THE FORMATION OF MASSIVE PLANETS IN BINARY STAR SYSTEMS

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Abstract. As of today over 40 planetary systems have been discovered in binary star systems. In all cases the configuration appears to be circumstellar, where the planets orbit around one of the stars, the secondary acting as a perturber. The formation of planets in binary star systems is more difficult than around single stars due to the gravitational action of the companion on the dynamics of the protoplanetary disk. In this contribution we first briefly present the relevant observational evidence for planets in binary systems. Then the dynamical influence that a secondary companion has on a circumstellar disk will be analyzed through fully hydrodynamical simulations. We demonstrate that the disk becomes eccentric and shows a coherent precession around the primary star. Finally, fully hydrodynamical simulations of evolving protoplanets embedded in disks in binary star systems are presented. We investigate how the orbital evolution of protoplanetary embryos and their mass growth from cores to massive planets might be affected in this very dynamical environment. We consider, in particular, the planet orbiting the primary in the system \( \gamma \) Cephei.

1 Observational Data

Planet formation is obviously a process that occurs around single as well as in multiple star systems, a fact that is indicated by the detection of well over 40 planetary systems that reside in a binary or even multiple star configurations. All of the observed systems display a so called S-type configuration in which the planets orbit around one of the stars and the additional star, the companion or secondary star, acts as a perturber to this system. In this review we shall refer to the secondaries as single objects, even though they may be multiple. As indicated in Table 1 the distances of the secondaries from the host stars of the planetary systems range from very small values of about 20 AU for Gl 86 and \( \gamma \) Cep to several thousand AU. There are now 4 confirmed systems with a binary separation in the...
The mere existence of these 4 systems represents a special challenge to any kind of planet formation process, due their tightness. Interestingly, there appears to be a lack of planets for intermediate separations as there are no planets in binaries with separations between 20 and 100 AU. There are many more systems with larger separations (not listed in the table), but in most of the cases only projected distances can be given, and the real physical separations are necessarily larger.

| Star       | a_{bin} [AU] | a_p [AU] | M_p sin i [M_Jup] | e_p | Remarks |
|------------|--------------|----------|-------------------|-----|---------|
| HD 40979  | 640          | 0.811    | 3.32              | .23 |         |
| Gl 777 A  | 3000         | 3.65     | 1.15              | .48 |         |
| HD 80606  | 1200         | 0.439    | 3.41              | .93 |         |
| 55 Cnc B  | 1065         | 0.1-5.9  | 0.8-4.05          | .02-.34 | multiple |
| 16 Cyg B  | 850          | 1.66     | 1.64              | .63 |         |
| v And     | 750          | 0.06-2.5 | 0.7-4.0           | .01-.27 | multiple |
| HD 178911 B | 640      | 0.32     | 6.3               | .12 |         |
| HD 219542 B | 288       | 0.46     | 0.30              | .32 |         |
| τ Boo     | 240          | 0.05     | 4.08              | .02 |         |
| HD 195019 | 150          | 0.14     | 3.51              | .03 |         |
| HD 114762 | 130          | 0.35     | 11.03             | .34 |         |
| HD 19994  | 100          | 1.54     | 1.78              | .33 |         |
| HD 41004A | 23           | 1.33     | 2.5               | .39 | multiple |
| γ Cep     | 20.2         | 2.04     | 1.60              | .11 | e_{bin} = 0.4 |
| HD 196885 | 17           | 2.63     | 2.96              | .46 | e_{bin} = 0.4 |
| Gl 86     | 20           | 0.11     | 4.0               | 0.046 | White Dwarf |

Table 1. Some observed planets in binary star systems. This is a selection with emphasis on the shorter period binaries (see Eggenberger et al. (2004); Raghavan et al. (2006); Correia et al. (2008)). The list is very incomplete for larger separations.

Despite the actual detection of planets in binary systems there is additional circumstantial evidence of debris disks (which are thought to be a byproduct of the planet formation process) in binary systems as indicated by Spitzer data. Here, for S-type configurations it is found that disks around an individual star of the binary exist mainly for binary separations larger than 50 AU, while P-type circumbinary debris disks are detected only in very tight binaries with a_{bin} smaller than about 3 AU (Trilling et al. (2007, 2008); Zuckerman et al. (2008)).

As first pointed out by Eggenberger et al. (2004), see also these proceedings, there is statistical evidence for two interesting features in the mass-period and eccentricity period distribution of planets residing in binary systems: planets with periods smaller than about 40 days tend to have larger masses than their counterparts in single star systems, while at the same time their eccentricities are smaller. This trend has been supported by the more recent findings of Desidera & Barbieri (2007) who tried to correlate this with the tightness of the binary, but the statistics...
are still based on small sample sizes and more data are required.

As the influence of the secondaries on the planet formation process will obviously be smaller for larger distances, we shall focus in this contribution on the more challenging tighter binaries and have used the physical parameters of the γ Cep system for our models. Interestingly, γ Cep was one of the very first stars which has been suggested to contain an extrasolar planet (of 1.7 M\textsubscript{Jup}): “This star has the firmest evidence of a very low mass companion” (Campbell et al., 1988). A statement unfortunately retracted later by the same team (Walker et al., 1992), only to be rediscovered by Hatzes et al. (2003). Today, this system is one of the tightest binary system known to contain a Jupiter-sized protoplanet. For this reason, it has attracted much attention in past years. Several studies looked at the stability and/or the possibility of (additional) habitable planets in the system (Dvorak et al. 2004; Turrini et al. 2004; Haghighipour 2006; Verrier & Evans 2006). In our studies we have taken the data for γ Cep from Hatzes et al. (2003). The more recent data by Neuhäuser et al. (2007) only slightly change the dynamical status.

2 Constraints on the planet formation process in binary star systems

In a binary star system, the tidal torques of the companion generate strong spiral arms in the circumstellar disk of the primary and angular momentum will be transferred to the binary orbit which in turn leads to a truncation and restructuring of the disk. The truncation radius \( r_t \) of the disk depends on the binary separation \( a_{\text{bin}} \), its eccentricity \( e_{\text{bin}} \), the mass ratio \( q = M_2/M_1 \) (where \( M_1, M_2 \) denote the primary and secondary mass, respectively), and the viscosity \( \nu \) of the disk. For typical values of \( q \approx 0.5 \) and \( e_{\text{bin}} = 0.3 \) the disk will be truncated at a radius of \( r_t \approx 1/3a_{\text{bin}} \) for disk Reynolds numbers of \( 10^5 \) (Artymowicz & Lubow 1994; Armitage et al. 1999). For a given mass ratio \( q \) and semi-major axis \( a_{\text{bin}} \) an increase in \( e_{\text{bin}} \) will reduce the size of the disk while a large \( \nu \) will increase the disk’s radius.

Whether these changes in the disk structure have an influence on the likelihood of planet formation in such disks has been a matter of debate. However, the dynamical action of the secondary induces several consequences which appear to be adverse to planet formation: i) it changes the stability properties of orbits around the primary, ii) it reduces the lifetime of the disk, and iii) it increases the temperature in the disk.

Using numerical hydrodynamical studies, Nelson (2000) argued that both main scenarios of planet formation, i.e. core accretion and gravitational instability, are strongly handicapped, because an eccentric companion may induce a periodic heating of the disk up to temperatures above the sublimation point of solids. Since the condensation of particles as well as the occurrence of gravitational instability require lower temperatures, planet formation will be made more difficult in both scenarios. Numerical studies of the early planetesimal formation phase in rather close binaries with separations of only 20–30 AU show that it is indeed possible to form planetary embryos in such systems (Lissauer et al. 2004; Turrini et al. 2005).
Quintana et al., 2007). Clearly, the possibility of embryo formation will depend strongly on the binary orbital elements, i.e. \(a_{\text{bin}}\) and \(e_{\text{bin}}\) and its mass ratio \(q\).

Already in ordinary planet formation around single stars, the lifetime of the disk represents a limiting factor in the formation of planets from the disk. It has been suspected that the dynamical action of a companion will limit the lifetime of disks substantially and place even tighter constraints on the possibility of planet formation. However, a recent analysis of the observational data of disks in binary stars finds no or very little change in the lifetimes of the disks, at least for separations larger than about 20 AU (Monin et al., 2007).

In summary, in a binary star system the formation of planets is altered and most likely is handicapped due to the dynamical action of the companion and the subsequent change in the internal structure of the protoplanetary disks.

3 Disk evolution in binary stars

In the first study on the evolution of embedded Jupiter type protoplanets in disks in binary stars it was found that migration and mass growth occur faster in tighter binaries (Kley, 2001). Even though this finding is in rough agreement with the aforementioned statistical evidence from the mass-period and eccentricity-period distributions, the simulations are unrealistic in the sense that they start from the artificial condition of unperturbed initial disks. However, before inserting the planet into the disk it is necessary to first relax the disk in the binary to its equilibrium configuration in the presence of the secondary. This makes sure that the planetary evolution is not spoiled by long term transients due to the dynamical influence of the secondary star. In this section we present the result of this equilibration process of disks in binaries without embedded planets, with more details laid out in Kley & Nelson (2008).

We have chosen a binary with parameters very similar to the \(\gamma\) Cephei system. Specifically, we use \(M_1 = 1.59 M_\odot\), \(M_2 = 0.38 M_\odot\), \(a_{\text{bin}} = 18.5\) AU and \(e_{\text{bin}} = 0.36\), which translate into a binary period of \(P = 56.7\) yr. The primary star is surrounded by a flat circumstellar disk, where the binary orbit and the disk all lie in one plane, i.e. they are coplanar. The typical dynamical timescale in the disk, the orbital period at a few AU, is substantially shorter than the binary period, but in a numerical simulation the system’s evolution can only be followed on these short dynamical time scales. To simplify the simulations we assume that the disk is vertically thin and perform only 2D hydrodynamical simulations of an embedded planet in a circumstellar disk which is perturbed by the secondary. The disk is assumed to be non-selfgravitating. We assume that the effects of the intrinsic turbulence of the disk can be described approximately through the viscous Navier-Stokes equations, which are solved by a finite volume method (code RH2D) which is second order in space and time (Kley, 1999). Finally, we assume that the disk is locally isothermal where the ratio of the vertical thickness \(H\) to the distance \(r\) from the primary is constant, with \(H/r = 0.05\). For the viscosity an \(\alpha\) type parameterization is used with \(\alpha = 0.02\).

In the runs presented here the computational domain covers a radial range from
Fig. 1. The numerical setup for simulations of disks in a binary star system. Here the binary parameters are $M_1 = 1.59 M_\odot$, $M_2 = 0.38 M_\odot$, $a_{\text{bin}} = 18.5$ AU and $e_{\text{bin}} = 0.36$. For the disk, the radial grid extends from 0.5 to 8.0 AU. The left position of the secondary refers to the semi-major axis distance, the right to the periastron.

Fig. 2. Azimuthally averaged disk structure at different evolutionary times given in binary orbits. On the left the azimuthally averaged surface density $\Sigma(r)$ is displayed and on the right the mean disk eccentricity at each radius, $e_{\text{disk}}(r)$ is shown.

0.5 to 8 AU, and 0 to $2\pi$ in azimuth. This is covered with an equidistant $300 \times 300$ grid. The numerical setup is displayed in Fig. 1. To allow for parameter studies we have found it highly useful to increase the performance of the code and have implemented the FARGO-algorithm to our code RH2D which is especially designed to model differentially rotating flows. For our chosen radial range and grid resolution
we find a speed-up factor of about 7.5 over the standard case. Then, applying a Courant number of 0.75, about 160,000 timesteps are still necessary for only 10 binary orbits using our setup, and we require hundreds of orbits. (Masset, 2000).

In Fig. 2 we display the end result of such an initial settling of the disk in γ Cep with no embedded planet. The disk is truncated very early in the simulations (in fact, after one or two binary orbits) and then re-adjusts as a whole on longer, viscous timescales to reach equilibrium at around 60–70 binary orbits. The disk is still perturbed periodically at each orbit due to the eccentric orbit of the secondary. At around each periastron strong spiral arms appear in the disk which are then damped until apoastron. However, the azimuthally averaged density structure at $t = 80$ and $t = 100$ no longer changes. During the process of equilibration the average eccentricity of the disk, $e_{\text{disk}}$, settles to a value of about 0.1–0.15 in the most massive part of the disk. The eccentricity remains high only in the outer, low-density parts of the disk, where this is caused by the secondary.

In Fig. 3 the time evolution of the global disk eccentricity and periastron are displayed. In the presence of the companion the disk attains a non-zero eccentricity which oscillates about 0.12 and the disk as a whole experiences a coherent slow retrograde precession with a period of about 700 years or 14 binary orbits. The generation of a finite, non-zero disk eccentricity and precession is not restricted to the existence of an eccentric binary orbit but also occurs in circular systems, driven by an eccentric disk instability (Lubow, 1991). The conditions for the eccentricity growth have been analyzed for a wider parameter range more recently by Kley et al. (2008). The direction and rate of the disk precession are determined by the disk temperature, i.e. by the (relative) scale height $H/r$. With respect to the γ Cephei system this feature has been described by Paardekooper et al. (2008), Kley & Nelson (2008).
4 Evolution of protoplanets in disks

![Graph showing evolution of semi-major axis and eccentricity for different setups.](image)

**Fig. 4.** Evolution of the semi-major axis and eccentricity for fiducial models where either the disk or the binary have been switched off individually to test their influence separately. The models that include the eccentric disk (here $h26$: standard; $h26a$: no secondary eccentric disk) display the fastest growth in the planetary eccentricity.

The final two-dimensional density structure of the above equilibration process (here at time $t = 100$ binary orbits) is then used as the initial condition for the embedded protoplanet simulations. The total mass of the disk is rescaled to $3M_{\text{Jup}}$ and the planet of $36M_{\text{Earth}}$ is placed on a circular orbit at a given semi-major axis (distance) from the primary star, ranging from $2.0\text{AU}$ to $3.5\text{AU}$.

After inserting the protoplanet on a circular orbit at $2.5\text{AU}$ we generally expect that, in addition to the typical planet-disk interaction, its orbital elements will change due to the gravitational influence of the binary and the distorted disk. To differentiate the different contributions we have decided to check the origin of the dynamical behavior for a non-accreting planet, through a variation of physical conditions. The standard model resembles the true physical situation where the planet feels the full influence of the binary and the disk which is perturbed by the binary. In the other setups we switch the various contributions on and off. The results, displayed in Fig. [4](image) show that the main contributor to the initial growth of planetary eccentricity $e_p$ is the eccentric disk and clearly not the eccentric binary, for more details see [Kley & Nelson (2008)](#).

4.1 Evolving planets without mass accretion

Planetary cores form in the outer cooler regions of protoplanetary disks beyond the so called ice-line. However, in a binary star system the outer disk is affected most by the secondary, and to find possible restrictions on the planet forming regions
in the disk it is important to analyze the evolution of cores near the outer parts of the disk. To study the effect of initial position we start our embryos at different locations in the disk between 2.5 and 3.5 AU, always on a circular orbit, and again choose non-accreting cores. Because the initial characteristic growth time of the cores may be long, even in comparison to the orbital period of the binary, this set of runs constitutes a test suite to estimate the orbital evolution of small protoplanets in the disk. The results for the semi-major axis and eccentricity evolution of the 36\(M_{\text{Earth}}\) planet are displayed in Fig. 5 where the only difference in the four cases is the release distance of the planet. From all four locations the planet migrates inwards at approximately the same rate with the tendency for a slow down for the two outer cases. However, the different initial starting radii lead to a very different eccentricity evolution. Only the two innermost cases (starting at 2.5 and 2.7 AU) show weak eccentricity evolution, the two outer cases display a very strong increase in their eccentricity beyond \(e_p = 0.5\) after about 55 binary orbits. Clearly, the strongly disturbed disk in the outer regions at around 4 AU significantly perturbs the orbits of the protoplanet and initially induces such high eccentricities that the resulting elongated orbits successively become more and more influenced by the action of the binary. This increases the eccentricities to such high values that the orbits will eventually become unstable. The region of stability in this orbital domain has been analyzed through simple \(N\)-body simulations [Dvorak et al., 2004; Turrini et al., 2004], which match the results displayed here very well.

As the planets move on non-circular orbits in an eccentric disk and binary, a temporal change of the apsidal line may be expected. However, the planets do not show a periastron precession but have a stationary orientation instead, with some small oscillations of the periastron angle about the mean with the same period as the oscillations in the eccentricity. The innermost planet has a phase

Fig. 5. The evolution of the semi-major axis and eccentricity for planets released at different distances from the binary, i.e. 2.5, 3.0 and 3.5 AU.
shift of approximately 180 deg with respect to the binary and is nearly in an anti-symmetric state, while the other planets are lagging behind this configuration (Kley & Nelson 2008).

Fig. 6. Mass growth of a protoplanet released at an initial distance of 2.3 AU after having evolved with constant mass (36 $M_{\text{Earth}}$) from 2.5 AU to this location, see Fig. 5.

Fig. 7. The evolution of the semi-major axis and eccentricity for planets released at an initial distance of 2.3 AU as in Fig. 6.

4.2 Evolution with mass accretion

To estimate the influence of protoplanetary accretion on the orbital evolution we have simulated models where the mass of planets is allowed to grow due to
accretion from the ambient disk. This accretion process is modelled by taking out mass within a given radius $r_{\text{acc}}$ from the Roche-lobe of the planet with different rates, for detail see [Kley, 1999]. For the medium accretion rate the mass of the planet reaches about $1.6M_{\text{Jup}}$ after 3200 yr while the other models take longer.

The migration rate is initially similar for all accretion rates but then accelerates as the mass of the planet increases (left panel of Fig. 7), and finally slows down because the mass reservoir of the disk becomes exhausted. For the same reason (faster reduction of disk material) the final eccentricity of the planet is smaller for higher accretion rates. Hence, the detailed evolution of the orbital elements of the planet depends on the rate of mass accretion onto the planet. The efficiency of the accretion process cannot be determined straightforwardly, but is given for example by thermal processes in the vicinity of the growing planet. In our simulations we did not find a single case of outward or highly reduced migration among the cases of smaller planetary masses. These assumed accretion rates are certainly much higher than realistic ones, but they provide an upper limit to how mass accumulation influences the orbital properties of growing planets. The migration rate may also be affected by thermal processes in the disk.

Fig. 8. Grayscale plot of the two-dimensional density distribution of the medium accretion model at time 3125 yr. The shading is scaled $\propto \Sigma^{1/4}$ between $4.8 \times 10^{-4}$ (white) and 2400 g/cm$^2$ (black). The location of the planet is marked by a small circle.
A massive embedded planet will open a gap in standard circular disks, and it is interesting to analyse this effect within the present context. In Fig. 8 we display the two-dimensional density distribution $\Sigma(r, \varphi)$ in the disk at a time 3125 yr for the medium accretion model. At this time the planet has reached a mass of approximately $1.5 M_{\text{Jup}}$. From the plot it seems that the disk inside the planetary orbit is apparently more circular than outside. This is confirmed by the corresponding one-dimensional radial distribution of the azimuthally averaged density and eccentricity of the disk at the same time. The gap is somewhat weaker than in circular disks, primarily due to the periodic disturbance of the secondary that tends to sweep material into the cleared region around the planet. Due to the shallower gap the planet is able to continue mass accretion from its surroundings more easily than a planet on a circular orbit in a single star system. The inner disk clearly has a lower eccentricity than the outer parts. The presence of the planet represents, in a sense, a barrier for the (spiral) wave induced by the binary, which consequently cannot propagate into the inner parts of the disk.

5 Summary

In this contribution we have concentrated on the planetary growth process in relatively tight binary stars with particular attention given to the system $\gamma$ Cep. To study the effect of the binary we have followed the evolution of planetary embryos interacting with the ambient protoplanetary disk, which is perturbed by the secondary star.

As suspected, the perturbations of the disk, in particular its non-zero eccentricity and the periodic creation of strong tidally induced spiral density arms, lead to non-negligible effects on the planetary orbital elements. While embryos placed in the disk at different initial distances from the primary star continue to migrate inwards at approximately the same rate, the eccentricity evolution is markedly different for the different cases. If the initial distance is beyond about $a \sim 2.7$ AU the eccentricity of the embryo continues to rise to very high values, and apparently the orbit remains bound only due to the damping action of the disk. The main excitation mechanism of the initial rise of the eccentricity is the perturbed disk and the spiral arms near the outer edge of the disk.

For a disk mass of $3 M_{\text{Jup}}$ a $1.6 M_{\text{Jup}}$ planet can easily be grown, and the final semi-major axis and eccentricity are also in the observed range of the $\gamma$ Cep planet for suitable accretion rates onto the planet. One of the major problems in forming a planet in such a close binary system via the core instability model is the problem of the formation of the planetary core in the first place. Due to the large relative velocities induced in a planetesimal disk, especially for objects of different sizes, the growth process is also problematic in itself.

Hence, the formation of the Jupiter-sized planet observed in $\gamma$ Cep via the standard scenarios remains difficult but may not be impossible. Future research will have to concentrate on additional physical effects such as radiative transport, three-dimensional effects and self-gravity of the disk.
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