Compact Objects and Binaries in Dense Star Clusters
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M67 in NBODY6++GPU and Gaia DR3

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Abstract. M67 (NGC 2682) is a dynamically evolved old (4 Gyr) open cluster in the Milky Way. Due to its nearness and relatively low levels of dust in the line-of-sight, it has been extensively observed both in surveys and targeted observations. We perform new N-body simulations of M67 using the updated NBODY6++GPU and also compare these models to observational data from the Gaia survey. While overall cluster parameters such as mass and main-sequence turnoff mass match observations, further simulations are needed to better match the blue straggler population. Further work is needed to investigate the binary transient systems in the models.

Keywords. open clusters, M67, N-body simulation, binaries

1. Introduction

The dynamic environment of a dense stellar system such as an open cluster is deeply tied to binary formation and evolution: high stellar density creates more opportunities for binaries to form, be disrupted, or participate in exchange interactions, and these interactions drive the global evolution of the cluster by injecting energy into the system (Hut et al. 1992). As a consequence, formation and evolution of binary transient systems – typically a compact object interacting with a companion – are affected by the cluster environment. These systems, along with other magnetically-driven types of active binaries, can be strong in X-ray and may have an optical counterpart.

M67 (NGC 2682) is relatively old (and thus dynamically evolved) for an open cluster at 4 Gyr. It has been extensively observed in multiple wavelengths, in both surveys and targeted observations (e.g. van den Berg et al. 2004; Reyes et al. 2024). Recently, Hunt & Reffert (2024) published the most complete open cluster catalogue, with over 5600 Milky Way open clusters, to date using data from Gaia Data Release 3 (Gaia Collaboration et al. 2016, 2023). Building off previous models by Hurley et al. (2005), we use the state-of-the-art direct N-body code NBODY6++GPU (Wang et al. 2015; Kamlah et al. 2022) to model M67.

2. Simulations

We carried out several simulations with slightly varying input parameters. All were initialised with $N = 24\,000$ particles with $N_{\rm b} = 12\,000$ primordial binaries (i.e. an initial binary fraction of 0.5). Metallicity Z was chosen to be between 0.01–0.02. Initial positions and velocities were generated from a Plummer model and the system is assumed to start in virial equilibrium at zero-age main sequence. Stellar masses were selected from the initial mass function (IMF) given by Kroupa (2001) in the range of 0.08–150 $M_\odot$. Initial masses for binary stars are also chosen from the Kroupa IMF and are either used as is, i.e. random pairings, or redistributed according to a chosen mass-ratio distribution.

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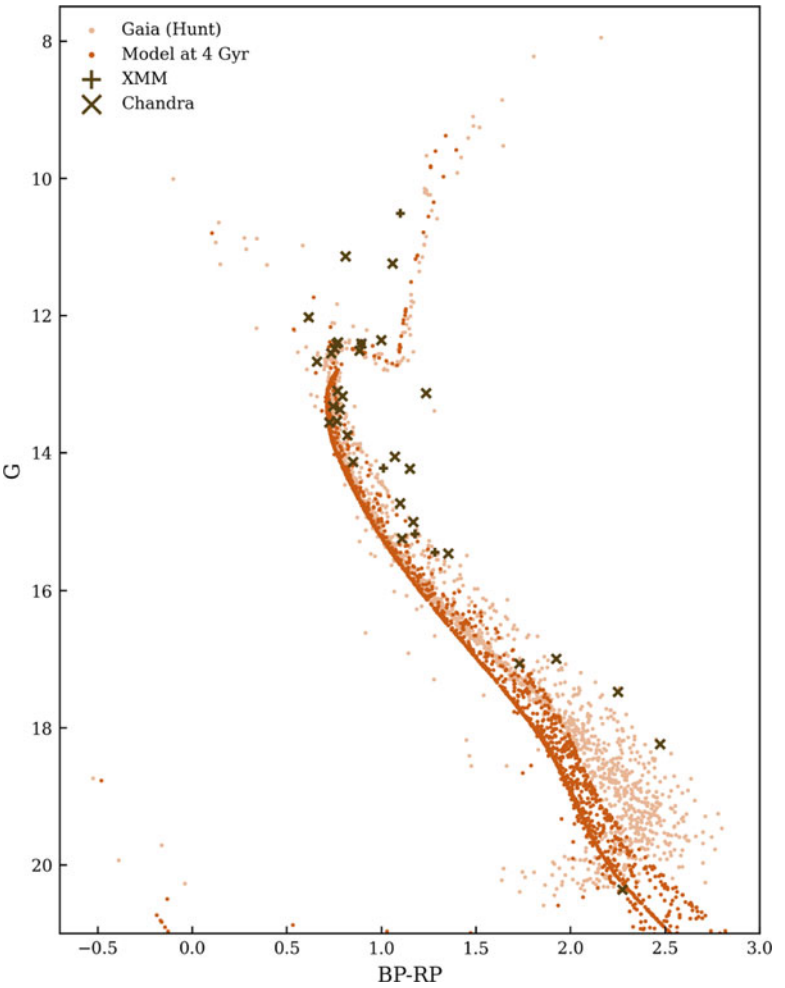


Figure 1. Colour-magnitude diagram for M67. Shown are the Gaia DR3 cluster members as determined by Hunt & Reffert (2024) (light circles), an N-body model at 4 Gyr (dark circles), XMM sources (+ symbols), and Chandra sources (× symbols). The model CMD has been truncated below Gaia's limiting magnitude.

Initial binary separations were chosen from a Gaussian distribution in $\log P$ (Duquennoy & Mayor 1991). A maximum semimajor axis was also imposed on the primordial binaries' initial orbits, ranging between 10–100 au. Initial binary eccentricities were selected either from a thermal distribution or from an exponentially decreasing distribution (Duquennoy & Mayor 1991). The cluster is put in a circular orbit at 8.0 kpc around a 10^{11} $M_{\odot}$ Galactic centre. M67 is estimated to be around 4 Gyr old (Reyes et al. 2024, and references therein), so we evolve the models to at least that point, following the dynamical, stellar, and binary evolution with NBODY6++GPU, and investigate the state of the cluster around this age.

3. Preliminary results

To construct colour-magnitude diagrams (CMDs) of the evolved clusters, MIST bolometric correction tables† were used to convert physical stellar parameters to Gaia G,

† https://waps.cfa.harvard.edu/MIST/index.html

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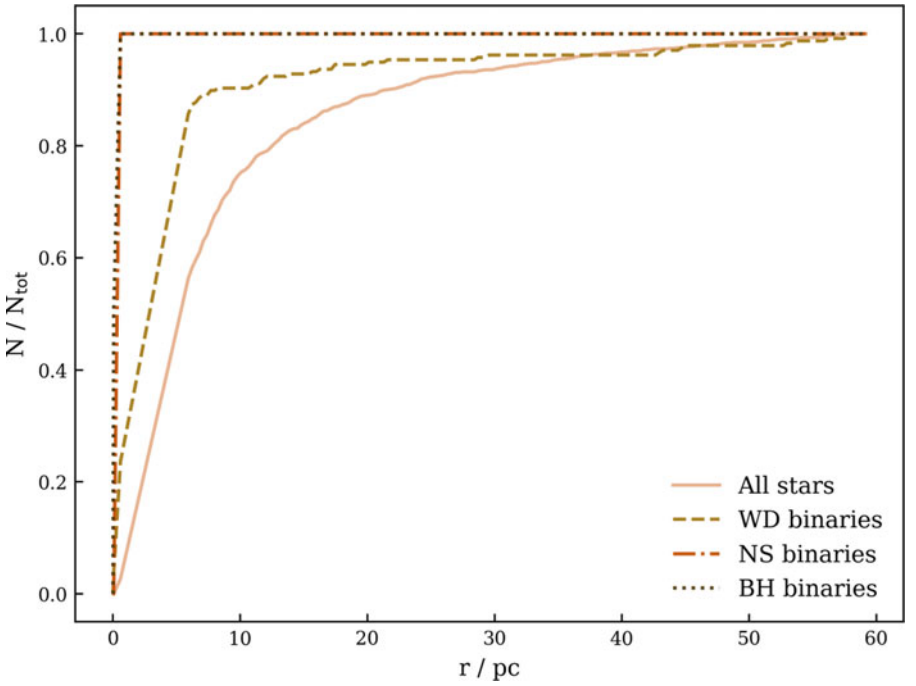


Figure 2. Cumulative radial distribution functions for stars in the same N-body model as Figure 1 at 4 Gyr. Shown are all stars in the cluster (solid line), all white dwarf binaries (dashed line), neutron star binaries (dot-dash line), and black hole binaries (dotted line).

BP, and RP magnitudes. These were then shifted down by a distance modulus of 9.73, corresponding to a parallax of 1.1325 mas, and right by a reddening of $E(B-V)=0.041$. One model is presented in Figure 1 as an example, alongside the same for Gaia-observed M67 members, as determined by Hunt & Reffert (2024). Also in this figure are XMM and Chandra X-ray sources associated with M67 members, as determined by Dage et al. (in prep). The model CMD matches the Gaia CMD well in terms of overall shape, however the number of model blue stragglers on the CMD do not match the Gaia cluster. In particular, the model shown in the figure has 10 blue stragglers (cf. 30 in observations). The average total cluster masses at 4 Gyr in the models is around 2500 $M_\odot$, which matches the estimate of 2762 $M_\odot$ given by Hunt & Reffert (2024).

We begin to investigate the populations of compact remnant binaries within the model cluster. Figure 2 shows that all types of binaries containing compact remnants are relatively centrally located, which is an expected consequence of the mass segregation process. In particular, for the model shown in the figure, at 4 Gyr there are 8 black hole binaries, 2 neutron star binaries, and 237 white dwarf binaries out of a total 1043 binaries. Further work is being done to understand these binary populations in detail.

4. Future

Further work is being done to better match the number of blue stragglers in the models to that seen in the observations. Additionally more investigation into the compact binary populations in the models is needed. Ultimately we aim to similarly investigate the binary transient systems in other Milky Way open clusters.

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Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1743921325104134

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