The Role of Accretion in Binary Star Formation

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Summary

The effects of accretion on the formation of a binary stellar system are studied. When a molecular cloud core undergoes gravitational collapse it may fragment into several protostars. This process is a promising mechanism for the formation of most binary systems and has been the subject of many numerical calculations. These demonstrate that protobinary systems can be formed with a wide variety of mass ratios, orbital separations and eccentricities. However, all these calculations must be halted soon after the protostars form, as the computation time required to evolve them further becomes prohibitive. Most of the computations are spent evolving the internal dynamics of the protostars, and the accretion of the rest of the collapsing cloud on to the protostellar system cannot be followed. Typically, the protostars contain only a few percent of the initial cloud when the calculations must be stopped. Thus, it is impossible to compare the results of the calculations with observations, as the parameters of the final stellar system depend upon the accretion of, or the interaction with, the rest of the cloud.

In this thesis, a new method for following fragmentation calculations beyond the formation of protostars is presented. The numerical technique of Smoothed Particle Hydrodynamics (SPH) is modified to incorporate sink particles. In standard SPH, high-density regions of gas are represented by many particles in a small volume of space. Short time steps are required to evolve these particles correctly, and this results in fragmentation calculations being halted soon after protostars are formed due to their high densities. In the new method, the many gas particles representing each protostar are replaced by a single, non-gaseous particle, with appropriate boundary conditions. These sink particles contain all the mass of the particles they replace, and accrete any infalling mass. This enables a collapse calculation to be followed to an arbitrary time after the protostars are formed, and, thus, for the final results to be determined.

Using this method, the effects of accretion on a forming binary system are studied. A binary is placed within a gaseous cloud from which it accretes. The effects of this accretion on the mass ratio and orbital separation of the system are studied. This study is performed first in the ballistic case, where the gas is modelled by non-interacting particles, and then by gaseous accretion using SPH with pressure and viscous forces. The effects of the accretion are found to depend primarily on the mass ratio of the binary and the angular momentum of the infalling cloud. For the accretion of low-angular-momentum material, the binary's separation deceases, and its mass ratio is lowered. For high-angular-momentum accretion, the binary's separation increases, and its mass ratio is forced toward unity. The magnitude of the effects depends on the mass ratio. The formation of circumstellar and circumbinary discs is also studied. It is found that circumstellar discs are formed around only the primary for low-angular-momentum material, around both protostars for intermediate-angular-momentum material, and around both protostars for the highest-angular-momentum material with a circumbinary disc also present. Finally, conclusions are drawn on how accretion may help to explain the mass-ratio distributions and the presence of discs that are observed for binary systems.

Contents

Chapter 1

Introduction

The field of star formation is of great importance in astronomy, not only for its own sake, but also for the role it plays in other fields. Understanding of star formation is required in fields as diverse as the energetics and abundances of the interstellar medium, stellar evolution, globular clusters, galaxy formation and evolution, accretion discs, and the formation of planetary systems.

Recently, theoretical studies of star formation have been turning from the formation of single stars, to the formation of binary and higher-order multiple systems. Most stars are observed to be members of multiple systems. Thus to understand star formation we must understand the formation of multiple systems.

The advent of new observational techniques and equipment is greatly aiding this study. The growth in the availability and capabilities of infrared and sub-millimeter telescopes, and the new high-resolution telescopes, such as the Hubble Space Telescope and ground-based telescopes using adaptive optics and speckle interferometry, now allow star-forming regions and multiple stellar systems to be studied in unprecedented detail. This provides a wealth of data to compare with the theoretical studies.

In this thesis, the effects of accretion early in the formation of a binary system are investigated. Following the formation of a binary protostellar system, we expect it to grow in mass by the accretion of more material from the cloud from which it formed. The accretion of this material alters the masses and orbital parameters of the original binary, and forms discs around the components. Thus, to understand binary star formation, the effects of this accretion phase must be understood.

1.1 Introduction to Star Formation

For stars to be formed from the interstellar medium, the absolute magnitude of the gravitational energy of a region of gas must exceed the combined thermal, magnetic, turbulent, and rotational energies of the gas. This allows gravitational collapse to occur, and a star to form.

Considering the thermal and gravitational energies of a uniform cloud of gas, the maximum radius of the cloud such that it is gravitationally bound can be defined, for a fixed mass and temperature. This radius is known as the Jeans length. A cloud with a radius less than the Jeans length is unstable to collapse. The Jeans length is given by

$$R < R_{\mathrm{J}_1} = \frac{2GM\mu}{5R_{\mathrm{g}}T}, \tag{1.1}$$

where M is the mass, T is the temperature, μ is the mean molecular weight, R_{g} is the gas constant, and G is the gravitational constant. An alternative definition, also frequently used, is formulated in terms of the density ρ of the cloud

$$R > R_{\mathrm{J}_2} = \left(\frac{5R_{\mathrm{g}}T}{2G\mu}\right)^{1/2}\left(\frac{4}{3}\pi\rho\right)^{-1/2}. \tag{1.2}$$

Using this definition, a cloud of fixed density and temperature must be **larger** than the Jeans length to collapse. These equations can be reformulated to give the minimum mass required for a cloud to be unstable as a function of density and temperature

$$M_{\mathrm{J}} = \left(\frac{5R_{\mathrm{g}}T}{2G\mu}\right)^{3/2}\left(\frac{4}{3}\pi\rho\right)^{-1/2}. \tag{1.3}$$

Rotational and magnetic support may also be important, however. When rotation is included, assuming a uniform angular velocity Ω, the new Jeans mass becomes

$$M_{\mathrm{J}} = \left(\frac{5R_{\mathrm{g}}T/\mu + \Omega^2R^2}{2G}\right)^{3/2}\left(\frac{4}{3}\pi\rho\right)^{-1/2}. \tag{1.4}$$

This condition for a cloud to be unstable to collapse can also be expressed as

$$\alpha + \frac{10\beta}{7} \leq 1, \tag{1.5}$$

where $\alpha = E_{\mathrm{T}}/|E_{\mathrm{G}}|$, $\beta = E_{\mathrm{R}}/|E_{\mathrm{G}}|$, and E_{T}, E_{R}, E_{G} are the thermal, rotational, and gravitational energies of the cloud, respectively. Assuming thermal and rotational support are negligible, a magnetic Jeans mass may also be derived. This is given by

$$M_{\mathrm{J}} = \frac{BR^2}{(3.6G)^{1/2}} = \frac{B^3}{(3.6G)^{3/2}(\frac{4}{3}\pi\rho)^2}, \tag{1.6}$$

where B is the magnetic field (Bodenheimer 1992).

1.1.1 Initial Conditions

We are now able to determine what conditions are necessary for the collapse of a cloud of gas to form a star. The typical interstellar environment consists largely of HI clouds. Typical conditions within these clouds are given in Table 1.1. The thermal Jeans mass for these clouds is $\approx 10^4\mathrm{M}_\odot$ and the magnetic Jeans mass $\approx 2\times10^4\mathrm{M}_\odot$. Thus, collapse directly from the interstellar environment cannot form single or small groups of stars. Instead, denser, cooler gas is required. This gas can be found in molecular clouds (Table 1.1). They are observed (e.g. in CO emission lines) to have structure on many scales, from clumps down to small, high-density cores. The thermal Jeans mass in these

Environment	Size (pc)	Mass ($M_\odot$)	Temp (K)	ρ (cm^{-3})	Magnetic Field (G)	Vel. Disp. ($km\ s^{-1}$)
Interstellar Gas			100	10	10^{-6}	
Molecular Clouds	few$-$50	$10^3 - 10^6$	10	10^2	3×10^{-5}	1-10
Cloud Clumps	$2 - 5$	$10^3 - 10^4$	10	$10^2 - 10^3$	3×10^{-5}	1-10
Cloud Cores	few$\times$0.1	few	10	$\gtrsim 10^4$		$0.2 - 0.4$

Table 1.1: Typical conditions in interstellar gas, molecular clouds, molecular cloud clumps, and molecular cloud cores (Bodenheimer 1992).

clouds is $\approx 10\ M_\odot$, therefore the clumps cannot be thermally supported against collapse. However, they cannot be in free-fall collapse either, because if they were, and all the mass went into stars, the star formation rate would be three orders of magnitude greater than currently observed (Zuckerman & Palmer 1974; Mouschovias 1976). Furthermore, the line widths of the material in these clumps are inconsistent with free-fall collapse, and with support from rotation (Myers et al. 1991). Moreover, although the observed line widths are supersonic, turbulence on its own cannot support the clouds as shocks would quickly damp the turbulence. Instead, magnetic fields must provide the support. Evidence for this is given by calculation of the magnetic Jeans mass which is $\approx 2\times10^3\ M_\odot$ - comparable to the clump size. Support could be due either to a static field, providing magnetic pressure support perpendicular to the field (Mouschovias & Spitzer 1976), or from fluctuating magnetic fields associated with magnetohydrodynamical (MHD) waves at sub-Alfvenic, but supersonic speeds (Arons & Max 1975; Lizano & Shu 1989; Calberg & Pudritz 1990). These MHD waves may persist significantly longer than hydrodynamic turbulence, as shocks would be cushioned by the field. They also provide support both parallel and perpendicular to the field and explain the observed supersonic, yet sub-Alfvenic, line widths (e.g. Myers & Goodman 1988).

Embedded in the clumps, high-density cores are found. These must be observed in emission lines of NH_3, CS, and other molecules as they are opaque both visually and in CO lines which are commonly used to trace molecular cloud material (e.g. Ho & Townes 1983; Myers, Lada & Fuller 1991). Their thermal Jeans mass is $\sim 10M_\odot$ and the line widths of NH_3 molecules in these cores are approximately thermal (Myers et al. 1991). This indicates that magnetic fields with turbulence are no longer the dominant mechanism for support. When calculated, the magnetic Jeans mass is $\sim M_\odot$, although the high densities make this less relevant as the material is only weakly coupled to the field. These clouds may, therefore, be expected to undergo collapse to form stars. Unfortunately, they are not observed to be collapsing, posing the question of what triggers their collapse, or if indeed these are the correct initial conditions for low-mass star formation. Evidence to support the hypothesis that these are the initial conditions for low-mass star formation is strong however, as regions with high-density cloud cores are frequently found to contain T-Tauri stars, embedded infrared objects, and sources with

Object	Specific Angular Momentum J/M (cm^2 s^{-1})
Molecular Cloud Clump ($\sim$ 1 pc)	10^{23}
Molecular Cloud Core ($\sim$ 0.1 pc)	10^{21}
Binary (10^4 yr period)	$4 \times 10^{20} - 10^{21}$
Binary (10 yr period)	$4 \times 10^{19} - 10^{20}$
Binary (3 day period)	$4 \times 10^{18} - 10^{19}$
T-Tauri star (start of contraction)	5×10^{17}
Jupiter (orbit)	10^{20}
Present Sun	10^{15}

Table 1.2: Characteristic values of specific angular momentum (Bodenheimer 1992).

bipolar outflows (Myers & Benson 1983; Beichman et al. 1986; Benson & Myers 1989; Myers et al. 1991). Thus, star formation has occured recently in these regions, and may be ongoing.

Rotation, although not significant for the support of the clumps and cores (Goodman et al. 1993), is too large if conservation of angular momentum is assumed during the collapse to a star. Characteristic values for the specific angular momentum of clouds, and various stellar objects are given in Table 1.2. Thus, angular momentum transport must occur during the formation of stars from cloud clumps. The specific angular momentum of large clouds must first be reduced to that observed for small cores. The presence of magnetic fields provides a mechanism to do this. In the low-density, molecular-cloud phase, when the gas is still tightly coupled to the gas, angular momentum can be extracted from a rotating cloud via torques exerted by the twisting of field lines which extend into the external medium (Ebert, von Hoerner & Temesvary 1960; Mouschovias & Paleologou 1979; Dorfi 1982). From small cores, the specific angular momentum must still be reduced many orders of magnitude to form stars. This may be achieved in several stages. During the collapse, angular momentum of the cloud material is conserved. However, the angular momentum of the material that forms each star may be reduced via fragmentation of the cloud into a binary or multiple system (Sections 1.3.3 and 1.3.4). The original angular momentum of the cloud is then contained primarily in the orbital angular momentum of the system. Once collapse is halted by rotation, angular momentum may be lost by the material which is required to form a star via an accretion disc phase (Section 1.1.3). Magnetic braking of the star by the disc may also occur. Finally, the star is also magnetically braked by the interaction between its field and its stellar wind.

1.1.2 Cloud Collapse

Once support for a molecular cloud core has been removed, collapse can proceed all the way to stellar densities. This has been studied by Larson (1969). The collapse passes through five phases. The temperatures and densities of all but the last phase are shown in Figure 1.1.

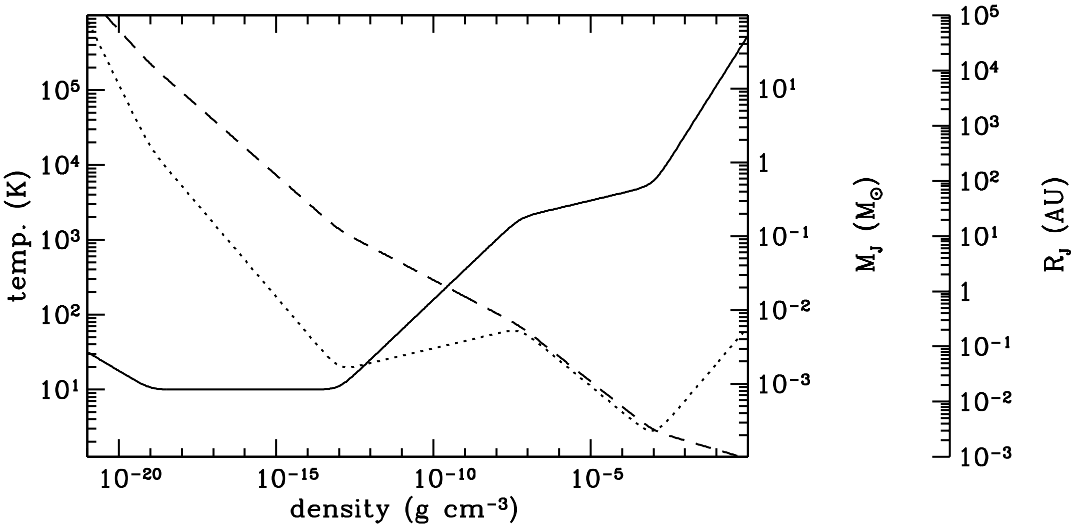

Figure 1.1: The temperature (solid), Jeans mass (dotted), and Jeans radius (dashed) of interstellar gas as a function of density, showing the different phases the gas passes through during collapse (Tohline 1982).

The first collapse phase occurs for densities from approximately 10^{-19} to 10^{-13} g cm^{-3}. The collapse is isothermal, with the temperature remaining at ≈ 10 K, since the heating due to compression is balanced by cooling from infrared radiation. The infrared radiation is emitted from dust grains and escapes because the cloud is optically thin at these wavelengths. Collapse continues because essentially all the gravitational energy released is radiated away. For a cloud with an initial density of 10^{-19} g cm^{-3}, the free-fall time,

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}}, \tag{1.7}$$

is around 2×10^5 yr. If the cloud is initially of uniform density, the collapse time is also uniform throughout the cloud. However, this does not remain the case. Density and pressure rise due to the collapse and the pressure increases compared to the outer boundary of the cloud which is constrained by the external pressure, forming a pressure gradient at the outside of the cloud. This pressure gradient propagates inward at the speed of sound relative to the gas. If the sound travel time from the outside to the centre of the cloud is less than or comparable to the collapse time for the cloud, then the entire cloud develops a pressure and density gradient, and the collapse time is longer than a pure free-fall time. At the same time, due to the density gradient, the collapse time becomes shorter in the central regions than near the outside as $t_{\rm ff} \propto \rho^{-1/2}$. This results in the inner regions collapsing faster than the outside, and the cloud effectively collapses from the inside out. The density of the central region increases, but the mass contained by it decreases. Bodenheimer and Sweigart (1968) showed that the general solution is independent of the initial density distribution and evolves to a $\rho \propto r^{-2}$ density distribution outside the central region. If the cloud initially had a uniform distribution, the central region stays uniform during the isothermal collapse.

The second phase begins when the collapse at the centre of the cloud becomes non-isothermal. This occurs because the centre of the cloud becomes optically thick to infrared radiation due to the increasing density (at $\rho \approx 10^{-13}$ g cm^{-3}). The radiation released by the collapsing gas is no longer able to escape freely, the gas heats, and a temperature gradient is established. As soon as the heating begins, the gas rapidly becomes optically thick because its opacity increases with temperature. This results in near-adiabatic contraction, as the diffusion time for radiation in the central regions quickly exceeds the free-fall time (see Bodenheimer 1992). This phase is well approximated by a polytropic equation of state

$$P = K\rho^{\gamma}, \tag{1.8}$$

where P is pressure, ρ is density, K depends on the entropy of the gas, and the polytropic index is $\gamma = 1.4$ (Figure 1.1). For a polytropic equation of state, the Jeans mass (Equation 1.3) goes as

$$M_{\rm J} \propto \rho^{(3\gamma-4)/2}, \tag{1.9}$$

since $T \propto \rho^{\gamma-1}$. Therefore, as $\gamma > 4/3$, contraction can only proceed in the central regions as gas is accreted (the thermal energy increases faster than the magnitude of the gravitational energy for a constant mass). Hence, a central core forms in hydrostatic equilibrium at about 200 K, with a shock at its outer edge. The rest of the cloud continues to fall on to the core, compressing it, and its central temperature increases.

When a temperature of 2000 K is reached within the central core, molecular hydrogen starts to dissociate giving a third phase, known as the second collapse phase. The effective polytropic index of the gas drops to $\gamma \approx 1.1 < 4/3$ (Figure 1.1) because energy released from the collapse gives hydrogen dissociation rather than heating of the gas.

The collapse is halted again when the molecular hydrogen has dissociated, and a second core is formed with a temperature of $T \approx 20000$ K. A shock forms around the second core, and the core contracts only under the accretion of gas through the shock as the dissociated hydrogen has $\gamma = 5/3$. The original shock at the outer edge of the first core does not remain long, as the first core is eroded from the inside out by the hydrogen dissociation.

The final phase is the long process of accretion on to the second core, or protostar. Only the central regions of the original cloud collapse to form the protostar due to the inside-out collapse process. The rest of the cloud is accreted by the protostar over another initial cloud free-fall time or longer. This process has been studied by several authors (Winkler & Newman 1980; Stahler, Shu & Taam 1980). They found a steady accretion flow is reached with an almost constant accretion rate $\dot{m}$. However, they assumed an initial $1/r^2$-density profile. In a recent paper, Foster and Chevalier (1993) considered the collapse of Bonnor-Ebert spheres and found no period of constant $\dot{m}$ occurs if there initially exists a roughly uniform-density region in the centre of the cloud that extends to $\gtrsim$5% of the cloud radius. Instead $\dot{m}$ is initially larger than predicted for a $1/r^2$-density profile and decreases with time.

As accretion decreases, the dusty envelope becomes optically thin, and material just behind the accretion shock is observed (Stahler, Shu & Taam 1980). The shock layer rapidly adjusts to a stellar photosphere, and the star enters the Hayashi phase of contraction down to the main sequence. The lower accretion rate ($< 10^{-5}$ $M_{\odot}$ yr^{-1}) continues to give the pre-main-sequence star a higher luminosity than the bare contraction luminosity until accretion ceases.

1.1.3 The Effects of Rotation on Cloud Collapse

The previous discussion assumed the initial cloud was not rotating, whereas, in reality, the cloud almost certainly contains some angular momentum. The presence of rotation stops the material from collapsing on to the protostar directly. Instead, a rotationally-supported disc forms around the protostar. The evolution of this disc occurs in three main phases.

The formation phase, where the disc is built up from infall of the initial cloud, lasts around 2×10^5 yr. This stage is identified with observed Class I objects (Lada 1987). The mass of the disc may initially be very high in comparison to the protostar making it gravitationally unstable, and leading to rapid accretion on to the protostar due to angular-momentum transport in the disc via gravitational torques. Models of Class I objects have been developed by Adams, Lada and Shu (1987) consisting of a central protostellar core, a thin disc, and an optically-thick, dusty, infalling envelope. These models have been successfully compared to observed spectra.

Once most of the envelope has fallen on to the star or disc, the object can be observed as an optically-visible star with an infrared excess from the disc. This stage is identified with Class II objects such as T-Tauri stars. Viscous transport of angular momentum then dominates the disc evolution, allowing disc material to be accreted on to the star (Pringle 1981). The source of this viscosity is not well understood. Viscosity could be due to convection (Lin & Papaloizou (1985)), or via magnetic fields or turbulence. The disc evolution under viscosity is such that angular momentum is transported outward, increasing the outer radius of the disc, while the mass falls inward and is accreted by the star and lost in outflows.

Finally, the disc is cleared away giving a Class III object. This may be due to a stellar wind blowing away the disc (Hayashi, Nakazawa & Nakagawa 1985; Ruden & Pollack 1991) and/or the accumulation of disc material into protoplanetary objects. Grains may settle to the centre of the disc (Nakagawa, Sekiya & Hayashi 1986) forming planetesimals and perhaps planets. The settling and aggregation of grains decreases the infrared flux from the disc, and makes it hard to observe.

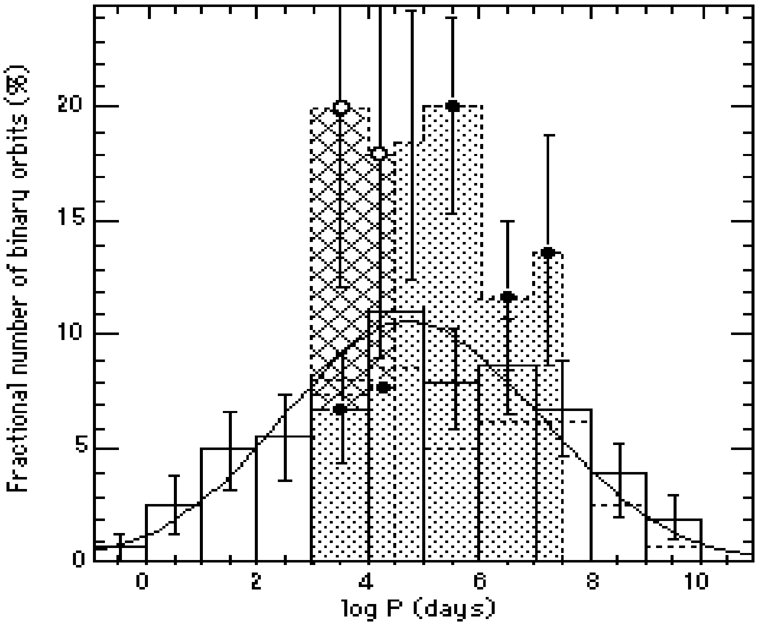

Figure 1.2: The period distribution (Richichi et al. 1994) for the main-sequence, G-dwarf binaries of Duquennoy and Mayor (1991) (solid-lined histogram and best-fit, log-normal distribution), and pre-main-sequence binaries (shaded regions).

1.2 Binary Star Formation: Observations

In the previous section, the general physical processes involved in the formation of a single star were discussed. However, star formation is observed to occur, not in isolation, but typically with small groups of stars formed at a similar time (Gomez et al. 1993). Furthermore, recent surveys have shown that most stars form in binary or multiple stellar systems (see below). Any viable theory of star formation must explain this favoured formation of binary and multiple systems over single stars. It must also reproduce the observational statistics on the masses and orbital parameters of these systems. The observational statistics of main-sequence and pre-main-sequence systems are now discussed.

1.2.1 Main-Sequence Systems

Recent studies of stars in the solar neighbourhood have provided the best current statistics on stellar multiplicity and the associated masses and orbital parameters of main-sequence multiple systems. By selecting stars within a volume of space rather than by magnitude, the biases present in some earlier surveys can largely be avoided. The results of these volume-limited and other surveys are:

Multiplicity

- A survey of 164 systems with G-dwarf primaries within 22 pc of the Sun estimates 57% are multiple systems with a mass ratio (ratio of secondary's to the primary's mass)

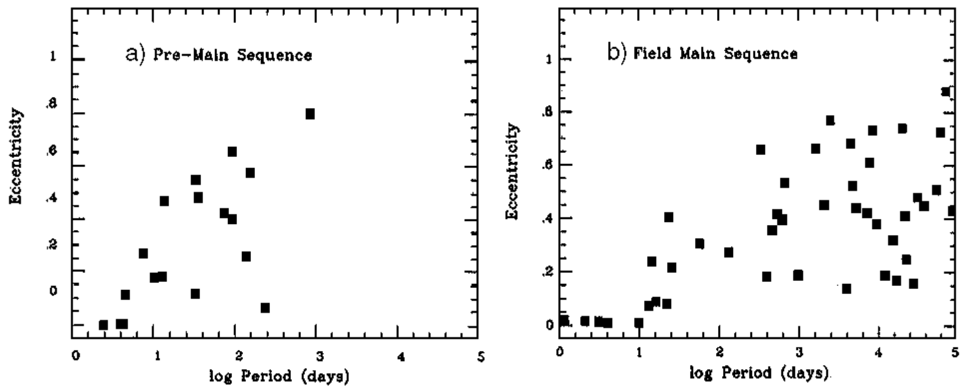

Figure 1.3: Eccentricity versus period for pre-main-sequence binaries and the main-sequence, G-dwarf binaries of Duquennoy and Mayor (1991) (Mathieu 1994).

$q = M_2/M_1 > 0.1$ (Duquennoy & Mayor 1991). Also, 5% of the systems are triple systems or higher order.

• From 172 systems with K-dwarf primaries, 45% are estimated to be multiple systems (Mayor et al. 1992).

• From 357 systems with M-dwarf primaries within 20 pc of the Sun, 42% are estimated to be multiple systems (Fischer & Marcy 1992). Furthermore, 8% are triple or higher-order systems.

• Surveys in other spectral classes are not as complete, however, the percentages appear similar (Abt 1983).

• In addition, Herczeg (1988) finds 1/3 of spectroscopic binaries have visual companions.

Periods (Separations)

In all three of the volume-limited surveys above, the period distribution is single-peaked. For G-dwarfs, the distribution of periods is consistent with a log-normal distribution ranging from less than a day to 10^6 years, with a peak at ≈ 180 yr (Figure 1.2). These correspond to separations from a few $R_\odot$ to 10^4 AU, with a peak at ≈ 30 AU. The K-dwarf and M-dwarf distributions are both consistent with the G-dwarf distribution, though the errors are large.

Eccentricities

In two of the volume-limited surveys, the eccentricity depends on the period of the orbit. Data is not available for the M-dwarf survey.

• For G-dwarfs (Figure 1.3), all systems with orbital periods $P < 10$ days have circular orbits. For systems with $P > 100$ days, all systems have an eccentricity $e > 0.1$. It is also observed that the maximum eccentricity of systems increases with their period.

• For K-dwarfs, all systems with orbital periods $P < 6$ days have circular orbits. For systems with $P > 30$ days, all systems have an eccentricity $e > 0.1$. Again, the maximum observed eccentricity increases with period.

Mass Ratios

The mass-ratio ($q = M_2/M_1$) distribution was originally thought to rise toward mass ratios of unity (e.g. Trimble 1974). Also, for spectroscopic binaries different mass-ratio distributions were found for single-lined and double-lined samples. However, these early observations were biased toward finding equal-mass-ratio stars because of selection effects such as the fact that they were magnitude limited (Trimble 1990; Tout 1991). A reanalysis of past surveys taking the selection effects into account finds there is no rise toward mass ratios of unity (Trimble 1990). Volume-limited surveys, and other carefully selected surveys, have recently helped to clarify the mass-ratio distribution.

• For G-dwarfs, the survey of Duquennoy and Mayor (1991) found the mass-ratio distribution rises toward smaller mass ratios, with a possible peak at $q \approx 0.25$. They originally claimed there was no evidence of a difference between short-period and long-period systems, however a re-analysis of their data shows that for short-period systems with $P < 1000$ days, the mass-ratio distribution may differ from that of long-period system, with it being consistent with a flat distribution, or rising toward mass ratios of unity (Mazeh et al. 1992). This agrees with the earlier results of Abt (1987) who also found a rising distribution for short-period systems. However, the G-dwarf survey contained only 23 short-period systems, so this difference is still to be confirmed. The long-period, G-dwarf mass ratios are independent of period and consistent with random pairing from the normal initial mass function.

• For K-dwarfs, the mass-ratio distribution appears to be flat for $q > 0.4$, with an excess of systems at $q \approx 0.3$, and a lack of systems with $q < 0.2$, though the number of systems is small.

• For M-dwarfs, the mass-ratio distribution appears to be flat for $q > 0.6$, with a possible drop off for $0.4 < q < 0.6$, and no data for $q < 0.4$. The rise in the mass-ratio distribution for systems with $q < 0.6$ that is present in the G-dwarf survey is not present for the M-dwarfs.

• Trimble (1990) re-analysed past surveys of spectroscopic binaries, and in all cases finds the mass-ratio distribution rises as the mass ratio decreases below $q \approx 0.5$.

Coplanarity

In addition to the above surveys, Hale (1994) considered 73 binary and multiple systems containing solar-type stars looking for evidence of coplanarity between the orbital plane of the binary and the equatorial planes of the stars. He found strong evidence for coplanarity of systems with separation less than ≈ 30 AU, and apparently uncorrelated orbital and equatorial planes for systems wider than this. There was no evidence to support a difference dependent on spectral type, eccentricity or age. Finally, hierarchical systems, did not appear to follow the above relation for coplanarity, with non-coplanarity even at small separations.

Reference	Type	Separation (AU)	Binary Freq.
Mathieu et al. 1989, 1994	Spectroscopic	$\lesssim 1$	11%
Simon et al. 1992	Lunar Occult.	$1 - 1500$	46%
Ghez et al. 1993	Speckle	$16 - 252$	34%
Leinert et al. 1993	Speckle	$18 - 1800$	42%
Richichi et al. 1994	Lunar + Speckle	$1.8 - 1800$	60%
Reipurth & Zinnecker 1993	Infrared Image	$150 - 1800$	16%

Table 1.3: Recent pre-main-sequence surveys.

For triple systems, coplanarity of the two orbital planes can also be studied. Fekel (1981) studied the properties of systems with three or more components and a maximum period of less than 150 years and found that of 21 orbital pairs, at least 7 (33%) were non-coplanar.

1.2.2 Pre-Main-Sequence Systems

A recent review of pre-main-sequence (PMS) binary statistics has been given by Mathieu (1994). Surveys of PMS stars are carried out using many different techniques by many authors to cover the full range of binary separations. For short-period systems spectroscopic surveys are used (e.g. Mathieu, Walter & Myers 1989). For intermediate separations speckle imaging is used (e.g. Ghez, Neugebauer & Matthews 1993; Leinert et al. 1993), while for larger separations direct infrared imaging is possible (e.g. Reipurth & Zinnecker 1993). Finally, lunar occultation can also cover a wide range of separations (e.g. Simon et al. 1992; Richichi et al. 1994).

The present surveys are primarily of T-Tauri stars in the nearby star-forming regions of Taurus-Auriga and Scorpius-Ophiuchus. The current binary-frequency statistics within different separation ranges are given in Table 1.3. The main conclusions from these surveys and others (still with small number statistics) are:

Multiplicity

There appears to be an excess of pre-main-sequence binaries over main-sequence binaries of $1.5 - 3$ times. Ghez, Neugebauer and Matthews (1993) found an excess corresponding to a factor of 3.5 ± 1 in the separation range of 16-252 AU. Leinert et al. (1993) found an excess of 1.9 ± 0.3 for 18-1800 AU, and Reipurth & Zinnecker (1993) found an excess of ≈ 1.5 for 160-1800 AU. Also, Richichi et al. (1994), when combining lunar occultation data with the surveys of Leinert et al. (1993), Ghez, Neugebauer and Matthews (1993) and Mathieu, Walter and Myers (1989), finds a binary frequency of 60 ± 9% in the range 1.8-1800 AU which is larger than the main-sequence binary frequency found by Duquennoy and Mayor (1991) over the same range (Figure 1.2). In contrast, however, Prosser et al. (1994) using HST images of the Trapezium cluster finds no enhancement over the Duquennoy and Mayor survey. Finally, Ghez, Neugebauer and

Matthews (1993) also extrapolated their results and estimated that 35% of pre-main-sequence systems may be multiple systems - much higher than the 5% of main-sequence systems observed by Duquennoy and Mayor. In conclusion, although hampered by small-number statistics, there seems to be an excess of pre-main-sequence multiple systems over the main-sequence.

Separations (Periods)

The separation distribution of pre-main-sequence systems is, thus far, indistinguishable from that of the main-sequence systems from the Duquennoy and Mayor (1991) survey (Reipurth and Zinnecker 1993; Leinert et al. 1993; Mathieu 1992a).

Eccentricities

The eccentricity-period distribution is similar to the main-sequence survey of Duquennoy and Mayor (1991) (Figure 1.3). Systems with periods $P < 6$ days are circular or near-circular. Intermediate-period systems have an increasing maximum eccentricity, and no systems are observed with an $e < 0.1$ with $P > 10$ days (Mathieu 1992b). The eccentricities appear larger than those observed for main-sequence systems, however. In the Duquennoy and Mayor survey close systems with $P < 11$ days are circular, whereas for the pre-main-sequence systems the cutoff appears at 6 days. Also, the maximum eccentricity observed for intermediate-period, pre-main-sequence systems tends to be higher than for binaries in the Duquennoy and Mayor survey with the same orbital period. Thus, there may be an ongoing circularisation process after the formation of the binary.

Flux Ratios (Mass Ratios)

Unfortunately, the mass ratios of pre-main-sequence binaries are not able to be determined directly. Thus far, only the flux ratios of angularly resolved systems have been considered (Simon et al. 1992; Leinert et al. 1993; Reipurth and Zinnecker 1993). So far, these are consistent with random pairings from the initial mass function of the main-sequence field stars, and with the Duquennoy and Mayor (1991) survey for main-sequence G-dwarfs. This suggests that binary membership is established within $\approx 10^6$ years of star formation.

Infrared Companions

A surprising finding in the past decade has been the discovery of optically-visible, pre-main-sequence stars with infrared companions that are not visible optically (see Mathieu (1994) and references within). Zinnecker and Wilking (1992) estimate the frequency of infrared companions to be $\sim 10\%$ of all T-Tauri binary systems. It is also common for the infrared companions to be more luminous than their optical counterparts (e.g. Chelli et al. 1988). The separations of these objects are greater than 100 AU.

Understanding why one star is so heavily embedded while the other is visible could be an important clue to understanding the star-formation process.

Classical versus Weak-lined T-Tauri Stars

Classical T-Tauri stars show strong emission lines (such as Hα) and are thought to be accreting from a disc, while weak-lined T-Tauri stars, although frequently having a far-infrared excess, have a lack of or very weak emission lines. The weak-lined systems are thus generally thought to be older stars that have depleted their inner discs and stopped accreting. Ghez, Neugebauer and Matthews (1993) find the relative frequency of classical T-Tauri stars in binaries decreases significantly with decreasing projected separation over 16-252 AU. This suggests the presence of a close companion may shorten the accretion and disc lifetime. This study disagrees with those of Simon et al. (1992) and Leinert et al. (1993), however, who find no difference in the frequency of Hα emission between close and wide systems.

Discs

At least $\approx 50\%$ of pre-main-sequence binary systems are observed to have infrared excesses at 2.2 μm presumably associated with either circumstellar or circumbinary discs (Strom et al. 1989). A mid-infrared survey by Strutskie et al. (1990) of binaries in Taurus-Auriga at 10-12 μm (indicative of material $\sim$ 1 AU from a star) suggests at least 50% of binaries have excess flux associated with circumstellar discs for all but the closest binaries.

The frequency of circumbinary discs is harder to determine. Two likely circumbinary discs have been resolved: GG-Tau (Dutrey, Guilloteau & Simon 1994), and T-Tau (Weintraub et al. 1989, 1992). In addition to these, many systems show unresolved continuum emission from far-infrared to millimetre wavelengths, however this may be from circumstellar discs rather than circumbinary discs. There is also confusion over whether extended emission is disc-like, or rather just an extended envelope.

1.3 Binary Star Formation: Theory

The first method of binary star formation was described by Laplace in 1796 (see Tassoul 1978). He suggested a binary was formed from separate stellar nuclei which somehow came to orbit each other. However, the physics of the mechanism was not described. Since then four general mechanisms for binary star formation have been proposed. The first, capture, was suggested by Stoney in 1867 (see Aitken 1935). In capture, two, independently-formed, unbound stars form a binary due to some dissipative process. The second mechanism, fission, is attributed to Kelvin and Tait in 1883 (see Tassoul 1978) and was strongly advocated by Jeans (1929). In this process, a single rapidly-rotating object splits in two due to a dynamic instability. The final two mechanisms are variations on fragmentation. Fragmentation was originally proposed by

Hoyle (1953). He noted that a dynamically-unstable isothermal cloud becomes unstable on smaller and smaller scales as it collapses due to the increasing density during collapse. This may allow several fragments to form in the overall collapsing cloud, each of which may form a star. Not only binaries, but also higher-order multiple systems may be formed by this method. This mechanism is the 'standard' method of fragmentation. However, recently there have also been investigations into the fragmentation of massive protostellar discs (Adams, Ruden & Shu 1989; Bonnell 1994). This fragmentation occurs when the disc becomes gravitationally unstable due to the growth of an $m = 1$ eccentric mode. These four mechanisms for binary star formation are now considered in more detail.

1.3.1 Capture

Two independently-formed unbound stars can become bound in a binary system if there is dissipation of the kinetic energy of the system. This dissipation can occur in one of three ways. First, a three-body encounter can occur where the third member takes excess energy from the other two components allowing them to form a binary. Second, if there is a close encounter between two stars, tidal forces can dissipate enough energy that the two stars become bound. Finally, a dissipative medium can remove the excess energy of the two stars. This medium can take the form of either residual gas left in a cluster after its formation, or gaseous discs surrounding one or both of the stars.

For stars in the galactic disc, or in young, dense clusters, the capture rates for three-body and tidal capture have been shown to be far too low to produce the observed binary-star frequency (Mansbach 1970; Hills 1976; Hills & Day 1976; Boss 1988). This leaves the possibility of capture due to a dissipative medium. The effects of distributed gas left over from the formation of a cluster on its dynamics has not yet been studied. The presence of discs surrounding young stars, however, has been shown to significantly affect capture rates, as the cross-section for interaction is increased dramatically over the three-body and tidal capture mechanisms. Larson (1990) estimated that disc-induced captures in very dense clusters such as the Orion Trapezium could occur at up to 0.4 captures per star per 10^6 years. This estimate was revised down by an order of magnitude by Clarke and Pringle (1991) who noted that although low-velocity encounters between stars with discs give captures, high-velocity encounters can destroy the discs. Heller (1991), using numerical calculations, found an intermediate result of 0.05-0.1 captures per star per 10^6 year in Orion.

McDonald and Clarke investigated dynamical biasing of binaries when formed by capture in small-N clusters (McDonald & Clarke 1993) and how this is affected by the inclusion of star-disc interactions (McDonald & Clarke 1994; McDonald 1995). For discless, small-N clusters, they found dynamical biasing can lead to a mass-ratio distribution consistent with the Duquennoy and Mayor (1991) survey if the stars are formed in clusters of 3-4 stars initially. With higher N however, more near-equal mass binaries are formed than unequal mass. Despite using an initial mass function that increases with decreasing mass beyond the hydrogen-burning limit, they found a turn-over in the mass-ratio distribution in all cases. The turn-over moves to higher mass ratio as N increases. Thus they concluded brown dwarfs are unlikely to be found in binaries if this is the most important binary-formation mechanism. This biasing results from the replacing of low-mass secondaries in binaries by more massive secondaries during three-body encounters. McDonald and Clarke (1994) then took these calculations and included the effects of star-disc interactions. These make the first binaries that form tighter than before, as energy and angular momentum are lost by unbinding the disc material, and thus more likely to survive later close encounters. The turn-over in the mass-ratio distribution at low mass ratios disappears as binaries are likely to be formed from the first encounter, and thus the secondary mass function is closer to a random sampling of the initial mass function. The binary fraction increases and is comparable to the fraction of intermediate and wide binaries observed by Duquennoy and Mayor (1991).

Disc captures typically form binaries with initial separations comparable to the disc's outer radius. Continued interaction may decrease the separations further, though it is likely that too few short-period binaries would be formed by capture alone. Capture does predict a wide range of eccentricities, and mass ratios which are essentially uncorrelated, as is observed. It also predicts that there should be non-alignment of the orbital and spin angular momenta of the system. From Section 1.2.1, there is some evidence for this for wide binaries, and against it for short-period binaries. Hence, capture may play an important role in the formation of binaries in dense, small clusters of stars.

1.3.2 Fission

When a protostar accretes material during its formation, or as it contracts toward the main-sequence with disc accretion, it tends to spin up. It is well known that if the ratio of the rotational energy to the absolute magnitude of the gravitational energy β exceeds a critical value, the object becomes unstable to non-axisymmetric perturbations (Lyttleton 1953; Ostriker & Bodenheimer 1973). It was theorised that the growth of these perturbations could lead to the breakup of the protostar into several orbiting condensations and thus form a binary system. Due to the small amount of angular momentum able to be contained by the protostar, only close binaries could be formed by this method. Also, fission predicts a small mass ratio ($\approx 1:10$) for the resulting binary, since it is most energetically favourable for a small amount of material to carry most of the angular momentum when fission occurs.

However, it has been demonstrated by independent, three-dimensional, hydrodynamical calculations that fission of a rapidly-rotating protostar does not occur (Durisen & Tohline 1985; Williams & Tohline 1988; Boss 1989b), as the fission mechanism depends crucially on the equation of state of the fluid. Fission can occur for incompressible fluids, but not for highly-compressible fluids. Instead, the protostar deforms into a bar-shaped object forming spiral arms at the ends of the bar. These spiral arms transport angular momentum outward from the core, via gravitational torques, to reduce β below the critical value. This material forms a disc around a dynamically-stable core. The whole process occurs on the time scale of several rotation periods. Thus, fission does not appear to be a viable process for binary formation.

1.3.3 Standard Fragmentation

Standard fragmentation can occur when a cloud becomes unstable on smaller and smaller scales as it collapses. This depends on the equation of state of the gas as collapse progresses. From Equation 1.9, if $\gamma < 4/3$ the Jeans mass decreases with increasing density and standard fragmentation is possible. The collapse of a cloud to form a protostar passes through several phases as discussed in Section 1.1.2 (see also Figure 1.1). The above limitation means standard fragmentation is generally only possible during the first, isothermal, collapse phase and the second, near-isothermal, collapse phase. In fact, standard fragmentation is still possible in some situations during the adiabatic phase, and standard fragmentation during the second collapse phase is difficult.

Standard fragmentation during the first collapse phase has been the subject of many numerical hydrodynamical calculations. Fragmentation depends heavily on the initial conditions in the cloud. One method of producing fragmentation is to give small initial density perturbations to an otherwise uniform-density cloud (e.g. Boss & Bodenheimer 1979). For a cloud in solid-body rotation, of spherical or spheroidal shape, the fragmentation is dependent on $\alpha_{\rm i}$ and $\beta_{\rm i}$, the ratios of the initial thermal and rotational energies to the magnitude of the initial gravitational energy of the cloud, respectively. According to Miyama, Hayashi and Narita (1984) fragmentation occurs if $\alpha_{\rm i}\beta_{\rm i} < 0.12$, so long as the cloud remains isothermal. For the system to remain isothermal until fragmentation, $\beta_{\rm i}$ must be fairly large, and thus long-period systems are produced.

Clouds with power-law density profiles ($\rho \propto r^{-p}$) of $1 < p < 2$ and that are initially in uniform rotation do not fragment (Boss 1987b; Myhill & Kaula 1992). Fragmentation is possible if they are differentially rotating initially (Myhill & Kaula 1992), but there is no observational evidence to support differentially rotating clouds. Instead, observations are consistent with solid-body rotation. Furthermore, the hypothesised magnetic breaking (see Section 1.1.1) required to remove rotational energy from the cloud cores to match observations, would drive these cores toward solid-body rotation. This is a problem as most stars are observed to be in binary or multiple systems, and if the clouds do in fact have power-law density profiles and solid-body rotation, then fragmentation to produce multiple systems will not occur. If the clouds have Gaussian-type density profiles as suggested by Ward-Thompson et al. (1994), however, fragmentation can still occur (Boss 1991). Better resolution observations are required to determine how centrally condensed typical star forming cloud cores are.

An alternative to near-spherical initial clouds, is to start with a elongated clouds. These can fragment purely due to their initial shape (Larson 1972; Bastien 1983). Collapse for elongated clouds occurs fastest perpendicular to the major axis. If the cloud contains many Jeans masses, a spindle is formed along the major axis of the cloud. This is unstable to fragmentation and many fragments can form. If the cloud has only a few Jeans masses, the collapse can form one fragment at each end of the cloud. Zinnecker (1990) observed that interstellar clouds often show elongated, filamentary structure, and suggested that binary and multiple systems may be formed if these clouds rotate about an axis perpendicular to the cloud's major axis. The fragments, once formed, would fall toward the centre of the cloud forming an elliptical binary or multiple system. Bonnell et al. (Bonnell et al. 1991; Bonnell et al. 1992; Bonnell & Bastien 1992) performed many numerical calculations exploring the fragmentation of elongated end-over-end-rotating clouds. The calculations typically produced wide ($10^2 - 10^4$ AU) binaries, with high eccentricities. The mass ratios of the binaries could be altered by introducing a small density gradient along the length of the cloud (Bonnell & Bastien 1992).

During the adiabatic collapse phase, fragmentation is suppressed as pressure tends to decrease any density perturbations in the cloud. Fragmentation can still occur if the pressure forces are very weak. For molecular hydrogen ($\gamma = 1.4$) the criterion for fragmentation is $\alpha_{\rm i} < 0.09\beta_{\rm i}^{0.2}$ (Tohline 1981; Boss 1981). This can form initial binary systems as close as ~ 1 AU (Boss 1986), although with such a low thermal energy the cloud may easily fragment earlier. This also still leaves the problem of how to form very close binaries with separations < 1 AU. Standard fragmentation during the second collapse phase, although possible in theory, is unlikely because the initial density perturbations that are needed for fragments to be produced are likely to be erased by pressure forces during the adiabatic collapse phase (Boss 1989b).

Thus, standard fragmentation depends critically on the shape, density and angular-momentum distributions of a cloud. Such fragmentation can produce medium and long-period binaries with a wide range of mass ratios and eccentricities.

1.3.4 Disc Fragmentation

Two types of fragmentation have been proposed to occur in rotationally-supported protostellar discs. If the Toomre parameter $Q \approx \Omega c_{\rm s}/(\pi G \sigma) > 1$, where Ω is the angular velocity in the disc, $c_{\rm s}$ is the sound speed, and σ is the surface density, the disc is locally stable against axisymmetric gravitational disturbances. It can, however, be unstable to non-axisymmetric gravitational disturbances for $1 < Q \lesssim 3$. Two disc fragmentation mechanisms have been proposed to operate for discs that are unstable to these non-axisymmetric disturbances.

First, Adams, Ruden and Shu (1989) hypothesised that the growth of a one-armed spiral mode may result in fragmentation. They found growth of an $m = 1$ occurs via a complex series of wave reflections and refractions if the ratio of the mass of the disc to the total mass of the system is greater than 0.238. However, Laughlin and Bodenheimer (1994) found fragmentation did not occur in numerical calculations. Also, it appears that the outer boundary condition for the disc that was used by Adams, Ruden and Shu (1989) actually causes the instability (Heemskerk, Papaloizou & Savonije 1992) and thus binary formation by this mechanism is unlikely.

The second mechanism was discovered by Bonnell (1994) in three-dimensional SPH simulations. This mechanism requires the rapid outward transport of angular momentum from the central regions of the disc via a source of the $m = 2$ (two-armed spiral) mode. The source of this disturbance can either be a rapidly-rotating central protostar (Bonnell 1994), a binary protostar (Bonnell & Bate 1994a), or the disc itself (Bonnell, Bate & Price 1995). In the first case, the rapidly-rotating protostar at the centre of a massive protostellar disc is unstable to non-axisymmetric perturbations (see Section 1.3.2). The protostar first becomes bar shaped, and then forms spiral arms from the two ends of the bar. These move outward into the disc. The spiral arms act to remove angular momentum from the central object, and inner regions of the disc, via gravitational torques. If there is any asymmetry in these spiral arms, then more angular momentum is removed from one side of the protostar than the other. This produces an $m = 1$ mode in the disc, where the protostar moves away from the centre of mass of the system. Finally, because the source of the spiral arms is no longer at the centre of mass of the system, the spiral arms can catch one another and collide. If there is enough material in the arms, this region can be unstable to gravitational collapse, and a companion may be formed. Continued infall from the cloud in which the binary formed is required for the spiral arms to contain enough material to form a gravitationally unstable fragment. Disc fragmentation forms binaries with separations less than the protostellar disc radius, and typically in low-eccentricity orbits. In the other two cases, the evolution is similar except that a central binary or the disc itself (if unstable to non-axisymmetric perturbations) is the central source of angular momentum. It is important to note that with the first and last central sources of the $m = 2$ mode, fragmentation does not occur if the disc results from the angular-momentum-conserving collapse of a cloud with a power-law density profile with an index $p \gtrsim 1$ (Bonnell & Bate 1994b; Bonnell, Bate & Price 1995). Thus it seems both standard, and disc fragmentation of these clouds is not possible, and whether or not these are the initial conditions for star formation must be questioned.

Finally, recent calculations have also shown that although fragmentation is suppressed during the adiabatic collapse phase when $\gamma = 1.4$, disc fragmentation becomes possible again during the second collapse phase, when molecular hydrogen is dissociating and the effective polytropic index of the gas drops to around $\gamma = 1.1$. Calculations by Bonnell and Bate (1994b) show that the formation of close binaries, with separations from a few $R_\odot$ to ~ 1 AU, is possible by disc fragmentation occuring near the end of this phase. The binaries thus formed, however, contain only a few percent of a solar mass and hence their evolution under accretion is critical to their final states.

1.4 The Role of Accretion During Binary Star Formation

We have seen that fragmentation (both standard, and disc) is the most likely formation mechanism for most binary and multiple systems. Capture probably also plays an important role in the formation of long-period binary systems when the stars are formed in small, dense groups. The major problem with numerical fragmentation calculations is that they must be stopped soon after the fragments form, due to the high densities reached in the calculation. The time steps that must be taken to evolve the simulation further become unacceptably short and the simulation takes too long to evolve. In calculations involving the isothermal collapse of molecular cores the fragments typically contain only 10-50% of the original mass of the cloud when the calculations must be halted (e.g. Myhill & Boss 1993), with the closer systems containing the least mass (Boss 1986). For the formation of close binaries, less than $0.01\mathrm{M}_{\odot}$ is contained in the fragments (Bonnell & Bate 1994b). Thus, although a wide range of mass ratios and orbital parameters can be produced, these 'seed' binaries have to grow in mass significantly, via the accretion of the rest of the cloud, before the star-formation process is complete. This makes it impossible to compare the results of fragmentation calculations with observations, since the final properties of the binaries depend on the accretion of, or the interaction with, the rest of the cloud material. Indeed, the accretion of the remaining material may even force some 'seed' binaries to merge.

The primary aim of this thesis is to determine the effects of accretion on to a binary system that is still in the process of formation. A 'seed' protobinary is envisaged to form, presumably by a fragmentation process. Not all of the gas in the initial cloud from which the 'seed' binary is formed has yet collapsed on to the system. Instead the 'seed' binary grows in mass, and its orbital characteristics evolve under accretion of the rest of the gas.

1.4.1 The Effects of Accretion

There are many effects that continued accretion may have. Questions that are considered in this thesis are:

• How does accretion affect the separation of the binary? Under what conditions does accretion increase or decrease the separation? If close 'seed' binaries are formed, do they merge under continued accretion, or do their separations increase?

• How does continued accretion affect the binary's mass ratio? Which component accretes most of the mass, and what parameters does this depend on?

• Under what circumstances are stellar discs formed? Are circumstellar discs formed around both components, one component, or not at all, and what does this depend on? When is a circumbinary disc formed? How does accretion from a circumbinary disc proceed?

Another question that is not considered in this thesis, but may be answered by future work is:

• How does accretion affect the binary's eccentricity? Is eccentricity excited or damped by accretion?

Importance is placed on comparison of the conclusions to the observations described in Section 1.2. For example:

• Can the observed mass-ratio distributions be explained by continued accretion? The observations show that short-period binary systems may favour mass ratios of unity, while intermediate and long-period systems favour unequal mass components.

• Do the conclusions reached about disc formation match observations? For example, not all pre-main-sequence stars are observed to have discs. Can the dynamics of accretion help explain this?

If the effect of accretion on eccentricity is studied, this will also help answer:

• Can the binary period-eccentricity relation be explained by continued accretion? If the main affect of accretion on eccentricity is to circularise orbits, then the tendency of the observed maximum eccentricity of systems to increase with increasing separation may be able to be explained.

Knowledge of the effects of continued accretion after the formation of a 'seed' binary from the initial cloud is essential for any of these questions are to be answered. Binary star formation can not be understood without such a study, and since most stars are formed in binary and multiple systems, neither can star formation in general.

1.4.2 Previous Work

Previous work that has been done in this area falls into two main categories. First, the effects of accretion of infalling gas left over from the initial cloud on to a 'seed' binary. Second, the interactions of a binary with circumstellar and circumbinary discs after accretion from the initial cloud has essentially ceased.

Accretion from an Infalling Cloud

Artymowicz (1983) studied the accretion of an infalling cloud on to a 'seed' binary. The effects of accretion on the mass ratio and separation of the binary as a function of initial mass ratio and the cloud's rotational velocity were considered. The simulations were performed by modelling the gas cloud by approximately 3000 particles that were initially distributed in a toroidal cloud around the binary, and which collapsed to be accreted by the binary's components. The binary orbit typically had a small eccentricity. The initial inner radius of the cloud was about three times the semi-major axis of the binary. The cloud's shape was generally flattened, with the vertical height from the plane of the binary about one fifth of the cloud radius. The magnitude of the rotation of the cloud, in the same sense as the binary, was varied, as was the initial, radial-infall velocity of the particles. Typically, the particles were non-self-interacting and had a mass much less than the binary mass. Thus the calculations were of ballistic, non-self-gravitating accretion. In a few calculations, a crude viscosity was included to investigate whether the results differed. Particles were accreted when they collided with the stars, the sizes of which could be varied.

Artymowicz found the effects of accretion were primarily dependent on the binary mass ratio, and the rotational velocity of the cloud. Mass ratios were varied between $0.3 < q \leq 1.0$. The rotation of the cloud was varied by setting the particles' initial transverse speeds to be a constant fraction ($0 \leq V_{\rm tr} \leq 1$) of the Keplerian speed at each radius. The initial, radial-infall velocity was also set as a constant fraction of this

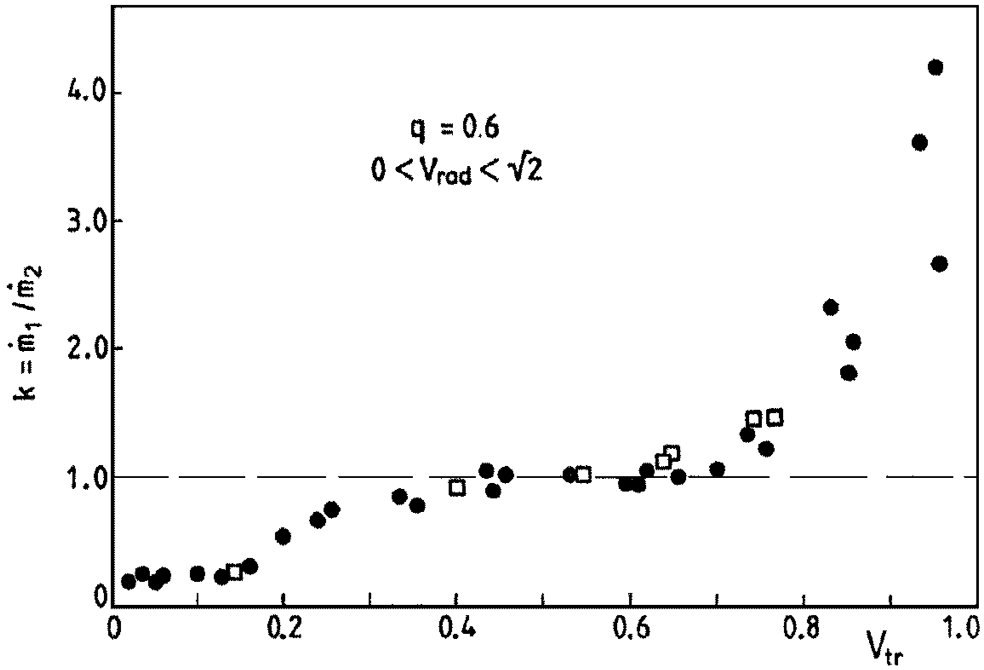

Figure 1.4: Dependence of the relative accretion rate $\dot{M}_2/\dot{M}_1$ on the mean rotational velocity of the cloud $V_{\rm tr}$. The results of 63 models with fixed mass ratio $q = 0.6$, with (squares) and without (filled circles) viscosity (Artymowicz 1983).

same speed ($0 \leq V_{\rm rad} \leq \sqrt{2}$). The primary was found to accrete more material than the secondary for a low-angular-momentum cloud. For a high-angular-momentum cloud, the secondary accreted more material than the primary. The results were found to be relatively independent of the initial radial-infall velocity of the cloud, and of the relative sizes of the stars. For a mass ratio of $q = 0.6$ (Figure 1.4), Artymowicz determined that accretion was dominated by the primary for $0 \leq V_{\rm tr} \lesssim 0.4$ and dominated by the secondary for $V_{\rm tr} \gtrsim 0.7$. For $0.4 \lesssim V_{\rm tr} \lesssim 0.7$, accretion on to both components was roughly equal.

When the mass ratio was varied, keeping the cloud's rotation fixed, Artymowicz found the relative accretion rates were well fit by a parameterisation of

$$\frac{\dot{M}_2}{\dot{M}_1} = q^{-c(V_{\rm tr})}, \tag{1.10}$$

where $c(V_{\rm tr})$ is an empirical parameter. For $V_{\rm tr} = 0.8$, when accretion on to the secondary dominates accretion on to the primary, a value of $c = 3/2$ provides a good fit to the results (Figure 1.5). In all models, Artymowicz found that the change from negative to positive values of c (i.e. from a relative accretion rate of less than unity to greater than unity) occured when $0.55 < V_{\rm tr} < 0.65$.

In terms of binary separation, Artymowicz found that when $V_{\rm tr} \lesssim 0.1$, the semi-major axis decreased, otherwise it increased. He noted that this was a surprisingly small value. The semi-major axis change was quantified in terms of the ratio $h_{\rm a} = (\Delta a/a)/(\Delta m/m)$ where a is the semi-major axis and m the total mass of the binary.

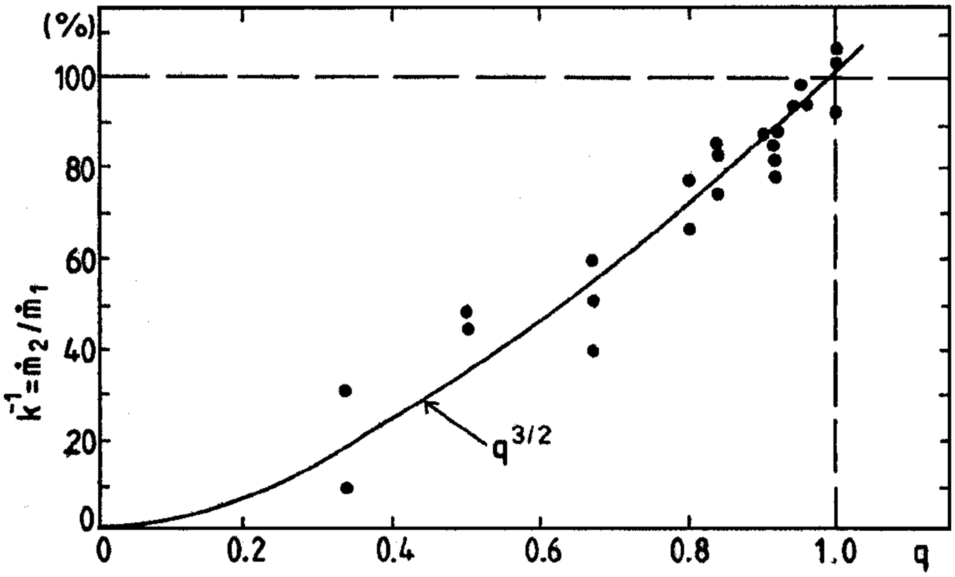

Figure 1.5: The reciprocal of the relative accretion rate $\dot{M}_1/\dot{M}_2$ as a function of the mass ratio q of a binary system. The mass ratio and sizes of the binary components are varied for the same cloud rotational velocity ($V_{\rm tr} = 0.8$). Accretion on to the secondary is greater than on to the primary. The best fit is indicated (Artymowicz 1983).

Figure 1.6 gives $h_{\rm a}$ as a function of the cloud's rotation for a $q = 0.6$ mass ratio binary. Artymowicz concluded that for a binary which increased its mass by a factor of 3 to 5 and roughly equalised its component masses, the semi-major axis could increase by an order of magnitude or more.

Also, Artymowicz noted that the overall change in eccentricity was a linear decrease with time for most models. Superimposed on the linear decrease, was a sine-shaped oscillation. Such periodic oscillations of orbital elements are known from analytic solutions of binary motion under a perturbing force (Kopal 1959). The value of $h_{\rm e} = (\Delta e/e)/(\Delta m/m)$ appeared to depend only on the mass ratio. The eccentricity was observed to increase for 1/4 of the models with $q = 0.6$, but only 1/25 of the models with $q = 0.75$. Thus, accretion from an external envelope was generally observed to decrease the eccentricity, especially for high mass ratios.

Finally, the rate of increase in spin angular momentum accreted from the cloud by the binary components was commented on by Artymowicz. He found the absolute magnitude of the change in spin angular momentum to be almost independent of $V_{\rm tr}$ with a decrease in the region $0.15 < V_{\rm tr} < 0.25$ from the average rate. In this region, the accreted spin angular momentum was found to change sign; for low $V_{\rm tr}$ the spin angular momentum was in the opposite sense to the cloud's rotation, whereas for high $V_{\rm tr}$ the sense was the same as that of the cloud. It was also noted that in most cases the primary accreted more angular momentum than the secondary.

Artymowicz concluded that the accretion of low-angular-momentum material could result in binaries with a low mass ratio, while the accretion of high-angular-momentum

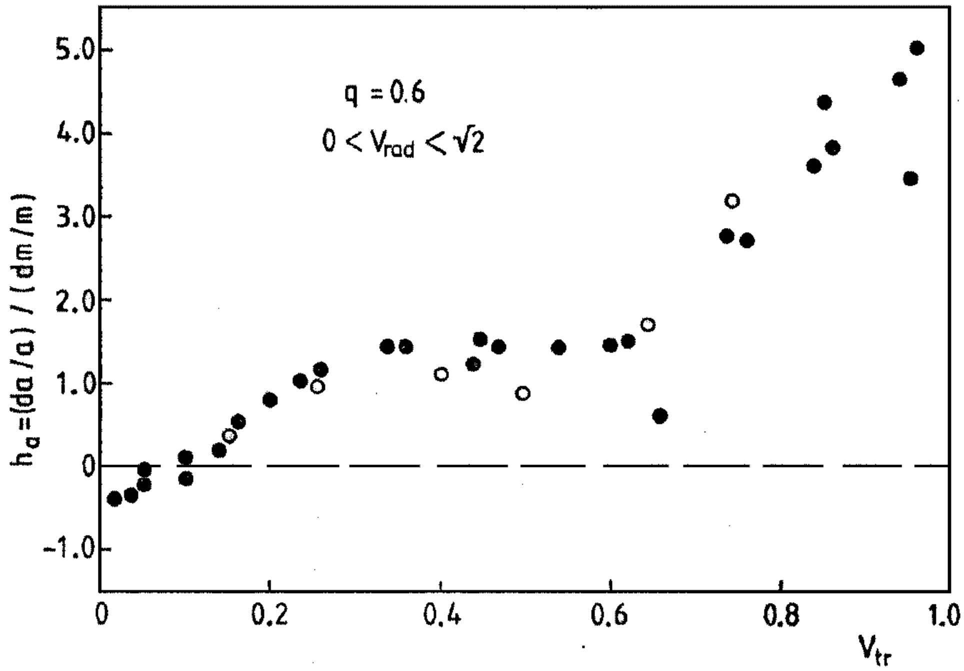

Figure 1.6: Relative change of the semi-major axis per unit relative mass change of the binary h_a subjected to accretion characterised by the rotation parameter V_{tr}. The results of 63 models with fixed mass ratio $q = 0.6$, with (circles) and without (filled circles) viscosity (Artymowicz 1983).

material could lead to mass ratios approaching unity. Also, for systems which accrete a lot of material from the cloud, the orbital separation could be increased by an order of magnitude or more.

Although Artymowicz (1983) determined the general effects of accretion on a 'seed' binary during its formation, many questions remain unresolved. Artymowicz was primarily interested in the formation of binaries with mass ratios near unity, as the observational evidence at that time showed binaries with mass ratios of unity were most common. This observational conclusion was biased, however, and recent surveys have now shown that in fact most binaries are of unequal mass, although short-period binaries may still favour mass ratios of unity (see Section 1.2.1). Due to the desire to produce equal-mass binaries, most of Artymowicz's calculations were for higher mass ratios ($q > 0.5$). The effects of accretion in the parameter space with $q < 0.5$ are largely unstudied. Furthermore, Artymowicz was unable to do a full parameter space study, even with high-mass-ratio 'seed' binaries, due to computational limitations. Hence, there is a need for more of the parameter space to be studied.

Also, although Artymowicz included a crude representation of viscosity in some calculations and found it made little difference to the results, it is important to check this conclusion with a more realistic fluid representation involving viscous and pressure forces. Even if the broad conclusions on the effects of accretion on mass ratio, separation and eccentricity do not change, some differences are to be expected and these should be quantified. For example, viscosity will result in the formation of a circumbinary disc for a high-angular-momentum cloud, whereas with ballistic accretion the particles will follow elliptical orbits.

Finally, there is the question of disc formation around the stars. Will circumstellar discs be formed, and what does this disc formation depend on? Also, as mentioned above, for high-angular-momentum infall the formation of a circumbinary disc around the binary is expected. How does accretion proceed through this disc? These questions can not be answered with a study of ballistic accretion. Gaseous accretion calculations must be performed.

Gaseous accretion on to a binary system has been studied for the accretion of a non-self-gravitating, zero-angular-momentum cloud (Monks & Rayburn 1978). They studied accretion using a finite-difference code in two dimensions for two mass ratios - $q = 0.5$ and $q = 0.25$. For the $q = 0.5$ case, they found a weak accretion wake formed on the inner, trailing side of the secondary, and a second weak accretion wake formed on the trailing side of the primary. With $q = 0.25$, the accretion wake behind the primary was significantly strengthened, while the wake behind the secondary weakened. Also, the accretion wake behind the primary moved to the outside, trailing side of the primary. They did not, however, have the required resolution to determine whether or not discs formed around the two stars. Also, the limitation of two dimensional calculations meant that the convergence of gas streams from above and below the orbital plane could not be modelled. They expected this to increase the strength of the wakes behind the two stars.

Binary-Disc Interactions

Recently, the dynamics of circumstellar and circumbinary discs in a binary system have been studied after accretion on to the binary system has ceased (Artymowicz et al. 1991; Artymowicz 1993; Artymowicz & Lubow 1994; Artymowicz & Lubow 1995). In the first two papers, the interaction, via gravitational torques, of a circumbinary disc with an embedded binary is studied. It is found that resonances between the binary and disc can cause a rapid increase in the eccentricity e, of the binary. This eccentricity increase is caused by loss of angular momentum from the binary to the disc near apastron, and also results in a decrease of the semi-major axis separation and the periastron distance. For $e < 0.2$ the 3:1 resonance dominates the disc response and causes the binary's eccentricity to grow rapidly. For $e > 0.5$, many resonances compete and nearly cancel each other, resulting in inefficient growth of eccentricity beyond this value.

Artymowicz and Lubow (1994) study gap formation in a circumbinary disc, and circumstellar disc truncation, due to gravitational torques from the binary. They find the circumbinary disc is cleared out inside the 3:1 resonance at $r = 2.08a$ for near-circular binaries. For $e \approx 0.2$ the truncation occurs near the 4:1 resonance at $r = 2.52a$, and the truncation radius increases further with increasing eccentricity due to Lindblad resonances. For the circumprimary disc, truncation occurs near the 1:3 resonance, $r = 0.46a$, for low-mass-ratio ($q \approx 0.1$), near-circular binaries and decreases to smaller radii for high-mass-ratio and high-eccentricity systems. Finally, the outer edge of the circumsecondary disc occurs at about $r = 0.2a$ for near-circular binaries with low mass ratios ($q \approx 0.1$). The radius increases with increasing mass ratio, and decreases with increasing eccentricity.

Finally, Artymowicz and Lubow (1995) study the interaction of a binary's torques on its circumbinary disc. The tides and resonant interactions between the binary and the disc form spiral density waves that travel through the disc, and deformations in the inner edge of the disc. They also find that for a sufficiently warm disc, accretion streams may be formed from the circumbinary disc on to the circumstellar discs, allowing accretion from the circumbinary disc to proceed. It is likely that if accretion from the circumbinary disc occurs in this way, the eccentricity driving (and separation reducing) interactions with the circumbinary disc will be affected, and may be negated. Further study of accretion from circumbinary discs is required.

1.5 Thesis Outline

In this thesis, the role of accretion during the early stages of binary star formation is examined. The work presented expands on the parameter space studied by Artymowicz (1983) for the effects of ballistic accretion during binary formation, and tests the conclusions Artymowicz reached. Following ballistic accretion, gaseous accretion is studied using Smoothed Particle Hydrodynamics and the differences between ballistic accretion and gaseous accretion are determined. The work expands on previous studies of gaseous accretion, filling in the gaps in our knowledge of accretion processes between zero-angular-momentum cloud accretion, and the formation of a wide, circumbinary disc around an embedded binary that interacts with the binary only via gravitational torques. This study provides information on how accretion affects the mass ratios and separations of binaries during their formation, and also how the process of disc formation proceeds in binary systems.

In Chapter 2, an introduction to the method of Smoothed Particle Hydrodynamics (SPH) is given. Details of the implementation are also described. These include the use of individual time steps to enable large ranges in dynamic time scales to be followed much quicker than if the same time step is used to evolve all particles.

Chapter 3 gives numerous tests of the SPH code to check the implementation. A particular emphasis is placed on tests involving the artificial viscosity of the code which determines the shock resolving capability of the code, and how well the problem of particle-particle interpenetration during the calculation of high-Mach-number shocks is handled. The appropriate artificial viscosity that should be used in the code when high-Mach-number shocks are to be simulated is determined from these tests.

Once the testing of the SPH technique has been completed, and the best viscosity parameters for the simulations that are the main focus of this thesis have been chosen, attention is turned to the modelling of high-density objects in SPH. High-density regions in SPH are represented by many particles in a small volume. Thus, as the density in an SPH calculation increases, the time steps required to evolve the particles accurately decrease and the calculation time increases. In fragmentation calculations, this results in the calculations being stopped when protostellar fragments form, as the time steps required to evolve the particles in the fragments are too short. Typically, at this stage, a large fraction of the initial cloud is still to be accreted by the protostars, and the final state of the system is unknown. A new method is required to represent stellar-type objects and allow accretion on to them to be followed.

In Chapter 4, the implementation of 'sink' particles in SPH is presented and tested. The many SPH gas particles representing stellar-type objects are replaced by a single, massive, non-gaseous particle. SPH gas particles falling within a specified radius of one of these sink particles are accreted by it and are no longer evolved. In this way, the time steps required to evolve all particles are kept finite. This allows fragmentation calculations to be evolved beyond the formation of protostars, to follow the accretion of the remaining gas on to the system. They also are essential for the study of accretion on to a 'seed' binary system which is presented in Chapters 5 and 6.

The study of the effects of accretion on to binary stars during their formation begins in Chapter 5. Ballistic accretion on to a protobinary system is studied. The mass of the gas being accreted by the binary is very much less than the mass of the binary, and thus the gas is non-self-gravitating. Particles are ballistic; there are no particle-particle interactions such as pressure or viscous forces. The effects of this accretion on the mass ratio and orbital separation of the 'seed' binary are quantified as a function of mass ratio of the 'seed' binary, and the angular momentum of the infalling cloud material.

Chapter 6 repeats the study of the effects of accretion, but this time using gaseous accretion modelled by SPH with accreting sink particles. Particles no longer fall into the system ballistically, but interact with each other via pressure and viscous forces. Again, the gas is non-self-gravitating. The effects on mass ratio and orbital separation are studied, along with circumstellar and circumbinary disc formation.

Using the results from Chapter 6, the evolution of a binary under the accretion of a cloud many times its mass is followed in Chapter 7. The final state of a binary may be determined by integrating the effects of the accretion of each part of the cloud over the infall of the entire cloud. In the example presented here, the initial cloud is assumed to be in solid-body rotation and have uniform-density. Using this technique, however, the effects of accretion of various distributions of gas will be able to be studied in future.

Finally, in Chapter 8, the conclusions are given. The advantages of including sink particles in SPH calculations of fragmentation and accretion problems are expounded upon, and the conclusions reached about the role of accretion during binary star formation are discussed.