Introductory Remarks

David W. Latham

The general concept of this workshop is to create an interaction between observation and theory; between the observers who are producing new information about the orbital characteristics of binaries and multiple stars in a variety of populations, and the theorists working on the formation and evolution of stars and stellar systems. The immediate excuse for holding this workshop in September 1991 is the expectation that Paper 100 in Roger Griffin's series "Spectroscopic Binary Orbits from Photoelectric Radial Velocities" will be published about two weeks from now. Just to make sure that I had my facts correct, I decided I had better go back and look through my personal collection of *The Observatory*. Paper I was published in the February 1975 issue, with B. Emerson as coauthor. The very first sentence reads:

> "The solution of the orbits of spectroscopic binaries has long been an important purpose of the measurement of stellar radial velocities."

Then, after a paragraph or two muttering about the importance of determining stellar masses, the paper outlines some of the history of the Cambridge effort:

> "Nearly all the observations have been made with the Cambridge 36-inch telescope in conjunction with the original radial-velocity spectrometer. Because of the heavy demand on that instrument for the purposes of narrow-band spectrophotometry for which it was originally designed, and the inconvenience of frequent alterations between the narrow-band and radial-velocity configurations, for several years the measurement of velocities was restricted to about three observing runs per annum. This was far from ideal for the observation of spectroscopic binaries having periods between a few months and a few years; and in any case the binary programme was not at that time regarded with high priority. Recently, however, changing patterns of telescope use have enabled the spectrometer to remain set up for comparatively long periods in its radial-velocity form, so that the observations have been much better distributed in time. Nevertheless, the twin constraints of telescope scheduling and local climate still conspire to prevent rapid progress in documenting any binary orbit, whatever its period. The situation may well, however, be regarded philosophically: the results of measuring almost any time-varying astronomical phenomenon are improved by increasing the time base, so this is one project where delay is of the essence!"

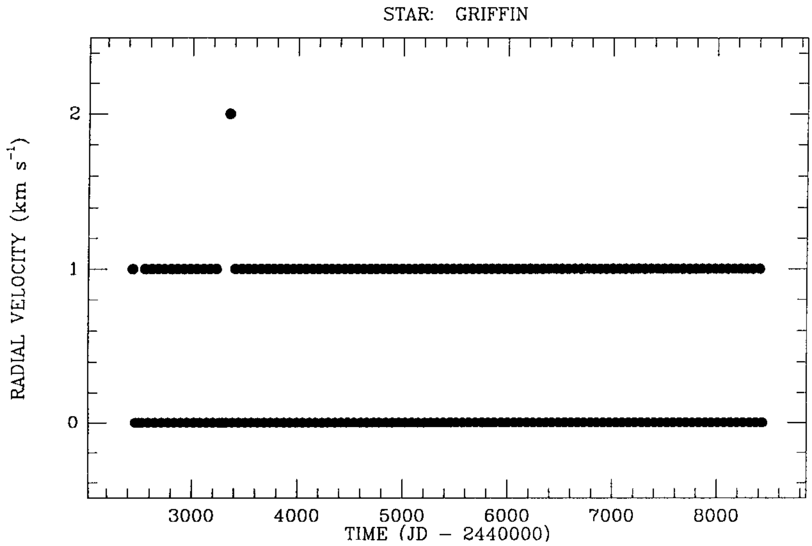

Figure 1. The time history of the publication of papers in the series "Spectroscopic Binary Orbits from Photoelectric Radial Velocities."

When I proceeded to look through the very next issue of *The Observatory*, for April 1975, I discovered that there was no Paper 2. For all these years I had been suffering the delusion that these papers had appeared one by one in every consecutive issue, like clockwork. I took some reassurance from finding Paper 2 in the next issue, June 1975, with Papers 3 through 13 following as expected. "Ah, it was just a slight hitch in getting started," I decided. But then, to my horror, I found another naked issue, June 1977. I took little comfort from the fact that both Papers 14 and 15 appeared in the following issue. With my confidence now badly shaken in the reliability of my expectation that Paper 100 would appear on 1 October 1991, I decided that I should do a proper analysis of the actual publication history.

In Figure 1 I plot the time history of publication. In a recent issue of *The Observatory* I found the statement that the nominal date of publication was the first of the month. So, to show that a paper was published, I assigned a velocity of 1 km s^{-1} to the corresponding Julian Day. *The Observatory* only appears every other month, so for the odd months in between I assigned a velocity of 0 km s^{-1}. You can see the gaps in April 1975 and June 1977 when no paper was published, and the anomalous issue of August 1977 when two papers appeared.

The power spectrum for these data, shown in Figure 2, has a very ugly window function, with quite a strong spurious peak near 20 days as well as the correct one near 60. Indeed, these data were rather cantankerous in resisting my efforts to find a satisfactory orbital solution, despite the fact that 98 points covering 198 months

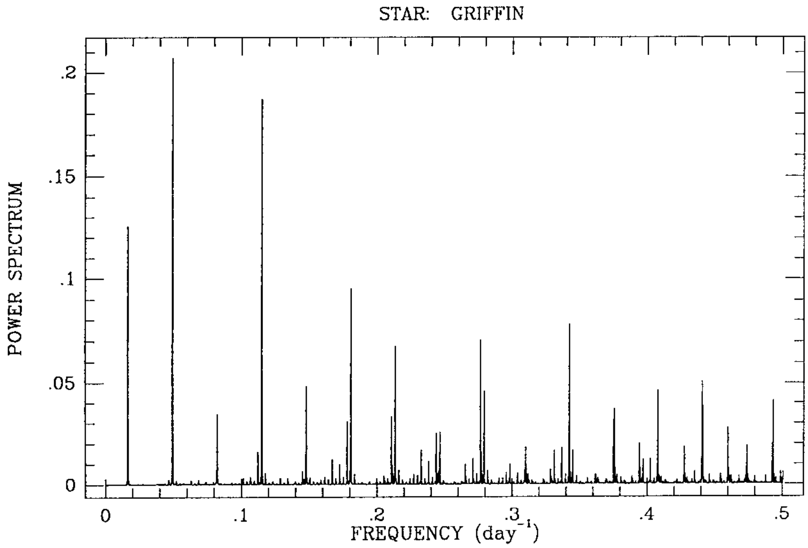

Figure 2. The power spectrum for the publication history shown in Figure 1.

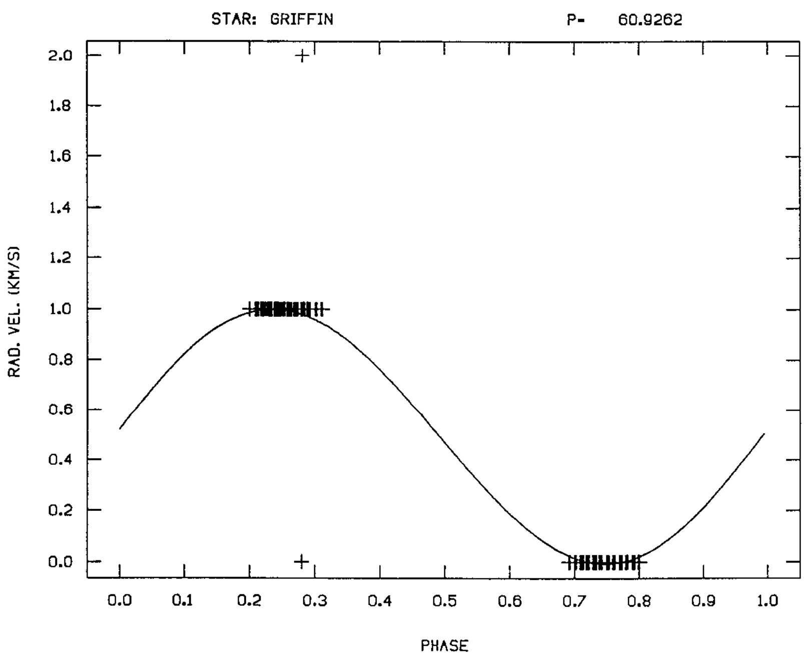

Figure 3. The orbital solution for the publication history.

were available (the August 1991 issue had not arrived at the other Cambridge by 3 September 1991). For example, Tsevi Mazeh's program found a curious beat solution with a period of almost exactly 60 days, when clearly this could not be correct, because the year is 365.25 days long, not 360. The best solution I could get without throwing away the two spurious points, shown in Figure 3, still gave a much better period, but a rather unsatisfactory error to the epoch.

To get serious again, you may rest assured that Paper 100 will indeed appear in the October 1991 issue.

But, this workshop is not just a Centennial Celebration for the long-running series of papers from Roger Griffin. It is really a celebration of the flowering of a branch of astronomical research that was pioneered by Roger and his collaborators; and I should acknowledge right away that among his collaborators not the least is another R. Griffin, who is also with us here in Bettmeralp - Cindy, it pleases me that you can join us in this mutual celebration. And, perhaps I should also mention Dr. G. A. Radford, who was a coauthor on Papers 3 through 17.

What is this flowering that I alluded to? I am not talking about blossoms that open in the morning after one night of observing. Instead we are now seeing the results of long-term research programs, some of them requiring as much as 10 or 20 years of observing before a proper analysis can be done. The point is that samples must be carefully selected, observed, and analyzed in order to take proper account of biases; in Roger Griffin's own words, from Paper 50, I give you the following example:

> "Therefore, despite the heavy bias still remaining against the discovery of binary systems having small amplitudes of velocity variation, a class of binaries which until now was grossly under-represented in the literature is gradually being documented ... It is no accident that the longest periods derived in the present series of papers are comparable with the length of the time which has elapsed since photoelectric observations began. By way of marking Paper 50, we put forward here the orbit with the longest period yet shown in this series of papers; but the periods of a number of systems still under observation are longer and still indeterminate."

and

> "For six years its [HD 185662's] velocity remained obstinantly constant - providing, incidently, an object lesson to those who might try too hastily to designate new radial-velocity standard stars. In 1976 there were at last slight signs of a change of velocity in the anticipated direction, and they were confirmed and amplified in 1977. In 1978, with majestic deliberation, the velocity passed the 1966 figure ..."

Or, from Paper 56:

"There are severe selection effects militating against the discovery of spectroscopic binaries with very high eccentricities. Such objects spend most of their time at velocities very close to the γ-velocity, and have short-lived and sometimes dramatic velocity excursions at periastron. Unless they are observed systematically over a long period of time, or else an observation happens to be made at a fortunate phase, the periastron passage can easily be missed and the small velocity changes at intervening times may be lost in the measurement noise. For large eccentricities the probability of discovery of a binary of given amplitude appears to be proportional to $(1 - e)$.
Even when a high-eccentricity binary has been discovered, there may be considerable difficulty in determining its orbit. Several revolutions can easily elapse before the observer is fully alerted to the abruptness of the periastron event or knows the period accurately enough to schedule intensive observations at the proper time; and when at last he *has* this information, it all too frequently happens that the next periastron passage occurs at the season when the object is lost in the daytime sky!"

So the sequence of 100 papers and Roger Griffin's dedication to the study of spectroscopic binaries is in several ways a model of the kind of approach that is needed for understanding the general characteristics of binaries, and how they formed, and how they can evolve.

Over the next two days we will hear about exciting new observational results on the characteristics of binaries in a wide variety of stellar populations: pre-main-sequence stars, main-sequence solar-type dwarfs, late-type main-sequence dwarfs, halo and thick-disk dwarfs, open cluster dwarfs, open cluster giants, field late-type giants, supergiants, and eclipsing binaries. Just about the only population that will not be covered is globular clusters.

And, I think you will find that the new observational results are bringing in to focus some tough challenges to the theoreticians. Can a general theory of star formation be developed that predicts the binary characteristics that we actually observe? What sets the initial distribution of secondary masses, orbital eccentricities, and periods? How do orbits evolve with time, both with and without mass transfer and mass loss? For example, can we understand orbital circularization well enough to use it as a clock for dating the age of coeval populations of binaries? Can we understand in detail the chemical abundances in systems where one or more of the stars has evolved and transferred mass? Can we model the dynamical evolution of clusters, and the role that binaries play in this evolution?

I do not expect answers to all these questions to emerge from this workshop, but as an observer I do hope that the theorists can give us some guidance about what are the key observations which must be made. And, in the meantime, we can continue to look forward to each new issue of *The Observatory*, and another paper in the series.

N-Body Simulations of Primordial Binaries and Tidal Capture in Open Clusters

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Abstract

We present results of N-body simulations pertaining to two aspects of open star cluster evolution. First we discuss the dynamics of a primordial population of circular binaries with short (10 to 100 days) periods. Although a large fraction of the binaries escape as a result of close encounters, the remaining population shows very little evidence of departure from zero eccentricity, suggesting that non-eccentric orbits above the observed cut-off period have a cosmogonic origin. The second part is concerned with computer modelling of tidal two-body capture. Provisional results indicate that dissipative close encounters may occur in high-density regions of open clusters containing a significant proportion of giants.

1. Introduction

Star clusters form ideal laboratories for testing the outcome of stellar evolution and mutual gravitational interactions. On the observational side there has been a big effort in establishing cluster membership. Radial velocities, which form the theme of the present meeting, play a vital part in this formidable task. On many occasions, stars which were thought to be single have been resolved using improved techniques to yield two close components with high orbital velocity (Griffin [Gri75]). By now, considerable evidence has accumulated that cluster binaries may be nearly as common as for the nearby field stars in both open clusters (Mathieu and Latham [ML86]; Mermilliod and Mayor [MM89]) and globular clusters (Pryor *et al.* [PCHF89]). Although observational selection favours the detection of shorter periods (< 1000 days), an open cluster such as $M67$ appears to have a binary frequency of 10% among its brightest members (Mathieu *et al.* [MLG90]). By analogy with the solar neighbourhood stars we may therefore expect a wide range in periods, corresponding to hard binaries which can survive the external perturbations of other stars in the cluster.

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This 'molecular' nature of open clusters presents a considerable challenge for the dynamical experimentalist who is obliged to include interactions between the binaries and other cluster members in a more realistic treatment.

In the present paper, we concentrate on some aspects of the binary phenomenon in open clusters. Section 2 describes briefly the basis for the N-body simulation models. Taking the cue from recent determinations of the tidal circularization period in $M67$ (Latham *et al.* [LMMD92]), we attempt to shed light on the question of how long a population of relatively hard binaries may maintain an initial circular orbit in the presence of external perturbations. Section 3 also contains a general discussion of cluster evolution in the absence of mass loss from evolving stars. In Section 4 we consider the process of tidal two-body capture by close encounters. Although less important for systems composed of single stars, this type of binary formation may play a role in actual clusters containing hard binaries where the latter form compact subsystems by temporary capture and hence increase the probability of close encounters. Finally, Section 5 contains some discussions of the numerical results.

2. Simulation models of open clusters

Open star cluster dynamics is well defined and such systems are therefore quite amenable to numerical studies. The motion of most cluster stars are subject to a dominant gravitational force from the other members which holds the cluster together as it orbits the Galaxy. The perturbations due to the Galactic mass distribution exerts a smooth tidal force which is linear with respect to the cluster centre since typical cluster radii are very small compared to the size of the Galaxy. Assuming a circular orbit in the Galactic plane, we can then write the equations of motion for a mass-point m_i in rotating coordinates as

$$\frac{d^2x_i}{dt^2} = F_x + 4A(A-B)\,x_i + 2\omega_z\,\frac{dy_i}{dt}, \frac{d^2y_i}{dt^2} = F_y - 2\omega_z\,\frac{dx_i}{dt}, \frac{d^2z_i}{dt^2} = F_z - Cz_i. \quad (1)$$

Here the terms F_x, F_y, F_z denote the gravitational attraction due to the other $N-1$ stars, A and B are Oort's Galactic constants, ω_z is the angular velocity and C is the force gradient in the vertical direction. These equations are also applicable to open clusters during small oscillations out of the Galactic plane.

The main computational effort of a cluster simulation is to obtain the sum of all individual attractions acting on a given star. A self-consistent treatment requires frequent updating of the total acceleration for each star over long time intervals in order to yield significant solutions. Even so, it is possible to follow the entire evolution of an open cluster with a few thousand members, using a direct solution method (see Aarseth [Aar85a] for full details of the numerical scheme). The main numerical problems of such simulations are connected with the need to study a variety of close encounters; *i.e.* between two single stars, a single star and a binary or two binaries. Such encounters are often very energetic and provide the main mechanism which drives the internal dynamical evolution. The smooth tidal field, on the other hand, exerts a more gentle influence; it lowers the escape barrier in the xy-direction, whereas the z-component gives rise to a tidal flattening. An irregular external perturbation, due to passing interstellar clouds, may also be included in the modelling; however, such effects appear to be quite small (Terlevich [Ter87]) and may be ignored here.

Initial cluster models with $N = 1000$ point-mass particles are generated from a Plummer distribution which has a modest central density concentration. The corresponding velocities are first selected from an equilibrium distribution (Section 3) and later (Section 4) taken to be nearly at rest, producing an early collapse which may be of interest for testing tidal two-body capture. For a realistic cluster simulation it is desirable to select individual stellar masses from a general mass function. Here we adopt a Salpeter-type power-law with exponent 2.35 and a modest mass ratio of 5:1 between the most massive and least massive star, and take the algebraic mean mass as $0.6\, m_\odot$. The effect of the tidal field is modelled by adopting a scaled length unit of 1 pc, corresponding to an equilibrium half-mass radius $R_h = 0.8$ pc. These cluster parameters, together with appropriate values of A, B and C then define an initial tidal radius $R_t = 11.9$ pc. Stars outside twice R_t are defined as having escaped from the cluster and are removed from the calculations; the resulting mass loss leads to a slow decrease of the tidal radius, determined from the first equation (1).

A population of initial binaries is now introduced as follows. Starting with the most massive member, every fifth star is subdivided into two equal-mass components of specified semi-major axis and eccentricity. This conservative choice of binary masses has been adopted in view of the lack of precise data for actual clusters. Hence the simulated binaries will not be subject to any preferential mass segregation compared to the massive single stars. We consider three models (denoted $M1$, $M2$, $M3$) with $N = 950$ initial single stars and a binary membership of $N_b = 50$, representing 5% of the total population or 20% of the 250 most massive stars. Bearing in mind that many of the observed binaries in $M67$ have rather shorter periods than the model binaries, this fraction may be a good compromise since the simulations do not include wide (but still hard) binaries. The models differ only in the choice of semi-major axis, with $a = 0.1$, 0.22 and 0.48 $A.U.$ in models $M1$, $M2$, $M3$. This corresponds to periods of about 10, 30 and 100 days, respectively, for the most massive binary of $1.6\, m_\odot$ and about 15, 45 and 150 days for the least massive binary. Since the main aim of these simulations is to place some limits on eccentricity changes due to external perturbations we adopt initial circular orbits for simplicity.

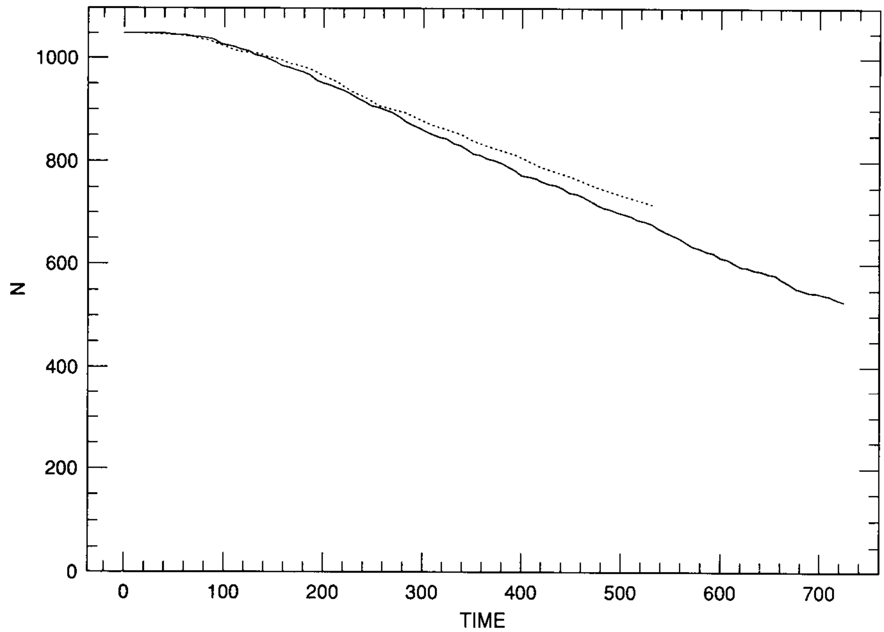

Figure 1. The number of cluster members as a function of time. Solid line: model $M2$; dotted line: model $M3$. Time is in units of 1×10^6 yrs.

3. Dynamics of primordial binaries

The general aspects of cluster evolution in the presence of primordial binaries have been discussed in several recent papers (McMillian *et al.* [MHM90], [MHM91]; Heggie and Aarseth [HA92]), while other similar work has explored the observational consequences of runaway stars (Leonard and Duncan [LD88], [LD90]). In the present investigation we concentrate on the fate of the binaries, with special reference to the so-called period-eccentricity diagram which has featured prominently at this meeting. A key question here is concerned with the upper cut-off of the tidal circularization process and the extent to which this value may be affected by perturbations due to close encounters. The simulation models $M1$, $M2$, $M3$ do not include dissipative effects; hence any departures from circular binary orbits will be a direct measure of the gravitational perturbations and even small eccentricities will not be subject to the circularization process.

To illustrate the general behaviour of the numerical models, we show in Figure 1 the number of cluster members (single stars and binary components) inside $2R_t$ as a function of time, in units of 1×10^6 yrs, for models $M2$ and $M3$. Following a plateau during the early phase when the cluster expands to its tidal radius, the escape rate is nearly constant with a half-life $T_h \simeq 7 \times 10^8$ yrs (model $M2$), in reasonable accord with observed ages; *i.e.* *median* life-times of $\simeq 2 \times 10^8$ yrs. During this interval the population of hard binaries declines steadily from 50 to 35; this is somewhat slower than for the single stars because of their greater average mass.

Fixing our attention on the cluster binaries at the half-life epoch, 34 members retain their original components and the 35th forms a hierarchical triple with the inner binary also an original. Apart from the outer binary component (which has high eccentricity), only three of these binaries have an eccentricity which is non-zero to three significant figures, with respective values $e = 0.001, 0.008, 0.009$. Moreover, 28 out of the 34 primordial binaries retain their original sequential order which suggests they have not experienced any dominant perturbations; *i.e.* impact parameters comparable to the semi-major axis would normally involve switching to one of the special procedures. This simulation was continued until only $N = 148$ stars remained bound. At this stage (age 1.3×10^9 yrs) there were 17 binaries left, with 15 having zero eccentricity (to three figures) and two new rather soft binaries deviating significantly from circular motion.

An examination of the escaping binaries provides interesting clues about the type of interactions involved. At the half-life epoch, 17 hard binaries have been ejected from the cluster. Of these, 13 retain their original components with zero orbital eccentricity to three significant figures, whereas two have exchanged one companion each and one binary is a hierarchical triple with non-primordial components. However, these outcomes are not necessarily due to strong interactions. A total of 84 critical triple encounters and 26 encounters between two binaries took place during this interval. Such interactions are calculated by accurate regularization procedures which are only invoked if the impact parameter of an approaching particle is less than twice the binary semi-major axis (or the sum for two binaries) and there are no other significant perturbers. The nature of these interactions are confirmed by noting at least five well separated examples each of triple and quadruple encounters with minimum two-body separations $\simeq 3 \times 10^{-7}$, compared to an initial semi-major axis of 1.1×10^{-6} scaled length units (here 1 pc). This compares with minimum separations of $\simeq 2 \times 10^{-9}$ between single particles for models $M2$ and $M3$, corresponding to less than a tenth of the solar radius.

Closer inspection of the results show that 10 of the 13 primordial binaries which escape with zero eccentricity do not appear to have experienced any dominant encounters involving new regularizations. In these cases, the escape mechanism can be ascribed to more distant two-body (or multiple) encounters which may not affect the eccentricity. Thus the critical encounters referred to above are connected with temporary capture and/or exchange of components, as well as successive grazing encounters of hierarchical systems. Even so, non-dominant encounters involving very hard binaries may give rise to relatively high escape velocities.