

Disks and Planets in Binary Systems

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Abstract. The star formation process in molecular clouds usually leads to the formation of multiple stellar systems, mostly binaries. Remaining disks around those stars may be located around individual stars (circumstellar disks) or around the entire binary system (circumbinary disk). We shall briefly review the present observational evidence for both types of disks in binary stars, in particular the properties of circumbinary disks.

We then present recent results of the theoretical modeling of the collapse and fragmentation of gravitationally unstable molecular cloud cores and their implications for binary and disk formation, and discuss the dynamical influence of the binary companions on disk truncation and gap formation. The presence of binaries may have profound influence on the process of planet formation as well. We present results on the stability and evolution of orbits of planets in disks around binaries.

1. Observational Properties

This contribution is dealing primarily with theoretical aspects, however for completeness, we summarize first some basic observational features of disks and planets in binary stars. An excellent recent review on this topic has been given at PPIV by Mathieu et al. (2000).

1.1. Binary Stars

The majority of stars is found in binary or multiple systems. To quantify the occurrence of multiplicity one usually defines the *Binary Frequency* (BF) as

$$BF = \frac{\text{Number of multiples}}{\text{Total Number of Systems}}$$

The seminal study of Duquennoy & Mayor (1991) found for field stars (not members of a stellar cluster) having an age larger than 1Gyr a binary frequency of $BF = 60\%$. The distributions of the orbital elements of binary stars such as a mass ratio q , periods P , or eccentricities e are typically very broad and they have mean values of

$$\langle q \rangle = 0.3$$

$$\langle \log(P[\text{days}]) \rangle = 5.0$$

$$\langle e \rangle = 0.5$$

For pre main-sequence stars one finds a bimodal binary frequency. Dense clusters in giant molecular clouds, such as the Trapezium cluster in Orion (with a stellar density of over 2000 stars per pc^3), tend to have a binary frequency similar to the field value, (60%). In low stellar density clusters (such as the Taurus or Ophiuchus T Tauri associations) the binary frequency is much higher than the field value, about 80 – 100% (Ghez et al. 1993, Leinert et al. 1993). This difference in the BF may be the result of several mechanisms the most important of which are (see Mathieu et al. 2000): a) observational effects due to incompleteness may lead to a wrong determination of the BF, b) evolutionary effects may change the BF with time, c) in higher density clusters more frequent stellar encounters may lead to the disruption of systems and a lowering of the BF, and d) the BF may just depend on the environment, such as the temperature or density of the cloud core.

From these results one may infer that most of the field stars originated in dense clusters.

1.2. Disks in Binaries

The classical signatures for the presence of disks around stars are an excess in IR to mm radiation, Balmer and forbidden lines, polarization, and optical veiling, see contribution by L. Hartmann (this volume).

Disks in binary star systems may be divided into two main configurations 1) In the case of a *Circumbinary Disk* the complete binary system is surrounded by a disk which may have in inner clearing. 2) If the two disks surround each component of the binary individually the situation is similar to single stars and one refers to this configuration as *Circumstellar Disks*

The *mm-flux* from systems gives an indication for the mass of the disk. For binaries with larger separations ($d > 100AU$) and for spectroscopic binaries ($d < 1AU$) the mm-flux is similar to the field value. This indicates that in the first case (large separations) the two stars are surrounded individually by circumstellar disks behaving just as disks around unperturbed single stars. In the second case (very close stars) the system is surrounded by one circumbinary disk which, when observed from far away, resembles a disk around one single star.

In binaries with intermediate orbital separations d between 1 and 100 AU the mm-flux is mostly undetected, which may indicate that in this case the binary system has neither extended circumstellar disks, as a consequence of the gravitational disturbance of the companion, nor luminous circumbinary disks. However, there are classical TTau signatures for disks with $d = 10 - 100AU$.

Additionally, speckle and mid-IR observations give evidence for circumstellar disks around the stars HK Tau, HR 4796A, or GG Tau3.

The most prominent observational example of a circumbinary disk is presented by GG Tau, where the disk has been directly imaged in the CO 1.3mm line (Guilloteau 1999), in the J-Band at $1.2\mu m$ (Roddier et al. 1996) and in the optical. The central binary system consists of two stars with a total mass of $1.3M_{\odot}$ at a separation of $d = 45AU$, which are surrounded by a disk with an inner radius of $r_{disk} = 180AU$. The inferred mass of the disk (ring) is about $0.12M_{\odot}$. Additional systems with imaged circumbinary disks are UY Aur and BD+31°643.

In several spectroscopic binaries (eg. UZ Tau, DQ Tau or GW Ori) mm-observations have indicated disk masses of about 0.03 to $0.05M_{\odot}$. At the same time there is evidence for inner disk clearing (lack of near IR-emission), but there are signs for hot gas near the stars which may indicate the flow of material through the cleared inner disk (leaking gaps).

An interesting example of the simultaneous occurrence of circumstellar and circumbinary disks in a quadruple system is given by UZ Tau (Jensen et al. 1996).

1.3. Planets in Binaries

Among the known 32 extrasolar planets around main sequence stars three (16 Cyg B, 55 Cnc, τ Boo) are definitely known to be in binary systems with relatively wide orbital separations (see table 1). Additionally, in one system (Gl 86) there is some evidence for a stellar companion with a distance which may be as close as $10AU$. It has been argued that the high eccentricity of 16 Cyg B

Table 1. The Properties of known planets in binary stars

Parameter	16Cyg B	55 Cnc	τ Boo	Gl 86
Binary d (AU)	700	1150	240	> 10
M $\sin i$ (M_J)	1.5	0.84	3.87	4
Planet a (AU)	1.72	0.11	0.046	0.11
Planet e	0.63	0.05	0.02	0.04

may be caused by the presence of a companion star. However, as the ratio of distance d of the secondary over the semi-major axis a of the planets falls into the range

$$\frac{d}{a} = 400 - 10000$$

the companion has basically no influence on the eccentricity of the planet.

2. Star Formation

The observational evidence strongly suggests that binary formation is closely related to the star formation process. Stars form in dense molecular cloud cores (Myers, 1985, 1987) with scales of order 0.1 pc, masses in the range of a few solar masses, number densities of order $10^4 - 10^5 \text{ cm}^{-3}$ and temperatures of 10 K. In general, pre-stellar cores appear to be elongated and irregular. They are centrally condensed with Gaussian or power-law density distributions (Ward-Thompson et al. 1994; Henriksen et al. 1997). Rotation has been detected in about 50% of all cases with values for the angular velocity ranging between $\Omega \approx 10^{-13} - 10^{-15} \text{ s}^{-1}$ (Goodman et al. 1993).

The initial conditions for protostellar collapse could be strongly affected by magnetic fields, which can support the cores against collapse. In magnetically subcritical cores, ambipolar diffusion (Shu et al. 1993) leads to central contraction and the formation of an r^{-2} -density distribution at which point the core

experiences an inside-out collapse. If the initial conditions are produced in this manner, numerical simulations have shown that the core would not fragment, leading to the formation of single stars (Myhill & Kaula 1992) Binary formation

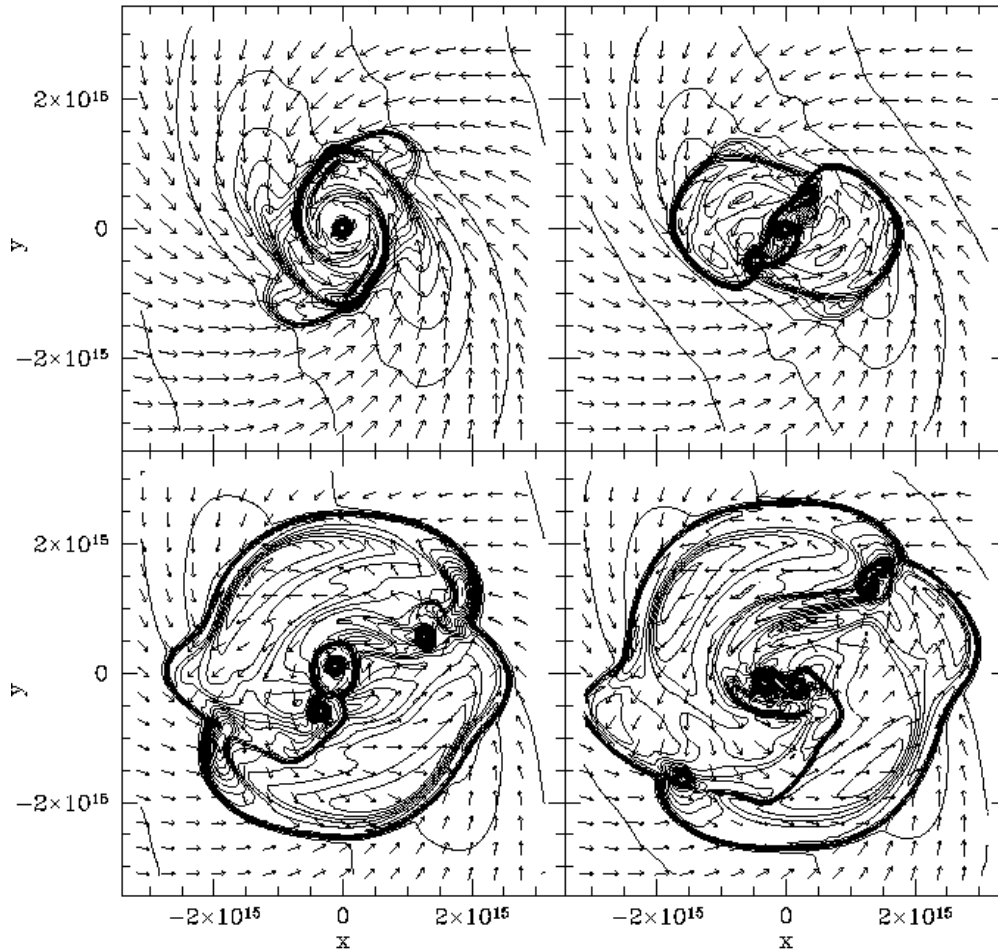


Figure 1. Evolution of a collapsing gas cloud with an initial power-law density distribution. Logarithmically spaced contours of equal density and velocity vectors in the equatorial plane are shown for the innermost region (outer cloud radius: 5×10^{16} cm). The maximum density is 10^{-10} g cm $^{-3}$, the maximum velocity is 3×10^5 cm s $^{-1}$.

results from the fragmentation of magnetically supercritical cores. A wide variety of (often idealized) initial conditions has been explored numerically, adopting 3-dimensional hydrodynamical codes, for example, a sphere (constant density or centrally condensed) in uniform rotation with a density perturbation in the form of an $m=2$ mode (Burkert & Bodenheimer 1993, 1996; Truelove et al. 1997), or elongated cylindrical, rotating clouds (Boss 1996, Bonnell et al. 1992). Most of these calculations treated the isothermal collapse phase. Radiation has been

included in some simulations adopting simplified approximations (Boss 1993, Myhill & Kaula 1992).

In general, the resulting fragmentation process occurs in various modes. The most simple cases are non-linear initial density perturbations which lead to fragmentation into wide binaries with separations of order 100 - 1000 AU during the early collapse phase (Bonnell et al. 1992, Monaghan 1994). In this case, the result depends strongly on the adopted initial conditions.

Fig. 1 shows the collapse of a centrally condensed gas cloud with a linear $m=2$ density perturbation (Burkert et al. 1997). In this case, the perturbation has not enough time to grow and become non-linear during the early gravitational collapse phase. The gas instead settles into a rotationally supported, partly self-gravitating protostellar disk. The subsequent evolution of the disk depends critically on its temperature (Bate & Burkert 1997, Boss et al. 2000). If the transition from the optically thin to the optically thick regime occurs before disk formation, fragmentation will be inhibited. Otherwise strong spiral arms form around a central condensation which continually wrap-up, interact and reform because of differential rotation. Ultimately, density maxima appear at the ends of the arms, leading to a binary around the central object. As higher angular momentum material falls in, spiral arms extend beyond the triple system which rapidly breaks up into a hierarchical triple. Further fragmentation occurs in the outer parts of the disk. The multiple system will ultimately break-up into single stars and eccentric binaries with wide period distributions.

3. Influence of Companions on Disks

Let us first consider the case of a disk surrounding one star (circumprimary disk) which is orbited by another secondary star. The presence of a companion excites tidal waves in the disk which carry angular momentum and energy (see eg. Lin & Papaloizou 1995, and contribution by C. Terquem, this volume). If the disk lies inside the orbit of the companion the wave will carry negative angular momentum because the companion has a smaller orbital velocity than the disk material. Dissipation of the wave, for example through shock waves, will slow down the matter in the disk and lead to an inward drift of the material. This truncates the outer edge of the disk.

In case of a binary star within a circumbinary disk, the torques created by the binary lead to angular momentum transfer from the binary's orbit to the disk, and eventually to an inward truncation or clearing of the inner disk (gap formation).

The location of this (inner and outer) truncation radius is determined by the balance of viscous (gap-closing) and gravitational (gap-opening) torques. In linear theory the gravitational potential is expanded into a Fourier series and for each component the effect on the disk is determined. For the general case of a companion on an eccentric orbit this analysis has been performed for circumprimary and circumbinary disks by Artymowicz & Lubow (1994).

Their main results are displayed in Fig. 2. The label $\mu = 0.3$ refers to the reduced mass $\mu = M_2/(M_1 + M_2)$. In case of the circumprimary disk a larger viscosity (lower Reynolds number) leads to a larger truncation radius r_t while for a circumbinary disk it reduces the truncation radius. For typical values

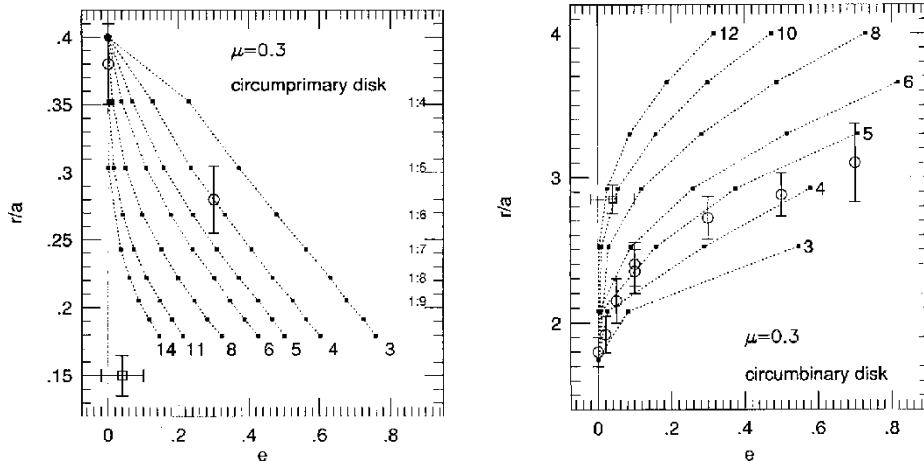


Figure 2. The truncation radius of the disk in units of the semi-major axis of the binary for a mass ratio $q = M_2/M_1$, and an eccentricity $e = 0.5$. Different values of the viscosity are labeled by the logarithm of the Reynolds number in the disk. Adapted from Artymowicz & Lubow (1994).

of protostellar disks $Re \approx 10^5$, and for typical binary parameter (see above, $q = 0.5$, $e = 0.5$) we obtain for the circumprimary disk $r_t/a = 0.17$ and for the circumbinary disk $r_t/a = 3.0$.

4. On the Formation of Planets in Binaries

In this final section we consider the restrictions the presence of a secondary companion has on the efficiency of planet formation. The secondary acts as a perturber for the disk and alters directly the environment in which planets form.

4.1. Planetesimal disk

The influence a secondary has on the growth process from planetesimals to planetary embryos was studied by Heppenheimer (1978) and Whitmire (1999). They considered a planetesimal disk at runaway phase where collisions and subsequent merging between different particles lead to a rapid growth. The collisions are only non-destructive if the relative velocities U_{rel} are smaller than a critical value $U_{crit} = 100m/s$.

They integrated a 4-body system consisting of 2 stars and 2 planetesimals using a symplectic mapping procedure and an integration time over a few $10^4 yrs$. For different physical parameter, varying the semi-major axis of the binary stars, their eccentricities, mass ratios, and the initial separation in semi-major axis $\Delta a_0 = 0.001 - 0.01 AU$ of the planetesimals, they analyzed if U_{rel} was exceeding U_{crit} . They deduced a critical semi-major axis below which the disturbing companion does not allow for sticking (growing) collisions. Their main results are summarized in Fig. 3 where the critical semi-major axis is plotted for an equal mass binary versus eccentricity. If the separation of the binary falls below

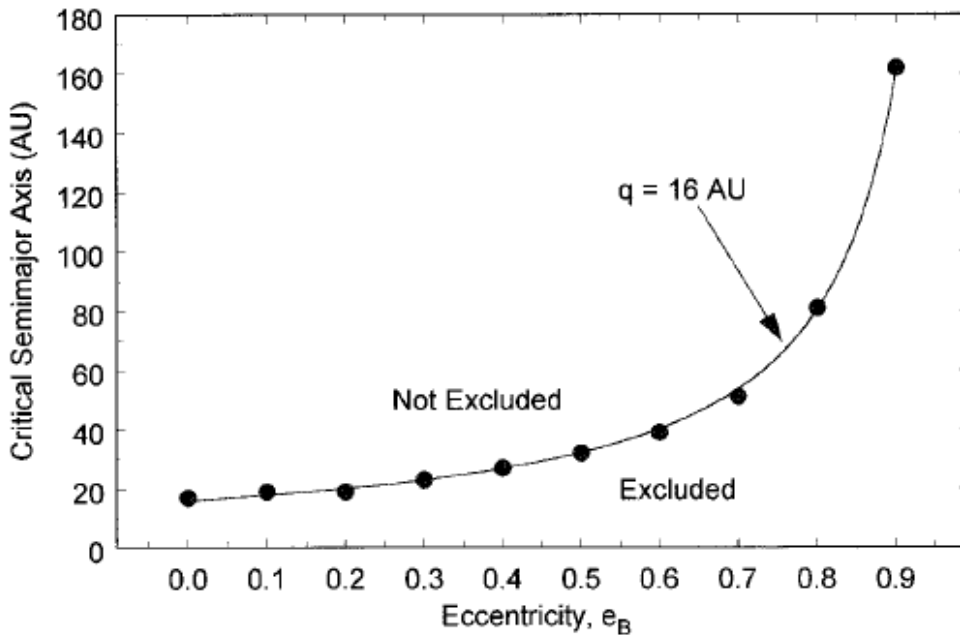


Figure 3. Critical semi-major axis for which collisions between planetesimals are too large to allow for particle growth. The mass of the central star was $1M_{\odot}$, the mass-ratio $q = 1.0$, and the initial semi-major axis of the planetesimals was $1AU$. Adapted from Whitmire et al. (1999).

the curve the induced relative velocities are too large and planetesimals cannot grow. The results are normalized to the initial mean separation $\bar{a} = 1AU$ of the planetesimals. The results of the numerical computations are given by the black dots, and the solid curve gives the location where, for the given eccentricity, the minimum separation (peri-astron) of the stars is exactly 16 AU.

The result implies that for a one-solar mass star the minimum distance to an orbiting companion, such that planetesimals at 1AU can grow to larger bodies, must always be larger than 16 AU. The critical semi-major axis scales only weakly, $a_{crit} \propto (\bar{a}/AU)^{0.8}$, with distance from the star.

4.2. The case of L 1551

Another path of studying the formation of planets in binary stars was taken by A. Nelson (2000), who studied the interaction of two binary stars each of which is surrounded by its own circumstellar disk. The physical motivation is based on the radio (VLA) observations of the system L1551 (Rodriguez et al. 1998), which consists of a binary system of two half solar mass stars separated by $50AU$.

This system is modelled numerically by solving the full hydrodynamic equations for the two disks using the method of Smoothed Particle Hydrodynamics

(SPH), where the continuum equations are modelled by an ensemble of interaction particles.

Each disk is modelled by 60,000 particles. The model includes the self-gravity of the disks, an ideal equation of state, dissipative heating and radiative cooling.

During the evolution the initially axisymmetric disks (with respect to their central stars) are strongly perturbed at the time of periaapse. Spiral waves are induced in them and they are tidally truncated. At times of apoapse the spiral features tend to disappear and the disks become more axisymmetric again. These periodic changes of the distortions alter the internal structure of the disk as well. The question arises what influence do these changes have on the planet formation process. Planet formation is believed to proceed along two different lines: **a)** Through gravitational collapse of a spiral structure. Instability is given when the so called Toomre parameter Q , which measures the importance of pressure versus gravity, becomes (locally) smaller than unity. Then pressure forces are not sufficient to prevent gravitational collapse. **b)** Through coagulation of solid material and subsequent gas accretion. As can be inferred from Fig. 4 the Q -parameter is always much larger than 1, indicating a gravitationally stable disk. On the other hand, the temperatures in the disk during periaapse are so high that even the most abundant species (water ice) cannot condense to form the seeds for further growth of the planetesimals.

Hence, from the computations one may conclude that, at least for these chosen parameters of the disks, planet formation is inhibited in binary stars. One has to keep in mind however, that the heating and cooling of the disk is treated still approximative and the calculations are only two-dimensional. For larger orbital separations of a few hundred AU say, the effects of the secondary become smaller and planet formation will not be affected.

4.3. Stability of Orbits

An important pre-requisite for the formation of planetesimals is the long term stability of their orbits. Dvorak (1986) and Holman & Wiegert (1999) have studied the restricted 3-body problem, in which the planet is treated as a test particle in the potential of two orbiting stars. As for this problem no analytic description of the orbital evolution of the planet exists they perform numerical integrations using a symplectic mapping or Bulirsch-Stoer integrator. The total integration time covers more than 10^4 orbits of the planet. The mass ratio of the stars, their eccentricity and semi-major axis are varied. The critical distance a_{crit} a planet must have to be on a stable orbit is determined as a function of these orbital parameter of the binary star.

Two different configurations of orbits have been studied. Following the designation of Dvorak (1986), the first are planetary or P-type orbits which are well outside the binary. The second type studied are S-type orbits, where the planet orbits near one of the stars, with the second star to be considered as a perturber. For P-type orbits there exist a minimum a_{crit} a planet must have to be on a stable orbit around the binary. For S-type orbits there is a maximum a_{crit} such that the perturbations of the perturber remain finite. The S-type orbits are certainly more relevant to the properties of the observed extrasolar planets (see table 1).

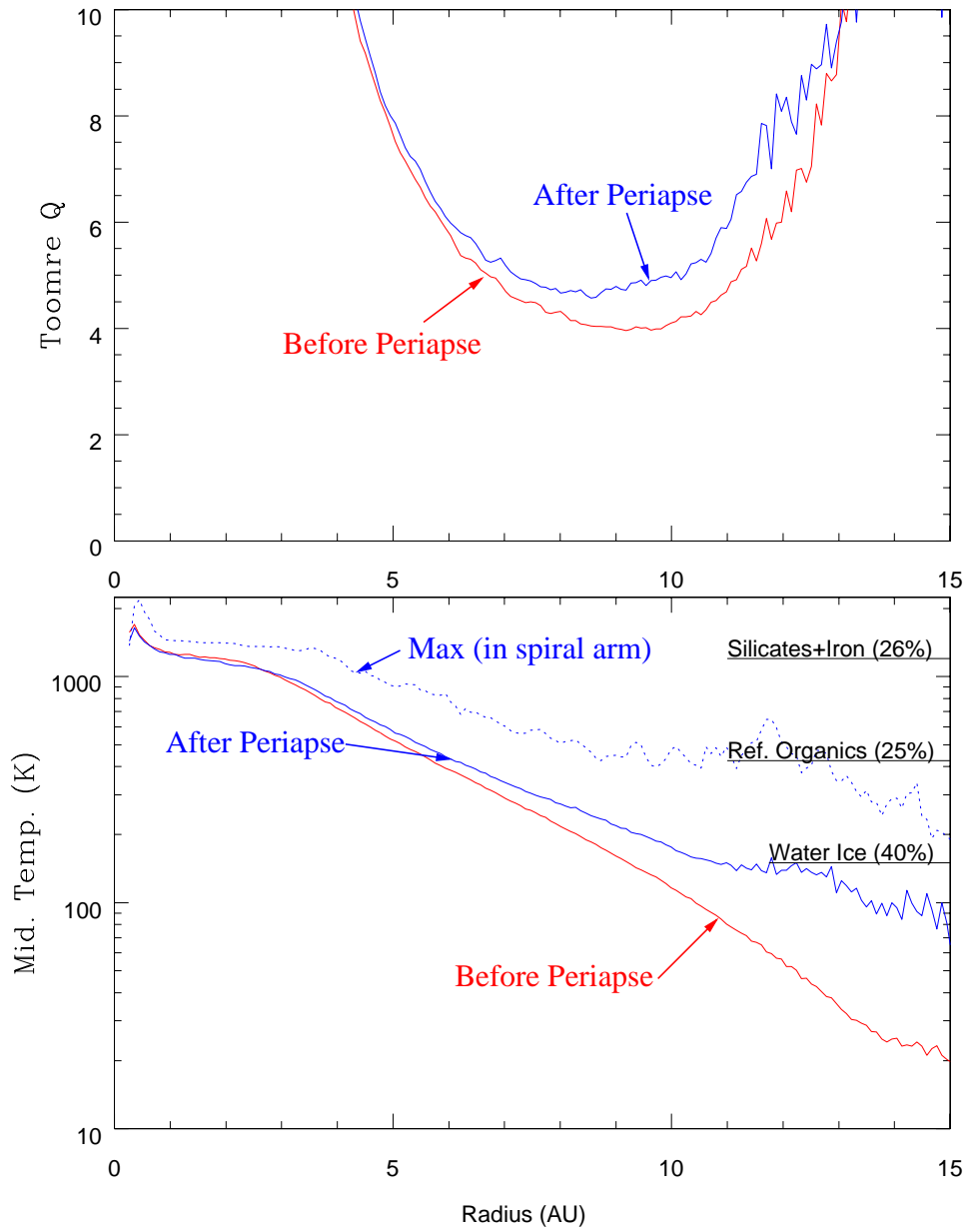


Figure 4. Azimuthally averaged Toomre-parameter Q (top) and the midplane temperature in the disk versus radius. Indicated are the vaporization temperatures of various species.

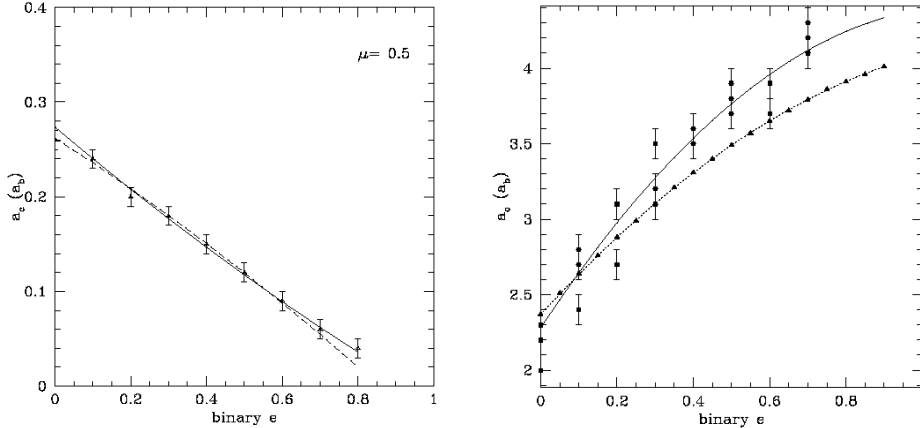


Figure 5. Critical semi-major axis for an equal mass binary. After Holman & Wiegert (1999). **Left:** For S-type orbits. Separations smaller than the solid curve (which is a fit the numerical data points) are stable. **Right:** Evolution of the mass (bottom) and semi-major axis (top) of P-type orbits. Separations above the solid curve are stable.

The main results are displayed in Fig. 5 where, for an equal mass binary, the critical distance (in units of the semi-major axis of the binary star system) is given as function of eccentricity. For an average eccentricity of $e = 0.5$ one finds for S-type orbits $a_{crit} \approx 0.14$. All observed extrasolar planets have semi-major axis well below this limit. For P-type orbits the minimum distance a planet must have from the binary is $a_{crit} \approx 3.6$. This value lies beyond the inner truncation radius of a circumbinary disk ($r_{gap} = 3.0$).

4.4. The evolution of an embedded planet in a binary star

Another approach to analyze the influence of a companion on the formation of a massive planet has been taken by Kley (2000) who studied the evolution of a massive planet still embedded in a protoplanetary disk.

A planet with the mass $1M_{Jup}$ is placed initially on a circular orbit around a $1M_{\odot}$ star at a distance of $a_J = 5.2AU$. The surrounding protostellar disk has a mass of $M_d = 0.01M_{\odot}$ within $1 - 20AU$, a surface density profile $\Sigma(r) \propto r^{-1/2}$, and a Reynolds number of 10^5 . The *secondary* has a given fixed mass of $M_2 = 0.5M_{\odot}$ and an eccentricity of $e_2 = 0.5$. The semi-major axis a_2 of the secondary is varied from about 50 to 100 AU for different models. To minimize initial disturbances, the secondary is placed at apastron in the beginning.

During the evolution, the planet may accrete material from the disk and increase its mass. At each timestep the gas density in the inner half of the Roche lobe is reduced by a given fraction. Initially, the disk is axisymmetric with respect to the primary star and has a gap imposed to speed up the computations (Kley 1999; Lubow, Seibert & Artymowicz 1999).

In the presence of the secondary the disk becomes truncated at the outer radius. At the same time the planet will truncate the disk from the inner side such that the disk material will be confined to a narrow ring (see Fig. 6). The

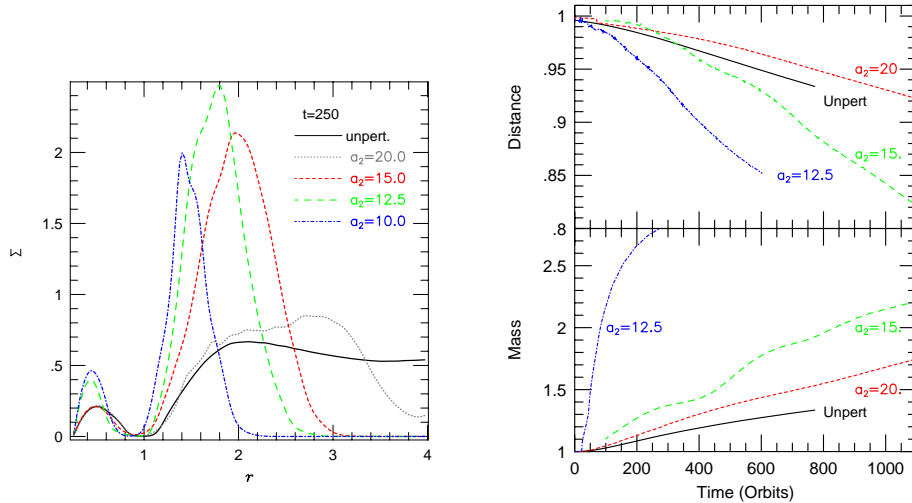


Figure 6. **Left:** Azimuthally averaged surface density for models with varying distance (a_2) of the secondary, given in units of the planetary distance ($5.2AU$), after 250 orbits of the planet. The solid black line indicates the initial surface density profile. **Right:** Evolution of the mass (bottom) and semi-major axis (top) of the planet. The evolution of an unperturbed planet (i.e. no secondary star) which is described in detail in Nelson et al. (2000) is given by the solid lines (denoted "Unpert").

obtained values for the outer truncation radius agree favourably with the value $r_r/a = 0.17$ as obtained above. The very steep density and pressure gradient near the planet lead to an increased mass accretion rate onto the planet, and to a faster inward migration, cf. Fig. 6.

The reduced migration time may then also reduce the growth of a protoplanet and planet formation will again be inhibited by the presence of a companion.

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