High-mass X-ray Binaries: Illuminating the Passage
from Massive Binaries to Merging Compact Objects
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IGR J16318-4848: optical and near-infrared spectroscopy of the most absorbed B[e] supergiant X-ray binary with VLT/X-Shooter†

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Abstract. The supergiant high-mass X-ray binary IGR J16318-4848 was detected by *INTEGRAL* in 2003 and distinguishes itself by its high intrinsic absorption and B[e] phenomenon. It is the perfect candidate to study both binary interaction and the environment of supergiant B[e] stars. We report on VLT/X-Shooter observations from July 2012 in both optical and near-infrared, which provide unprecedented wide-range, well-resolved spectra of IGR J16318-4848 from 0.5 to 2.5 μm. Adding VLT/VISIR and Herschel data, the spectral energy distribution fitting allows us to further constrain the contribution of each emission region (central star, irradiated rim, dusty disc). We derive geometrical parameters using the numerous emitting and absorbing elements in each different sites in the binary. Various line shapes are detected, such as P-Cygni profiles and flat-topped lines, which are the signature of outflowing material. Preliminary results confirm the edge-on line of sight and the equatorial configuration of expanding material, along with the detection of a potentially very collimated polar outflow. These are evidence that the extreme environment of IGR J16318-4848 is ideal to have a better grasp of highly obscured high-mass X-ray binaries.

Keywords. infrared: stars - optical: stars, X-rays: binaries, X-rays: IGR J16318-4848, stars: binaries: general

1. Introduction

Since 2002, *INTEGRAL* (INTErnational Gamma-Ray Astrophysics Laboratory) has been observing the sky looking for gamma-ray sources of various nature. On top of significantly increasing the number of known X-ray binaries, *INTEGRAL* was able to discover a new type of highly obscured supergiant high-mass X-ray binaries (sgHMXB), as reviewed in Walter *et al.* (2015). These peculiar binaries host either a neutron star (NS) or a black hole (BH) in orbit around an early type supergiant star. Depending on the configuration of the binary, the compact object can be fed through the intense stellar wind of its giant companion, or by Roche Lobe overflow. The study of such extreme objects is crucial for understanding both the environment of supergiant stars and the products of binary interaction.

IGR J16318-4848 is the first source detected by *INTEGRAL*, and is the most absorbed sgHMXB known to this day. Discovered on January 29, 2003 (Courvoisier *et al.* 2003)

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†Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under program ID 089.D-0056(A).

with *INTEGRAL/IBIS* in the 15–40 keV band, the X-ray column density is so high ($N_H \simeq 2 \times 10^{24}\,\mathrm{cm}^{-2}$, Matt & Guainazzi 2003, Walter *et al.* 2003) that it becomes nearly invisible below 2 keV. It is known to be a galactic persistent X-ray source with recurrent outbursts that last up to ∼20 days.

Filliatre & Chaty (2004) use optical and nIR spectra to derive an absorption of A_V=17.4, which is far greater than the neighbouring value of 11.4, while still a hundred times lower than in X-rays. This leads the authors to suggest a concentration of X-ray absorbing material local to the compact object, and the presence of a shell around the whole binary absorbing optical/nIR wavelengths. The nIR spectrum in Filliatre & Chaty (2004) shows many prominent emission features in the same way CI Cam does, the first HMXB to be detected with an sgB[e] companion. P-Cygni profiles and forbidden [FeII] lines, also present in the nIR spectrum, are the evidence of a complex and rich environment, local to the binary.

Later, Kaplan *et al.* (2006) use photometry to show evidence of mid-infrared excess in IGR J16318-4848. The authors find that a ∼1000 K blackbody can be fit to the mid-IR excess in the spectral energy distribution (SED) and they associate it to the presence of warm dust around the central star. Moon *et al.* (2007) provide *Spitzer* spectra from 5 to 40 μm that reveal a rich environment composed of an ionised stellar wind, a lower density region giving birth to forbidden lines, a photodissociated region and a two-component circumstellar dust ($T > 700$ K and $T \sim 180$ K). Rahoui *et al.* (2008) performed photometry on IGR J16318-4848 with VISIR and reach a similar conclusion, i.e. that warm circumstellar dust is responsible for the MIR excess. However, Ibarra *et al.* (2007) suggests that the column density is inhomogeneous and that the circumstellar matter could very well be concentrated in the equatorial plane, seen almost edge-on, hence the very high N_H. The outflow might then be bimodal, with a fast polar wind and a slow, dense equatorial outflow. Chaty & Rahoui (2012) use VLT/VISIR mid-IR along with NTT/SofI and Spitzer spectra to fit the SED of IGR J16318-4848. They report the presence of an irradiated rim around the star at $T_{rim} = 3500$–5500 K and a warm dust component at $T_{dust} = 767$ K in the outer regions of the binary using models of Herbig AeBe stars, as the authors suggest that IGR J16318-4848 has circumstellar material analogous to this class of objects.

Jain *et al.* (2009) suggest a possible 80 d period based on *Swift*-BAT and *INTEGRAL* data. Recently, Iyer & Paul (2017) provide the results of a long-term observation campaign on IGR J16318-4848 with *Swift/BAT*. An orbital period of 80.09± 0.01 d is derived.

2. Observations

The observations of target IGR J16318-4848 and standard star HD145412 were performed in July 2012 (P. I. S. Chaty) at the European Southern Observatory (ESO, Chile) under program ID 089.D-0056(A). Spectra from 300 to 2480 nm were acquired on the 8-meter Very Large Telescope Unit 2 Cassegrain (VLT, UT2) on three different arms (UVB, VIS and NIR) of the X-Shooter instrument. Because of the high intrinsic absorption of the source, the UBV spectra yielded no signal and we only present VIS and NIR data.

Optical echelle spectra were obtained through a 0.7”×11” slit giving a spectral resolution of $R = 10640$ ($28\,\mathrm{km\,s}^{-1}$) over a spectral range of 533–1020 nm. Four exposures of 300 s were taken, for a total integration time of 1200 s. Near-infrared echelle spectra were obtained through a 0.6“×11” slit giving a spectral resolution of $R = 8040$ ($37\,\mathrm{km\,s}^{-1}$) over a spectral range of 994–2480 nm. Twenty exposures of 10 s were taken, for a total integration time of 200 s. All the acquisitions followed the standard ESO nodding pattern. The data reduction was performed with ESOReflex, using the dedicated X-Shooter pipeline. It consists of an automated echelle spectrum extraction along with standard bias, dark and sky subtraction along with airmass correction. Median stacking was used to add individual spectra in order to correct for cosmic rays. Telluric absorption features were corrected using Molecfit (Kausch *et al.* 2015, Smette *et al.* 2015), a software that fits atmospheric features using a radiation transfer code and various parameters from the local weather.

3. Spectral features analysis

3.1. *P-Cygni lines*

We extracted, normalized and combined each hydrogen lines of the spectrum into an average profile, which is characteristic of expanding material (P-Cygni, see Fig. 1). The difference in velocity between the emitting and absorbing regions is 265±4 km s^{-1}. The shape of the emission line is asymetric and we reckon that a careful modeling of the profile may provide further information about the emitting medium.

3.2. *Flat-topped lines*

[FeII] lines show a peculiar flat-topped profile (Fig. 2), which are supposed to arise from a low-density medium that undergoes a spherical expansion. The width of the line yields the terminal velocity of the corresponding outflow. We averaged every [FeII] line into a single profile, and fit it with a convolution of a Gaussian and a rectangle function. The half-width of the rectangle provides a terminal velocity of 262±3 km s^{-1}. The Gaussian half-width of 53±2 km s^{-1} may correspond to the orbital motion of the medium.

3.3. *Narrow lines*

The Hα line and its surroundings shows abnormally narrow emission lines (Fig 3) compared to the rest of the spectrum. In Fig. 3, the dashed line is the average HI P-Cygni profile, and it highlights the presence of another narrow component on top. Other similar lines from [OI], [NII] and [SII] are also present in this region of the spectrum. The widths of those narrow lines are up to 15 times smaller than the rest of the lines. Such lines are known to arise from the polar wind of T-Tauri stars as suggested in Edwards *et al.* (1987). We note that these lines are not resolved in our spectrum, so that we do not detect any peculiar profile aside from a single Gaussian.

4. Spectral energy distribution

The fit of the SED reveals that no stellar component is necessary to reproduce the data (Fig. 4). We thus suggest that the P-Cygni HI and HeI lines are emitted from the irradiated rim and absorbed further away in the disc in outflowing material at 265 km s^{-1}. Then their large width (HWHM=170 km s^{-1}) can be explained by the orbital velocity of the rim.

The narrow lines of Hα, [NII], [OI] and [SII] all point towards the presence of a fast polar wind. The fact that we neither detect significant broadening nor detect evidence of a double peaked profile suggests that the polar wind, and thus the whole system, is seen almost edge-on (i=90±2° for a fiducial wind velocity of 1 000 km s^{-1}). Moreover, their slight blueshift of -32±2 km s^{-1} should be indicative of the intrinsic velocity of the system. We found in Russeil (2003) that a star forming region (SFR) with the same velocity is present in the line of sight, located at 2.4±0.3 kpc. We suggest IGR J16318-4848 can be associated to this SFR and is thus located at 2.4±0.3 kpc.

While the expansion velocity derived from the flat-topped lines is consistent with the one of P-Cygni lines, they are likely coming from different regions: the iron lines may come from a spherical medium much further away than the rim where the hydrogen and helium lines form.

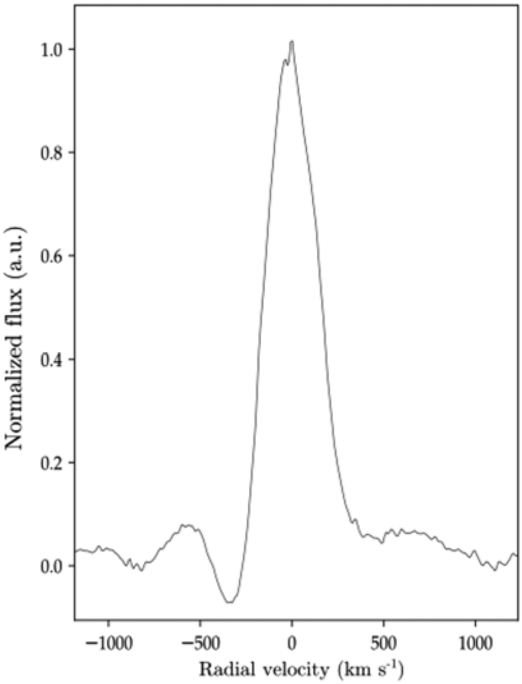

Figure 1. Average HI P-Cygni profile.

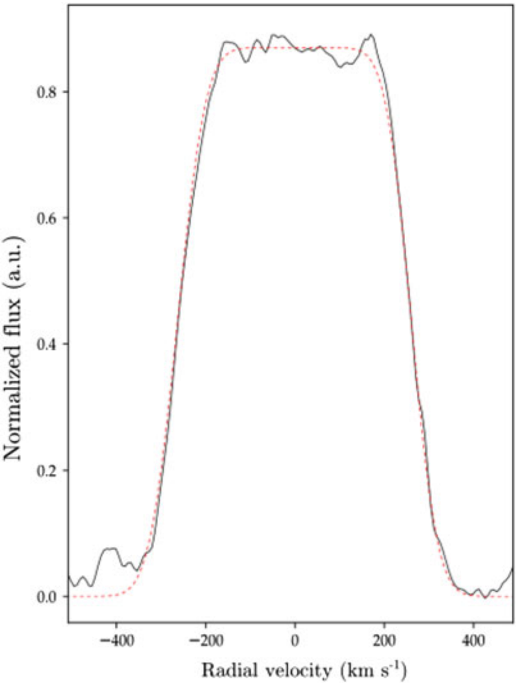

Figure 2. Average [FeII] flat-topped profile (*black*), fitted model (*red*).

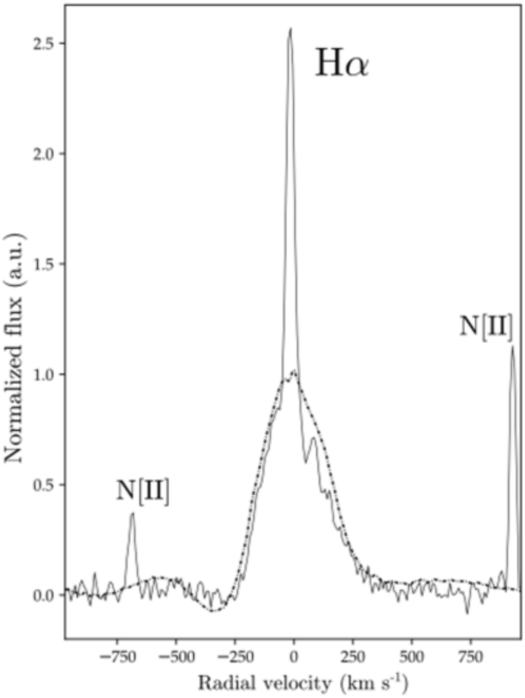

Figure 3. Hα region of the spectrum (*plain*), average P-Cygni profile (*dotted*).

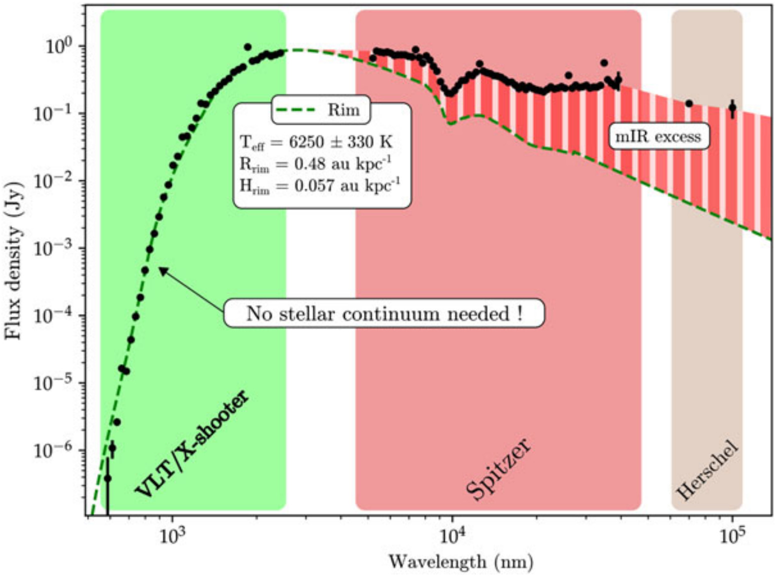

Figure 4. Spectral energy distribution of IGR J16318-4848.

5. Deductions from spectroscopy and SED fitting

From the polar wind lines, we derived an inclination of 90±2° and estimated the distance to IGR J16319-4848 to be 2.4±0.3 kpc. Using the orbital period from Iyer & Paul (2017), we fit the absolute irradiated rim scales: its radius is 1.15±0.2 au, and its half-height is 0.14±0.03 au. Since we neither detect any stellar feature nor need stellar

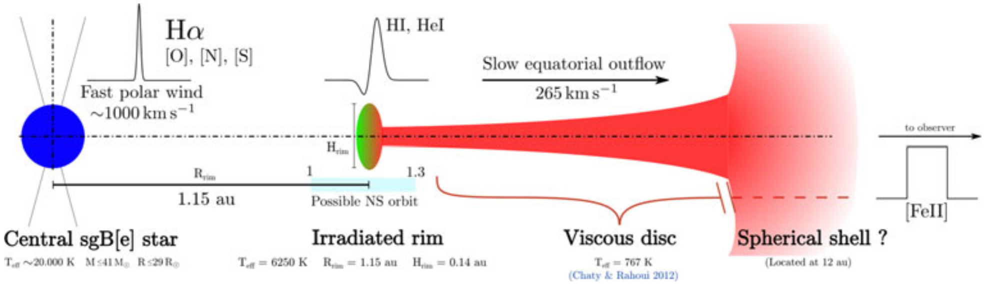

Figure 5. Schematics of IGR J16318-4848's geometry derived in this study (edge-on view).

continuum to fit the SED, we suggest that the rim might be obscuring the star from us. Given its size, this means the star cannot be bigger than $R_{sgBe} \leqslant 29\,R_{\odot}$. If we also assume that the rim is in keplerian orbit, the width of the emission lines in HI P-Cygni profiles provides us an orbital motion of $170\,km\,s^{-1}$ at 1.15 au, thus meaning that the mass of the central star should be $M_{sgBe} \leqslant 41\,M_{\odot}$. Finally, if we associate a keplerian velocity to the gaussian broadening of the [FeII] flat-topped iron lines, we find that the corresponding medium is located at $R=12^{+2}_{-4}$ au from the central star. All this information is compiled under a graphical representation of IGR J16318-4848 in Fig. 5.

6. Conclusion

We acquired a broadband medium resolution spectrum of IGR J16318-4848 with VLT/X-Shooter, and it revealed many lines with peculiar profiles. We detected an equatorial outflow of $265\,km\,s^{-1}$ from hydrogen and helium lines, which is likely correlated to the velocity measured on [FeII] flat-topped lines arising in the outer regions of the binary. We detected narrow lines from a polar wind, with no evidence of deviation from a perfect edge-on configuration. The flat-topped lines may indicate that on top of having a flat disc, IGR J16318-4848 might have an extra outer region undergoing spherical expansion. We reckon there is still much to discover about both the inner and outer parts of the binary, in particular the properties of the polar wind and the external region giving rise to flat-topped lines.

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