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# The Formation of Non-Equal Mass Binary and Multiple Systems[1]

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**ABSTRACT:** Calculations of the formation of non-equal mass binary and multiple systems are presented. Binary formation results from the elongated shape of the initial cloud, one fragment forming on each side of the equatorial plane. Slight linear density gradients along the cloud's major axis are sufficient to form non-equal mass fragments. Resultant mass ratios range from 0.1 to 1.0, in agreement with observations.

In the presence of rotation, the fragments form with surrounding disks. The primary forms with a larger disk than does the secondary. Due to it's orbital motion around the primary, the secondary can directly accrete the matter that has gathered in the primary's disk. The secondary is thus less likely to have an appreciable disk, accounting for a redder primary. The binary system's initially high eccentricity decreases with the continued accretion of higher specific angular momentum at apastron and lower specific angular momentum matter at periastron. Non-coplanar multiple systems with unequal mass components are also formed. The systems are composed of an inner binary and a more distant companion. The mass ratio of the companion binary system is usually less than that of the binary.

## 1. INTRODUCTION

Binary mass ratios, $q = m_2/m_1$, have been observed to vary extensively (from 0.1 to 1.0; Duquennoy & Mayor [1991]). The formation of binary systems as the result of the fragmentation of elongated clouds has been studied in the context of rotation about an axis perpendicular to the cloud's major axis, "end over end" rotation, (Bonnell *et al.* 1991) and in the more general case of rotation about an arbitrary axis (Bonnell *et al.* 1992). The resultant binary systems agree with observed binary eccentricities (Duquennoy & Mayor 1991) but have equal masses due to the assumed initially uniform density along the major axis.

Observations have repeatedly found elongated molecular cloud cores (e.g., Loren 1989; Lada *et al.* 1991; Myers *et al.* 1991). A quick glance at these cores shows that, projected in the plane of the sky, they have definite variations along their major axes. Numerical simulations taking these asymmetries into account demonstrate that the fragmentation of elongated clouds can form binary systems with the observed distribution of mass ratios.

## 2. CALCULATIONS AND RESULTS

The calculations were performed with a smooth particle hydrodynamics code (*SPH*) with a variable smoothing length (Benz 1990). In order to simulate the

[1]This contributed paper was judged outstanding by the Colloquium participants and is therefore included in the proceedings with the invited papers – *eds*

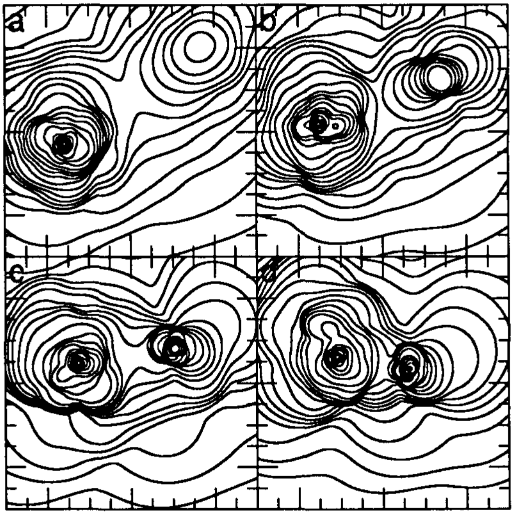


**FIGURE 1.** **The evolution of the simulation with $J_0 = 1.8$, $\beta_\perp = 0.01$, $\beta_\parallel = 0.00$, and an initial density contrast of 1.17. Column density contours are plotted in panels (a) through (d). The central $1 \times 10^4$ A.U. are shown.**

asymmetries observed in elongated cloud cores, the initial density profile was made to vary linearly along the length of the cylinder:

$$\rho(z) = \rho_0\left[1 + (A-1)\left(\frac{2z}{L}\right)\right], \quad -\frac{L}{2} \leq z \leq \frac{L}{2}, \tag{1}$$

where $L$ is the cloud length, $\rho_0$ is the average cloud density and $A$ is the density contrast. The initial cloud length and aspect ratio, $L/D$, were chosen to be 0.23 pc and 2.0, respectively. Solid–body rotation around an axis perpendicular to the cloud's major axis (as in Bonnell *et al.* 1991) and rotation about an arbitrary axis (as in Bonnell *et al.* 1992) were included.

Binary formation results from the elongated shape of the initial cloud, one fragment forming on either side of the equatorial plane. With an initial density contrast $A \neq 1$, the secondary (less massive) fragment forms slower and therefore closer to the primary (see Figure 1.

$J_0$ is the ratio of the absolute value of gravitational to thermal energies while $\beta_\perp$ and $\beta_\parallel$ are the ratios of the absolute value of rotational to gravitational energies for the components of rotation perpendicular and parallel to the major axis, respectively. The primary forms much earlier than the secondary. The difference in mass of the two fragments is evident. The more massive (primary) fragment has a larger surrounding disk than does the secondary. As the primary forms earlier and is more massive, it is able to accrete matter from a greater volume and thus with a larger specific angular momentum. This angular momentum is incorporated into the fragments' spin, allowing for a larger rotationally supported disk.

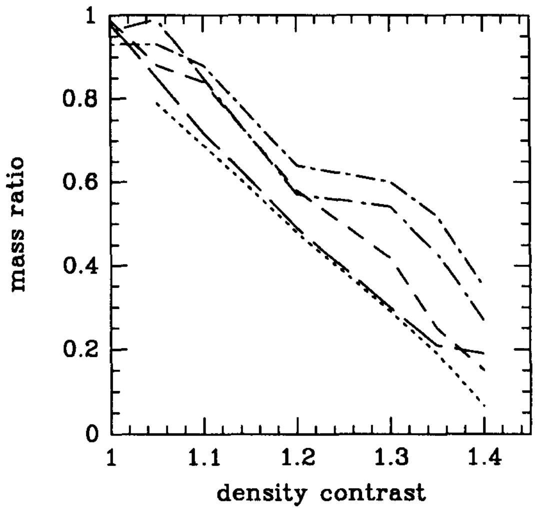


**FIGURE 2.** The mass ratio is plotted versus the density contrast for simulations with $J_0 = 2$. The dotted curve represent the mass ratios in the non-rotating case. The short and long dashed curves represent the initial mass ratios, for the fragments and the fragments plus disks, respectively, when rotation is included $\beta_{\perp} = 0.02$. The short dash-dotted and long dash-dotted curves represent the same systems after closest approach.

## 3. BINARY MASS RATIOS

For calculations with $J_0 = 2$ and $\beta_{\perp} = 0.02$, the general trend is of increasing primary and decreasing secondary masses with increasing density contrast with or without rotation (see Figure 2.

The presence of rotation reduces both the primary and secondary masses. The primary's mass reduction due to the rotation is greater than that of the secondary's due to its greater spin and hence rotational support. The resultant mass ratios are therefore higher than in the non-rotating case. When the matter comprising the circumfragmentary disks is included, the mass ratios decrease since the primary's disk is the more massive. Comparing the masses and mass ratios before and after the closest approach, the masses increase during the evolution but the secondary's mass increases more than does the primary, due to the facility in which it can accrete the high angular momentum matter that forms in the disk around the primary. Thus the mass ratio tends to increase. For cases with smaller $J_0$, $J_0 = 1.8$ and $J_0 = 1.5$, the general trend is the same but requires smaller density contrasts. Further details can be found in Bonnell & Bastien (1992).

## 4. EFFECTS OF CONTINUED ACCRETION

Both fragments continue to accrete matter from their surrounding disks and the infalling cloud matter. The infalling matter has either high or low specific

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angular momentum. The low specific angular momentum matter falls directly towards the cloud's centre of mass (approximately the primary). Thus the extinction towards the primary will be greater during the infall stage. The high specific angular momentum matter forms into a disk-like shape rotating around the centre of mass (the primary) in the binary's orbital plane. For the primary to accrete this matter, a method to transfer angular momentum is necessary (i.e. a viscous accretion disk, or gravitational torques due to the presence of a companion). The secondary, also orbiting around the cloud's centre of mass, has a similar rotational velocity as this disk and can thus directly accrete it (especially at closest approach). Thus, accretion onto the primary has a greater tendency to be spherically symmetric than that onto the secondary which is mostly from a disk. Furthermore, as the transfer of angular momentum is much more important for the primary to accrete from this high specific angular momentum matter, it will retain a more significant disk for longer periods than will the secondary. All of this means that the primary will, throughout the PMS evolution, have more surrounding material to reprocess its photons to longer wavelengths (Adams, Lada, & Shu 1987). The observed tendency for the more massive component also to be the redder component (Moneti & Zinnecker 1991, Zinnecker 1990) can therefore be explained in terms of the dynamics of the continued accretion in an unequal mass binary system.

Continued accretion from the disk in the orbital plane also affects the orbit. Due to the initially eccentric orbit, accretion onto the secondary of lower specific angular momentum matter at periastron and higher specific angular momentum matter at apastron tends to circularize the orbit. This should be contrasted with the increase in eccentricity expected due to interactions with a circumbinary disk when accretion is not occurring (Artymowicz *et al.* 1991). Thus, as long as accretion is significant, the mass ratio will increase during the evolution while the eccentricity decreases.

## 5. THE FORMATION OF MULTIPLE SYSTEMS

The collapse of elongated clouds rotating about an arbitrary axis has been shown to form multiple systems (Bonnell *et al.* 1992). In these cases one of the fragments' disk subfragments due to tidal forces from the other fragment. The multiple systems formed in this manner are hierarchical, being composed of an inner binary and a less massive and more distant companion. They are also non-coplanar, in agreement with observations that show that at least 35% of multiple systems are non-coplanar (Fekel 1981). Figure 3 shows the multiple system resulting from the collapse of an elongated cloud with $J_0 = 2, \beta_\perp = 0.02, \beta_\| = 0.04$ and a density contrast $A = 1.10$.

Contours of the column density are included in Panel a. Panel b shows the contours of the radial velocity component. This system is similar to the observations of the $\rho$ Ophiuchus core B1 (Wadiak *et al.* 1985). The two fragments, that form the inner binary, have aligned spin and orbit (i.e. the rotation axis of each component are parallel to each other and perpendicular to the line joining them). The third fragment is neither in the inner binary's orbital plane, nor is its spin aligned with that of the other two.

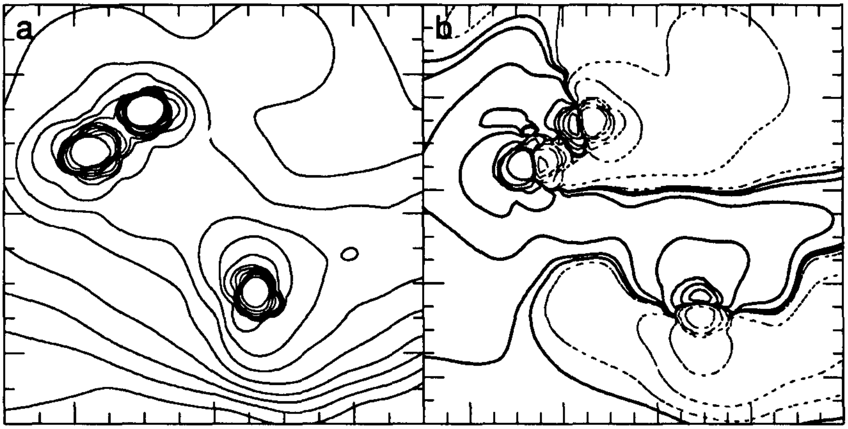


**FIGURE 3.** The column density (a) and radial velocity structure (b) of a non-coplanar multiple system. In (b), the heavy and dotted lines represent positive and negative velocities, respectively.

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## 7. DISCUSSION

**POVEDA:** From the table you have shown it seems that you tend to have equal masses, indeed the mass ratio tends to one!

**MAZEH:** Would your scenario predict any correlation between the mass-ratio and the eccentricity of the formed binaries?

**BONNELL** In the formation of low mass ratio binaries, the secondary forms later and therefore does not fully benefit from the cloud's elongation and would

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therefore have a lower eccentricity. Simulations do show this correlation of lower eccentricities with lower mass ratios, but significant scatter is also present — probably due to the accretion of low angular momentum matter at periastron.

**BOSS:** Do you include the disk masses in the fragment mass estimates? Apart from losses to the secondary, the disk should accrete onto the primary (through viscous evolution) and so should tend to lower this mass ratio if the primary's disk is much more massive than the secondary's.

**BONNELL** Fragment masses and mass ratios are calculated using both the fragment mass and the fragment plus disk mass. The inclusion of the disk mass does substantially reduce the mass ratio as the primary's disk is much more massive than the secondary's. Losses to the secondary do occur, but the primary's disk is being consistantly replenished by the continuing infall of the surrounding cloud matter.

**ZINNECKER** How do you set up the initial conditions in your calculations?

**BONNELL** The initial conditoins are of a uniforn density with a superimposed linear density gradient along the cloud's major axis. Solid body rotation around an axis perpendicular to the cloud's major axis or about an arbitrary axis are present.

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