The Formation of Binary Stars
IAU Symposium, Vol. 200, 2001
H. Zinnecker and R. D. Mathieu, eds.

Impulsively Triggered Binary Star Formation

Anthony P. Whitworth

Department of Physics & Astronomy, Cardiff University, Wales, UK

Abstract. We discuss the important rôles which impulsive processes seem likely to play in the formation of binary star systems and higher multiples. On the basis of numerical simulations and theoretical considerations, we show (i) that when a dense layer is produced by a cloud/cloud (or clump/clump) collision, or a dense shell is swept up by an expanding nebula (HII Region, Stellar-Wind Bubble or Supernova Remnant), fragmentation leads to the formation of small-N subclusters of massive protostellar discs, including many wide binaries; (ii) that impulsive interactions between these protostellar discs are frequent and can lead to an hierarchical cascade, spawning new protostellar discs in closer binary systems, plus some escapers. This cascade is particularly effective if there is continuing infall replenishing the protostellar discs. The binaries formed have a wide range of separations and orbital eccentricities, and the Mass Function of the new protostars has an exponent ~ -1.

1. Introduction

The interstellar medium is a chaotic and violent environment. Nowhere is this more true than in regions of star formation, where the non-linear interplay of self-gravity and magneto-hydrodynamics – moderated by complex thermal, chemical and radiative effects – converts diffuse gas clouds ($n \lesssim 10^3$ cm^{-3}) into stars ($n \gtrsim 10^{24}$ cm^{-3}). It has long been realized (Öpik 1953) that dynamical processes are likely to play an important rôle in triggering star formation. Cloud/cloud collisions produce dense shock-compressed layers which, if they can cool radiatively fast enough, fragment into gravitationally unstable cores. Similarly, expanding nebulae (HII Regions, Stellar-Wind Bubbles and Supernova Remnants) sweep up dense shock-compressed shells which then fragment in the same manner (Whitworth et al. 1994a). On a galactic scale, star formation triggered by expanding nebulae is presumed to be the basis of sequentially self-propagating star formation and flocculence; and star formation triggered by cloud/cloud collisions is presumed to make a major contribution to the enhanced star formation rates seen in interacting galaxies.

In Section 2, I shall describe the phenomenology of layer fragmentation, and explain (a) how it produces small-N subclusters of massive and extended protostellar discs, and (b) why it is a very general mechanism (i.e. relevant to a wide range of initial conditions). In Section 3, I shall discuss how these small-N subclusters evolve, and in particular the consequences of collisions between protostellar discs in the dense subcluster environment. It turns out that collisions between massive protostellar discs can be quite prolific in creating new smaller protostellar discs, and delivering them into closer orbits with a wide range of eccentricities. Moreover, the process can repeat itself hierarchically, populating ever closer orbits – at least down to a few tens of AU, i.e. the peak in the distribution of binary separations. This mechanism will be particularly effective if, as seems likely, the discs are replenished by continuing infall. We posit that the wide range of observed binary properties (mass ratios, separations and eccentricities) and the high proportion of triples, quadruples and even higher multiples amongst pre-Main–Sequence stars point unequivocally to a chaotic origin in an environment which bears no resemblance to the well-ordered (and too predictable) world of the Standard Model, i.e. inside-out collapse from a singular isothermal sphere (Shu, Adams & Lizano 1987).

2. Cloud/Cloud Collisions and the Formation of Multiple Protostellar Discs

We have simulated cloud/cloud collisions using SPH (Chapman et al. 1992; Pongracic et al. 1992; Turner et al. 1995; Whitworth et al. 1995; Bhattal et al. 1998). The clouds are modelled as truncated self-gravitating isothermal spheres, contained by a hot, low-density interclump medium. Individually they are stable. However, if they collide at quite modest Mach No., $\mathcal{M} \lesssim 10$, and if radiative cooling quickly reduces the post-shock sound-speed below the pre-shock sound-speed, then the resulting shock-compressed layer fragments while it is still confined by the ram-pressure of the inflowing gas (i.e. when only the front parts of the colliding clouds have been shocked, and the back parts have yet to enter the layer). We are here using the term sound-speed to mean an effective sound-speed which represents both thermal pressure and magneto-hydrodynamic turbulent support.

It has been suggested (comment from RI Klein at meeting), on the basis of very accurate simulations using AMR, that cloud/cloud collisions at finite impact parameter and low Mach No. will lead to shredding of the clouds, rather than the formation and subsequent fragmentation of a layer. However, Klein's simulations represent interstellar clouds as a smooth inviscid fluid, whereas real interstellar clouds have a wealth of internal structure – sometimes described as fractal – and hence a very high effective viscosity (Whitworth 2001, in preparation). Therefore the Klein simulations are not relevant to the situation with which we are concerned here, and the layer fragmentation which we model is physically realistic.

The fragmentation of a shock-compressed layer produced by two colliding clouds has a well defined phenomenology. Moreover, this phenomenology is generic, in the sense that it applies also to clump/clump collisions (i.e. collisions between clumps within a single cloud), to collisions between transient sheet-like structures of the sort that arise in models of interstellar turbulence (e.g. Vázquez-Semadeni et al. 1996), and to shells swept up by expanding nebulae (Whitworth et al. 1994b). In particular we note the following general features.

(i) The layer usually has angular momentum, and is therefore usually tumbling end-over-end. For example, a collision between two clouds of mass M at relative velocity $\mathbf{v}$ and finite impact parameter $\mathbf{b}$ has angular momentum

$\mathbf{L} \sim M\,\mathbf{b} \wedge \mathbf{v}$, so the resulting layer tumbles about $\mathbf{L}$, i.e. about an axis in the plane of the layer and perpendicular to the approach velocity.

(ii) The layer fragments due to motions in the plane of the layer, first into a network of filaments with mean separation $\lambda_{\rm J} \sim a_{\rm S}(\mathcal{M}/G\rho_{\rm S})^{1/2}$ (where $a_{\rm S}$ and $\rho_{\rm S}$ are the effective sound-speed and density in the layer), and then into cores distributed along the filaments at intervals $\sim \lambda_{\rm J}$. This evolutionary pattern is a generic property of gravitational fragmentation.

(iii) Because the layer is confined by ram-pressure, the separation between the cores $\lambda_{\rm J}$ is markedly greater than the thickness of the layer Δz, $\lambda_{\rm J} \sim \mathcal{M}^{1/2}\Delta z$, so the cores are quite massive and quite well separated, and they evolve independently for some time. We identify an individual core as the raw material from which a subcluster will form.

(iv) The cores accrete anisotropically, i.e. mainly along the filaments out of which they have just condensed; and the filaments are tumbling, because they are part of a layer which is tumbling. Consequently the material accreting onto a core has steadily increasing specific angular momentum, so the core spins up, becomes rotationally unstable, and breaks up into a small-N subcluster of rotationally supported protostellar discs. The main instability leading to the fragmentation of an accreting core is one in which a rapidly spinning primary protostellar disc develops spiral arms; the spiral arms then sweep up matter until they become self-gravitating and detatch from the primary to produce a secondary. Core break-up is also helped by the fact that the material flowing in along the filaments tends to be lumpy already before it arrives.

The idea that tumbling filaments play a key rôle in binary formation was first suggested by Zinnecker (1989) and subsequently explored using SPH simulations by Bonnell et al. (1991) and by Nelson & Papaloizou (1993). The phenomenology of cloud/cloud collisions explains how such tumbling filaments might be realized rather frequently in nature.

3. Impulsive Interactions between Protostellar Discs

The internal evolution of an isolated protostellar disc has been studied in great detail (e.g. Laughlin, & Różyczka 1996; Nelson et al. 1998; Adams, Ruden, & Shu 1989). Ultimately the 2nd Law of Thermodynamics inexorably drives a redistribution of angular momentum, and eventually most of the mass loses angular momentum and collects in the centre to form a star, while most of the angular momentum is carried by a low-mass residual disc (Lynden-Bell & Pringle 1974). This disc may then spawn a planetary system. In massive discs the redistribution of angular momentum is probably due to non-axisymmetric gravitational instability and the resulting gravitational torques. In low-mass (Toomre-stable) discs, redistribution of angular momentum may be due to the Balbus-Hawley magneto-hydrodynamic instability (Balbus & Hawley 1991).

However, in the crowded environment of a dense small-N subcluster of protostellar discs, this relatively secular internal evolution has to compete with impulsive perturbations, i.e. collisions and tidal interactions with other protostellar discs and with naked stars. Such interactions can greatly accelerate the dissipation of a protostellar disc, *both* by perturbing the disc and thereby speeding up accretion onto the central star, *and* by breaking the disc up into smaller

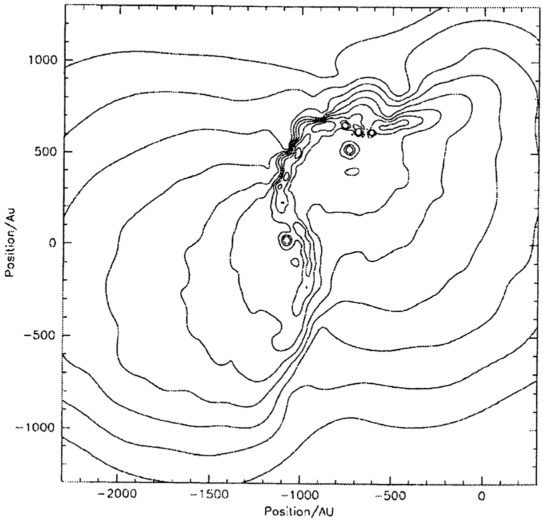

Figure 1. A coplanar collision between two discs with antiparallel spins. The filament swept up between the two discs fragments into numerous condensations, many of which survive as companions to the original protostars; one is ejected. The contours represent constant column-density at 5×10^{23} H_2 cm^{-2}, 10^{24} H_2 cm^{-2}, 2×10^{24} H_2 cm^{-2}, etc.

protostellar discs. We explore the possible outcomes of such interactions in this section.

We have used SPH to simulate collisions between two protostellar discs, and between a single protostellar disc and a naked star (Boffin et al. 1998; Watkins et al. 1998a,b). The protostellar discs in our simulations consist initially of a $0.5\,M_\odot$ central star surrounded by an extended (1000 AU) massive ($0.5\,M_\odot$) disc. The naked stars have a mass of 1 $M_\odot$. Our results are easily scaled to different masses. The individual discs are stable, in the sense that, if evolved in isolation for several rotation periods they do not develop gravitational instabilities, and the changes in their surface-density profiles ($\Sigma \propto R^{-1}$) are slow. Therefore the fragmentation which occurs when they interact must be due to their interacting.

We have simulated interactions for a range of periastra and relative orientations of the spin and orbital angular momenta. In all cases the result is to speed up the dissipation of the discs, (i) by exciting tidal density waves which transport angular momentum and thereby accelerate accretion onto the central star; (ii) by unbinding the outer disc; and (iii) by causing large parts of the disc to condense into new protostars. Some of these new protostars get cannibalized by other more massive protostars, some remain bound to the original protostars, some of them become bound to one another, and some are ejected.

In approximately coplanar encounters (i.e. with the spins and orbital angular momenta approximately parallel or antiparallel) the main mechanism triggering the formation of additional protostars is shock compression. The disc ma-

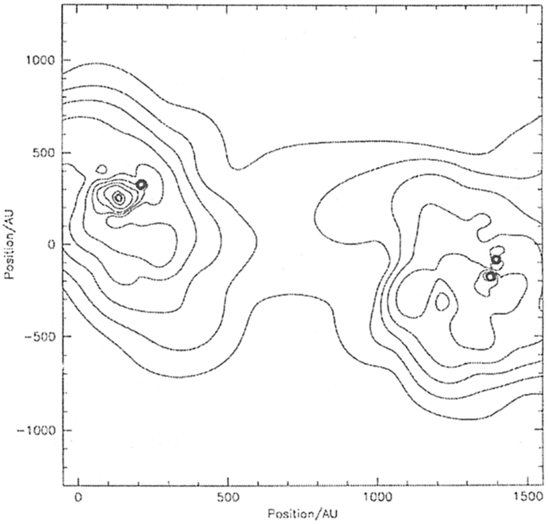

Figure 2. An hierarchical quadruple system formed by the collision of two massive protostellar discs. The collision was colpanar, and the spins were aligned, but this is not critical. The contours represent constant column-density at 5×10^{23} H_2 cm^{-2}, 10^{24} H_2 cm^{-2}, 2×10^{24} H_2 cm^{-2}, etc.

terial is shunted up into a dense filament which then fragments gravitationally to produce new protostars (see Figures 2 and 3). We note that protostellar discs of the sort we are modelling are quite plump, and so approximately coplanar collisions do not require a very precise alignment. Some of the fragments formed are short-lived because they get swallowed by the original protostars, some are captured into binary and higher multiple systems, and a few are ejected. These ejecta might be the origin of the diaspora of Weak-Line T Tauri Stars detected around nearby young associations, and of the free-floating brown dwarves in the Pleiades (Bouvier et al. 1998).

In non-coplanar encounters, the main mechanism triggering the formation of additional protostars is mutual tidal perturbation of the discs. This excites high amplitude spiral arms which sweep up material until they become sufficiently massive to be self-gravitating, at which stage they detach and condense out.

In our simulations, the orbits of the binary systems created have semi-major axes up to ten times smaller than the periastron of the initial encounter. Their eccentricities are distributed fairly uniformly between 0 and 0.9, in accordance with observations of young binary systems – excepting those very close systems which have been able to circularize by tidal interaction. The Mass Function of the newly-formed protostars has exponent ~ -1, extending down into the Brown Dwarf domain. This is compatible with the exponent inferred observationally for low-mass stars and Brown Dwarves in clusters (e.g. Luhman et al. 2000). However, we should emphasize that this Mass Function would have to be be combined with the masses of the primary protostars and then convolved with the mass-distribution of cores and the efficiency of star formation in a core to obtain the overall Initial Mass Function.

If the spins and orbits of the discs are randomly orientated with respect to one another, each encounter generates on average 1.2 new protostars. If – as seems more likely, given the mechanism for creating small-N subclusters described in the previous section – the spins and orbits are approximately parallel, the number of new protostars per encounter increases to 2.2.

This process of interacting protostellar discs spawning new protostellar discs can repeat itself in an hierarchical cascade populating ever smaller orbits, at least down to a few tens of AU. Since the binary systems in our simulations are normally created with a circumbinary disc produced by wrapping tidal tails around themselves, the possibility exists to harden many binaries still further. These processes will be particularly effective if – as again seems likely, indeed inescapable – there is continuing infall to replenish the protostellar and circumbinary discs. The evolution will then also be influenced by the competitive accretion process studied in detail by Bonnell et al. (1997).

4. Conclusion

Impulsive interactions between interstellar clouds or clumps are likely to play an important rôle in triggering and propagating star formation, by producing shock-compressed layers which then fragment to produce dense small-N subclusters of protostellar discs. The fragmentation of shells swept up by expanding nebulae produces small-N subclusters of protostellar discs in a similar manner

In the dense subcluster environment, violent interactions between these discs can produce additional protostars, with many being born in binary systems, and these binary systems having a wide range of separations and eccentricities. If infall continues to replenish the protostellar and circumbinary discs, then the mechanism can operate hiearchically to populate a wide range of binary orbits.

We do not concur with the assertion (e.g. Elmegreen 2000) that interactions between protostars cannot be important if the Initial Mass Function is the same in high-density and low-density star forming regions. Firstly, the interaction cascade can be scale-free over a large range. Indeed, given all the complex thermodynamics between the scale of cores and the scale of stars (viz. the switch from molecular-line cooling to optically thin cooling by dust, to optically thick cooling by dust, and the switch from magnetically coupled to magnetically decoupled and back again) a cascade process of the type described here is an attractive and essentially scale-free way to ensure a linear mapping from core masses into stellar masses. Secondly, the size-distribution of the subclusters within which such interactions occur may be approximately universal, with the overall density of the star-formation environment being determined by the mean separation between subclusters. Thirdly, a large fraction of protostars has discs with diameters $\gtrsim$ 100 AU and "viscous" lifetimes $\gtrsim 10^5$ years, and a large fraction is born in eccentric binary systems with separations $\lesssim$ 30 AU and orbital periods $\lesssim$ 100 years. Unless these two fractions represent two independent modes of star formation – which seems unlikely, since they are routinely found in the same star-formation regions – frequent interactions are inevitable.

References

Adams, F. C., Ruden, S. P., & Shu, F. H. 1989, ApJ, 347, 959

Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214

Bhattal, A. S., Francis, N., Watkins, S. J., & Whitworth, A. P. 1998, MNRAS, 297, 435

Boffin, H. M. J., Watkins, S. J., Bhattal, A. S., Francis, N., & Whitworth, A.P. 1998, MNRAS, 300, 1189

Bonnell, I. A., Martel, H., Bastien, P., Arcoragi, J.-P., & Benz, W. 1991, ApJ, 377, 553

Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 1997, MNRAS, 285, 201

Bouvier, J., Stauffer, J. R., Martin, E. L., Navascues, D. B. Y., Wallace, B., & Bejar, V. J. S. 1998, A&A, 336, 490

Chapman, S. J., Davies, J. R., Disney, M. J., Nelson, A. H., Pongracic, H., Turner, J. A., & Whitworth, A. P. 1992, Nature, 359, 207

Elmegreen, B. G. 2000, ApJ, 530, 277

Laughlin, G., & Różyczka, M. 1996, ApJ, 456, 279

Luhman, K. L., Rieke, G. H., Young, E. T., Cotera, A. S., Chen, H., Rieke, M. J., Schneider, G., & Thompson, R. I. 2000, ApJin press

Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603

Nelson, A. F., Benz, W., Adams, F. C., & Arnett, D. 1998, ApJ, 502, 342

Nelson, R. P., & Papaloizou, J. C. B. 1993, MNRAS, 265, 905

Öpik, E. J. 1953, Irish Astron. J, 2, 219

Pongracic, H., Chapman, S. J., Davies, J. R., Nelson, A. H., Disney, M. J., & Whitworth, A. P. 1992, MNRAS, 256, 291

Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23

Turner, J. A., Chapman, S. J., Bhattal, A. S., Disney, M. J., Pongracic, H., & Whitworth, A. P. 1995, MNRAS, 277, 705

Vázquez-Semadeni, E., Passot, T., & Pouquet, A. 1996, ApJ, 441,702

Watkins, S. J., Bhattal, A. S., Boffin, H. M. J., Francis, N., & Whitworth, A. P. 1998a, MNRAS, 300, 1205

Watkins, S. J., Bhattal, A. S., Boffin, H. M. J., Francis, N., & Whitworth, A. P. 1998b, MNRAS, 300, 1214

Whitworth, A. P., Bhattal, A. S., Chapman, S. J., Disney, M. J., & Turner, J. A. 1994a, MNRAS, 268, 291

Whitworth, A. P., Bhattal, A. S., Chapman, S. J., Disney, M. J., & Turner, J. A. 1994b, A&A, 290, 421

Whitworth, A. P., Chapman, S. J., Bhattal, A. S., Disney, M. J., Pongracic, H., & Turner, J. A. 1995, MNRAS, 277, 727

Zinnecker, H. 1989, Low Mass Star Formation and Pre-Main Sequence Objects (Proceedings of ESO Workshop), ed. B. Reipurth, 447