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A YOUNG STELLAR QUADRUPLE WITH NON-COPLANAR ORBITS

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Abstract. Stars form in clusters and associations; some of the multiple systems born in such environments will remain gravitationaly bound for their entire life. Multiplicity is thus an inherent property of stellar populations. Recent large spectroscopic surveys have harvested many spectroscopic multiple systems with two and three components but those with four components (SB4) remain comparatively very rare. Here we report on the preliminary properties of the first SB4 found within a cluster: HD 74438, located in the close-by young open cluster IC 2391. It is the youngest (43 My) SB4 discovered so far. Identified in the context of the Gaia-ESO Survey, this system benefited from HRS/SALT, HERCULES/UCMJO spectroscopic follow-up and archival observations from ESO. We show that the system consists of a 2+2 bound hierarchical stellar system, *i.e.* two SB2 gravitationaly bound. We derived orbital and astrophysical parameters for the two inner pairs and found that their orbits are non-coplanar. The outer pair is characterized by a preliminary orbit of 6 y with an eccentricity of 0.5. The non-coplanarity of the two inner pairs sheds light on secular evolution of quadruple systems that can lead to merger end-points of stellar evolution in multiples.

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

1 What do we known about HD 74438 before the discovery of its quadruple nature?

Identifying multiple stars in clusters is fundamental because the evolution of stars are well-understood only for single stars, and their study can reveal important clues on the formation of stars and its interplay with its environment. Monitoring radial velocities (RV) of stars allow to identify spectroscopic binaries (SB), *i.e.* binary stars with orbital period lower than a few 10^4 d ($\sim$ 20 y). Quadruple hierarchical systems in a 2+2 or 3+1 configurations are challenging objects because of the complexity of their dynamics (Hamers et al. 2015; Hamers 2019). But these rare objects offer unique opportunity to study tidal interactions between the components.

The *Gaia*-ESO Survey (Gilmore et al. 2012; Randich et al. 2013) is a ground based multi-object spectroscopic large public survey targetting 10^5 stars in all stellar populations until $V = 20$ to complement RV and chemical composition characterization of a fraction of stars observed by the ESA space mission *Gaia* (Gaia Collaboration et al. 2016, 2018b). It was not designed to monitor RV variables but allow Merle et al. (2017, 2020) to discover hundreds of SB1 and SB2, a ten of SB3 and one SB4 candidate, the latter being the subject of this proceedings.

HD 74438 system is born in the young IC 2391 cluster, one of the closest open clusters to the Sun, located at 146^{+8}_{-7} pc in the Vela constellation and aged of 43^{+15}_{-7} My (Randich et al. 2018; Gaia Collaboration et al. 2018a). The RV of the system is compatible with the cluster's mean RV of 14.8 ± 0.7 km s^{-1}and its membership is reliable (Platais et al. 2007). By intrinsic brightness and color, Pasinetti Fracassini et al. (2001) provides a radius of 1.8 R$_\odot$. Bochanski et al. (2018) reported a higher radius of 2.76 ± 0.27 R$_\odot$, a mass of 2.11 ± 0.07 M$_\odot$ as well as an age of 759 My, more than 15 times older than the parent cluster. Contrary to Siegler et al. (2007) who reported no sign of binarity, Platais et al. (2007) noticed that this system should be a triple because it lies 0.9 mag above the cluster's main sequence, but they did not detect the presence of several RV components in the CCF. In addition, this system appears well above the fitted isochrone of the main sequence of IC 2391 cluster as well as the binary sequence taken with $q = 0.8$ (Randich et al. 2018).

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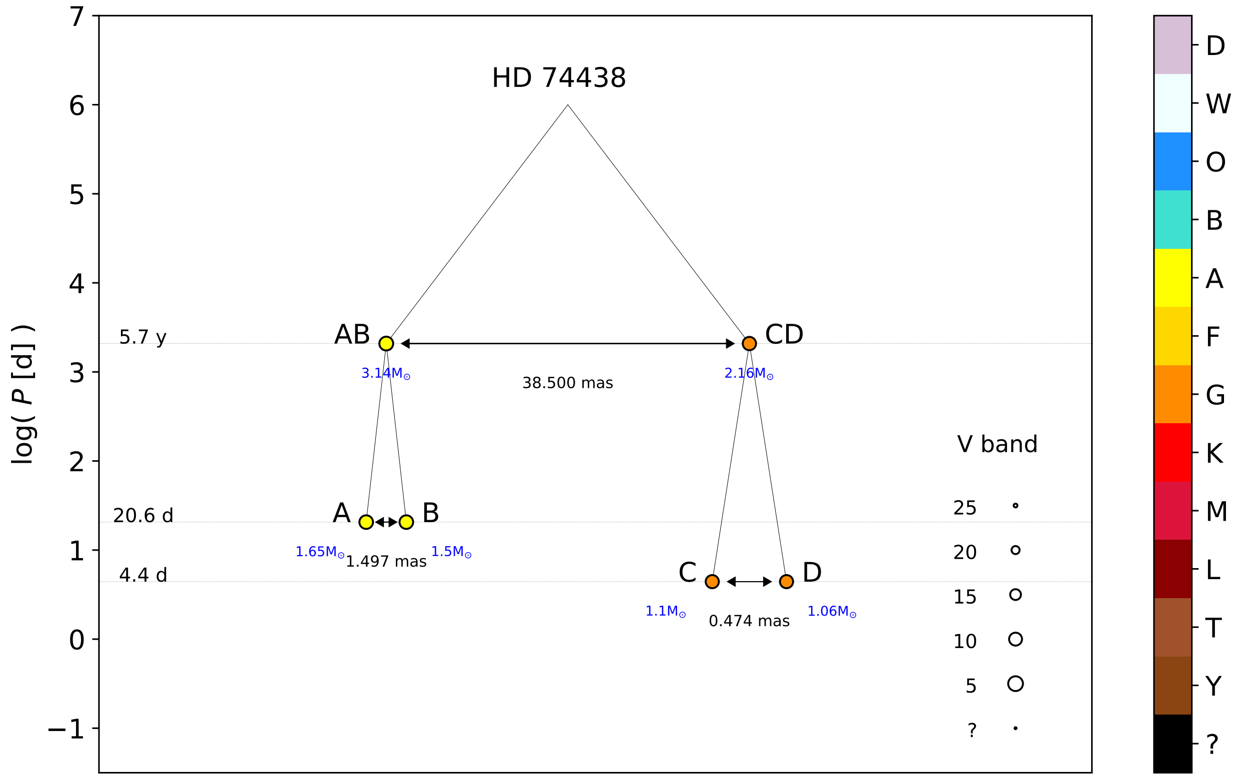

Fig. 1. The hierarchical 2+2 quadruple stellar system HD 74438 discovered in the Gaia-ESO Survey. The full characterization of the architecture and the orbital parameters were obtained thanks to several follow-up with HRS/SALT, HERCULES/UCMJO and ESO archival data from GIRAFFE. The astrophysical parameters are still preliminary.

2 What are the orbital and astrophysical parameters of HD 74438?

We obtain follow-up spectroscopic observations of this SB4 with high resolution spectroscopy on HRS/SALT* in South Africa (Crause et al. 2014) and HERCULES/UCMJO† in New Zealand (Hearnshaw et al. 2002, 2003). They are complemented with GIRAFFE observations at medium resolution retrieved in the ESO archive‡ and taken ~ 10 years before the GES. Such medium resolution does only allow to resolve the two brightest components. RVs of the time series spectra are analyzed to find orbital solutions of the two SB pairs. The preliminary orbital parameters for the two inner orbits were reported by Merle et al. (2019). The inclinations on the sky of the AB and CD pairs are 52° and 86° respectively, making the two inner orbits not coplanar. The mutual inclinations are not reachable with spectroscopy alone (see Sect. 4). The architecture of the system and the main preliminary orbital parameters are displayed on Fig. 1.

The astrophysical parameters were derived using HRS/SALT spectra taken on 2018-10-14 and 2018-12-31 because they show four well-separated components at the highest resolution. Because this system belongs to a young cluster, we assumed solar metallicity and main sequence components (*i.e.* [Fe/H] = 0 and $\log g = 4.5$). The radiative transfer code Turbospectrum (Plez 2012) was used, with Kurucz's model atmosphere grid§. (Kurucz 1991). We built a grid of synthetic spectra on the wavelength region [3 850 − 5 500] Å combining four models with temperatures ranging from 4 000 to 10 000 K (with a step of 250 K) shifted at the RV of each component. The composite model that best fits the four components is taken to be the one with the smallest standard deviation on the residuals distributions. The best combined synthetic spectrum together with its

*Southern Africa Large Telescope
†University of Canterbury Mt John Observatory
‡http://archive.eso.org
§http://kurucz.harvard.edu/grids.html

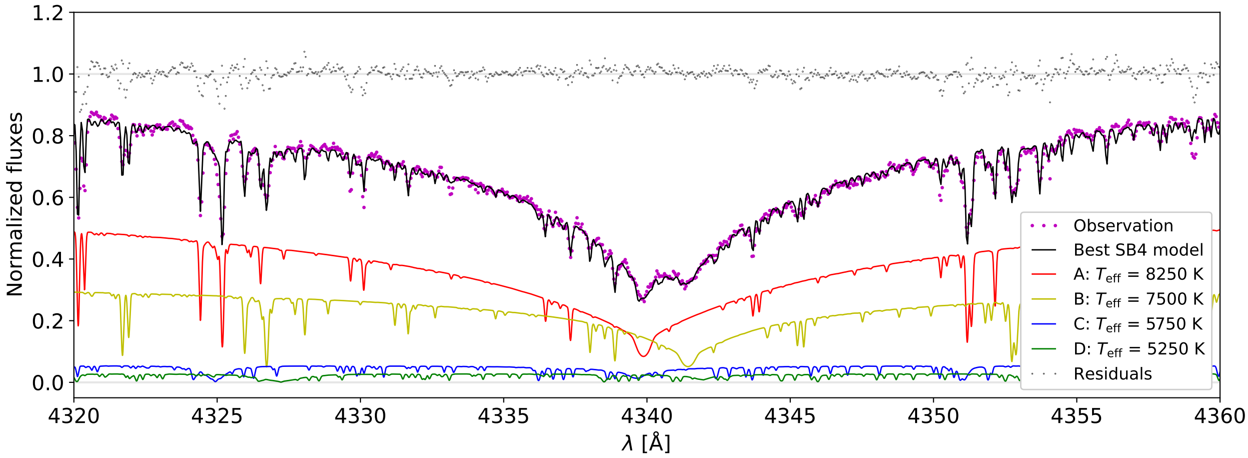

Fig. 2. Display around Hγ of the observed composite spectrum (magenta dots) taken on night 2018-12-31 with HRS/SALT, when the four components were well separeted and resolvable. The best fitted SB4 composite model is shown in black and the residuals in grey, shifted around $y = 1$ for clarity. The individual spectra are also shown and color-coded as given in the legend; they give an idea of the contribution of each component to the total flux.

individual components is compared to the 2018-12-31 observed spectrum on Fig. 2 as an illustration of the fit. Once the effective temperatures are derived for each component, we derived their spectral type using conversion table from Gray & Corbally (2009, Appendix B3). Determination of masses and luminosities were performed by using stellar evolution models (PARSEC, Bressan et al. 2012) with solar metallicity $Z = 0.0147$. We first select three isochrones corresponding to the most recent age determination of the parent cluster: $t = 43^{+15}_{-7}$ My (Randich et al. 2018). The masses and luminosities are interpolated at the spectroscopic temperatures on the main sequence for each component. Radii are also deduced. The spectroscopic masses and spectral type are displayed on Fig. 1. The spectroscopic mass ratio for each orbit is also determined. Combining orbital and astrophysical parameters, we can also deduce the inclinations and the separations of the three orbits: the two inner and the outer ones. The periods satisfied the dynamical stability criterion for a 2+2 architecture (Naoz 2016). The consolidated orbital and astrophysical parameters for each component will be available soon (Merle et al., submitted).

3 What is so special with the spectroscopic quadruple system HD 74438?

HD 74438 turns out to be especially interesting because:

- It belongs to a very young (43 Myr) and nearby (146 pc) open cluster, IC 2391 (Randich et al. 2018), so its age is known;
- It has the shortest outer orbital period when compared to other quadruples in clusters reported in the MSC (Tokovinin 2018);
- It is one of the rare SB4 systems with non-coplanar inner orbits (as inferred from the inclinations derived from the spectroscopic masses);
- The CD subsystem has a higher eccentricity than SB2s of similar spectral types and periods, as seen in the eccentricity–period diagram from the SB9 catalogue (Pourbaix et al. 2004);
- According to Fig. 2 of (Geller et al. 2013) giving the circularization period (derived from population synthesis simulations) as a function of the cluster age, all systems with $P_{\rm orb} \leq 8$ d in clusters of the age of IC 2391 should be circularized, which is not the case of the CD pair of HD 74438, calling for an eccentricity-pumping mechanism.

To date, less than 10 SB4 are reported in the literature, and when the inclinations are known, they turn out to be nearly co-planar.

4 What's next?

To fully characterize this SB4 system, one needs the orientation of the orbits on the sky that will allow to determine the mutual inclinations between the inner orbits and the outer one. Spectroscopy alone cannot afford the longitudes of ascending nodes of the three orbits, and astrometery with Gaia/ESA and/or interferometry with PIONIER/ESO is required to constrain these parameters. Characterizing such systems are indeed important as they might be one kind of progenitors of type Ia supernovae. Recent simulations demonstrated that quadruple systems with 2+2 architecture undergoing secular evolution could produce SNIa at an higher rate compared to triples when inner binaries merge (Fang et al. 2018).

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