Highlights of Spanish Astrophysics XI, Proceedings of the XV Scientific Meeting of the Spanish Astronomical Society held on September 4–9, 2022, in La Laguna, Spain. M. Manteiga, L. Bellot, P. Benavidez, A. de Lorenzo-Cáceres, M. A. Fuente, M. J. Martínez, M. Vázquez- Acosta, C. Dafonte (eds.), 2023

The blue supergiant 2MASS J20395358+4222505, a Rosetta stone in the realm of massive stars.

Herrero, A.[1,2], Berlanas, S. R.[3,4], Maíz Apellániz, J.[5], and Comerón, F.[6]

[1]Instituto de Astrofísica de Canarias, 38200, La Laguna, Tenerife, Spain
[2]Departamento de Astrofísica, Universidad de La Laguna, 38205, La Laguna, Tenerife, Spain
[3]Departamento de Física Aplicada, Facultad de Ciencias II, Universidad de Alicante,Spain
[4]Astrophysics Group, Keele University, Keele ST5 5BG, Staffordshire, UK
[5]Centro de Astrobiología (CAB), CSIC-INTA, Campus ESAC, E-28 692 Villanueva de la Cañada, Madrid, Spain
[6]European Southern Observatory, Karl Schwarzschild Str. 2, 85748, Garching, Germany

Abstract

2MASS J20395358+4222505 is a highly extincted (Av= 9.6 mag) early B-supergiant located in the nearest massive star forming region, Cyg-X, in the outskirts of the massive star association Cyg OB2. A mass of M= 46 $M_\odot$ and a luminosity of $\log(L/L_\odot)$= 5.7 make it one of the most massive and luminous stars in the Milky Way. Interestingly, the star seems to be in a transition stage, in the way to become one of the few (half a dozen) early-type hypergiants in the Galaxy. Moreover, the star is orbiting an unknown companion, with a semi-amplitude of the radial velocity curve of ∼100 km/s. We especulate about the possibility that the unseen companion is a compact object, a back hole of ∼18 $M_\odot$, or a fast rotating main sequence star of that mass.

1 Introduction

Since its discovery by [11], the massive star population of the Cyg OB2 association has been subject to numerous studies. In particular, there have been a number of census in the region, like, f.e., those by [16, 10, 4]. The initial list of the first authors contained 11 candidate members, whereas the lists presented by the last authors contain 102 OB stars, plus 61 new OB candidates. [1] carried out a spectroscopic survey of those candidates. They confirmed 11 new O-type stars and 31 B-type stars earlier than B3.

The analysis of [1] included an estimation of extinction, from which the peculiarities of one of the object classified as a B0 I star were evident: the star had an estimated extinction A_v ≈11, from which the luminosity could also be estimated, adopting the observed NOMAD magnitude in the B-band (B= 15.9, [17]), a standard extinction law and a bolometric correction appropriated for the spectral type. Together with the distance to Cyg OB2 determined

Table 1: Main stellar parameters for 2MASS J20395358+4222505. The gravity includes the centrifugal correction and $\epsilon = \frac{N(He)}{N(H)+N(He)}$ is the helium abundance with respect to hydrogen, by number. The whole set of values is given for the adopted distance, together with the statistical errors of the analysis. Full details of the analysis can be found in [6]

V sini (km s^{-1})	$T_{\rm eff}$(K) (K)	log g (dex cgs)	ϵ	V_∞ (km s^{-1})	R ($R_\odot$)	M ($M_\odot$)	M_{bol} (mag)	$\dot{M}\times10^6$ ($M_\odot$ a^{-1})
110	24 000	2.88	0.12	1500	41.2	46.5	-9.52	2.40
±25	±500	±0.15	±0.04	±200	±4.0	±15.0	±0.10	$^{+0.20}_{-0.30}$

by [2] (1.76 kpc), this results in an estimated luminosity $\log L/L_\odot \approx 6.6$, which would place 2MASS J20395358+4222505 among the most luminous stars in the Galaxy.

2 2MASS J20395358+4222505: a very luminous blue supergiant

Because of the peculiar characteristics of 2MASS J20395358+4222505, we decided to have a look at the object. During the commisioning of the MEGARA spectrograph attached to the Gran Telescopio Canarias ([5]) we obtained R= 6000 spectra with the LR-U and LR-B gratings, and R= 20 000 spectra with the HR-R grating, thus covering a spectral range from 3655 to 5200 Å and from 6405 to 6797 Å. We note that the LR-U and LR-B spectra were further degraded to R= 3000 to increase the Signal-to-Noise ratio.

The observations were analyzed in [6] by means of FASTWIND ([15, 13, 14]), an atmosphere code that calculates the emergent stellar spectrum in spherical geometry with mass-loss and NLTE conditions. Their results (see Tab. 1) confirmed that 2MASS J20395358+4222505 is a massive hot B-supergiant. It is very luminous, but not as extremely luminous as the first estimations (its luminosity is "only" $\log L/L_\odot$= 5.71±0.04, if the adopted distance from [2] is correct).

The luminosity however is somewhat uncertain, and can be a bit lower or clearly higher. This uncertainty comes from the uncertainty in the distance. The projected position of the star in the sky lies not far from the core of the Cyg OB2 association, but actually a bit further out to the North-East. Extinction indicates that the star cannot be closer than 1.5 kpc, whereas the work by [12] makes very unprobable that the star is beyond 2.3 kpc from the Sun. The adopted distance (the distance to Cyg OB2, as determined by [2]) lies in between and in addition the proper motion of 2MASS J20395358+4222505 is consistent with that of the stars in Cyg OB2. However, there is no direct evidence of its membership, and the Gaia parallaxes have a large error. Therefore, although probable, we cannot be completely sure that 2MASS J20395358+4222505 belongs to the Cyg OB2 association.

What makes 2MASS J20395358+4222505 a very interesting object to study in relation to its parameters is that it has a very large wind terminal velocity for its spectral type (see Tab. 1) combined with a large mass-loss rate (which by the way results in a spectacular H_α emission profile). This places the star between the normal B-supergiants and the hot hypergiants, from which only a handful are known in the Milky Way. Therefore, the star seems to be in a transition stage (see Fig. 1) whose study can shade new light on the structure of this kind of stars. But surprisingly, there were more findings that made 2MASS J20395358+4222505 even more interesting.

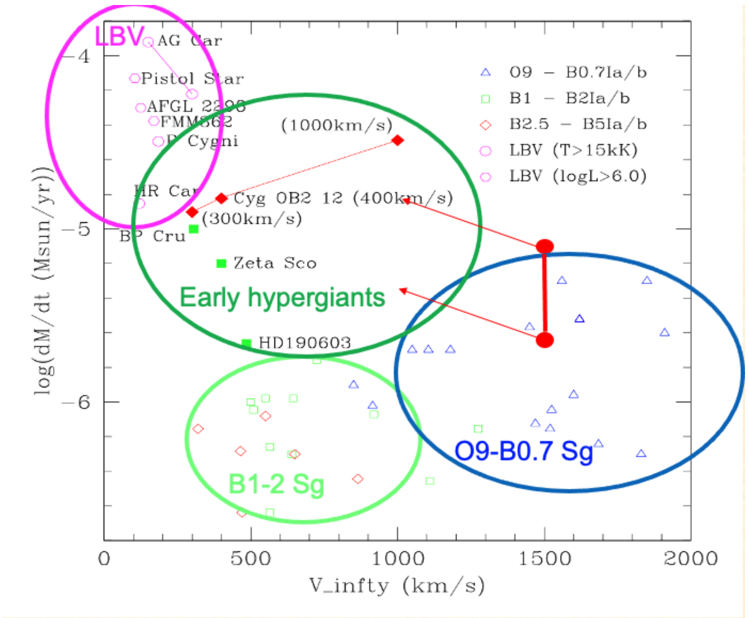

Figure 1: (adapted from [3]) Terminal wind velocity versus mass loss rate for different groups of massive hot stars. The two red points indicate the position of 2MASS J20395358+4222505 in this diagram (taking the distance uncertainty into account) whereas the two arrows indicate the direction in which the terminal velocity is expected to evolve (according to the $T_{\rm eff}$ vs. $(V_\infty/V_{\rm escape})$ diagram in [9] (see their Fig. 12)

.

3 Is 2MASS J20395358+4222505 a binary?

During the commissioning of the MEGARA spectrograph we took spectra with the LR-B, LR-U and HR-R gratings. But because of the needs of the commissioning tasks, these observations couldn't be taken consecutively. The observations with the LR-B grating were carried out on the night of August 29, 2017, whereas those with the LR-U and HR-R gratings were taken the night after, with some time difference. The surprise came when later inspecting the data: while the HR-R and LR-U observations gave radial velocities of -10 and +15 $\mathrm{km\,s^{-1}}$(with a large uncertainty of ± 20 $\mathrm{km\,s^{-1}}$), the spectrum taken the day before with the LR-B grating showed a radial velocity of 68 ± 23 $\mathrm{km\,s^{-1}}$. We can see those variations in Fig. 2. Interestingly, the lightcurve of 2MASS J20395358+4222505 obtained by the TESS satellite shows two small dips, separated by 13.25 days. Although at this stage the possible binarity of 2MASS J20395358+4222505 was still based on circumstancial evidence, it was a clear possibility.

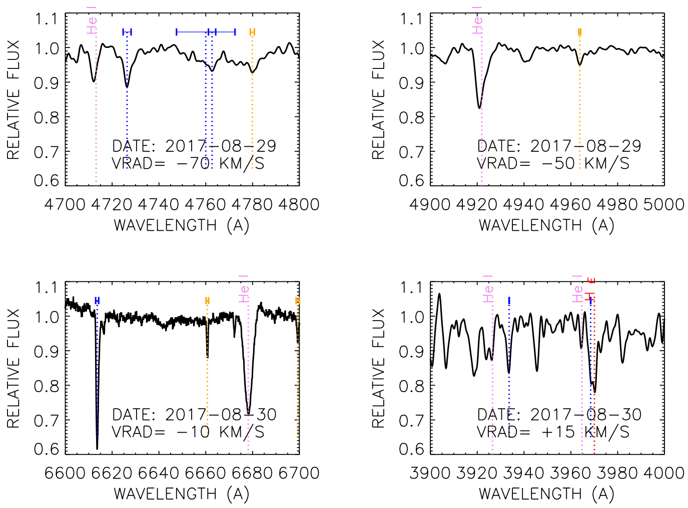

Figure 2: Radial velocity variations in the MEGARA observations of 2MASS J20395358+4222505. Top: observations with the LR-B grating on August 29, 2017; Bottom: observations with the HR-R (left) and LR-U (right) gratings. We have marked the stellar spectral lines and interstellar features (bars indicate their widths; orange features are usually weaker than blue ones)

4 The nature of the binary 2MASS J20395358+4222505

We have obtained new observations of 2MASS J20395358+4222505, but now with more spectrographs: MEGARA@GTC, FIES@NOT and CARMENES@3.6m. Fig. 3 shows three spectra obtained in different nights, where we can easily see the radial velocity variations spanning nearly 200 $\mathrm{km\,s^{-1}}$.

In addition to the three spectra shown in Fig. 3 we have 12 additional spectra taken at different nights from which we can determine the radial velocity. We have used those spectra to estimate a possible period and velocity amplitude from the radial velocity curve using the rvfit procedure in idl (see [7]). We obtained a best-fitting period of 12.4 days and a value of the semi-amplitude of the radial velocity curve of 95 $\mathrm{km\,s^{-1}}$. Thus we confirm that 2MASS J20395358+4222505 is a binary, whose present primary is a massive early B-supergiant orbiting at high velocity around the center of mass of the system.

The confirmation of the binarity of 2MASS J20395358+4222505 is the most important

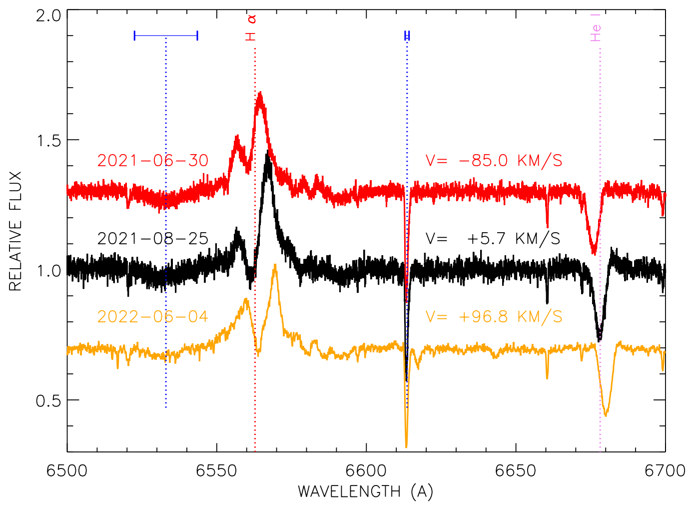

Figure 3: Spectra of the H_α region obtained in three different nights with CARMENES@3.6m (upper two spectra) and MEGARA@GTC (bottom spectrum). We have marked the H_α and HeI 6678 lines, as well as the interstellar line at 6613.62 Å and the interstellar band centered at 6533 Å

.

firm result of the present work. However, with due caution, we can especulate about the nature of the companion. From the radial velocity curve, and assuming an spherical orbit, an inclination of the orbital plane of 90 degrees, a period of 13 days (intermediate between the dips separation in the TESS lightcurve and that obtained with rvfit) and a semiamplitude of the radial velocity curve of 100 $\mathrm{km\,s^{-1}}$, we obtain a mass function of 1.35 $M_\odot$, implying a secondary mass of $\sim$18 $M_\odot$.

What could be the nature of such a companion? If still in the main sequence, it should be an O9V star with $T_{\rm eff}\sim$ 33 000 K, and an absolute visual magnitude of $M_v \sim -4.0$. That would imply a difference of $\Delta m\sim$ 3.3 mag. with the primary. Simulations indicate that we should see such a star in high quality spectra, like those presented in Fig. 3. If correct, that would imply that the companion should be a compact object and, with the estimated mass, a massive stellar black hole. However, there are several problems with this interpretation: (a) the O9V star could be hidden in the spectrum due to a large rotational velocity (if the orbital and rotational velocities are synchronized, the secondary should rotate at about 250 $\mathrm{km\,s^{-1}}$); and (b) we see neither X-rays nor ellipsoidal variations in the light curve, which would be expected in a system with a supergiant filling its Roche lobe (as the parameters of the system indicate) close to a black hole.

Therefore we conclude that the binary nature of 2MASS J20395358+4222505 has been confirmed. But the nature of the companion, key to characterize the system and its past and future evolution, is still open.

References

[1] Berlanas, S.R., Herrero, A., Comerón, F. et al., 2018, A&A, 612, A50

[2] Berlanas, S.R., Wright, N., Herrero, A., et al., 2019, MNRAS, 484, 18

[3] Clark, J.S., Najarro, F., Negueruela, I. et al., 2012, A&A, 541, A145

[4] Comerón, F., & Pasquali, A. 2012, A&A, 543, A101

[5] Gil de Paz, A., Carrasco, E., Gallego, J., et al., 2018, Proc. SPIE, 10702, p.1070217

[6] Herrero, A., Berlanas, S.R., Gil de Paz, A. et al., 2022, MNRAS, 511, 3113

[7] Iglesias-Marzoa, R., López-Morales, M., Arévalo Morales, M.J., 2015, PASP, 127, 567

[8] Maíz Apellániz, J., Evans, C.J., Barbá, R.H. et al., 2014, A&A, 564, A63

[9] Markova, N. & Puls, J. 2008, A&A478, 823

[10] Massey, P. & Thomson, A.B. 1991, AJ 101, 1048

[11] Münch, L. & Morgan, W. W., 1953, ApJ, 118, 161

[12] Pantaleoni González, M., Maíz Apellániz, J., Barbá, R.H. & Reed, B.C., 2021, MNRAS, 504, 2968

[13] Puls J., Urbaneja M. A., Venero R., Repolust T., Springmann U., Jokuthy A., Mokiem M. R., 2005, A&A, 435, 669

[14] Rivero-González, J.G., Puls, J. & Najarro, F., 2011, A&A, 536, A58

[15] Santolaya-Rey, A.E., Puls, J., Herrero, A., 1997, A&A, 323, 488

[16] Schulte, D.H., 1958, ApJ, 128, 41

[17] Zacharias, N., Monet, D.G., Levine, S.E. et al. , 2004, AAS 205, 4815