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The role of tidal interactions in star formation

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ABSTRACT

Nearly all of the initial angular momentum of the matter that goes into each forming star must somehow be removed or redistributed during the formation process. The possible transport mechanisms and the possible fates of the excess angular momentum are discussed, and it is argued that transport processes in discs are probably not sufficient by themselves to solve the angular momentum problem, while tidal interactions with other stars in forming binary or multiple systems are likely to be of very general importance in redistributing angular momentum during the star formation process. Most, if not all, stars probably form in binary or multiple systems, and tidal torques in these systems can transfer much of the angular momentum from the gas around each forming star to the orbital motions of the companion stars. Tidally generated waves in circumstellar discs may contribute to the overall redistribution of angular momentum. Stars may gain much of their mass by tidally triggered bursts of rapid accretion, and these bursts could account for some of the most energetic phenomena of the earliest stages of stellar evolution, such as jet-like outflows. If tidal interactions are indeed of general importance, planet-forming discs may often have a more chaotic and violent early evolution than in standard models, and shock heating events may be common. Interactions in a hierarchy of subgroups may play a role in building up massive stars in clusters and in determining the form of the upper initial mass function (IMF). Many of the processes discussed here have analogues on galactic scales, and there may be similarities between the formation of massive stars by interaction-driven accretion processes in clusters and the buildup of massive black holes in galactic nuclei.

Key words: binaries: general – stars: formation.

1 INTRODUCTION

A long-standing problem in the theory of star formation is the ‘angular momentum problem’, or the problem of understanding how most of the initial angular momentum is removed from the material that condenses into each star. Because the sizes of stars are tiny compared with the sizes of the cloud cores in which they form, individual stars can contain only a tiny fraction of the angular momentum typically found in these cores; therefore nearly all of the angular momentum of the gas that goes into each star must somehow be removed or redistributed during the star formation process (Mestel & Spitzer 1956; Mestel 1965; Spitzer 1968; Bodenheimer 1995). What mechanisms might account for this efficient removal of angular momentum, and where does the excess angular momentum go? Understanding the fate of the excess angular momentum is an important aspect of the problem, because this can put strong constraints on the mechanisms involved; however, the fate of the angular momentum that is removed has received relatively little attention in most discussions of the problem.

One possibility that has been much studied is that viscous torques in a protostellar accretion disc carry away most of the angular momentum of the gas that goes into each star and deposit it in the outer part of the disc (Shu, Adams & Lizano 1987; Papaloizou & Lin 1995; Stahler 2000; Stone et al. 2000). A second possibility that has long been recognized is that most of the angular momentum of a collapsing cloud core goes into the orbital motions of the stars in a binary or multiple system (Mestel & Spitzer 1956; Larson 1972; Mouschovias 1977); this is plausible because most stars do indeed form in binary or multiple systems, and because the typical angular momentum of a star-forming cloud core is comparable to that of a wide binary (Bodenheimer 1995; Larson 1997, 2001). If most of the excess angular momentum of the gas going into each star ends up in the orbital motions of the companion stars in a binary or multiple system, protostellar interactions must then play a central role in the star formation process, and tidal torques must transfer most of the excess angular momentum from the gas that forms each star to the orbital motions of its companions.

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The current status of the angular momentum problem and the possible mechanisms that might redistribute angular momentum during star formation are reviewed in Section 2, and it is argued there that internal transport processes in discs are probably not sufficient by themselves to solve the problem, but that tidal interactions with companion stars in forming binary or multiple systems can be of quite general importance in redistributing angular momentum during the star formation process. The dynamical evolution of circumstellar discs is discussed further in Section 3, and it is suggested that even if no companion is present initially, one or more companions may eventually be formed by the fragmentation of such a disc. Any companions thus formed, including massive planets, can then play an important role in the further evolution of the system through their tidal effects on the remaining disc. The formation of companions may then be a very general feature of star formation, and it may be how nature solves the angular momentum problem.

If protostellar interactions and tidal torques play a major role in star formation, this will have important implications for the earliest stages of stellar evolution as well as for the properties of stellar and planetary systems. Section 4 discusses some of the implications of tidal interactions for early protostellar evolution, planet formation, the formation of massive stars and the origin of the stellar initial mass function (IMF); also discussed is the possibility that similar effects may play a role in the growth of black holes in galactic nuclei. The main conclusions of the paper are summarized in Section 5.

2 THE ANGULAR MOMENTUM PROBLEM

Early discussions of the angular momentum problem considered the angular momentum of a solar mass of material in an interstellar cloud rotating with the Galaxy, and showed that this is many orders of magnitude more than can be accommodated in a single star even when rotating at breakup speed (Mestel 1965; Spitzer 1968). We have learned since then that stars form in dense molecular cloud cores that rotate much more slowly than would be expected on this basis (Goodman et al. 1993), plausibly because magnetic fields have already removed much of the initial angular momentum during early stages of cloud contraction (Mestel 1965; Mouschovias 1977, 1991). However, magnetic fields are predicted to decouple from the gas in star-forming cloud cores by ambipolar diffusion long before stellar densities are reached, and angular momentum is then approximately conserved during the later stages of the collapse (Basu & Mouschovias 1995; Basu 1997; Mouschovias & Ciolek 1999). Observations of collapsing cloud cores confirm that angular momentum is approximately conserved on scales smaller than a few hundredths of a parsec (Ohashi et al. 1997; Ohashi 1999; Myers, Evans & Ohashi 2000). An important part of the angular momentum problem therefore remains unsolved, as the observed typical angular momentum of the collapsing cloud cores is still three orders of magnitude larger than the maximum that can be contained in a single star (Bodenheimer 1995). This means that only a tiny fraction of the mass in a star-forming core can end up in a star unless non-magnetic torques remove or redistribute most of the remaining angular momentum.

Where does this excess angular momentum go? In principle, there are two possibilities: it could go into residual diffuse gas at large distances from the star, for example gas in an extended disc as in standard protostellar accretion disc models, or it could go into the orbital motions of the stars in a binary or multiple system. In the first case, the excess angular momentum must somehow be transported to large radii in the residual gas, for example to the outer part of an extended circumstellar disc, while in the second case, the excess angular momentum of the gas forming each star must be transferred to the orbital motions of its companions. We consider below the mechanisms that might be involved in each case. In principle, a centrifugally driven disc wind could also remove angular momentum from a protostellar disc (Ouyed & Pudritz 1999; Königl & Pudritz 2000), but completely self-consistent models based on this hypothesis have not yet been developed. In any case, if the wind is launched from a small region close to the central star, as seems likely, it cannot contribute much to the solution of the angular momentum problem because the matter in this region must already have lost most of its initial angular momentum.

2.1 Transport processes in discs

In the ‘standard model’ for isolated star formation (Shu et al. 1987), a central stellar object of very small mass forms first, and a disc is then built up around it by the infall of gas that has too much angular momentum to fall directly on to the star. The star acquires most of its final mass from the disc via an accretion flow driven by an assumed viscosity that transfers angular momentum outward and mass inward; most of the angular momentum of the system then ends up in the outer part of the disc. In order to absorb all of this angular momentum, the disc must expand by a large factor in radius (Bodenheimer 1995; Calvet, Hartmann & Strom 2000); for example, if the residual disc has 25 per cent of the initial mass, it must expand by a factor of 16 in radius, while if it has 10 per cent of the initial mass, it must expand by a factor of 100, becoming larger in this case than the original cloud core. Because most of the angular momentum resides in the outer part of the disc, most of the angular momentum must then be transported out to these very large radii.

This simple model, however, encounters both observational and theoretical difficulties. Observationally, the residual discs seen around most nascent stars are too small in size and mass to contain a significant fraction of the angular momentum of a collapsing cloud core (Beckwith 1999; Mundy, Looney & Welch 2000). On the theoretical front, despite extensive study, no mechanism has yet been identified that is clearly capable of transporting angular momentum throughout an extended protostellar disc (Larson 1989; Adams & Lin 1993; Papaloizou & Lin 1995; Stahler 2000; Stone et al. 2000). The effect originally suggested by Shakura & Sunyaev (1973), hydrodynamic turbulence, has no clear justification, as discs are stable against the spontaneous development of turbulence. Even if turbulence is somehow generated in a disc by an external stirring mechanism, it can only transport angular momentum relatively inefficiently by a diffusion process, and it is not clear that this process will actually transport angular momentum outward, as required. Numerical simulations show that turbulence is indeed inefficient as a transport mechanism, and moreover that it tends to transport angular momentum *inward*, not outward as required in standard disc models (Stone et al. 2000; Quataert & Chiang 2000). Therefore hydrodynamic turbulence does not appear promising as a mechanism for transporting angular momentum outward in discs.

More recently, much attention has been given to the magnetorotational or ‘Balbus–Hawley’ instability as a transport mechanism that can be much more effective than hydrodynamic turbulence if there is sufficient ionization present (Stone et al. 2000). The outermost part of a protostellar disc may be kept sufficiently ionized by ambient cosmic rays, and the part inside 0.1 au may be kept ionized by radiation from the central star, but this still leaves an extended 'dead zone' at intermediate radii where ionization is negligible and this mechanism cannot operate, except perhaps in a surface layer (Gammie 1996). Even if the entire region inside 1 au could be kept sufficiently ionized by self-sustaining magnetohydrodynamic (MHD) turbulence, as suggested by Terquem (2001), this would still leave much of the mass of the disc in the dead zone. In any case, this mechanism yields accretion rates that are only marginally sufficient to be important for star formation (Stahler 2000), so it probably does not contribute much to the solution of the angular momentum problem. It might still be of some importance, however, for the final stages of protostellar accretion after most of the stellar mass has been accreted, and it might help to explain the evidence for continuing accretion of matter at a low rate by many T Tauri stars.

If viscous torques do not transport angular momentum effectively, infalling matter may accumulate in a disc until its self-gravity becomes important, and gravitational effects may then dominate the subsequent evolution of the system (Larson 1984, 1989; Adams & Lin 1993; Bodenheimer 1995; Stahler 2000; Stone et al. 2000; Gammie 2001). One possibility suggested by these authors is that weak gravitational instabilities in a marginally stable disc generate transient spiral density fluctuations whose gravitational torques transfer angular momentum outward and drive an accretion flow. However, most observed protostellar discs have masses that are at least an order of magnitude too small for such self-gravitational effects to be important (Beckwith 1999; Mundy et al. 2000). It is not clear, in any case, whether a marginally stable state can be created and sustained, as this requires fine tuning: the disc must be assembled carefully in a way that brings it just to, but not beyond, the threshold of stability without significant disturbances, because otherwise it may break up into clumps. Such idealized formation processes may not often occur in reality because real star-forming cores are turbulent and irregular and show structure on all resolvable scales that probably typically forms binary or multiple systems (Mundy et al. 2000; Mundy, Looney & Welch 2001). Any circumstellar disc that forms in such a complex environment will be subject to continuing strong perturbations, and if it acquires enough mass, it may fragment into clumps rather than remain in a marginally stable state.

Even if one or more of the transport mechanisms mentioned above does operate, the time-scale for angular momentum transport becomes unacceptably long if the disc expands to the large radii required by standard accretion disc models. For example, if the disc expands to a radius larger than 1000 au, the transport time-scale becomes longer than 10^5 yr even in the most optimistic case where the alpha parameter is of the order of unity (Larson 1989). More realistic values would yield time-scales that are much longer than this, and longer than any observed time-scale associated with star formation. Therefore the transport of angular momentum to large radii by internal processes in protostellar discs does not appear promising as a solution to the angular momentum problem. If internal transport mechanisms are not effective and infalling matter continues to accumulate in a disc, the disc may then become strongly gravitationally unstable and may fragment into one or more companion objects. Once this has happened, interactions between the newly formed companions and the residual disc will dominate the subsequent evolution of the system, and additional transport processes such as tidally generated waves in discs can begin to play a role, as will be discussed further in Section 3.2.

2.2 Effects of interactions and tidal torques

If transport processes in discs are not sufficient by themselves to solve the angular momentum problem, the alternative possibility is that most of the angular momentum in a collapsing cloud core goes into the orbital motions of the stars in a binary or multiple system (Mouschovias 1977; Spitzer 1978; Bodenheimer 1995; Larson 2001). Even in the context of standard accretion disc models, a binary companion may play an important role by limiting the growth in radius of the disc and thus preventing the accretion time from becoming too long (Calvet et al. 2000); in this case most of the angular momentum of the system must go into the orbital motion of the companion. As gravity is the only force capable of significantly altering stellar orbital motions, gravity must be the force that ultimately transfers the excess angular momentum from the gas around each forming star to the orbital motions of the companions in a binary or multiple system. The tidal torques exerted by the companions on the gas orbiting around each forming star must then play a fundamental role in the dynamics of the system and in the evolution of any remaining circumstellar disc.

Both analytical theory (Ostriker 1994) and numerical simulations (Heller 1993, 1995) show that tidal interactions typically remove angular momentum from circumstellar discs, regardless of the orbit of the perturber. This effect can be substantial; for example, a single fly-by can reduce the angular momentum of a disc by as much as 10 per cent (Ostriker 1994). Thus, multiple encounters in a forming cluster of stars could in principle extract much of the angular momentum from a circumstellar disc and drive protostellar accretion (Larson 1982, 1990b), but the frequency of close passages is probably too small for purely random encounters to be very important, even in dense clusters like the Orion Nebula cluster (Scally & Clarke 2001). The importance of interactions is greatly increased, however, if most stars, even in clusters, actually form in close proximity to other stars in binary or multiple systems (Larson 1995; Simon 1997). Interaction with a binary companion can be much more important than interactions with passing stars in a cluster because a binary companion can continually strongly perturb a circumstellar disc (Lubow & Artymowicz 2000). Numerical simulations of forming binary systems show that tidal torques can indeed be very effective in transferring angular momentum from circumstellar discs to stellar orbits and thus in driving accretion on to the forming stars (Bate 2000; Nelson 2000). More generally, tidal torques may be important in driving accretion flows in many types of binary systems containing circumstellar discs (Matsuda et al. 2000; Menou 2000).

The simulations mentioned above have all assumed nearly circular orbits for the stars, but tidal effects may be even more important in the more typical case of eccentric binaries, as the two stars then make repeated close passages. In an eccentric binary with a typical period of the order of 100 yr, 1000 or more close passages may occur during the time when most of the stellar mass is being accreted, and much of the mass may then be acquired during episodes of enhanced accretion triggered by the resulting strong tidal disturbances, as illustrated by the numerical simulations of Bonnell & Bastien (1992). Tidally induced bursts of rapid accretion could plausibly account for some of the most energetic phenomena characterizing the very earliest stages of stellar evolution, such as FU Orionis flare-ups (Bonnell & Bastien 1992) and Herbig–Haro jets (Reipurth 2000), as will be discussed further in Section 4.1.

Given the high frequency of binary and multiple systems and the possibility that *all* stars form in such systems (Heintz 1969; Larson

1972, 2001; Abt 1983), it seems very likely that most of the angular momentum in star-forming cloud cores ends up in the orbital motions of the stars in these systems. The angular momentum of a typical collapsing cloud core is comparable to that of a wide binary (Simon et al. 1995; Bodenheimer 1995), and this suggests that wide binaries may form directly by the collapse of such cores. Close binaries can only form in the same way if there is a substantial population of cloud cores with angular momenta much smaller than the detectable limits, but simulations of turbulent velocity fields (Burkert & Bodenheimer 2000) do not support this possibility and do not predict enough cores with very small angular momenta to account for the observed broad distribution of binary periods. However, the dispersion in binary properties can plausibly be accounted for if most binaries actually form in more complex systems where interactions with dense surrounding matter, for example other forming stars, can efficiently remove energy and angular momentum from the orbits of the forming binaries (Larson 1997, 2001; Heacox 1998, 2000). For example, if most stars actually form in multiple systems that disintegrate into a combination of binaries and single stars, the chaotic dynamics of these systems can create binaries with a wide range of properties, and this can account for at least part of the broad spread in binary periods (Sterzik & Durisen 1998, 1999; Larson 2001). The formation of multiple systems may be a quite general outcome of star formation, since this is suggested by many simulations of the collapse and fragmentation of cloud cores (e.g. Larson 1978; Burkert, Bate & Bodenheimer 1997; Bodenheimer et al. 2000; Boss 2001a; Whitworth 2001; Klein, Fisher & McKee 2001).

Theory and observation are thus both consistent with the hypothesis that most of the angular momentum of collapsing cloud cores goes into the orbital motions of the stars in binary or multiple systems. Protostellar interactions and tidal torques must then play a central role in redistributing angular momentum during star formation and in allowing stars to accrete most of their mass. In this respect, there may be an analogy between protostellar interactions and the interactions that occur between galaxies, as galaxy interactions are known to play a major role in driving gas to the centres of galaxies and triggering starburst and active galactic nucleus (AGN) activity there. AGN activity involves the growth by accretion of a central massive black hole, and the growth of central black holes in galaxies could share some similarities with the building up of massive stars by tidally induced accretion processes in clusters (see Section 4.5).

3 FRAGMENTATION AND TIDAL EFFECTS IN DISCS

3.1 The formation of companions

If interactions with companions are primarily responsible for redistributing angular momentum during star formation, the formation of companions must itself be an intrinsic part of the star formation process. The frequency and other statistical properties of binaries imply that binary or multiple systems are the normal if not universal outcome of star formation (Larson 2001), and this is also suggested by the complex structure of many observed star-forming cloud cores (Mundy et al. 2000, 2001). Moreover, it is possible that even in the more idealized standard model for isolated star formation, one or more companion objects may eventually be formed by the fragmentation of the predicted circumstellar disc. The disc in this model becomes gravitationally unstable well before most of the final stellar mass has been accreted (Stahler 2000), and it can then avoid fragmentation only if it can settle into a marginally stable state in which spiral density fluctuations continually transport angular momentum outward. It is not clear whether a such marginally stable state can be created and sustained, as was noted in Section 2.1, but even if it is, the torques produced by transient spiral density fluctuations may not be strong enough to drive accretion on to the central star faster than the rate at which the disc gains mass. The time-scale for transport of angular momentum by such torques was estimated by Larson (1989) to be of the order of 10^5 yr at a radius of 5 au and 10^6 yr at a radius of 100 au, and this is longer than the predicted time-scale for the growth in mass of the disc (Stahler 2000), especially if the accretion rate is higher than in the standard model (Larson 1998). The disc may then gain mass faster than it can be restructured by internal torques, making a runaway gravitational instability unavoidable.

The outcome of such an instability is not yet clear (Durisen 2001), but analytical theory (Shu et al. 1990; Adams & Lin 1993) and some numerical simulations (Bonnell & Bate 1994; Burkert et al. 1997; Boffin et al. 1998; Nelson et al. 1998; Boss 2000; Bonnell 2001) have suggested that the result is the fragmentation of the disc and the formation of one or more companion objects. Other simulations do not show the formation of bound objects, but only show some restructuring of the disc by large transient spiral density fluctuations (Nelson, Benz & Ruzmaikina 2000; Pickett et al. 2000a,b); however, these results are very sensitive to the thermal behavior of the disc, which has not yet been calculated in full detail. According to Gammie (2001), if the time-scale for radiative cooling is sufficiently long, a quasi-steady state with transient spiral fluctuations can exist, while if cooling is sufficiently rapid, the disc will fragment into clumps. Recently Boss (2001b) has found, in simulations that include radiative transfer, that radiative cooling is effective enough to allow a marginally stable disc to fragment and form a bound companion object. The formation of a companion may in fact be a rather general result, as it represents the lowest energy state that the matter in the disc can attain subject to conservation of its angular momentum. Once a companion has formed, it is no longer a transient feature of the system, and it can only grow in mass through further interaction with its surroundings; thus a density fluctuation large enough to form a bound companion only has to occur once to change irreversibly the evolution of the system.

Once formed, a bound companion, as a coherent mass concentration, will produce stronger and more persistent torques than transient spiral density fluctuations, and it will drive faster disc evolution. Even an object with a mass as small as that of Jupiter could influence the evolution of a disc by tidally extracting angular momentum from the inner region and transferring it to the outer region (Goldreich & Tremaine 1980, 1982; Lin & Papaloizou 1993; Goodman & Rafikov 2001.) The disturbance created by such an object generates acoustic waves in the disc that propagate away from the source, and these waves can in principle transport angular momentum over large distances if they are not damped out too quickly; for a Jupiter-mass object, this effect could drive disc evolution on a time-scale of 10^6 yr, so it might be important for the later stages of protostellar accretion (Larson 1989). Because the tidal torque between a companion object and a disc is proportional to the square of the companion's mass, objects more massive than Jupiter will produce much stronger effects, so that even massive planets could play an important role in redistributing angular momentum during star formation. Goodman & Rafikov (2001) have suggested that the combined tidal effects of many smaller planets could also provide an effective viscosity for protostellar discs.

If the formation of one or more companions is a normal or even unavoidable part of the star formation process, this may be nature's way of solving the problem of angular momentum transport. Since bigger companions produce stronger effects, the most efficient redistribution of angular momentum probably occurs in the formation of binary systems of stars with similar masses; if both stars are surrounded by residual discs, each star can then extract angular momentum tidally from the other's disc, causing material to be accreted by both stars, as happens in numerical simulations of binary formation (Bate & Bonnell 1997; Bate 2000). Most of the mass of a collapsing cloud core can then be accreted by the two stars and most of its angular momentum can go into their orbital motions. Binary systems of stars with similar masses are, in fact, a common outcome of the star formation process, at least for relatively close systems, because the typical ratio of secondary to primary mass in these systems is about 0.5 (Abt 1983; Mayor et al. 1992, 2001). Nature therefore seems to have a preference for forming systems whose properties are optimal for redistributing angular momentum by tidal torques.

If tidal interactions play a central role in star formation, star formation is then clearly a more chaotic and variable process than in the standard model, and it may not have such a predictable outcome. Indeed, in this case there may be no 'standard model,' and the processes by which stars form may vary considerably in their details. One implication of this more chaotic picture of star formation is that protostellar discs may often have a more violent and irregular early history than in the standard models, and they may experience strong disturbances or even disruption as a result of interactions with other stars. This clearly has important implications for planet formation, which will be discussed further in Section 4.2.

3.2 The effect of tidal perturbations on discs

Tidal torques cannot by themselves fully solve the angular momentum problem, however, as their effects are local and their importance falls off rapidly with distance from the perturber. Additional mechanisms are therefore needed if tidal effects are to influence the evolution of the inner parts of discs, far from the perturber. One possibility is that acoustic waves generated by tidal disturbances in the outer part of a disc propagate inward and transport angular momentum as they do so (Spruit 1987, 1991; Larson 1989, 1990a,b; Lin & Papaloizou 1993; Lubow & Artymowicz 2000; Stone et al. 2000; Boffin 2001). A desirable feature of wave transport in this respect is that any wave with a trailing spiral pattern always transports angular momentum outward, regardless of the nature or direction of propagation of the wave (Larson 1989). Many numerical simulations have shown the development of trailing spiral wave patterns in tidally disturbed discs, typically with a two-armed symmetry reflecting the symmetry of the tidal distortion (Sawada, Matsuda & Hachisu 1986; Sawada et al. 1987; Różyczka & Spruit 1993; Savonije, Papaloizou & Lin 1994; Murray et al. 1999; Haraguchi, Boffin & Matsuda 1999; Bate 2000; Makita, Miyawaki & Matsuda 2000; Blondin 2000). These tidally generated waves often develop into shocks, and the associated dissipation of the waves' angular momentum, which is negative for inward-propagating waves, then reduces the angular momentum of the disc and drives an inflow (Shu 1976; Spruit et al. 1987; Spruit 1991; Larson 1989, 1990a; Blondin 2000; Boffin 2001).

The effect of tidally generated waves on the evolution of a disc depends on how far the waves can propagate before being damped out, and this depends on many details of wave propagation and dissipation that are not yet well understood (Lubow & Artymowicz 2000). If waves can propagate to large distances, they can potentially drive an accretion flow through the entire region in which they propagate. For example, if waves produced by tidal disturbances in the outer part of a protostellar disc can propagate all the way to the region inside 1 au, where the magnetorotational instability becomes important, the combination of tidal waves in the outer region and the magnetorotational instability in the inner region might be able to drive an inflow through the entire disc. Magnetoacoustic waves can also exist if magnetic coupling is important, and they can contribute to the transfer of angular momentum. Understanding better the interaction between waves and magnetic fields may be an important part of the overall problem of understanding of the evolution of protostellar discs (Stone et al. 2000).

If wave transport does not occur in some regions because the waves are damped out there (Terquem 2001), inflow may occur only in those parts of a disc where wave transport is important, and the inflowing gas may pile up where the waves are damped (Larson 2001). Local self-gravity may then eventually become important in these regions, with the same possible consequences as were discussed above. Torques due to transient spiral density fluctuations might restructure the disc locally, but it is also possible that fragmentation will occur and lead to the formation of a new companion object such as a small star or massive planet; disc fragmentation induced by tidal effects has been found, for example, in the simulations of Boffin et al. (1998) and Horton, Bate & Bonnell (2001). Any new companion formed in this way could help to drive further disc evolution by its local tidal effects. The above conjecture that nature solves the angular momentum problem by forming companions might then be extended to the stronger conjecture that nature forms as many companions as are needed to redistribute angular momentum efficiently during the star formation process.

4 FURTHER IMPLICATIONS OF TIDAL EFFECTS

4.1 Early protostellar evolution

If tidal interactions are important in driving protostellar accretion at early times, the accretion process will then be time-variable, and it may occur mostly in bursts triggered by the interactions, as in the simulations of Bonnell & Bastien (1992). Considerable evidence indicates that the accretion rates of the very youngest stellar objects do, in fact, vary strongly with time. The observed luminosities of the youngest stars are lower than is expected for models with steady accretion, and this can be understood if most of the accretion occurs in short bursts (Kenyon & Hartmann 1995; Calvet et al. 2000). The jet-like Herbig–Haro outflows, which are believed to be powered by rapid accretion on to still-forming stars, are clearly episodic or pulsed, and this suggests that the accretion process itself is episodic (Reipurth 2000). It is especially noteworthy that the jet sources frequently have close companions; at least 85 per cent of the jet sources are members of binary or triple systems, which is the highest binary frequency yet found among young stars (Reipurth 2000, 2001). This strongly suggests a causal connection between the presence of a close companion and the launching of a jet, as would be expected if tidal interactions were responsible for the episodes of rapid accretion that produce the jets (Reipurth 2001; Larson 2001).

The same bursts of rapid accretion that create the jets may also produce FU Orionis outbursts, another phenomenon of very early stellar evolution that is believed to be caused by episodes of rapid accretion (Dopita 1978; Hartmann & Kenyon 1996; Reipurth 1989, 2000). The possibility that the FU Orionis phenomenon is caused by tidal interactions was first suggested by A. Toomre (private communication) in 1985, as quoted by Kenyon, Hartmann & Hewitt (1988) and Hartmann & Kenyon (1996), and it is supported by the numerical simulations of Bonnell & Bastien (1992), which show bursts of rapid accretion triggered by tidal interactions in a forming binary system. Bell et al. (2000) have suggested that episodic infall in a complex environment like a forming star cluster might also play a role in triggering the FU Orionis phenomenon. The most vigorous forms of activity in very young stars might then all result from bursts of rapid accretion caused by interactions in systems of forming stars.

4.2 Planet formation

If tidal interactions play an important role in star formation, this clearly has implications for planet formation too. Many planet-forming discs may have had more chaotic and violent early histories than that postulated in standard 'solar nebula' models, and quiescent discs suitable for forming regular planetary systems like our own may exist only around relatively isolated stars, many of which may have been ejected from forming multiple systems. The properties of the residual discs around these stars might then be quite variable from case to case, reflecting their chaotic earlier histories. Even our Sun could have been formed in a multiple system in which its protoplanetary disc was disturbed by interactions; this is suggested by the fact that the fundamental plane of our planetary system is tilted 8° with respect to the Sun's equatorial plane, a tilt that could plausibly have been caused by an encounter with another star in a forming multiple system (Herbig & Terndrup 1986; Heller 1993). Our solar system might then represent only a particular special case of planet formation, and it might not be typical.

A major change in our view of what is typical has, in fact, been forced by the discovery in recent years of many extrasolar planets that do not resemble anything seen in our Solar system (Marcy & Butler 1998, 2000; Marcy, Cochran & Mayor 2000). Most of the newly discovered planets have masses similar to that of Jupiter or larger, yet most of them have smaller and more eccentric orbits that are not readily accounted for by the standard models of planet formation. The broad distribution of their orbital parameters instead resembles that of binary systems, and it has been suggested on this basis that they might have a similar origin (Heacox 1999; Stepinski & Black 2000, 2001; Mazeh & Zucker 2001). The wide spread in the orbital properties of both binary systems and extrasolar planets might then result in both cases from their formation in dense and complex environments where interactions are frequent (Larson 2001). For example, if the massive extrasolar planets were formed in circumstellar discs that were strongly disturbed by interactions, their formation might have resembled that of binary companions more than that of the planets in our solar system, blurring the distinction between star formation and planet formation, just as the extrasolar planets seem to be blurring the distinction between stars and planets (Stepinski & Black 2001). If they formed early enough, the known extrasolar planets could have contributed to the redistribution of angular momentum during the formation of their associated stars, and their existence would then strengthen the case for the importance of tidal interactions in star formation.

Another consequence of a chaotic picture of star formation in which circumstellar discs are often disturbed by interactions is that shocks generated by tidal disturbances can produce transient heating events that might account for the high-temperature inclusions observed in meteorites. Chondrules, for example, show evidence for recurrent short heating events reaching temperatures of the order of 2000 K (Jones et al. 2000). Standard disc models offer no natural explanation for such events, but tidally generated shocks could readily produce temperatures of the required order for the required short times, as this would need shock speeds of only a few km s^{-1} which are easily produced by tidal disturbances. As discussed by Jones et al. (2000), nebular shocks with Mach numbers of from 3 to 8, corresponding to shock speeds of this order, would provide a viable heating mechanism if there were a way to generate such shocks. Tidal disturbances in a dense star-forming environment might provide the required mechanism. In this case the chondrules may bear witness to a violent early history of our Solar system.

4.3 Formation of massive stars

Massive stars must evidently accrete more mass when they form than low-mass stars, and more angular momentum must therefore be redistributed during this process by mechanisms such as tidal torques. Because radiation pressure and winds from massive stars can blow away diffuse gas, the matter accreted by a forming massive star must also be very dense and probably very clumpy to overcome these effects (Larson 1982, 1999; Bonnell, Bate & Zinnecker 1998; Stahler, Palla & Ho 2000). Massive stars may therefore only be able to form in very dense and complex environments like those found in dense forming clusters, where interactions with other nearby stars and dense clumps can contribute to the accretion process. Massive stars do, in fact, tend to form in very dense environments, and preferentially near the centers of dense clusters (Larson 1982; Zinnecker, McCaughrean & Wilking 1993; Hillenbrand & Hartmann 1998; Garay & Lizano 1999; Clarke, Bonnell & Hillenbrand 2000; Stahler et al. 2000). Since stronger torques are needed to transfer angular momentum away from the more massive forming stars, more numerous and/or more massive close companions may also be required than is the case for the less massive stars; this possibility is consistent with the fact that massive stars have a particularly high frequency of close companions, and often occur in multiple systems with other massive stars (Mason et al. 1998; Preibisch et al. 1999; Stahler et al. 2000; Preibisch, Weigelt & Zinnecker 2001; Mermilliod & García 2001).

If the companions that help to redistribute angular momentum during the formation of the massive stars were themselves formed by processes involving interactions with less massive stars, this suggests that massive stars are formed by a bootstrap process that builds up stars of progressively larger mass in a hierarchical fashion (Larson 1999). The most massive stars may then represent the culmination of such a process, forming as a result of a series of many interactions in a very dense and complex environment. Such a chaotic and complex formation process contrasts with that envisioned in models which postulate a smooth and centrally condensed structure for massive collapsing cloud cores (Garay & Lizano 1999). At present, the formation of massive stars remains very poorly understood, both observationally and theoretically, and the best evidence we have concerning how they form may be the fossil evidence provided by systems of young massive stars. The high incidence of close companions to these stars, and the fact that these companions are themselves relatively massive, suggest that gravitational interactions have played a particularly important role in the formation of the most massive stars. Such interactions might even include direct collisions and mergers between newly formed stars (Bonnell et al. 1998) or star-forming cores (Stahler et al. 2000). Mergers might be regarded as an extreme type of accretion event, which as before requires angular momentum to be lost from the material being accreted; in this case the angular momentum may be lost through interactions with other forming stars and gas in a dense environment, perhaps similar to the processes involved in the formation of close binaries (Section 2.2). The building up of massive stars by mergers might then be viewed as an extension of the formation of close binaries to the case where so much angular momentum is lost that a merger occurs.

4.4 The stellar IMF

If massive stars are built up progressively by interactions with less massive stars, this has implications for the relative numbers of stars of different masses that can be formed. The tidal effects discussed above imply a dynamical coupling between the masses of stars that form near each other, since the most efficient redistribution of angular momentum occurs when stars interact with other stars of similar or not much smaller mass. As a result, a star of any given mass is most likely to form in association with other stars that have similar masses. As was noted above, the stars in close binary systems tend to have masses that are more nearly equal than would be expected if they had been randomly selected from a standard IMF (Abt 1983; Mayor et al. 1992, 2001), showing that the masses of stars that form near each other are correlated (Larson 2001). There should then be some relation between the numbers of stars that form in adjacent mass intervals, and the resulting IMF should be a continuous function without large gaps in mass; this would avoid the problem of simple accretion models (Zinnecker 1982) in which a large mass gap is created by the runaway growth in mass of the largest object. If the numbers of stars in adjacent mass intervals are coupled by dynamical effects that depend only on the mass ratio and not on the absolute mass, the resulting IMF will then be a scale-free power law, consistent with the evidence that the upper IMF has a power-law form similar to the original Salpeter function (Scalo 1998; Larson 1999; Meyer et al. 2000).

In order to redistribute angular momentum effectively during the formation of the more massive stars, the less massive ones probably must contain a comparable or larger total amount of mass. If, for example, efficient redistribution of angular momentum through the mass hierarchy requires the same amount of mass in each logarithmic mass interval, this would correspond to an IMF with a logarithmic slope of $x = 1$, which is not very different from the Salpeter slope of $x = 1.35$. With the Salpeter slope, the amount of mass per unit logarithmic mass interval increases by about a factor of 2 with each factor of 10 decrease in stellar mass, making the less massive stars moderately dominant in mass, and plausibly allowing them to redistribute angular momentum effectively enough to enable the formation of the more massive stars.

While these considerations are qualitative and do not yet provide any quantitative prediction of the slope of the upper IMF, this view of the origin of the IMF differs fundamentally from most previous theories in that gravitational dynamics here plays a central role in determining stellar masses and the IMF. The building-up of the upper IMF then occurs by processes that are at least partly deterministic in nature, in contrast with most previous theories where the origin of the IMF is based on statistical or geometrical hypotheses (Larson 1999). If the form of the upper IMF results from universal processes of gravitational dynamics rather than from complex astrophysical processes, this would make it easier to understand why the slope of the upper IMF seems to be universal and shows no clear dependence on any astrophysical parameters.

4.5 The growth of massive black holes

It is also possible that there are similarities between the star formation processes discussed here and the growth of black holes in galactic nuclei. In both situations, viscous accretion discs have been invoked to transfer angular momentum outward and mass inward, and similar problems have been encountered, such as a tendency for these discs to become gravitationally unstable (Shlosman & Begelman 1989; Begelman 1994; Larson 1994; Menou & Quataert 2001). As is the case for star formation, it is important to understand the fate of the angular momentum extracted from the matter that goes into a nuclear black hole, and it is difficult to see how all of this angular momentum could go into an extended gas disc; more plausibly, most of it goes into the orbital motions of other condensed objects such as stars or other black holes. Again, this requires that tidal torques remove the excess angular momentum from the gas being accreted, and these torques must come from large mass concentrations. One possibility is that interactions between two massive black holes in a merging system of galaxies may play an important role. Another possibility is that gravitational instability in the dense gas orbiting around a growing central black hole produces new mass concentrations such as massive clusters (Heller & Shlosman 1994). Collective modes such as bars may also play a role on larger scales. In any case gravitational effects of some kind seem likely to be involved in the black hole accretion process (Larson 1994).

On larger scales, galaxy interactions and mergers clearly play important roles in redistributing angular momentum and feeding gas into the nuclear regions of galaxies, and they provide a clear example of tidal torques at work. Many of the phenomena that have been discussed in this paper may thus be small-scale analogues of processes that also occur on galactic scales, where they have been better studied because observations are easier. The formation of massive stars in clusters and the formation of massive black holes in galaxies may be closely related problems.

5 SUMMARY AND CONCLUSIONS

Although magnetic fields may remove much of the angular momentum from star-forming clouds during early stages of their contraction, this still leaves an important part of the angular momentum problem unsolved because these fields decouple from the gas long before stellar densities are reached. Angular momentum is then approximately conserved during the later stages of the collapse, and the angular momentum observed in collapsing cloud cores is still three orders of magnitude larger than the maximum that can be contained in a single star. Nearly all of the angular momentum of the matter that condenses into each forming star must therefore be removed or redistributed during the formation process, and it could in principle go either into diffuse gas, for example in an extended disc as in standard accretion disc models, or into the orbital motions of the companion stars in a binary or multiple system.

Internal transport processes in discs are probably not sufficient by themselves to solve the angular momentum problem, because even if one or more such mechanism does operate, the transport time-scale becomes unacceptably long if the disc expands to the very large radius required by standard disc models. However, tidal interactions with other stars in a forming binary or multiple system can plausibly be of very general importance in redistributing angular momentum during the star formation process. Statistical evidence suggests that most, if not all, stars do indeed form in such systems, and in this case most of the angular momentum of a collapsing cloud core can go into the stellar orbital motions. The tidal torques acting in such systems can then effectively transfer angular momentum from the gas orbiting around each forming star to the orbital motions of the companion stars.

If tidal interactions with companions remove most of the excess angular momentum from forming stars, the formation of companions must itself be an intrinsic part of the star formation process. Observed star-forming cloud cores often show internal structure that is likely to form binary or multiple systems, but even in a more idealized situation such as the standard model for isolated star formation, one or more companions may eventually form by the fragmentation of a circumstellar disc. Companions formed in this way might include massive planets, which can also play a role in redistributing angular momentum by their tidal effects on the remaining disc. Waves generated in discs by tidal disturbances may contribute to the overall transport of angular momentum in the system. If the formation of companions is indeed a normal or even unavoidable part of the star formation process, this may then be nature's way of solving the problem of angular momentum transport.

If tidal interactions are responsible for redistributing angular momentum and driving protostellar accretion, the accretion process must be time-variable, and it may occur mostly in bursts triggered by the interactions. Tidally induced bursts of rapid accretion may account for some of the more energetic activity of very young stars, such as the jet-like Herbig–Haro outflows; a connection between interactions and outflows is indeed suggested by the fact that the outflow sources have an unusually high frequency of close companions (Reipurth 2000). The early evolution of planet-forming discs may also often be a less regular and more chaotic process than in standard models, and tidally induced shock heating events might account for the heating of the chondrules in meteorites.

Interactions with companions are probably especially important for the formation of massive stars, as these stars form in dense environments and have a high frequency of close companions which are themselves relatively massive. If stars gain most of their mass through interactions with companions that have similar or not much smaller masses, the numbers of stars that form in adjacent mass intervals will then be dynamically coupled, and this will have important implications for the form of the stellar IMF. If the form of the upper IMF is determined by universal processes of gravitational dynamics that have no intrinsic mass scale, this could help to explain why the upper IMF appears to have a nearly universal power-law form and shows no clear dependence on any astrophysical parameters.

Many of the processes that have been discussed here have analogues on galactic scales, where tidal interactions clearly play a very important role in driving gas to the centres of galaxies and triggering starburst and AGN activity there. The growth of massive black holes in galactic nuclei may involve processes similar to those involved in the formation of massive stars in clusters, and in this case the formation of massive black holes in galaxies and the formation of massive stars in clusters may be closely related problems.

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