidally or magnetically-induced disk gap, this does not necessarily solve the problem. If the flow is efficient in the protostellar and early PMS stage, but not toward the end of the inner disk lifetime, there would still be a sufficient time period when gravitational torques from the CB disk are dominating other effects and threaten the very existence of the binary.

3.2. Eccentricity: Damped or Pumped up?

The eccentricity evolution is another important, not yet fully explored, effect that requires much future work. From the discussion of gravitational interactions in Lubow & Artymowicz (1996, 2000), it follows that the eccentricity driving in most binary star systems obeys the relation $e\dot{e} \simeq -(1/2)\dot{a}/a$, in good agreement with the SPH results, except in nearly circular systems with $e < 0.03$, where $\dot{e} \sim e$. Eccentricity has a maximum growth rate at $e = 0.03$ (for the assumed disk parameters), characteristic doubling timescale being only hundreds of orbit.

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[2] This may seem impossible, at first, but in fact it is not. Notice that the unperturbed disk around a single mass has very mild density gradients, while the edge of the CB disk has a steep equilibrium slope of surface density vs. radius, generating a larger viscous flux.

Various claims have been made in the past about not just the magnitude but the sign of $\dot{e}$ in different situations, e.g. for one Jupiter-mass body in a standard solar nebula (e.g., Artymowicz 1992, Lin & Papaloizou 1993). There is little doubt that small, terrestrial-sized, protoplanets have their orbits rapidly circularized, while brown dwarfs interacting with disks would have their eccentricity pumped up (Artymowicz et al. 1991) to at least intermediate e values of order 0.3 to 0.5, although adequate simulations of the upper limit of e are still to be performed (Lubow & Artymowicz 2000).

To find the so-called crossover mass and its dependence on disk viscosity will require refined, perhaps multigrid, numerical techniques (Artymowicz 1992 estimated it at 10 Jupiter masses in early SPH work; analytical arguments support this value for standard $\alpha \sim 10^{-2}$ disks, and a smaller mass for less viscous disks). One reason why the eccentricity damping is so important is that it bears upon the origin of the observed wide distribution of e among the secondaries in both PMS and MS systems, mentioned in the Introduction. Another is the recently discovered need for some form of efficient e-damping mechanism during the formation of giant planets in the outer Solar System (Levison, Lissauer, & Duncan, 1998). Perhaps the past binary-disk interaction has indirectly protected the Earth from the possible destabilization by eccentric/chaotic giant planets.

4. Conclusions

Perhaps the main conclusion from our brief review is that there is still much to do about the binary-disk interaction, in particular about the binary evolution, despite or maybe because of many recent developments in this field.

Observationally, it would be very interesting to look for some of the observable diagnostic features of binary-disk interaction and to try to directly detect the orbital evolution of at least the short-period systems.

Many of the orbital evolution effects are interconnected. For instance, it would be difficult to make progress on the orbital migration issue without finding out about eccentricity and mass flow features during migration. Multidimensional hydrodynamics seems the method of choice. However, we do not yet have numerical methods that allow us to study with adequate spatial resolution the long-term evolution of systems. Such systems may interact with disks over 10^6 orbits or longer. Analytical understanding of what dominates the simulated evolution of eccentricity is also fragmentary.

Finally, we should emphasize that for certain kinds of binaries, such as wide binaries (periods >100 yr) or binaries in near contact, physical interactions other than those discussed here could be dominant (for instance, stellar 3-body encounters in young star clusters, magnetic and tidal star-star interaction).

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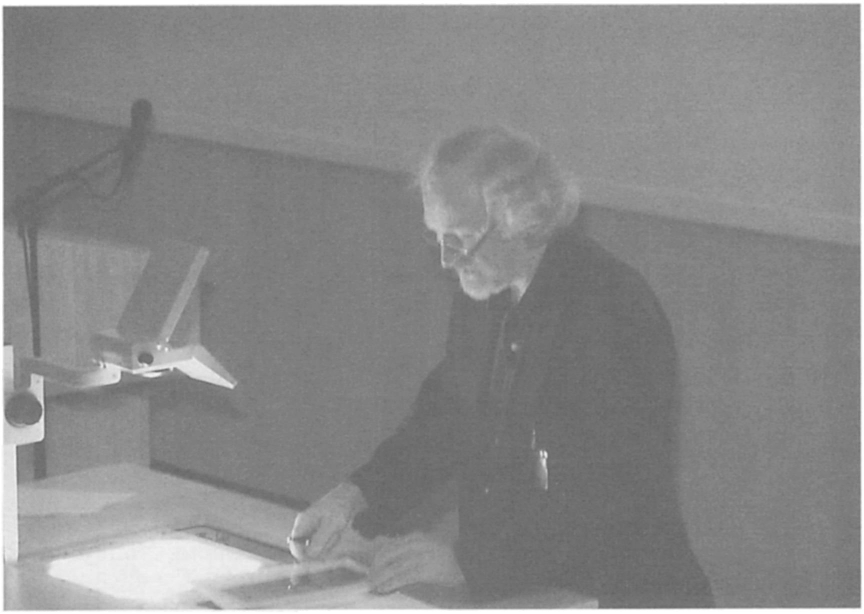
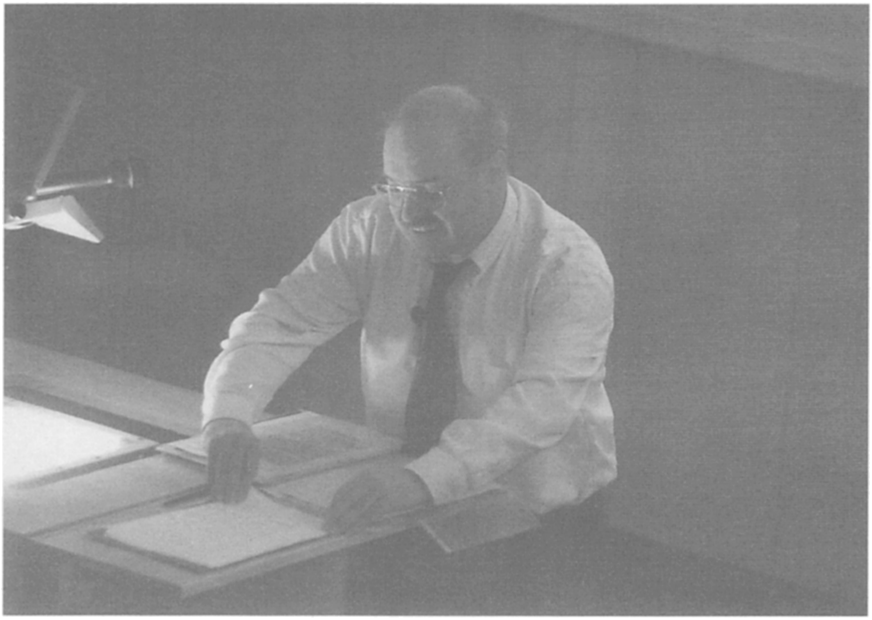
From left: Simon Portegies Zwart, Tsevi Mazeh, Pawel Artymowicz, Matthew Bate, Gibor Basri, Doug Lin and Frank Shu





top: Bo Reipurth (optical primary)
bottom: Hans Zinnecker (infrared secondary)