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HD 74438: a Young Spectroscopic Quadruple as a Possible Progenitor of Supernovae Ia

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Type Ia supernovae (SN Ia) are amongst the most energetic events in the Universe. They are used as standard candles to measure cosmological distances and they produce a rich nucleosynthesis; they are fundamental objects to understand the chemical evolution of galaxies. It is thought that SN Ia are produced by processes occurring in tight binaries including at least one carbon–oxygen white dwarf (WD). Such binaries could emerge from the dynamical evolution of high-multiplicity stellar systems such as the young spectroscopic quadruple HD 74438, recently detected in the Gaia–ESO Survey. Follow-up spectroscopic observations in South Africa and New Zealand, as well as the use of archival ESO spectra, allow us to characterise its orbital and astrophysical parameters. Modelling the dynamical evolution of stellar quadruples shows that such systems can produce WD mergers, possible progenitors of SN Ia.

Can we neglect stellar quadruples?

Amongst low-mass stars, quadruple systems represent only 1–5% of all systems (see, for example, Tokovinin, 2014; Reylé et al., 2021) while being, with triples, the dominant multiplicity amongst the most massive stars (Moe & Di Stefano, 2017) — leaving only a few percent of single stars. The shape and structure of a multiple system become relevant starting with quadruples, since triples are stable only in a configuration of a binary orbited by a distant companion, i.e., a 2+1 configuration. In quadruples, two architectures can be observed, although not with the same degree of stability: the 1+1+2 = 1+3 configuration and the 2+2 configuration, i.e., two short-period binaries gravitationally bound on a longer period. The 1+3 configuration is strongly bound and harbours 3 hierarchies while the 2+2 configuration is considered as weakly bound and harbours only 2 hierarchies: two inner short periods and one outer longer period. Statistically, more than 2/3 of quadruple systems are observed with the 2+2 configuration (Tokovinin, 2018), but it is not clear whether this comes from observational biases or whether there are physical grounds for such a situation.

Stellar multiplicity in the Gaia–ESO Survey

The Gaia–ESO Survey (GES; Gilmore et al., 2012; Randich et al., 2013) is one of the first large spectroscopic surveys with medium to high resolution designed to complement the Gaia mission as regards spectroscopy, given that the Gaia RVS spectrograph is limited to $G \sim 14$ and has a resolution of only 11 500. The GES was not optimised to detect stellar multiplicity, but Working Group 14, a specific working group aiming at detecting outliers, has focused on the detection of spectroscopic binaries (SB) with one or more visible components (SB1, SB2, SB3 and SB4) through radial velocity (RV) variations. Within the previous releases it was already possible to identify about 800 SB1 (Merle et al., 2020), 340 SB2, 10 SB3 and even one SB4 (Merle et al., 2017), most of them being new detections. The last release will increase the number of SB2 and SB3 detected thanks to the design of new templates for cross-correlating spectra (Van der Swaelmen et al., in preparation). After correcting for detection efficiency, we obtain an SB1 fraction of 10±2% and an SB2 fraction of about 2%, yielding a total GES SB fraction of 12%, well in line with the estimate of the close binary fraction of 15±3% by Moe & Di Stefano (2017) for solar-type stars.

The unique SB4 from the GES

HD 74438 is a bright target ($G = 7.5$) which shows four components in its GES spectrum, making this target the unique SB with 4 visible components (SB4) as revealed by the GES cross-correlation functions (CCF). From the preliminary analysis of the 46 GES epochs, we already suspected it to be a bright SB2 (components A and B) evolving around another dim SB2 (components C and D): i.e., an SB4 in a 2+2 configuration. Interestingly, this quadruple belongs to a young and close-by open cluster in the Vela constellation, and indeed the RVs of the pairs bracket the mean RV of the cluster. It was suspected to be a stellar triple by dint of lying 0.9 mag above the main sequence of the cluster (Platais et al., 2007). All the spectra within the GES were taken on the same night, 18 February 2014, within a period of 2.5 h. It was already possible to set upper limits to the inner periods, but monitoring this SB4 rapidly became mandatory. To be detected as an SB4, the outer period of the quadruple system cannot exceed a few years. This limitation makes spectroscopic quadruples very rare objects. Before the discovery of the SB4 nature of HD74438, fewer than 10 SB4 were known, most of them also being eclipsing binaries. In less than three years, we obtained sufficient follow-up observations with the High Resolution Spectrograph at the Southern African Large Telescope (HRS/SALT) and the HERCULES spectrograph at the University of Canterbury Mount-John Observatory (HERCULES/UCMJO) in New Zealand. Combined with archival ESO data from GIRAFFE spectra taken in 2004, it was possible to constrain the outer orbit.

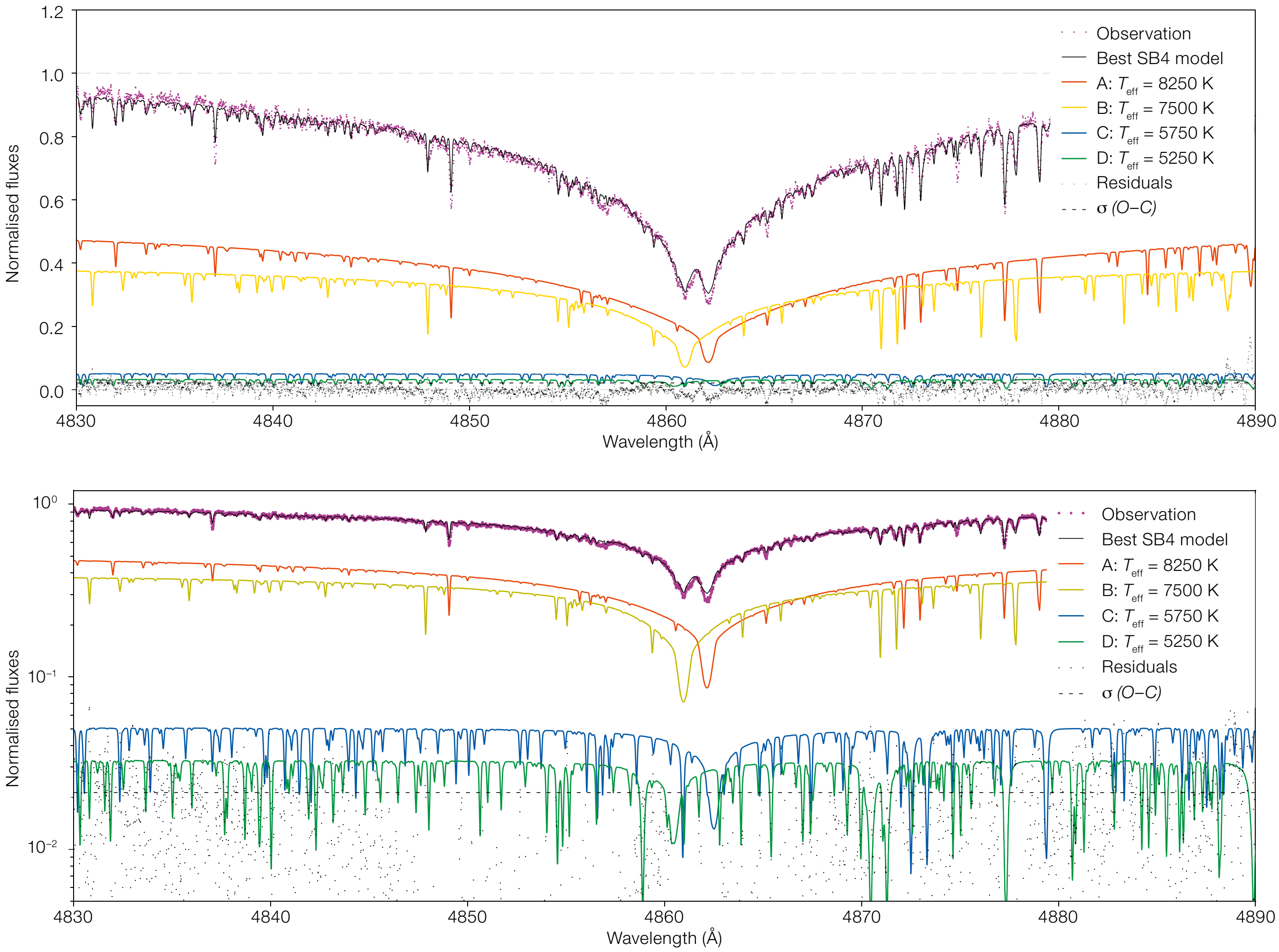

Figure 1. Spectral fitting of the UVES/GES observed composite spectrum (magenta dots) taken on JD 2 456 707.120 (2014.134) around Hβ with a S/N = 104. The best-fit SB4 composite model is shown in black. The individual spectra are also shown and colour-coded as given in the legend; they give an idea of the contribution of each component to the total flux. Normalised fluxes are represented on a linear scale (top) and a logarithmic one (bottom).

A tight quadruple with non-coplanar orbits?

Astrophysical parameters

An age of 43 Myr and a solar metallicity for the cluster IC2391 (Randich et al., 2018; Spina et al., 2017) indicate that the four components are still on the main sequence. From a grid of composite spectra, we fitted two HRS/SALT spectra (having a spectral resolution of 65 000) where the four components were well separated (see Figure 1 of Merle et al., 2022). For illustrative purposes, and using the derived effective temperatures, we compare in Figure 1 the observed Ultraviolet and Visual Echelle Spectrograph (UVES) spectrum (spectral resolution of 47 000) with a S/N > 100 taken at JD 2 456 707.120 (2014.134) with a synthetic composite spectrum computed using Kurucz atmosphere models[1] and the 1D LTE radiative transfer code Turbospectrum[2]. The individual spectra are combined, taking account of the RV and luminosity of each component. The residuals (grey dots) and their dispersion (black dotted horizontal lines) are shown; looking at the logarithmic version (bottom panel) we can see that the flux contribution of the weakest component, D, is higher than the 1% contribution of the noise and the 2% dispersion of the residuals, giving credence to the derived temperatures. Using Gaia DR2 parallaxes and photometry, it was possible to derive the individual luminosities that sum up to 15.7 ± 1.8 $L_\odot$, in excellent agreement with the luminosity computed in Gaia DR2 by Andrae et al. (2018). Interestingly, it means that in the optical it is therefore possible to detect components almost 20 times less luminous than the brightest one (luminosity ratio of 18.5). In addition, spectroscopic and dynamical masses are derived and are in good agreement, with a total mass of about 5.3 ± 0.1 $M_\odot$, much larger than the 3 $M_\odot$ inferred from the integrated spectral type (A2V).

Orbital parameters

Thanks to the high spectral resolution monitoring carried out with SALT in South Africa and HERCULES in New Zealand, and completed with the archival ESO GIRAFFE spectra, it was possible to derive the orbital parameters of the three

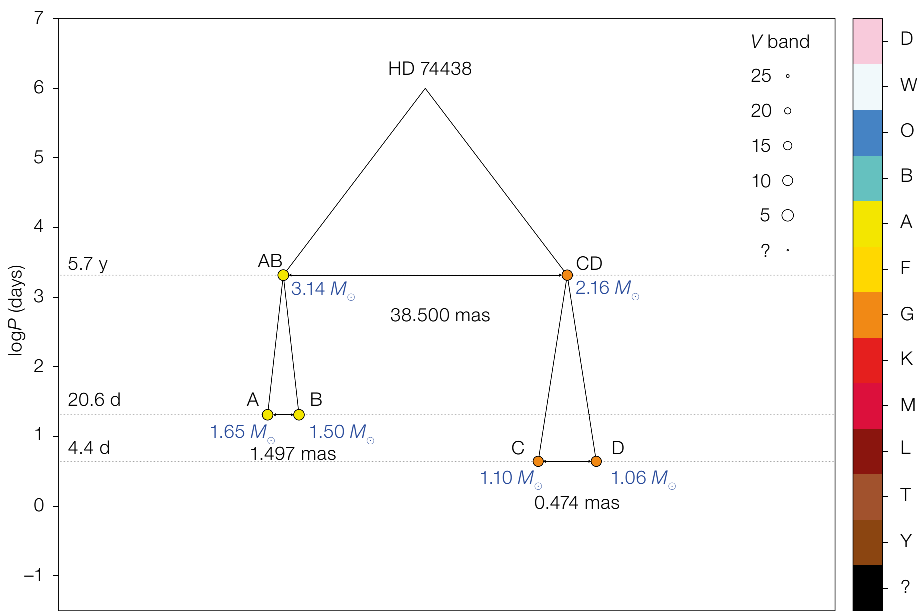

Figure 2. Mobile diagram of the 2+2 spectroscopic quadruple stellar system HD 74438. A G-type binary of 4 days is orbiting an A-type binary of 21 days in almost 6 years. The total mass of the system is 5.3 ± 0.1 $M_\odot$. Simulations show that such quadruples could undergo secular evolution leading to three merger events.

orbits (i.e., radial velocity amplitudes, orbital periods, eccentricities, periastron arguments and times, and the center-of-mass RV of 14.5 ± 0.2 km s^{-1} — in excellent agreement with the parent cluster RV from Bravi et al., 2018). Inclinations and semi-major axes are also deduced. The resulting global architecture of HD 74438 is presented in Figure 2. It was also possible to constrain the orientation of the outer orbit on the sky, using astrometric data from Tycho-1 and 2, and the mean proper motions (relative to the parent cluster) of Gaia DR2 and eDR3, and to remove the degeneracy on the ascending node and the inclination on the sky (see the methods described in Merle et al., 2022). Nevertheless, the ascending nodes of inner orbits are not reachable with Gaia data and would require specific interferometric observations with, for example, the Precision Integrated-Optics Near-infrared Imaging Experiment (PIONIER). The inclinations on the sky alone cannot allow one to decide whether the inner orbits are coplanar or not.

Secular evolution at work?

Indirect evidence

Despite the missing arguments of the ascending nodes of the inner orbits, indirect evidence favours non-coplanar inner orbits. Indeed, when the eccentricity of the C–D pair is compared to the eccentricities of other SB2 from the SB9 catalogue (Pourbaix et al., 2004) and eclipsing binaries (Zasche et al., 2019) with similar G spectral types and similar periods, it appears that they are all circularised. According to Geller, Hurley and Mathieu (2013), binaries with orbital periods lower than 7–8 days should already have been circularised, given the age of the parent cluster. This observational fact points toward the existence of a dynamical influence of the A–B pair on the C–D pair. In triple systems (1+2 configuration), such a dynamical effect of the distant star on the inner binary is produced by exchange of angular momentum between the inner binary and the outer orbit on a secular timescale, i.e., timescales larger than the orbital periods. This effect is called von Zeipel-Lidov-Kozai (ZLK) oscillations. The only condition for a such secular evolution to operate in triple systems is that the initial mutual inclination should be in the range 40° to 140°.

Future evolution of HD 74438

In quadruples, such dynamical effects can lead to even more complex evolution because a double effect can occur between any of the two inner binaries and the outer orbit. The restricted inclination range required in triple systems to pump up the inner eccentricities no longer applies in quadruple systems. We simulated the future evolution of HD 74438 using the state-of-the art Multiple Star Evolution code (Hamers et al., 2021) that includes gravitational dynamics with direct N-body integration and secular evolution, stellar evolution effects, and binary and triples interactions in eccentric orbits (such as mass/angular momentum transfer and common envelope evolution). The trajectories of one of these future evolutions are shown in Figure 3. Simulations based on the orbital parameters and their uncertainties show that in half of the cases, at least one merger event occurs. In a quarter of cases, inner binaries will merge, producing a double WD that also will ultimately merge leaving a WD with a sub-Chandrasekhar mass. Simulations of future evolutions of HD 74438 show that tight quadruple stellar systems offer a possible new way to form SN Ia.

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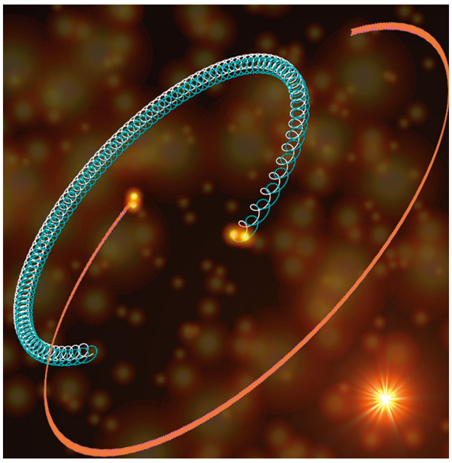

Figure 3. One simulation of the trajectories of the quadruple stellar system HD 74438: the two close pairs, having orbital periods of 21 and 4 days, orbit around their centre of mass in six years. At some point, the two pairs could merge into white dwarfs giving rise to a thermonuclear supernova, as illustrated in the bottom right.

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Links

1. Kurucz atmosphere models: http://kurucz.harvard.edu/grids.html, the ap00k2.dat in the GRIDP00 directory
2. Turbospectrum code: http://ascl.net/1205.004
3. GAIA website: https://www.cosmos.esa.int/web/gaia
4. DPAC website: https://www.cosmos.esa.int/web/gaia/dpac/consortium
5. Vizier website: https://vizier.cds.unistra.fr/

The beautiful edge-on spiral galaxy NGC 3190 with tightly wound arms and a warped shape that makes it resemble a gigantic potato crisp, as seen by ESO's Very Large Telescope. Supernova SN 2002bo is found in between the 'V' of the dust lanes in the south-western part of NGC 3190. SN 2002cv is obscured by a large amount of dust and is therefore not visible. This colour composite is based on images obtained with FORS1 on UT2 (Kueyen) in four filters (*B*, *V*, *R* and *I*). The observations were done in the framework of a programme aiming at studying the physics of Type Ia supernovae. The field of view is 6.15 × 5 arcminutes. North is up and East is to the left.