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# Models of M 67

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**Abstract.** The old open cluster M 67 is an ideal test case for current star cluster evolution models because of its dynamically evolved structure and rich stellar populations that show clear signs of interaction between stellar, binary and cluster evolution. Here we discuss a direct N-body model of M 67. This model of 12,000 single stars and 12,000 binaries is evolved from zero-age and takes full account of cluster dynamics as well as stellar and binary evolution. At an age of 4 Gyr the model cluster matches the mass and structure of M 67 as constrained by observations. We discuss the role of the primordial binary population and the cluster environment in shaping the nature of the stellar populations of M 67, with a focus on X-ray binaries and blue stragglers.

**Keywords.** stellar dynamics, methods: n-body simulations, binaries: close, blue stragglers

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Despite advances in computing power made over the last decade or so, the globular clusters of our Galaxy remain out of reach of the direct $N$-body method. However, old open clusters such as M 67 and NGC 188 with ages in the range 4 - 8 Gyr offer dynamically evolved systems where the number, $N$, of stars required in the starting model is less than 100 000 and within current limitations (which also depend on the primordial binary fraction). A large number (29) of blue stragglers (BSs) are observed in M 67 and there are a number of indicators that the cluster environment, in addition to close binary evolution, has played a role in shaping this population. These include: (*i*) the BSs are concentrated towards the centre of M 67; (*ii*) BSs are found in eccentric binaries (with an orbital period of $P \sim 4$ d in one case: see Latham, these proceedings); and, (*iii*) the ratio of BSs to main-sequence stars is excessive for an open cluster and greater than can be produced by standard binary population synthesis (see Hurley *et al.* 2001). An $N$-body model of M 67 was presented by Hurley *et al.* (2001) and showed that binary evolution in combination with 3- and 4-body interactions can create the variety of BSs and BS-binaries observed. However, this model was semi-direct in that the dynamical evolution was not modelled directly for the first 2.5 Gyr of the cluster lifetime. Thus it was not ideal.

A preferred model of M 67 was presented by Hurley *et al.* (2005). This started with 12 000 single stars and 12 000 binaries. Stellar masses were chosen from the initial mass function of Kroupa *et al.* (1993) between the limits of 0.1 - 50 $M_\odot$ to give a total mass of 18 700 $M_\odot$. The cluster was placed on a circular orbit at 8 kpc from the Galactic centre – the time averaged semimajor axis for M 67 which has a slightly eccentric orbit – with an orbital speed of 220 km s$^{-1}$. This gave an initial tidal radius of 32 pc. A Plummer density profile was assumed for the starting model with the stars in virial equilibrium. Solar metallicity was assumed.

The model was evolved to an age of 5 Gyr using `NBODY4` (Aarseth 1999) – a Hermite integration code utilising GRAPE-6 hardware with stellar and binary evolution included as described in Hurley *et al.* (2001). At an age of 4 Gyr the model cluster has a mass of $\sim 2000\,M_\odot$ within a tidal radius of 15 pc, a half-mass radius of 2.7 pc and a binary frequency of 50 %. This provides an excellent match to the properties of M 67 (see (Fan

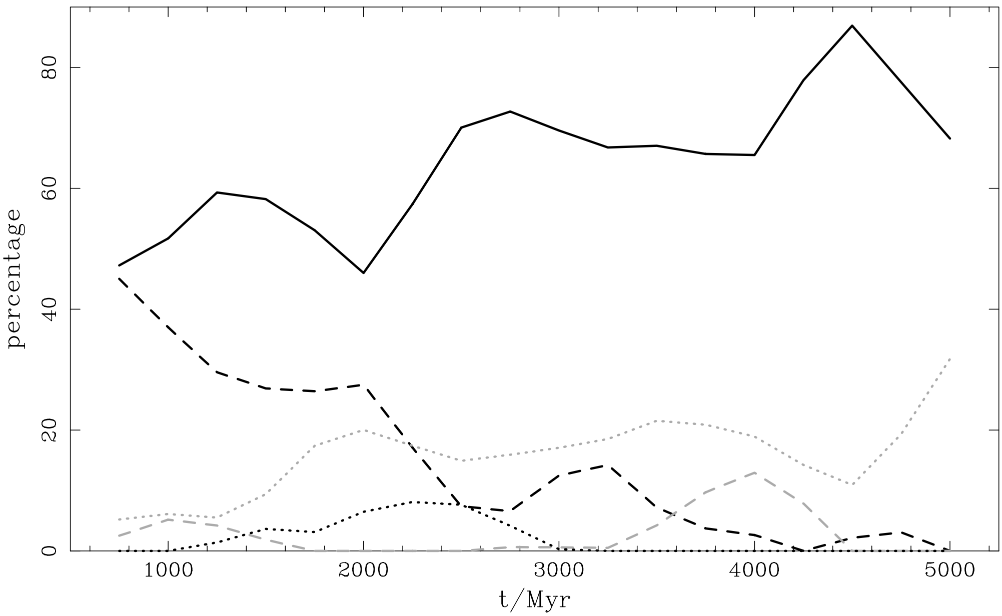


**Figure 1.** Blue straggler configurations as a function of time for the M 67 $N$-body model. Shown are single BSs (*solid* line) and BSs in binaries with $P < 1000$ d (*dashed* lines) or longer periods (*dotted* lines – bold/grey indicates circular/eccentric orbits).

*et al.* 1996, for example). We note that the core binary fraction rises from 0.5 to 0.8 during the simulation and is thus not depleted even if neglected soft binaries are counted.

The model at 4 Gyr contains 20 BSs with 8 in eccentric binaries. The half-mass radius of the BSs is 1.1 pc. Figure 1 summarizes the respective BS configurations as the model evolves – single BSs dominate but the proportion of BSs in eccentric binaries grows with time. Indications for M 67 are that 50 % of the BSs are single with 20 % in short-period binaries (all eccentric) and the remainder in long-period binaries ($\sim$ 20 % eccentric, $\sim$ 10 % circular). The 12 000 primordial binaries in the model had periods drawn from a flat distribution of log ($P$). Evolving these with a binary evolution algorithm (no dynamics) predicts 25 BSs at 4 Gyr with 75 % single and 25 % in circular binaries. So the cluster environment creates a more realistic configuration spread but also destroys potential BSs via hardening of close binaries. Repeating the $N$-body model with initial periods drawn from the distribution of Kroupa (1995) – which gives a 50 % reduction in short-period binaries – produces only one BS at 4 Gyr. This also leads to a reduced number of X-ray active BY Draconis binaries (see Hurley *et al.* 2005 for a full explanation and references).


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