THE FORMATION OF CLOSE BINARIES

L. B. Lucy
Department of Astronomy
Columbia University
New York, New York 10027, U.S.A.

INTRODUCTION

Although the formation of close binaries has been the subject of numerous investigations in the last 100 years (for a recent review, see Tassoul 1978), we cannot yet claim decisive observational support for any theory, a state of affairs probably reflecting insufficient development of the various theories, rather than a failure to propose the correct mechanism(s). If this is indeed so, we can look forward to significant progress soon, since numerical techniques now allow us - albeit crudely - to follow through to completion binary formation by the two most likely mechanisms, fission and fragmentation. (Herein a binary will be described as having formed by fission if it results from the bifurcation of a rotating protostar as it contracts quasi-statically towards the main sequence and by fragmentation if it results from a rotating protostar's break up into two or more components during, or immediately following, a phase of dynamical collapse).

In investigating these theories numerically, one is tempted to claim qualitative agreement with observation if a solution of the relevant equations has a model binary as its outcome. The consequences of the necessarily limited spatial resolution of three-dimensional gas dynamic calculations suggest, however, that we be more demanding. The effective addition of unintended physical effects as a result of the non-negligible errors of difference approximations is one consequence; another is the suppression of genuine, and perhaps crucial, effects that are implicit in the original equations but which involve short length scales. Thus, even if we adopt the right equations, impose the correct boundary conditions, and provide appropriate initial conditions, the final outcome of our calculations might not correspond closely to reality: a binary might form when it shouldn't and not form when it should.

Without discussing the merits of other observational tests, the view taken here will be that a critical test of the value of numerical simulations is that they provide an understanding of the formation of

M. J. Plavec, D. M. Popper and R. K. Ulrich (eds.), Close Binary Stars: Observations and Interpretation, 7–14.

close binaries with identical components (Lucy and Ricco 1979). This then is the context in which recent 3-D calculations will be discussed in the remainder of this paper.

FISSION

Calculations of binary formation by fission have been carried out by the present author (Lucy 1977) using a somewhat novel technique - the finite-size particle scheme - which has the particular merit of behaving well at low spatial resolution. Although numerical considerations dictated some modifications to the ideal problem, these calculations seem to indicate that binaries formed by fission will have small mass ratios ($q \sim 0.2$), a result not inconsistent with the classical investigations, according to which a binary is the evolutionary end-point of a sequence of pear-shaped figures. On this basis, Lucy and Ricco (1979) conclude that fission can only be responsible for the q=1 binaries if a post-formation dynamical mass-exchange instability brings them to q=1.

Gingold and Monaghan (1978, 1979), also using the finite-size particle scheme, have studied the fission of damped rotating polytropes. Their starting models rotate so rapidly that they have positive total energy; but the ensuing radial motions are damped artificially, so that the later configurations are gravitationally bound. By this device, models are brought to the onset of fission without first evolving along a quasi-static contraction sequence. In one such calculation, Gingold and Monaghan (1979) obtain a binary with q=0.28 and call attention to their solution's similarity to that of Lucy (1977), which did include the quasi-static phase.

FRAGMENTATION

Having argued against fission as the formation mechanism for q=1 binaries, Lucy and Ricco (1979) cited the investigations of Norman and Wilson (1978) and Cook and Harlow (1978) as grounds for suspecting that such systems result from the fragmentation of the toroidal configurations that form as rotating protostars collapse dynamically (Larson 1972). When the collapse is due to $\overline{\Gamma} < 4/3$, this mechanism can produce a close binary (Larson 1972; Bodenheimer 1978). Moreover, since prior to this collapse the protostar was pressure supported, it should then have been rather accurately axisymmetric; fragmentation at this phase therefore proceeds from rather perfect - i.e., noise-free - initial conditions, as one might conjecture to be necessary for the q=1 mechanism.

Although the above-mentioned investigators do report calculations ending with q=1 binaries, these all start with finite m=2 perturbations and so cannot be accepted as definitive demonstrations of the formation of such systems. Accordingly, the fragmentation of toroidal protostars has been re-investigated using the finite-size particle scheme

https://doi.org/10.1017/S0074180900064536 Published online by Cambridge University Press

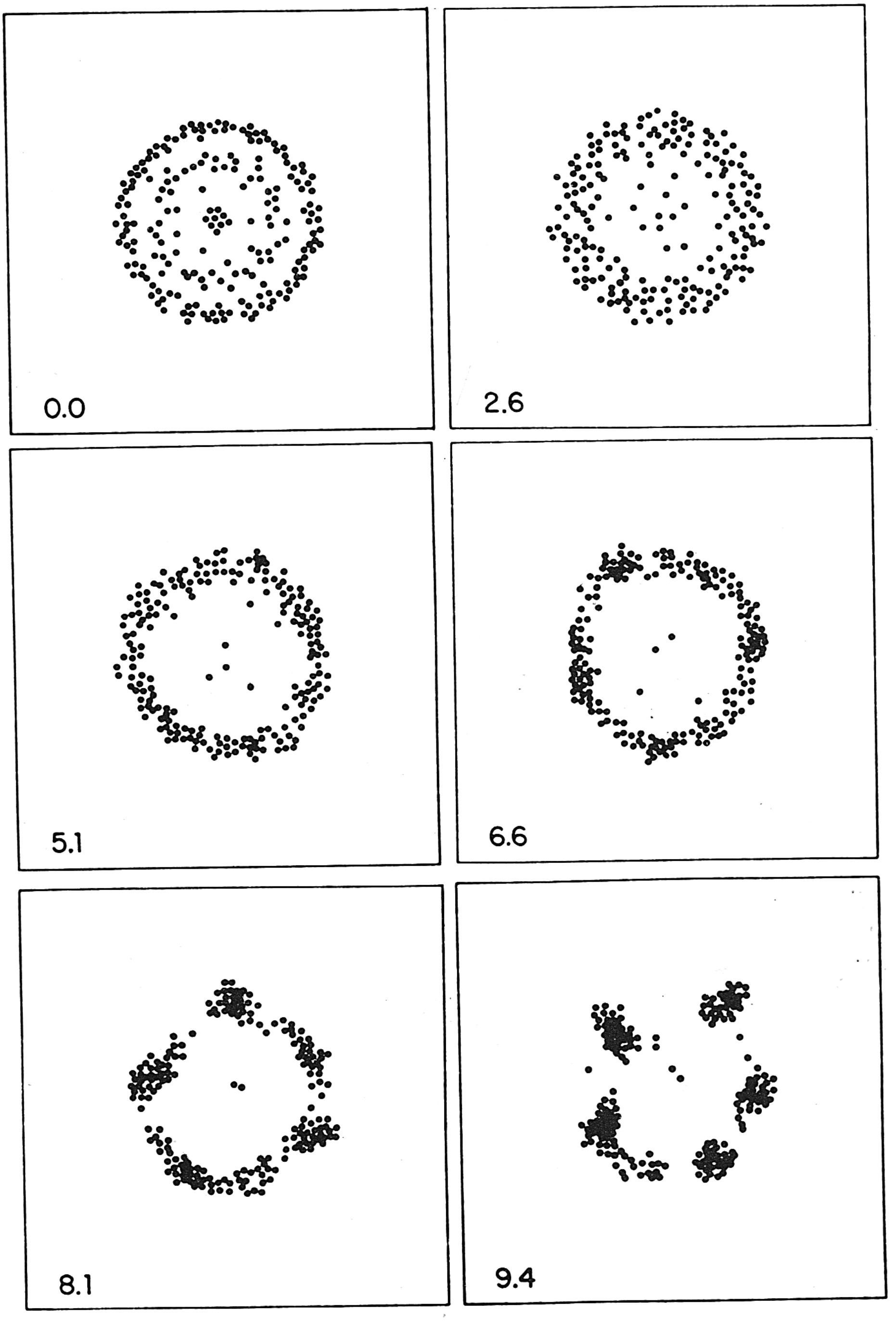

Fig. 1: Fragmentation of toroidal protostar having t_T=0.10 initiall

https://doi.org/10.1017/S0074180900064536 Published online by Cambridge University Press

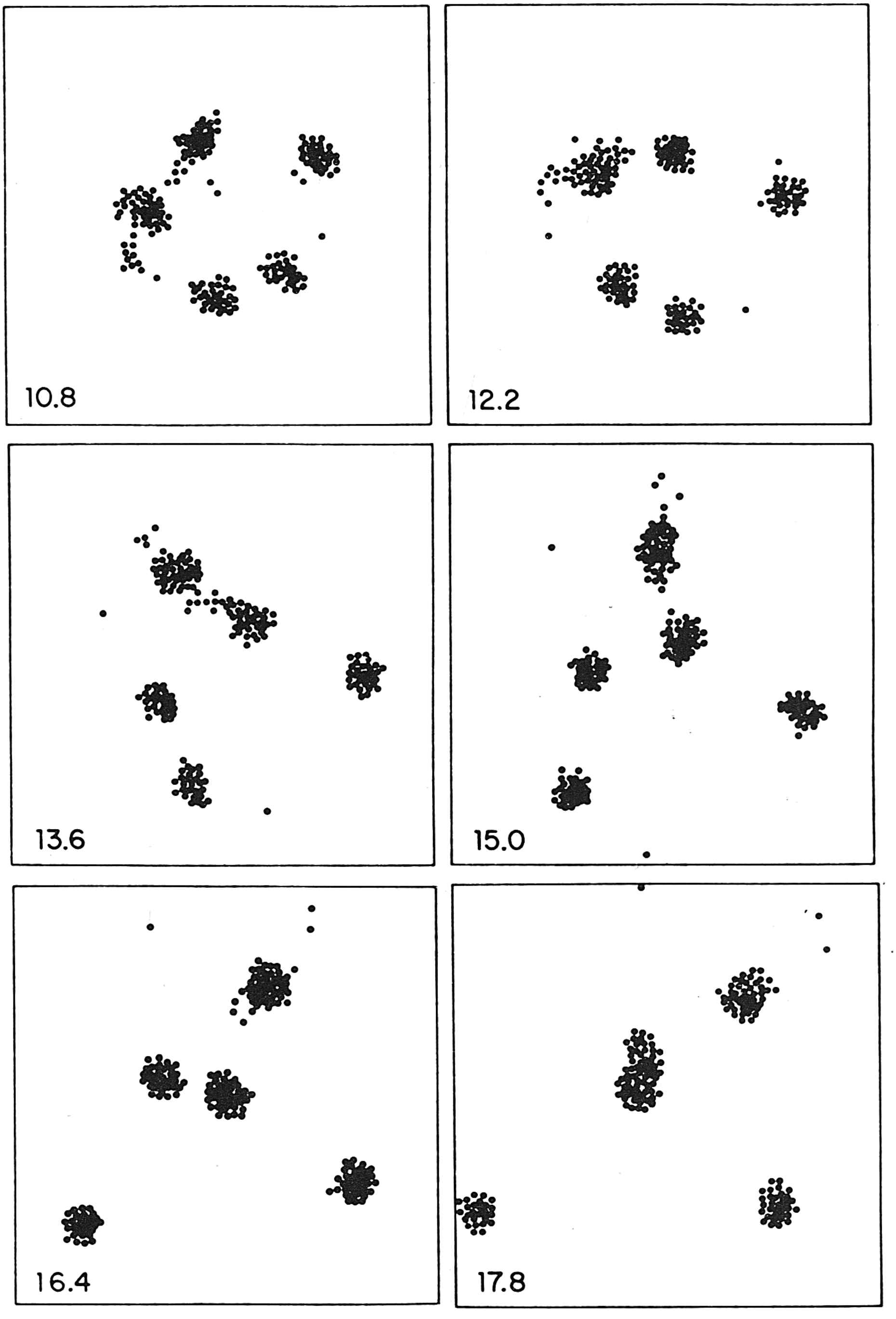

Fig. 2: Evolution of unstable 5-member multiple system formed in Fig.1.

https://doi.org/10.1017/S0074180900064536 Published online by Cambridge University Press

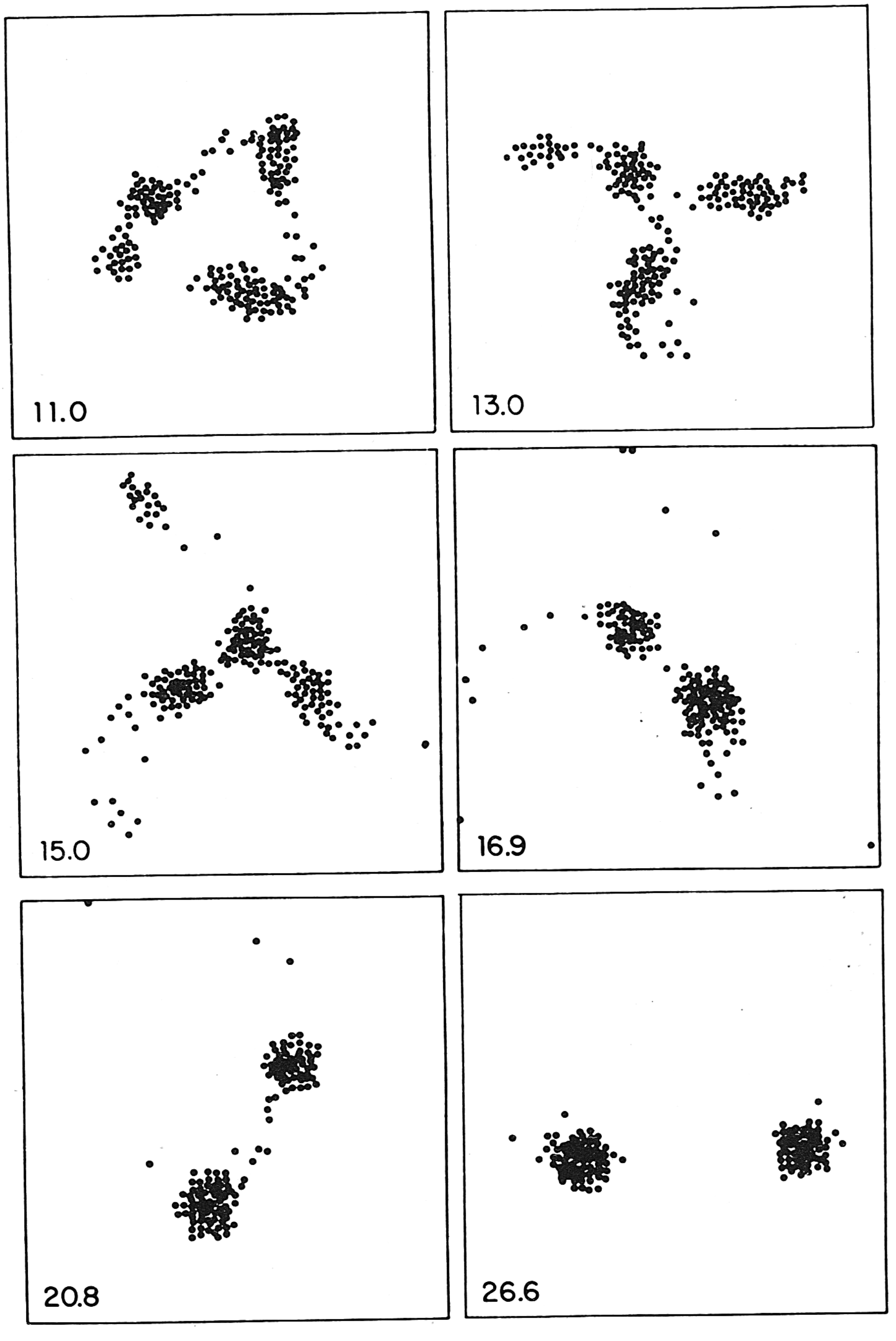

Fig. 3: Evolution of fragments of toroidal protostar having t_T=0.12 initially.

with initial conditions that avoid essentially pre-selecting the fragmentation mode. This is achieved by allowing numerical noise to provide seed amplitudes for unstable modes; a model's fragmentation should then, like that of a protostar, be determined by the non-linear growth of the most unstable mode. Such calculations will now be briefly reported; full details will be published elsewhere.

In these calculations, the initial models are highly flattened, slightly toroidal adiabatic configurations that are symmetric about the invariable plane, uniformly rotating, and in virial equilibrium. Subsequent changes are taken to be isentropic ($\Gamma = 5/3$), with a bulk viscosity term included to simulate the dissipation that would be expected to damp the oscillations of newly formed stars. Because of the simplicity of these assumptions, these models can be scaled to any mass and radius.

Figures 1 and 2 trace the evolution of a model whose initial ratio of thermal to gravitational energy is t_T=0.10; the initial rotation period is 13.5, and the initial time step is 0.35. These diagrams, each of which is an equatorial projection of the coordinates of the 400 particles being followed, show the model evolving into a rather thin torus ($\tau \simeq 5$) and then fragmenting ($\tau \simeq 8$) into an unstable five-component stellar system whose subsequent disruption is complicated by the coalescence of its members (e.g., τ=17.8).

Figure 3 traces the later stages of the evolution of a model with the same initial density structure but now t_T=0.12. After approximately one rotation period (τ=13.0), the model has fragmented into one minor and three major components. Two of the major components coalesce at τ=16.9, so that the final configuration is a binary (q=0.73) with a distant small companion.

Although these calculations have not demonstrated the formation of a q=1 binary, they do suggest the following tentative conjecture: Because of essentially perfect initial conditions, a protostar, following its $\bar{\Gamma} < 4/3$ collapse, fragments into an unstable multiple system with identical components that then evolves into a binary as a result of the coalescence and occasional ejection of members. A binary with $q \simeq 1$ will be a not infrequent outcome of this sequence of events if coalescence occurs with little mass loss.

DISCUSSION

The investigations reviewed and reported here have not yet settled any questions concerning the formation of close binaries. Nevertheless, these early results with 3-D codes are surely encouraging: we can now cleanly follow the growth of the instabilities that presumably convert single protostars into binaries and multiple systems. Provided therefore that our present ideas are basically correct and that effects requiring high resolution are not crucial, numerical simulations should soon decisively advance our understanding of this long-standing problem.

This work has been supported by the National Science Foundation under grant AST 79-13179. A grant of computer time at the Goddard Institute for Space Studies, NASA, is also acknowledged.

REFERENCES

Bodenheimer, P. 1978, Ap.J., 224, 488
Cook, T. L., and Harlow, F. H. 1978, Ap.J., 225, 1005.
Gingold, R. A., and Monaghan, J. J. 1978, M.N.R.A.S., 184, 481.
Gingold, R. A., and Monaghan, J. J. 1979, M.N.R.A.S., 188, 39.
Larson, R. B. 1972, M.N.R.A.S., 156, 437.
Lucy, L. B. 1977, A.J., 82, 1013.
Lucy, L. B., and Ricco, E. 1979, A.J., 84, 401.
Norman, M. L., and Wilson, J. R. 1978, Ap.J., 224, 497.
Tassoul, J-L. 1978, Theory of Rotating Stars (Princeton University Press).

DISCUSSION FOLLOWING LUCY

Nariai: Can you make the mass in your calculation larger and apply your results to the formation of a group of galaxies?

Lucy: Although the mass and radius can be scaled to values appropriate for a group of galaxies or even for a supercluster, the assumption of isotropic changes would not then be so well justified.

Zuiderwijk: What percentage for the thermal energy results in the formation of one single star?

Lucy: The next solution in the sequence has t_T = 14% and ends in a single star surrounded by debris in an equatorial disk.

Morton: I worry about finding such a sharp peak at unity in the mass-ratio distribution. It appears likely that your calculation will give a rather broad distribution.

Lucy: I fear you may be right. My hope, though, is that improved calculations will yield a pure mode, so that the multiple fragments have equal masses; the processes of coalescence and ejection may then end with a q = 1 binary often enough to explain the peak.

Shu: In the spherical calculations, one finds that the first core which forms constitutes only a small fraction of the total mass of the collapsing cloud. Subsequently, there ensues an extended accretion phase. Have you thought about the consequences of such an accretion phase for your models?

Lucy: For rotating protostars, much of the infalling outer envelope will often have too much angular momentum to reach the fragmenting ring.

Rajamohan: Normal single stars on the Main Sequence are essentially fast rotators with a small dispersion in their true rotational velocities, while slow rotators are either peculiar or members of close binary systems. Can this be reproduced by the formation process you have outlined?

Lucy: My calculations indicate that the components of newly-formed binaries are rapidly rotating (t_R = 10 to 15 %). For close systems, tidal dissipation will of course quickly slow down the spin until synchronism is achieved.

https://doi.org/10.1017/S0074180900064536 Published online by Cambridge University Press