THE FORMATION OF BINARY STARS

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INTRODUCTION

The speed and storage capacity of present-day computers have stimulated the development of numerical techniques allowing the investigation of three-dimensional gas dynamical problems of astronomical interest. Of the problems that can be attacked with these techniques, that of the formation of binaries has historically attracted the greatest interest. Several investigators have therefore tackled this problem, and their efforts will be discussed here insofar as they relate to the formation of close binaries. Earlier work, including the classical investigations of Kelvin, Poincaré, Jeans, and Cartan, have been reviewed by Chandrasekhar (1969) and Tassoul (1978).

Two mechanisms have dominated discussions of the origin of close binaries, and both can be at least crudely investigated with available computers and techniques. The first of these is fission, a term denoting the bifurcation of a rotating protostar during the quasi-static (i.e., Kelvin-Helmholtz) phase of its contraction to the ZAMS. The second is fragmentation, a term denoting the creation of a double or multiple system by the break up of a rotating protostar during, or immediately following, a phase of dynamical collapse. The possibility that a close binary might form by fragmentation following the dynamical collapse precipitated by the onset of dissociation and ionization of hydrogen in a protostar's deep interior was pointed out by Larson (1972) and has been illustrated quantitatively by Bodenheimer (1978).

The attraction of investigating these mechanisms with 3-D gas dynamic codes are: (1) that we can check earlier conjectures that they do indeed result in binary formation; and (2) that, if these conjectures are confirmed, the properties of the resulting model binaries can be compared with those of observed systems.

OBSERVATIONAL EVIDENCE

The large body of heterogeneous data that astronomers have compiled on binaries is far from an ideal sample if one wishes to

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discover clues to formation mechanisms: The sample is greatly affected by a variety of selection effects, and many catalogued binaries have undergone major evolutionary changes since formation. In addition, observational errors are by no means inconsequential - typically, for each type of binary, we have a handful of systems with well-determined elements and then a vast number whose elements are poorly-determined. Nevertheless, some progress has been made in isolating seemingly reliable formation clues.

With regard to long-period binaries ($P \gtrsim 100$ dys), the most reliable work is that of Abt and co-workers - see Abt (1979) - which is largely based on observational programs specifically designed to lessen or eliminate the above mentioned problems. This work has not revealed any formation clues of high information content: the distributions of these binaries' observable characteristics are smooth and featureless. This surely implies that their formation mechanism neither forgets nor is insensitive to initial conditions; consequently, since the spectrum of initial conditions is not likely soon to be known or predicted, decisive confirmation of a formation theory will not quickly be forthcoming. Thus, although we may well be convinced that hierarchical fragmentation (Heintz 1978; Bodenheimer 1978) is essentially correct, we are not likely soon to strengthen the observational basis for this conviction.

In contrast to the long-period binaries, those of short period ($P \lesssim 25$ dys) do appear to offer formation clues of high information content, and these seem to imply that such binaries are created by a mechanism that at least partially forgets initial conditions. If so, we can reasonably hope to demonstrate decisive observational confirmation for a theory of the formation of close binaries.

The strongest evidence for the forgetting of initial conditions is the spike at $q=1$ in the distribution of mass ratios (Lucy and Ricco 1979). Taken together with the work of Garmany and Conti (1980) on O-type systems, this result seems to imply that a formation mechanism operates over the entire range of stellar masses that, in its ideal form, creates close binaries ($P \lesssim 25$ dys) with identical components. That not all such detached binaries have $q=1$ can be interpreted as a lingering memory of initial conditions.

Further probable formation clues for close binaries come from the period - spectrum diagram for spectroscopic binaries. Figure 1 shows such a plot for SB2's with $q > 0.8$ catalogued by Batten *et al.* (1978) - contact binaries and eruptive variables are excluded. Also shown is the locus of zero-age contact binaries (ZACB) with $q=1$ calculated using the models of Morris and Demarque (1966) for the upper main sequence and extrapolating to later spectral types using observational data for the Sun and YY Gem.

The dashed lines in Fig. 1 indicate possible formation clues. Two of these show that the lower envelope to the observed systems

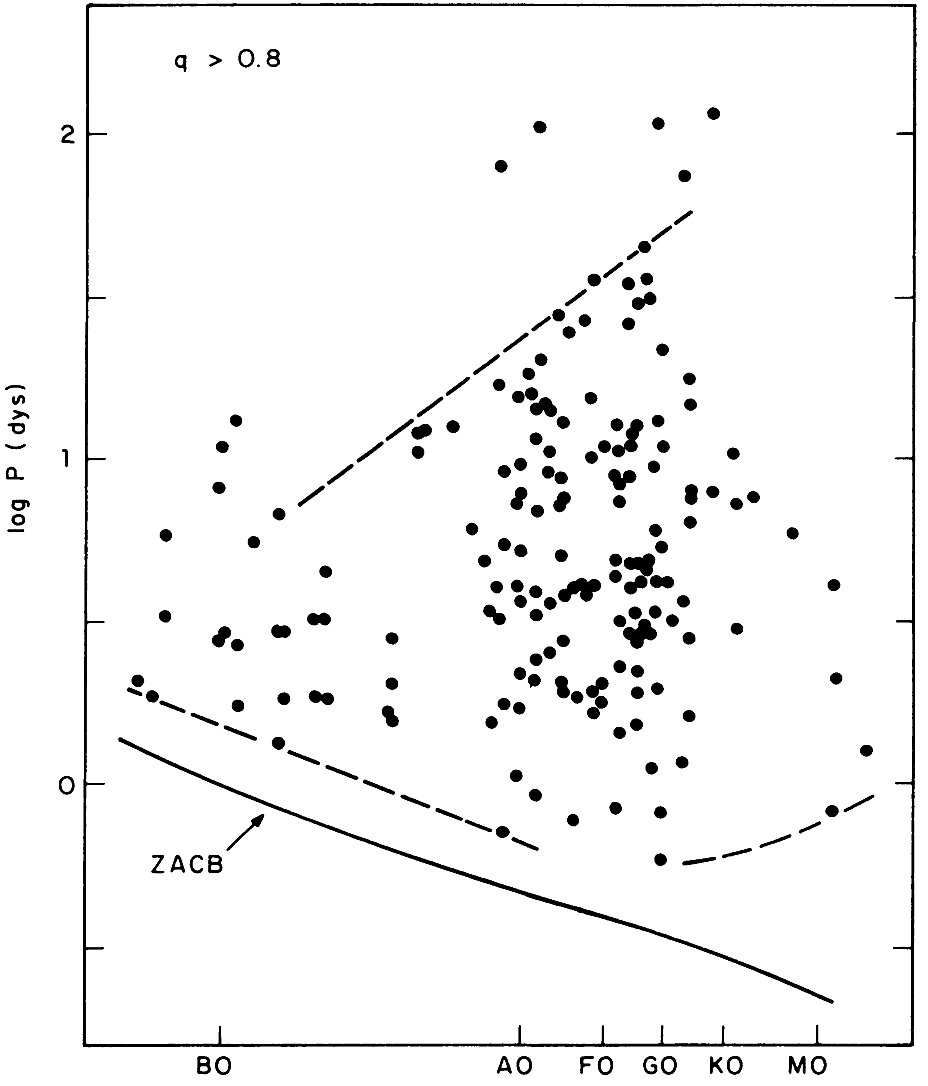

Fig. 1: Period-spectrum diagram for spectroscopic binaries with q>0.8.

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departs markedly from the ZACB locus. Because we can mentally construct binaries that would populate this gap and be readily discoverable, the gap cannot be attributed to selection effects. For upper main sequence binaries, the gap probably indicates that binary formation stops well before massive protostars complete their contractions to the ZAMS. For spectral types later than about Go, the increasingly pronounced gap is probably a consequence of post-formation orbital evolution in consequence of magnetic braking (cf. Huang 1966; Mestel 1968), with the more massive of such binaries ending up as W UMa and short-period β Lyrae systems.

The uppermost dashed line in Fig. 1 calls attention to a sharp drop in the number density of SB2's. This is probably a real and therefore significant effect, but an attempt (Lucy and Acierno, unpublished) to construct arguments against all possible selection effects has not yet proved successful.

Also worth noting is the fact that galactic clusters are not markedly deficient in SB's, when one allows for the incompleteness of searches (Batten 1973). Given the low escape velocity from clusters, this implies that short-period binaries seldom result from the disruption of close multiple systems.

FISSION

Three-dimension numerical calculations of binary formation by fission using the finite-size particle technique (Lucy 1977) have been carried out by Lucy (1977) and by Gingold and Monaghan (1978, 1979). In both these investigations, the ideal problem is substantially modified because of the difficulty in achieving adequate spatial resolution and in treating a problem with two widely different time scales. Nevertheless, despite their different compromises, these investigators agree in finding that fission can lead to the formation of a binary and that the resulting system has small mass ratio, $q \sim 0.3$.

Although improved calculations would be worthwhile, these initial numerical experiments, together with recent observational results, strongly suggest that fission is not the mechanism responsible for the bulk of close binaries. Firstly, in the absence of a post-formation mass-exchange instability on a dynamical time scale (Lucy and Ricco 1979), fission seems not to provide an explanation for the many close binaries with components of comparable mass. Secondly, and perhaps more decisively, it now seems clear observationally (Cohen and Kuhi 1979) that the Kelvin-Helmholtz contraction phase starts at rather small radii, thus severely limiting the orbital periods of binaries formed by fission. For example, taking $5R_{\odot}$ as the radius at which a $3\mathfrak{M}_{\odot}$ protostar first appears on the H-R diagram and assuming that this immediately fissions with conservation of mass and angular momentum into a binary

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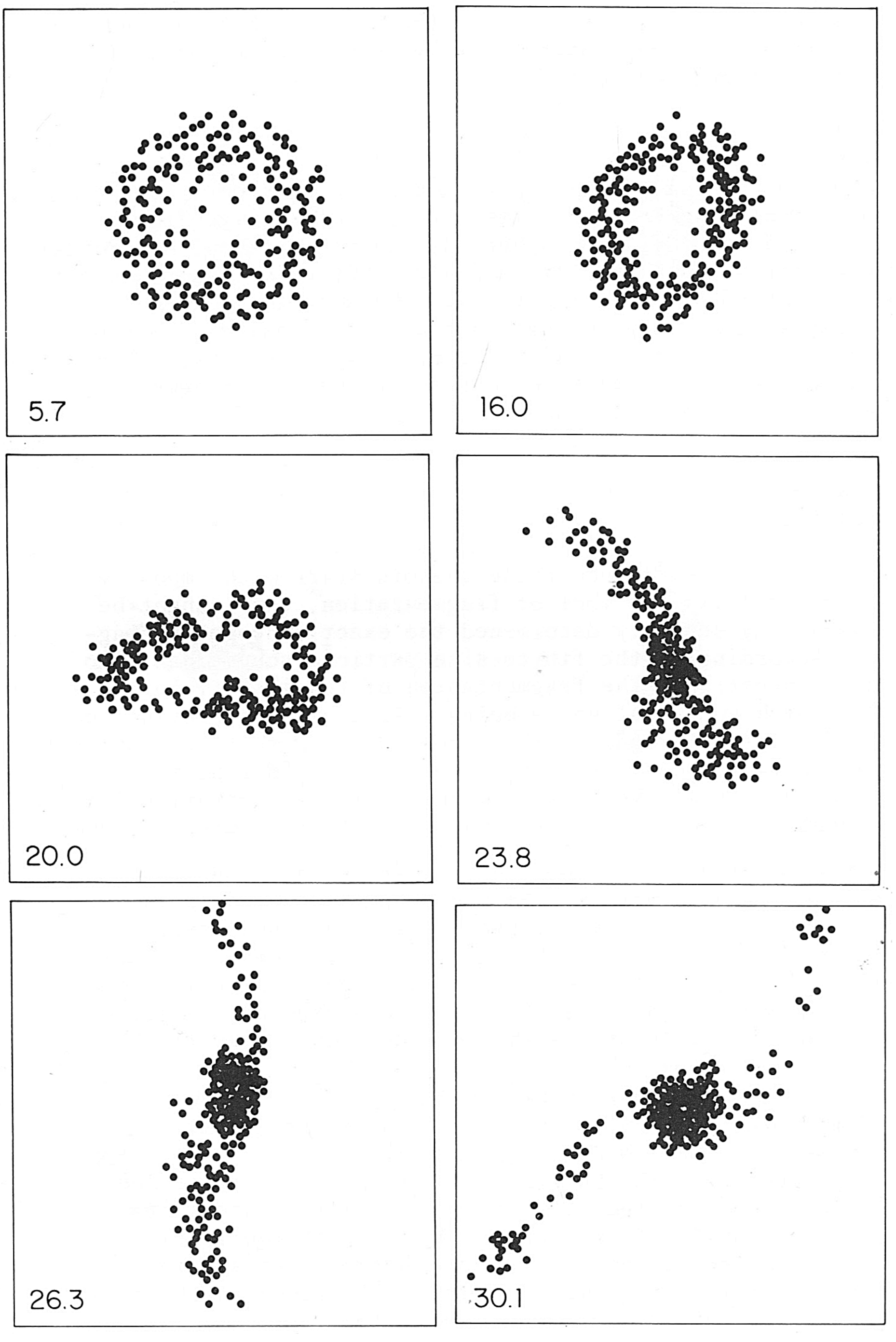

Fig. 2: Fragmentation of toroidal protostar having t_T=0.14 initially.

with q=1, we obtain P ~ 1.5 dys. Thus the bulk of short-period binaries in this mass range have too much angular momentum to attribute their formation to fission.

FRAGMENTATION

For this mechanism, there are two cases to consider, depending on whether or not dynamical collapse gives, immediately before fragmentation, a toroidal or a spheroidal configuration. A toroidal structure was first found by Larson (1972), but this result was not unanimously confirmed by later workers. The position now seems to be that most investigators agree that initial conditions exist from which toroidal structures do indeed result. Nevertheless, since not all initial conditions yield such configurations, the fragmentation of spheroidal protostars also needs to be investigated.

Norman and Wilson (1978) and Cook and Harlow (1978) were the first to carry out three-dimensional calculations of the fragmentation of toroidal protostars. Their results certainly confirm Larson's (1972) conjecture that such a protostar will break up into a binary or multiple system. But since these authors start with imposed perturbations that fix the mode of fragmentation, they cannot be regarded as having securely determined the exact outcome of fragmentation. Accordingly, the finite-size particle scheme has also been used to investigate the fragmentation of toroidal protostars (Lucy 1980), with numerical noise being relied upon to provide seed amplitudes for unstable modes. These results show that the dominant mode of fragmentation depends on t_T, the ratio of thermal to gravitational energy of the initial model, with fragmentation into many components occurring if t_T is small. As t_T is increased, one might anticipate finding a significant range for which an m=2 mode dominates, with a q=1 binary as the end result. That this is not the case is seen by comparing the previously published results (Lucy 1980) with those shown in Figure 2, which extends the earlier sequences to higher t_T. We see that the dominant mode now becomes a global distortion of the ring and that the subsequent evolution yields a rapidly rotating star with two companions of small mass.

The finite-size particle scheme has also been used to investigate the fragmentation of protostars that end their dynamical collapse phases with spheroidal structures. Figure 3 shows a typical evolutionary sequence. The initial model is a highly flattened ($a/c \simeq 6$) spheroidal configuration that is symmetric about its invariable plane, uniformly rotating and in virial equilibrium. As in the toroidal sequences, subsequent changes are isentropic ($\Gamma = 5/3$) and a small bulk viscosity term is included in the equation of motion. We see that the model evolves into a bar ($\tau = 16.2$), but any hope that this might subsequently bifurcate is thwarted by gravitational torques that transfer angular momentum from the bar to exterior debris. Thus the end result is a rapidly rotating axisymmetric single star star with an equatorial disc of debris.

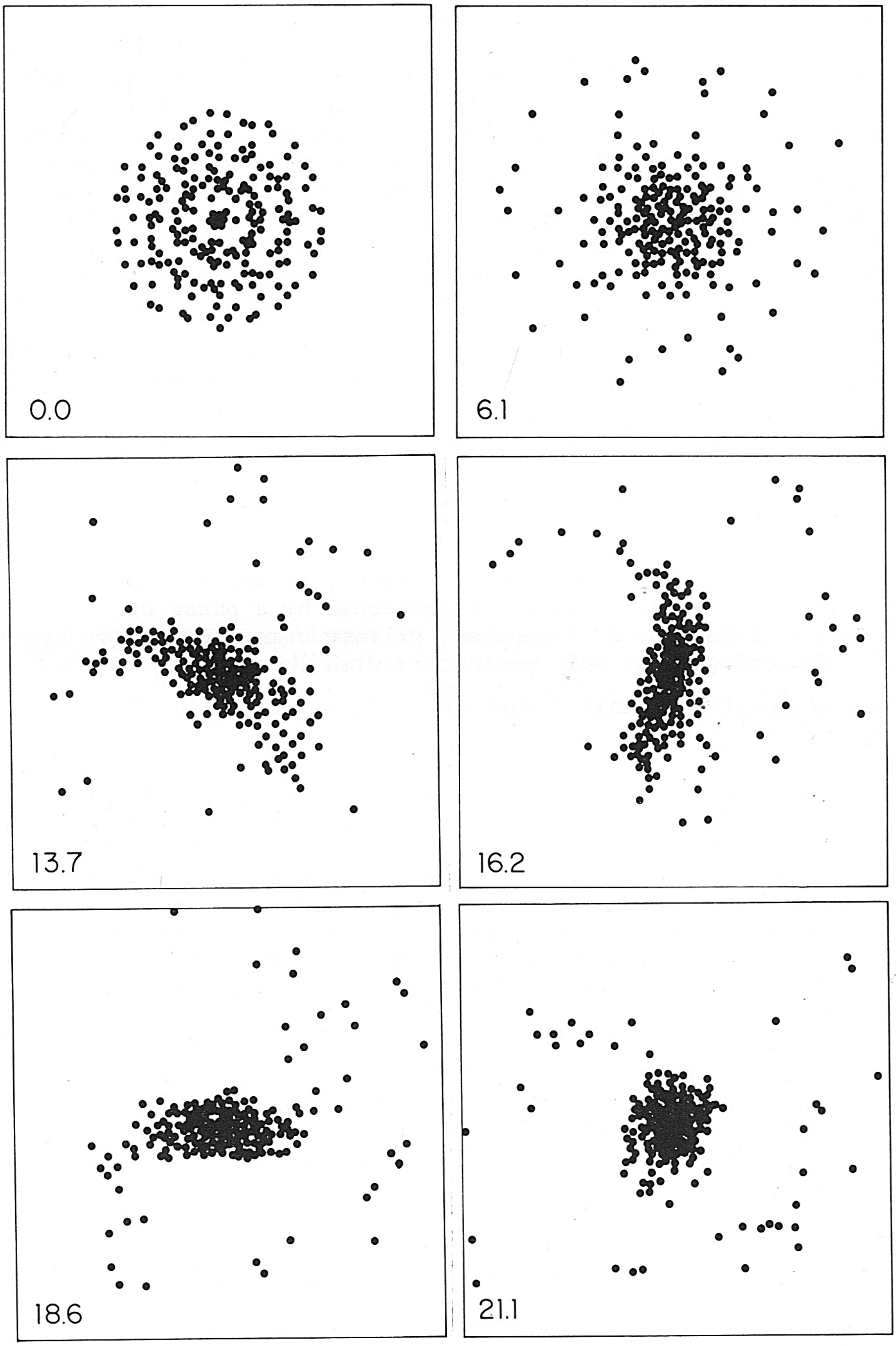

Fig. 3: Fragmentation of spheroidal protostar having t_T=0.12 initially.

DISCUSSION

The various 3-D calculations reviewed here have not yet provided a definitive explanation for the existence of any class of binary star. In particular, an understanding of the formation of q=1 systems has proved elusive. The belief (Lucy and Ricco 1979) arising from the work of Cook and Harlow (1978) and Norman and Wilson (1978) that such systems form directly by fragmentation is not confirmed since q=1 binaries do not appear when the initial models are not seeded with an m=2 perturbation of large amplitude. Nevertheless, these early 3-D calculations have suggested two conjectures for the formation of q=1 systems:

One possibility (Lucy 1980) is that, as a result of the dynamical collapse starting from a pressure-supported configuration, fragmentation proceeds from essentailly noise-free initial conditions and therefore yields a multiple system with identical components. The subsequent reduction to a binary through collisions will then fairly often produce a q=1 system if collisions occur with little mass loss.

A serious flaw in this conjecture, however, is the assumption that the $\overline{\Gamma} < 4/3$ dynamical collapse is preceeded by a phase of mechanical equilibrium (B. G. Elmegreen, private communication). As shown by Gaustad (1963), only protostars with $\mathfrak{M} \lesssim 0.3\,\mathfrak{M}_{\odot}$ have their free-fall collapses halted when dust opacity inhibits direct energy loss by radiation.

A second conjecture envisions a binary with nearly identical components forming in three stages: 1) fragmentation of a toroidal protostar into a close multiple system; 2) reduction of the multiple system to a binary via collisions; 3) a secular increase of the binary's mass ratio by accretion from an exterior disc formed from late-infalling gas. The first two stages are directly illustrated in the cited fragmentation calculations; the third stage is the gaseous analogue of the process invoked by Hayashi et al. (1977) to explain the growth of planets.

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DISCUSSION

Mouschovias: You mentioned at the beginning of your talk that observations do not give us a clue about the formation mechanism of binary stars. Wouldn't you consider Abt and Levy's (1976) result, that there is a single maximum in the period distribution for the 88 available systems, as at least evidence that a single mechanism may be responsible for the formation of all binaries with periods in the range 10 hours to 100 years -- as also suggested by theory (see, Ap. J., 211, 147)?

Lucy: When you bring together data for binaries with periods from 10 hours to 100 years into a single distribution, uncertain correction factors for different selection effects have to be applied. Such data is therefore not decisive in deciding whether or not a single mechanism is operative over such an enormous range of periods.

Tutukov: Even very close binaries have non-zero eccentricities. What is the reason for this?

Lucy: Binaries formed by fragmentation do in general have substantial eccentricities.

Tutukov: Unevolved double-line spectroscopic binaries with separation $a \lesssim 10\ R_\odot$ and mass $M \gtrsim 1.5\ M_\odot$ are absent (see Tutukov, Yungelson 1979 in Proc. IAU Symp. No.88), while the density in units of $\ell n\, a$ of double-line spectroscopic binaries with $a/R_\odot \lesssim 15\ M_\odot/M$ ($M \lesssim 1.5\ M_\odot$) is about 30 times lower than the same density for wider systems. These peculiarities seem very important for the problem of close-binary formation and, possibly, for their pre-nuclear evolution.

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