Chapter 8

Conclusions and Observational Implications

The purpose of this thesis is to investigate the role of accretion in binary star formation. It is found that accretion on to a 'seed' binary from the cloud that remains after its formation can dramatically alter the system, giving a final state where the mass ratio, and separation may differ by an order of magnitude from that of the initial protobinary.

This study of accretion was performed using the smoothed particle hydrodynamics (SPH) technique for simulating fluids. SPH cannot be used in its standard form as usually high-density regions, such as protostars, are represented by many SPH particles close together. The time steps that these particles must be evolved with are dependent on the dynamical time scale of the protostar. However, for a study of accretion, the simulations must be followed over an infall time scale - many orders of magnitude longer than the dynamical time scale of a protostar. All the effort is spent calculating the internal dynamics of the protostars, and the accretion cannot be followed.

To allow accretion to be followed, sink particles are added to standard SPH (Chapter 4). A protostar is modelled by a sink particle which has the mass of the protostar and only interacts with the rest of the material via gravity. It also has boundary conditions so that the fluid flow is not affected by its presence, except by gravity. A gas particle that falls within the accretion radius of, and that is sufficiently bound to, a sink particle is accreted on to the sink particle. This is done by combining the mass, and momentum of the gas particle with the mass, linear momentum, and spin angular momentum of the sink particle. In this way, the internal evolution of the protostar is ignored, and the minimum time step of all particles in the code is kept large enough that accretion on to the system can be followed. The success of this method is demonstrated in Chapter 4, where a fragmentation calculation that is usually forced to halt at 1.3 initial cloud free-fall times $t_{\rm ff}$, because of the formation of a binary protostellar system, is followed to $4.5t_{\rm ff}$. The protobinary contains only $\approx 20\%$ of the original cloud mass at $1.3t_{\rm ff}$, but with the use of sink particles the binary contains $\approx 80\%$ by the end of the calculation, with most of the rest being expelled by gravitational torques from the binary.

With a viable method of modelling accretion, attention is turned to studying the effects of accretion on a protobinary system. The effects on the mass ratio q and separation a of a binary are studied, first with ballistic accretion (Chapter 5), and later with gaseous accretion (Chapter 6). Only initially-circular binary orbits are considered. A 'seed' binary is constructed, surrounded by a gas cloud that falls on to the system. The effects of the accretion of this gas on the binary are studied for initial mass ratios $0.1 \leq q \leq 1.0$, as a function of the specific angular momentum of the infalling material, the accretion radii of the protostars, and the radial-infall velocity at the outer boundary of the calculation.

It is found that for both ballistic calculations and gaseous calculations the accretion of low-angular-momentum cloud material decreases the mass ratio and separation of the binary, and the accretion of high-angular-momentum material increases the mass ratio and separation of the binary. For the ballistic calculations, however, the quantitative effects depend critically on the assumed sizes of the protostars. Thus, the gaseous accretion calculations are required to determine the quantitative effects of accretion on the mass ratio and separation. They are also necessary for the determination of when circumbinary disc formation starts, and how much of the infalling material goes into forming this disc as opposed to being accreted by the protostars or their circumstellar discs.

The results from the gaseous calculations, are found to match the ballistic calculations closest when the protostars have sizes equal to the mean-Roche-lobe sizes of the protostars. The agreement is good for low-angular-momentum infall, but fails for high-angular-momentum infall when a circumbinary disc begins to form.

For the gaseous calculations, it is found that the mass ratio decreases if the infall is from a cloud with specific angular momentum less than the specific orbital angular momentum of the secondary. If the cloud has higher angular momentum, the mass ratio increases. The separation of the binary decreases due to accretion if the cloud has a specific angular momentum less than the critical value of $j \approx 0.6\sqrt{GM_{\rm b}a}$, where $M_{\rm b}$ is the mass of the binary, and a the separation. This critical value is almost independent of the mass ratio of the binary. Above this value the separation increases due to accretion. When a circumbinary disc begins to form, however, the separation is affected by the loss of the binary's orbital angular momentum to the circumbinary disc via gravitational torques. In some cases, this loss is strong enough to negate the increase in separation due to accretion, and force the separation to decrease.

In terms of disc formation, it is found that a critical value of the specific angular momentum of the infalling material is required for the formation of circumstellar discs. If the material has a lower specific angular momentum than the specific orbital angular momentum of a protostar, the protostar does not form a disc. Rather, material is accreted via a Bondi-Hoyle-type accretion flow. Higher specific angular momentum is required for the protostar to form a circumstellar disc. When circumstellar discs are formed, the specific spin angular momentum of the material in the secondary's disc (and thus the radius) is always less than that of the primary's disc, and the radii of the discs increases with increasing specific angular momentum of the infall. The circumstellar discs have maximum radii given by the Roche-lobe radii of the protostars. A circumbinary disc starts to form if the infalling material has a specific angular momentum greater than or approximately equal to that required for the gas to form a circular orbit at the radius of the secondary from the centre of mass.

The effects of accretion on a binary are now known over a wide parameter space. These effects can be used to calculate the final state of a 'seed' binary after the accretion of a cloud many times its mass which remains after the 'seed' binary is first formed. An example of this evolution was given in Chapter 7. In the future, 'seed' binaries will be evolved using this method under the infall of clouds of various initial density profiles and angular momentum distributions to constrain the initial conditions for binary star formation.

The consequences of the evolution of a 'seed' binary under massive accretion are as follows. The accretion of low-angular-momentum material lowers the mass ratio of a binary, while high-angular-momentum accretion forces the mass ratio toward unity. This behaviour suggests that medium to long-period binaries are likely to have low-mass ratios, while close binaries are likely to have high-mass ratios as the specific angular momentum of the infalling material, relative to the binary, is likely to be higher for close binaries than wide binaries. Note, however, that close binaries may also form massive circumbinary discs which may fragment, complicating this picture. There is observational evidence that low mass ratios are favoured for medium to long-period binaries. There is also weak evidence that equal-mass ratios may be favoured for closer binaries, although more observations need to be done to confirm this (Section 1.2.1).

If a 'seed' binary system grows to its final mass via the accretion of low-angular-momentum material, it is possible that the primary may have a circumstellar disc while the secondary is essentially naked. This may offer another explanation as to why some pre-main-sequence stars are observed to be disc-less (Section 1.2.2). It may also explain the observations of infrared companions. A significant fraction of pre-main-sequence stars are observed to have infrared companions, with the companion deeply embedded in gas while the pre-main-sequence star is optically visible (Section 1.2.2). A possible explanation, is that the embedded star is the primary and is surrounded by a circumstellar disc, whereas the secondary is disc-less due to the low-angular-momentum accretion on to the system after its formation. Thus, the secondary is the optically visible star, and the embedded object is viewed through the edge of its circumstellar disc.

In conclusion, understanding of the effects of accretion during binary star formation is essential if we are to explain the observational statistics on binary stars. This study of the effects of accretion will allow the final states of 'seed' binaries produced in clouds of different density profiles and angular momentum distributions to be determined. These results of final binary mass ratios, separations and disc properties can then be compared to observations to better constrain the initial conditions required for binary star formation, and thus star formation in general.

Bibliography

Abt H. A., 1983, ARA&A, 21, 343

Abt H. A., 1987, ApJ, 317, 353

Adams F. C., Lada C., Shu F. H., 1987, ApJ, 312, 788

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

Aitken R. G., 1935, The Binary Stars. McGraw-Hill, New York, p. 275

Arons J., Max C. E., 1975, ApJ, 196, L77

Artymowicz P., 1983, Acta Astronomica, 33, 223

Artymowicz P., 1993, PASP, 105, 1032

Artymowicz P., Clarke C. J., Lubow S. H., Pringle J. E., 1991, ApJ, 370, L35

Artymowicz P., Lubow S. H., 1994, ApJ, 421, 651

Artymowicz P., Lubow S. H., 1995, in Staude H. J., Beckwith S., et al. ed., Disks and Outflows around Young Stars, Springer-Verlag, Berlin

Bastien P., 1983, A&A, 119, 109

Beichman C. A., Myers P. C., Emerson J. P., Harris S., Mathieu R. D., Benson P. J., Jennings R. E., 1986, ApJ, 307, 337

Benson P. J., Myers P. C., 1989, ApJS, 79, 89

Benz W., 1984, A&A, 139, 378

Benz W., 1988, Comput. Phys. Comm., 48, 97

Benz W., 1990, in Buchler J. R., ed., The Numerical Modeling of Nonlinear Stellar Pulsations: Problems and Prospects. Kluwer, Dordrecht, p. 269

Benz W., Bowers R. L., Cameron A. G. W., Press W., 1990, ApJ, 348, 647

Bodenheimer P., 1992, in Tenorio-Tagle G., Prieto M., Sanchez F., ed., Star Formation in Stellar Systems. Cambridge University Press, Cambridge, p. 1

Bodenheimer P., Boss A. P., 1981, MNRAS, 197, 477

Bodenheimer P., Sweigart A., 1968, ApJ, 152, 515

Bodenheimer P., Tohline J. E., Black D. C., 1980, ApJ, 242, 209

Bondi H., 1952, MNRAS, 112, 195

Bondi H., Hoyle F., 1944, MNRAS, 104, 273

Bonnell I. A., 1994, MNRAS, 269, 837

Bonnell I. A., Arcoragi J. -P., Martel H., Bastien P., 1992, ApJ, 400, 579

Bonnell I. A., Bastien P., 1992, ApJ, 401, 654

Bonnell I. A., Bate M. R., 1994a, MNRAS, 269, L45

Bonnell I. A., Bate M. R., 1994b, MNRAS, 271, 999

Bonnell I. A., Bate M. R., Price N. M., 1995, in preparation

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

Boss A. P., 1981, ApJ, 250, 636

Boss A. P., 1986, ApJS, 62, 519

Boss A. P., 1987a, ApJ, 316, 721

Boss A. P., 1987b, ApJ, 319, 149

Boss A. P., 1988, Comments Astrophys., 12, 169

Boss A. P., 1989a, ApJ, 345, 554

Boss A. P., 1989b, ApJ, 346, 336

Boss A. P., 1991, Nature, 351, 298

Boss A. P., Black D. C., 1982, ApJ, 258, 270

Boss A. P., Bodenheimer P., 1979, ApJ, 234, 289

Calberg R. G., Pudritz R. E., 1990, MNRAS, 247, 353

Chandrasekhar S., 1939, in Gale H. G., Seares F. H., Struve O., ed., An Introduction to the Study of Stellar Structure. University of Chicago Press, Chicago, p. 84-101

Chelli A., Zinnecker H., Carrasco L., Cruz-Gonzalez I., Perrier C., 1988, A&A, 207, 46

Clarke C., Pringle J. E., 1991, MNRAS, 249, 584

Cox J. P., 1980, in Ostriker J. P., ed., Theory of Stellar Pulsations. Princeton University Press, Princeton, p. 74-111

Dodd K. N., 1952, MNRAS, 112, 374

Dodd K. N., 1953, Proc. Cam. Phil. Soc., 49, 486

Dodd K. N., McCrea W. H., 1952, MNRAS, 104, 205

Dorfi E., 1982, A&A, 114, 151

Duquennoy A., Mayor M., 1991, A&A, 248, 485

Durisen R. H., Tohline J. E., 1985, in Black D. C., Matthews M. S., ed., Protostars and Planets II. University of Arizona Press, Tucson, p. 534

Dutrey A., Guilloteau S., Simon M., 1994, A&A, 286, 149

Ebert R., von Hoerner S., Temesvary S., 1960, in Die Entstehung von Sternen durch Kondensation diffuser Materie. Springer-Verlag, Berlin, p. 311

Evrard A. E., 1988, MNRAS, 235, 911

Fairclough N., 1932, MNRAS, 92, 644

Fekel F. C., 1981, ApJ, 246, 879

Fischer D. A., Marcy G. W., 1992, ApJ, 396, 178

Foster P. N., Chevalier R. A., 1993, ApJ, 416, 303

Frank J., King A. R., Raine D. J., 1985, Accretion Power in Astrophysics. Cambridge University Press, Cambridge, p. 56

Fulbright M. S., Benz W., Davies M. B., 1995, ApJ, 440, 254

Ghez A. M., Neugebauer G., Matthews K., 1993, AJ, 106, 2005

Gingold R. A., Monaghan J. J., 1977, MNRAS, 181, 375

Gingold R. A., Monaghan J. J., 1982, J. Comput. Phys., 46, 429

Gomez M., Hartmann L., Kenyon S. J., Hewett R., 1993, AJ, 105, 1927

Goodman A., Benson P., Fuller G., Myers P., 1993, ApJ, 406, 528

Hale A., 1994, AJ, 107, 306

Hayashi C., Nakazawa K., Nakagawa Y., 1985, in Black D. C., Matthews M. S., ed., Protostars and Planets II. University of Arizona Press, Tucson, p. 1100

Heemskerk M. H. M., Papaloizou J. C., Savonije G. J., 1992, A&A, 260, 161

Heller C. H., 1991, Ph.D. Thesis, Yale University

Herczeg T. J., 1988, Astrophys. Sp. Sci., 142, 89

Hernquist L., Katz N., 1989, ApJS, 70, 419

Hills J. G., 1976, MNRAS, 175, 1P

Hills J. G., Day C. A., 1976, Astrophys. Lett., 17, 87

Ho P. T. P., Townes C. H., 1983, ARA&A, 21, 239

Hoyle F., 1953, ApJ, 118, 513

Hoyle F., Lyttleton R. A., 1939, Proc. Cam. Phil. Soc., 35, 405

Hoyle F., Lyttleton R. A., 1940a, Proc. Cam. Phil. Soc., 36, 323

Hoyle F., Lyttleton R. A., 1940b, Proc. Cam. Phil. Soc., 36, 325

Hoyle F., Lyttleton R. A., 1940c, Proc. Cam. Phil. Soc., 36, 424

Hunt R., 1971, MNRAS, 154, 141

Hunt R., 1979, MNRAS, 188, 83

Jeans J. H., 1929, Astronomy and Cosmogony, 2nd ed. Cambridge University Press, Cambridge

Kopal, Z., 1959, Close Binary Systems (International Astrophysics Series, Vol. 5). Chapman & Hall Ltd., London, p. 79-80

Lada C. J., 1987 in Peimbert M., Jugaku J., ed., Star Forming Regions (IAU Symposium 115). Reidel, Dordrecht, p. 1

Larson R. B., 1969, MNRAS, 145, 271

Larson R. B., 1972, MNRAS, 156, 437

Larson R. B., 1990, in Capuzzo-Dolcetta R., Chiosi C., DiFazio A., ed., Physical Processes in Fragmentation and Star Formation. Kluwer, Dordrecht, p. 389

Lattanzio J. C., Monaghan J. J., Pongracic H., Schwarz M. P., 1985, MNRAS, 215, 125

Laughlin G., Bodenheimer P., 1994, ApJ, 436, 335

Leinert Ch., Weitzel N., Zinnecker H., Christou J., Ridgeway S., Jameson R., Haas M., Lenzen R., 1993, A&A, 278, 129

Lin D. N. C., Papaloizou J., 1985, in Black D. C., Matthews M. S., ed., Protostars and Planets II. University of Arizona Press, Tucson, p. 981

Lizano S., Shu F. H., 1989, ApJ, 342, 834

Lucy L., 1977, AJ, 82, 1013

Lyttleton R. A., 1953, in The Stability of Liquid Rotating Masses. Cambridge University Press, Cambridge

Mansbach P., 1970, ApJ, 160, 135

Mathieu R. D., 1992a, in McAlister H. A., Hartkopf W. I., ed., Complementary Approaches to Double and Multiple Star Research (IAU Colloquium 135). ASP, San Francisco, p. 30

Mathieu R. D., 1992b, in Duquennoy A., Mayor M., ed., Binaries as Tracers of Stellar Formation. Cambridge University Press, Cambridge, p. 155

Mathieu R. D., 1994, ARA&A, 32, 465

Mathieu R. D., Walter F. M., Myers P. C., 1989, AJ, 98, 987

Mayor M., Duquennoy A., Halbwachs J. -L., Mermilliod J. -C., 1992, in McAlister H. A., Hartkopf W. I., ed., Complementary Approaches to Double and Multiple Star Research (IAU Colloquium 135). ASP, San Francisco, p. 73

Mazeh T., Goldberg D., Duquennoy A., Mayor M., 1992, ApJ, 401, 265

McCrea W. H., 1955, in Burgers J. M., van de Hulst H. C., ed., IAU Symp. 2, Gas Dynamics of Cosmic Clouds. North-Holland, Amsterdam, p. 186

McDonald J. M., 1995, Ph. D. dissertation, University of Cambridge

McDonald J. M., Clarke C. J., 1993, MNRAS, 262, 800

McDonald J. M., Clarke C. J., 1994, in Clemens D. P., Barvainis R., ed., Clouds, Cores, and Low Mass Stars (ASP Conference Series Vol. 65). ASP, San Francisco, p. 370

Meglicki Z., Wickramasinghe D., Bicknell G. V., 1993, MNRAS, 264, 691

Miyama S., Hayashi C., Narita S., 1984, ApJ, 279, 621

Monaghan J. J., 1985, Comput. Phys. Rep., 3, 422

Monaghan J. J., 1988, Comput. Phys. Comm., 48, 89

Monaghan J. J., 1989, J. Comput. Phys., 82, 1

Monaghan J. J., 1992, ARA&A, 30, 543

Monaghan J. J., Gingold R. A., 1983, J. Comput. Phys., 52, 374

Monaghan J. J., Lattanzio J. C., 1985, A&A, 149, 135

Monaghan J. J., Lattanzio J. C., 1986, A&A, 158, 207

Monks A. W., Rayburn D. R., 1978, PASP, 90, 574

Mouschovias T. Ch., 1976, ApJ, 206, 753

Mouschovias T. Ch., Paleologou E. V., 1979, ApJ, 230, 204

Mouschovias T. Ch., Spitzer L. H., 1976, ApJ, 210, 326

Myers P. C., Benson P. J., 1983, ApJ, 266, 309

Myers P. C., Fuller G. A., Goodman A. A., Benson P. J., 1991, ApJ, 376, 561

Myers P. C., Goodman A. A., 1988, ApJ, 326, L27

Myers P. C., Lada C. J., Fuller G. A., 1991, ApJ, 372, L95

Myhill E. A., Boss A. P., 1993, ApJS, 89, 345

Myhill E. A., Kaula W. M., 1992, ApJ, 386, 578

Nakagawa Y., Sekiya M., Hayashi C., 1986, Icarus, 67, 375

Nelson R., Papaloizou J. C., 1994, MNRAS, 270, 1

Ostriker J. P., Bodenheimer P., 1973, ApJ, 180, 171

Press W. H., 1986, in Hut P., McMillan S. L., ed., Springer Lecture Notes in Physics, Vol. 267, The Use of Supercomputers in Stellar Dynamics. Springer, Berlin, p. 184

Price N. M., Bate M. R., Bonnell I. A., 1995, MNRAS, submitted

Pringle J. E., 1981, ARA&A, 19, 137

Prosser C. F., Stauffer J. R., Hartmann L., Soderblom D. R., Jones B. F., Werner M. W., McCaughrean M. J., 1994, ApJ, 421, 517

Reipurth B., Zinnecker H., 1993, A&A, 278, 81

Richichi A., Leinert Ch., Jameson R., Zinnecker H., 1994, A&A, 287, 145

Ruden S. P., Pollack J. B., 1991, ApJ, 375, 740

Ruffert M., Arnett D., 1994, ApJ, 427, 351

Shima E., Matsuda T., Takeda H., Sawada K., 1985, MNRAS, 217, 367

Simon M., Chen W. P., Howell R. R., Slovik D., 1992, ApJ, 384, 212

Stahler S., Shu F. H., Taam R. E., 1980, ApJ, 241, 637

Steinmetz M., Müller E., 1992, A&A, 268, 391

Strom K. M., Strom S. E., Edwards S., Cabrit S., Strutskie M. F., 1989, AJ, 97, 1451

Strutskie M. F., Dutkevich D., Strom S. E., Edwards S., Strom K. M., Shure M. A., 1990, AJ, 99, 1187

Tassoul J. L., 1978, Theory of Rotating Stars. Princeton University Press, Princeton.

Thomas P. A., 1982, Ph.D. Thesis, University of Cambridge

Tohline J. E., 1981, ApJ, 248, 717

Tohline J. E., 1982, Fund. of Cos. Phys., 8, 1

Tout C. A., 1991, MNRAS, 250, 701

Trimble V., 1974, Astr. J., 79, 967

Trimble V., 1990, MNRAS, 242, 79

Ward-Thompson D., Scott P. F., Hills R. E., Andre P., 1994, MNRAS, 268, 276

Weintraub D. A., Kastner J. H., Zuckerman B., Gatley I., 1992, ApJ, 391, 784

Weintraub D. A., Masson C. R., Zuckerman B., 1989, ApJ, 344, 915

Williams H. A., Tohline J. E., 1988, ApJ, 334, 449

Winkler K. H., Newman M. J., 1980, ApJ 236, 201

Zel'dovich Y. B., Raizer Y. P., 1966, in Hayes W. D., Probstein R. F., ed., Physics of Shock Waves and High Temperature Hydrodynamic Phenomena, Vol I. Academic Press Inc., New York, p. 45-49

Zinnecker H., 1990, in Reipurth B., ed., Low Mass Star Formation and Pre-Main-Sequence Objects. ESO, Garching, p. 447

Zinnecker H., Wilking B. A., 1992, in Duquennoy A., Mayor M., ed., Binaries as Tracers of Stellar Formation. Cambridge University Press, Cambridge, p. 526

Zuckerman B., Palmer P., 1974, ARA&A, 12, 279