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HD 74438: A TIGHT SPECTROSCOPIC QUADRUPLE AS POSSIBLE PROGENITOR OF THERMONUCLEAR SUPERNOVAE?

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Abstract. Stars often form in multiple systems and may follow a complex evolution involving mass transfer and collisions, leading to mergers that are possible progenitors of Type Ia supernovae (SNe). The nature of the progenitors is still not well understood, but relies on processes occurring in binaries. Nevertheless, the long-term secular dynamics in tight triple or quadruple systems could also play a key role. Here, we summarize the properties of the first spectroscopic quadruple found within a star cluster: the hierarchical system HD 74438 made of two short-period binaries orbiting each other on a longer period (2+2 configuration). This system is one of the 2+2 quadruple systems with the shortest outer orbital period, and its orbits are not coplanar. We compute the future evolution of HD 74438 by considering gravitational dynamics, stellar evolution, and binary interactions, and show that this system is an excellent candidate progenitor of sub-Chandrasekhar Type Ia SNe through multiple merger events that lead to a white dwarf binary that ultimately merges too. This specific type of SNIa better accounts for the chemical evolution of iron-peak elements in the Galaxy.

Keywords: stars: individual: HD 74438 – binaries: close binaries: spectroscopic – techniques: radial velocities

1 Characterization of HD 74438

HD 74438 is a spectroscopic quadruple stellar system (SB4), member of the nearby and young open cluster IC 2391 in the Vela constellation. Its spectroscopic quadruple nature was discovered in the Gaia-ESO Survey (Gilmore et al. 2022; Randich et al. 2022), when hunting for spectroscopic binaries (SB) with several visible components (Merle et al. 2017). Follow-up observations were obtained with HRS/SALT[*] in South Africa (Crause et al. 2014) and HERCULES/UCMJO[†] in New Zealand (Hearnshaw et al. 2003). Supplemented with archival GIRAFFE/VLT (ESO) data, and Gaia/Hipparcos astrometry, we were able to deduce the 2+2 architecture as well as the orbital parameters for the three orbits (the two inner, and the outer) and the astrophysical parameters of each components (masses, radii and luminosities). In short, a bright AB pair made of A-type stars is orbited by a faint CD pair made of G-type stars (Merle 2019; Merle et al. 2019, 2021). Interestingly, the CD pair has an eccentricity higher than expected for its spectral type, probably due to secular gravitational effects produced by the AB pair. The detailed analysis of this system is presented in Merle et al. (2022), where simulations of the possible future evolution of this quadruple are performed. We develop here that later aspect because merger events in such high-order stellar systems are relevant when estimating, *e.g.*, SNIa rates.

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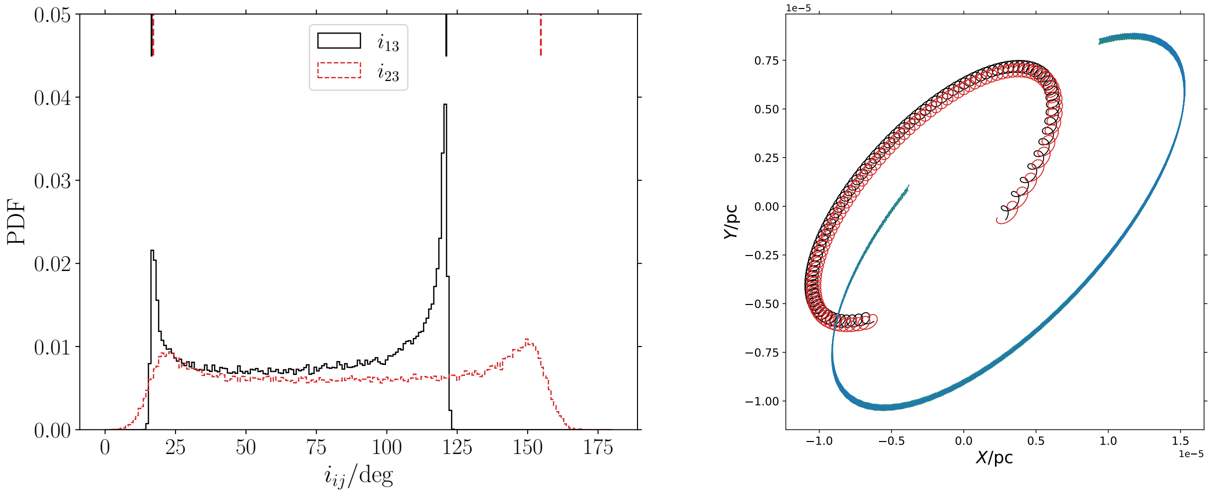

Fig. 1. Left: Probability distribution functions of the mutual inclinations of the inner pairs with respect to the outer one within the simulations. Indexes '13' means pair AB relative to pair AB-CD, and '23' means pair CD relative to pair AB-CD. **Right:** Orbital evolution of the two pairs with respect to the center-of-mass of the quadruple system for a given simulated system.

2 Numerical simulations of the future evolution of HD 74438

We use the Multiple Stellar Evolution (MSE) code to model the future evolution of HD744381. Here, we give a succinct overview of the code, and refer to Hamers et al. (2021) and references therein for full details. The MSE code models the evolution of multiple stellar systems with an arbitrary number of stars, as long as the initial system is hierarchical. The code takes into account gravitational dynamics, stellar evolution, and binary interactions such as mass transfer and common envelope (CE) evolution. Simple recipes for 'triple' interactions are also included such as triple CE evolution, when a tight binary star enters the envelope of a giant star.

We use Monte Carlo methods to sample a set of realizations of the quadruple system considering the observational uncertainties. Specifically, for each system we sample the four masses and five orbital elements for each of the three orbits, *i.e.*, 19 parameters in total, from Gaussian distributions centered at the observed values, and with standard deviations given by the error bars affecting the measurements. An exception to the latter applies to the longitudes of the ascending nodes of the inner orbits, which are not observationally constrained and are sampled from flat distributions, leading to the probability distribution functions of the mutual inclination between inner and outer orbits as displayed in the left panel of Fig. 1.

We sampled 10^4 systems and evolve them with MSE until a system age of 10 Gy was reached, or until the maximum allowed CPU wall time of 20 hr was reached. Given the highly compact nature of HD 74438 and the spectral types of its components, the system is computationally prohibitively expensive to evolve, since the secular time-scales are short compared to 10 Gy. Therefore, a significant fraction of systems, 67%, reached the maximum CPU wall time. However, we do not believe this is a major problem since most interacting systems have initially large mutual inclinations, and the systems in which the CPU wall time was exceeded have significantly longer ages than the typical time of the first merger event in interacting systems. The orbital motions of each pair with respect to the center-of-mass of one simulated quadruple system are presented in the right panel of Fig. 1, over a time range slightly smaller than the outer period of about 6 y.

In Fig. 2, we show an example system from the Monte Carlo simulations which is representative of those undergoing triple CE evolution. Within the first My, one of the inner binaries collides due to eccentricity increase driven by secular evolution (called Kozai-Lidov oscillations in stellar triples). The merger remnant, an $\sim$3.3 $M_{\odot}$ MS star, subsequently evolves and fills its Roche lobe around the companion binary at $\sim$364 My. The outcome of the triple CE is an unstable system in which a collision quickly occurs between the two inner binary stars (masses $\sim$1.3 and 1.0 $M_{\odot}$, respectively). A tight white dwarf (WD) + main sequence (MS) binary remains. As the MS companion evolves, it fills its Roche lobe at around 1134 Myr, ultimately causing a merger. The final remnant is a single 1.0 $M_{\odot}$ WD. Other simulated systems can lead to WD-WD binaries leaving a single remnant that can reach 1.3 $M_\odot$. The simulated evolution leading to such a remnant is presented in the Extended Data Fig. 10 of Merle et al. (2022).

3 HD 74438 as a progenitor of sub-Chandrasekhar type Ia supernovae?

About half of the realizations involve interactions such as triple CE evolutions and stellar mergers. In particular, about 25% of the realizations involve three merger events: the merging of the AB pair, the one of the CD pair, and finally the merging of the two mergers. Most of the time, the two mergers can evolve until the WD stage before ultimately merging into a WD with a mass below the Chandrasekhar limit, and so the merger is unlikely to result in SNe explosion.

We remark, however, that some sub-Chandrasekhar mass mergers might also lead to SNe Ia. In the sub-Chandrasekhar mass model, an explosion from a mass significantly below the Chandrasekhar mass may be triggered through dynamical processes producing double detonations such as mergers in very tight systems and even head-on collisions in dense environment like globular clusters (Wang & Han 2012). This model has difficulties in matching the observed light-curves but could account for the range of the observed SNe Ia brightness and birthrate. In particular, high-resolution spectroscopic observations with a non-LTE analysis of the iron-peak elements provide strong evidences that the sub-Chandrasekhar mass channel plays a major role in the chemical evolution of our Galaxy (Flörs et al. 2020; Eitner et al. 2022).

The channel consisting in WD-WD mergers in hierarchical quadruple systems for producing SNe Ia was recently proposed by Fang et al. (2018). These authors, based on simulations of stellar triples and quadruples, conclude that triple + quadruple systems are an important channel for stellar mergers. In particular, the fraction of systems that can reach high eccentricities is significantly enhanced in quadruple systems (compared to triples), with a correspondingly higher probability of producing WD-WD and stellar mergers. The rates of type Ia SNe originating from WD-WD mergers in quadruple star systems have also been investigated by Hamers (2018). The high multiplicity fraction of A-type stars (*e.g.*, Offner et al. 2022) suggests that it is common for WD-WD binaries to live in triple and quadruple systems, although their detection in triple or quadruple systems is difficult, mainly due to selection effects.

In that respect, the 2+2 quadruple system HD 74438 is a good progenitor candidate since (i) the AB pair is made of A-type stars, (ii) the orbits are not coplanar (iii) the Kozai-Lidov oscillations is probably at work between the CD pair and the outer one because the eccentricity of the CD pair is higher compared to classical SB made of G-type stars and (iv) the modeling of its future evolution leads to three merger events in 25% of cases. Interferometric observations are required to determine the longitudes of ascending nodes of the two inner orbits and to conclude about the fate of this tight stellar quadruple.

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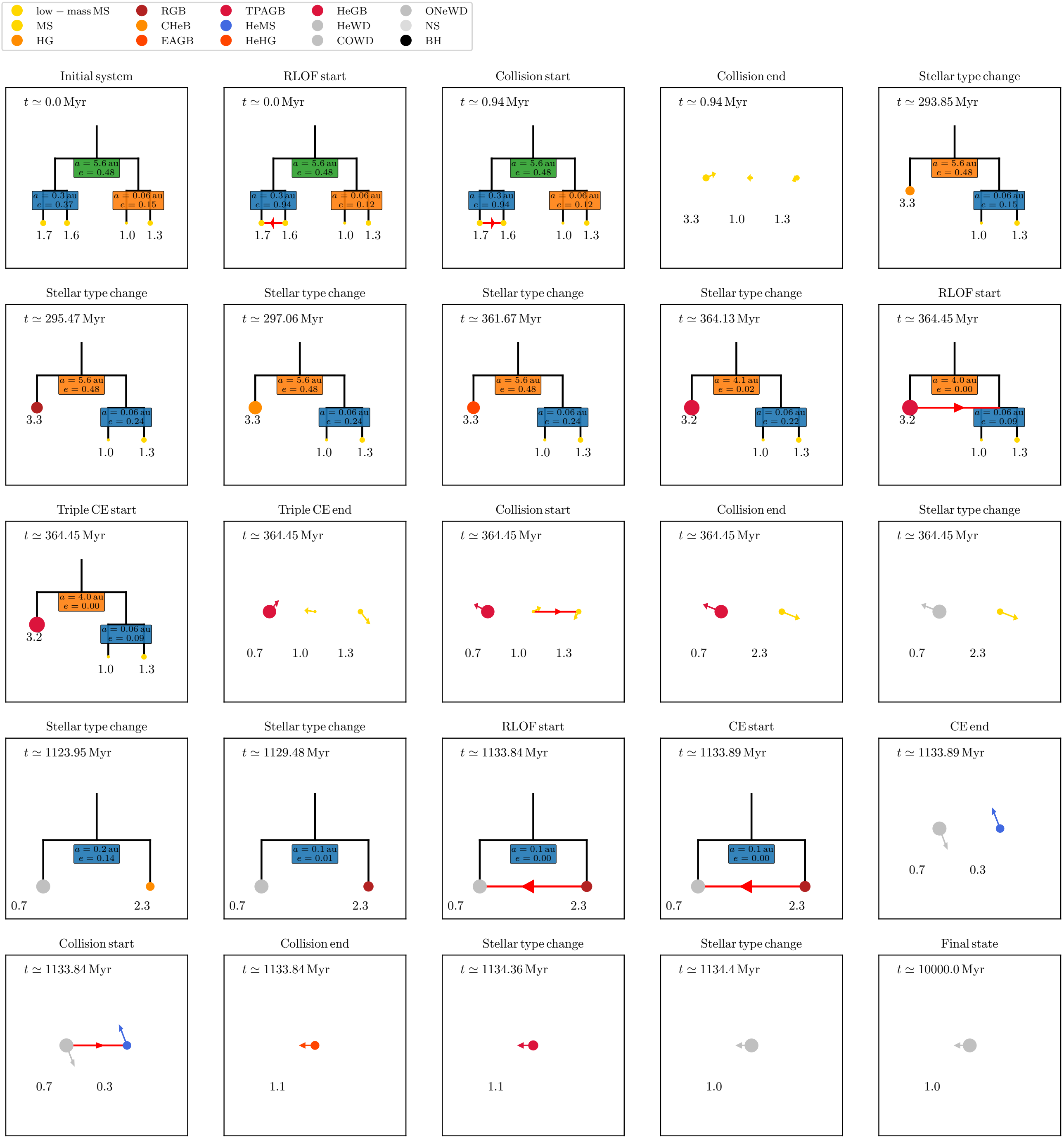

Fig. 2. Example of the future evolution of of HD 74438 as modeled with MSE (Hamers et al. 2021). Each panel shows an event of interest labeled at the top, with the time indicated and the system schematically represented in a mobile diagram, with orbital parameters (semi-major axes a and eccentricities e) and masses (in units of $M_\odot$) indicated. The stellar colors are related to the evolutionary stages and are indicated in the legend at the top.

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