Classification of 3 accreting binaries with VLT/X-Shooter spectra
Tristan Bouchet, Sylvain Chaty, Francis Fortin, John A. Tomsick

To cite this version:
Tristan Bouchet, Sylvain Chaty, Francis Fortin, John A. Tomsick. Classification of 3 accreting binaries with VLT/X-Shooter spectra. Monthly Notices of the Royal Astronomical Society, 2022, 517 (2), pp.3034-3044. 10.1093/mnras/stac2819. hal-03826570

HAL Id: hal-03826570
https://hal.science/hal-03826570
Submitted on 31 Mar 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Classification of 3 accreting binaries with VLT/X-Shooter spectra

T. Bouchet, S. Chaty, F. Fortin and J. A. Tom sick

1Université Paris Cité, Université Paris-Saclay, CEA, CNRS, AIM, F-91191, Gif-sur-Yvette, France
2Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France

Accepted 2022 September 28. Received 2022 September 26; in original form 2022 January 20

ABSTRACT

Since its launch, the INTERnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite has discovered hundreds of X-ray sources, many of which lack proper classification. This mission also led to the discovery of new categories of high mass X-ray binaries (HMXB). We use the spectra of the X-Shooter instrument at the Very Large Telescope (VLT) of the European Southern Observatory (ESO) to better understand the nature of 3 accreting binaries (IGR J10101−5654, IGR J11435−6109, and IGR J12489−6243) discovered by INTEGRAL. We mainly focused on the lines and continuum from the X-Shooter spectra. We used atlasses to constrain the nature of the sources and also complemented the spectra with measurements taken by Spitzer and the Wide-field Infrared Survey Explorer (WISE) in infrared, and parallaxes from Gaia for the distances. We determined the nature of each binary system: a BeHMXB system with a companion star of spectral type B0.5Ve with peculiar carbon emission for IGR J11010−5654 and IGR J11435−6109, and a CV system with an evolved K star (KOIV−K2IV) for IGR J12489−6243. We also estimated some geometrical parameters of the decretion disc and neutron star’s orbit in the case of IGR J11435−6109.

Key words: binaries; general – stars: fundamental parameters – X-rays: binaries.

1 INTRODUCTION

In the 1960s, the first X-ray sources of extra-solar origin have been detected and quickly identified as accreting binary systems (Giacconi et al. 1962). Afterwards, other surveys were done in the soft X-ray domain (<20 keV) to carry on the study of those sources (Uhuru in 1970, ROSAT in 1990, and ASCA in 1993). In the last two decades, more missions have been launched in various energy bands, for instance Chandra and XMM–Newton in soft X-ray, and INTEGRAL, which has provided hard X-ray images of the Galactic plane. This in turn led to the discoveries of many more X-ray sources and our understanding of those peculiar binaries has greatly improved since then (Kretschmar et al. 2019).

X-ray binaries are systems with a compact object accreting matter attracted from a companion star, which leads to the emission of high energy radiation mainly detected in the X-ray domain or above. Here, we report on the study of two types of accreting binaries: high mass X-ray binaries (HMXB), which consist of a high mass (M ≥ 10 M⊙) companion, generally an O- or B-type star, while the compact object is a black hole or neutron star; the other type consists of cataclysmic variables (CV), involving a low mass star (M ≤ 1 M⊙) with a white dwarf as the compact object.

Furthermore, we can distinguish 2 sub-categories of HMXB depending on the accretion process of the compact object. When the companion star is a main sequence Be, its fast rotation will shed matter around itself, forming a decretion disc; the compact object will then accrete matter periodically due to its eccentric orbit (Okazaki & Negueruela 2001; see also Martin & Franchini 2021 for aperiodic Type I outbursts). This process can sometimes be detected in the evolution of the X-ray spectrum, where the luminosity will be modulated by the rotation of the neutron star and its orbit around the Be star. The decretion disc will also be detectable in the spectrum at lower energy, in the near-infrared and optical domain, and will appear as emission lines with peculiar shapes that depend on the shape and inclination of the disc. This disc is also highly variable in time and contributes to the continuum, which significantly affects the brightness of the source. In the case of a supergiant companion, the compact object will accrete a fraction of the wind coming from the companion star (Chaty 2013; Chaty et al. 2018). These sources show very little variability in X-ray, NIR, or at optical wavelengths. When the star or the binary is surrounded by cold material, it can lead to the emission of forbidden lines, which can be detected near optical wavelength. It can sometimes be attributed to the stellar wind itself (Clark et al. 1999). The study of those binary systems has been of particular interest in the recent years with the novel observations of gravitational waves. Indeed, HMXB are a common stage in the life of high-mass binaries, and understanding this stage better can help to constrain parameters of latter stages that eventually lead to the merging of compact objects, or lack thereof (Abbott et al. 2016).

In CV, the accretion is done through Roche lobe overflow, meaning that the companion star will fill its Roche lobe and lose matter through the L1 Lagrange point. The white dwarf will then accrete matter through two different processes: with an accretion disc if the magnetosphere is weak, or through its poles if its magnetosphere is too strong for a disc to form around it, in this case, the system is called a polar. There also exists an in-between case where a disc can form outside the magnetosphere called an intermediate polar (Warner 2014).

In our case, the discoveries of the 3 X-ray sources were made with the INTEGRAL satellite observing between 20 and 10 MeV, but the high energy observations alone don’t allow us to understand the physical processes at play in detail, especially the nature of the companion star. Those sources were also previously studied at near-infrared wavelength but for each of these sources, some questions...
remain that we aim to answer: IGR J10101−5654 has an unclear presence of forbidden lines and double lines despite being identified as an sgB[e], IGR J11435−6109 has a similar spectrum to IGR J10101−5654, although it was found to be a BeHXMB, and IGR J12489−6243 has a surprising lack of molecular bands in the K band despite being identified as a CV system. This will be detailed in Section 3.

Hence, we need to study the spectra of those sources on a broader range of wavelength, which is possible with the X-Shooter instrument at the VLT in Chile. We aim to understand the nature of those sources using spectroscopy. We will first describe the observations made and how the data were reduced, and then make a detailed analysis of the spectra of each object.

2 OBSERVATIONS AND REDUCTION

2.1 Observations

The observations of the sources were carried out by the X-Shooter spectrograph at the VLT in February of 2019. This instrument has 3 different arms that can observe in the ultraviolet (UVB), optical, and near-infrared (NIR) domains, covering between 300 and 2480 nm. The observation of the 3 sources is summarized in Table 1, where we give observation times, exposure times, and airmass. For all 3 sources, the slit dimensions and spectral resolutions were 1.0 arcsec x 11 arcsec in the UVB (R = 5400), 0.9 arcsec x 11 arcsec in VIS (R = 8900) and 0.9 arcsec x 11 arcsec in NIR (R = 5600). Slit losses were accounted for with atmospheric dispersion compensators in UVB and VIS and by a tip-tilt mirror in NIR.

2.2 Spectra processing

The reduction of the data was done with the X-Shooter pipeline of the ESOREFLEX software. It combines the different spectral orders of the spectrum and takes into account the bias, dark, sky subtraction, and airmass correction. The wavelength calibration and normalization is done using calibration lamps (ThAr for VIS and UVB, Hg/Ar/Ne/Xe for NIR). The flux calibration uses standard star spectra taken at the same time (see Table 2).

Sky subtraction was done with the nodding procedure of the ESOREFLEX pipeline except for IGR J10101−5654, which had another source polluting the spectrum. Therefore, we had to subtract the sky emission manually which led to the UVB and some of the visible part of the spectrum to become negative since we could not totally get rid of the polluting star.

To correct for telluric absorption, we used the MOLECFLUX software (Smets et al. 2015; Kausch et al. 2015) which creates a transmission curve of the atmosphere using the theoretical molecular absorption and parameters depending on the local weather. Unfortunately the regions near two important lines at 2 μm could not be corrected; these regions correspond to CO2 absorption bands. The final spectra can be seen in Fig. 1.

We compared the photometric flux measured by the Gaia mission (at 504, 582, and 762 nm) and 2MASS (at 1240, 1650 nm) with the flux of our spectrum at the same wavelengths. IGR J11435−6109 and IGR J12489−6243 have compatible flux, while IGR J10101−5654 shows a discrepancy of around 50 per cent, which could be explained by the temporal variation of the emission, previously noticed in X-ray (Tomsick et al. 2008).

2.3 Complementary data

We also used observations from other missions to complete our analysis, in particular when modelling the continuum.

For near-infrared data above 2.4 μm, we used photometric measurements from the Spitzer and WISE missions, which give the magnitude of the sources in the L, M, N, and Q bands. For the distances, we relied on the last release available of the Gaia astrometric mission Gaia EDR3 (Gaia Collaboration et al. 2016, 2021). Distances for the sources were computed by Bailier-Jones et al.
Figure 1. Full X-Shooter spectra after reduction, some residual absorption features from the atmosphere are still visible.

Table 3. Complementary data for the 3 sources.

| Sources        | L band (mJy) | M band (mJy) | N band (mJy) | Q band (mJy) | Distance (kpc) | X-ray flux $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ | X-ray luminosity $10^{33}$ erg s$^{-1}$ |
|----------------|--------------|--------------|--------------|--------------|----------------|--------------------------------------------|----------------------------------------|
| IGR J10101−5654 | $31.1 \pm 0.6^a$ | $25.3 \pm 0.4^b$ | $8.2 \pm 0.3^c$ | $\varnothing$ | $4.5_{-1.2}^{+1.1}$ | $2.03_{-0.25}^{+0.35}$ | $4.9_{-1.9}^{+3.9}$ |
| IGR J11435−6109 | $13.3 \pm 0.3^a$ | $9.5 \pm 0.2^b$ | $3.3 \pm 0.2^c$ | $3.1 \pm 0.6^d$ | $7.9_{-1.2}^{+1.4}$ | $9.1_{-1.7}^{+4.8}$ | $67_{-18}^{+30}$ |
| IGR J12489−6243 | $0.63 \pm 0.03^e$ | $0.43 \pm 0.06^e$ | $\varnothing$ | $\varnothing$ | $2.6_{-0.5}^{+0.8}$ | $0.54_{-0.11}^{+0.25}$ | $0.42_{-0.08}^{+0.67}$ |

*a at 3.3526 µm, b at 4.6028 µm, c at 11.5608 µm, d at 22.0883 µm, e at 3.6 µm, f at 4.5 µm

This distance is uncertain due to the presence of the associated Gaia measurements.

X-ray corresponds to the integrated flux between 0.3 and 10 keV and are taken from Tomssick et al. (2008, 2012).

The corresponding luminosities were computed using the distances and X-ray fluxes.

Distances from Bailer-Jones et al. (2021)

3 ANALYSIS

After the spectra have been properly reduced and calibrated, we can start to analyse their two main attributes:

(i) the lines, which can tell us about the chemical composition of the stellar photosphere and the environment of the binary, as well as the type of environment (motion, presence of a disc of dust...)

(ii) the continuum, which corresponds to the spectral energy distribution (SED) that relates to the source(s) of luminosity in the binary system and the extinction induced by the material between us and the source. In our case, we extracted the continuum by making a logarithmic binning of the X-Shooter spectrum.

After identifying the lines in each spectrum, we fitted them with a Gaussian or Lorentzian profile when single peaked. Profiles where an absorption component is close to or lower than the local continuum were considered as a shell profile and fitted by a sum of an absorption and emission component (see Fig. 2). Otherwise double peaked profile were fitted by a sum of 2 emissions (see Fig. 3), in this case, the relevant parameters are the separation between the two peaks noted $\delta v_p$ and the ratio of intensity between the two peaks, noted $V/R$ (V, for Violet, being the intensity of the blueshifted peak and R for the redshifted peak). The $V/R$ ratio can give an indication on the asymmetry of the disc and can be particularly useful to follow the evolution of the shape of the disc through time when several spectra are available (Hanuschik et al. 1995). In our case, the uncertainty on this ratio is always higher than 50 percent so it is of limited interest.

As for the continuum, the fitting process was done using the least-square method with the LMFIT PYTHON library and the high sky absorption regions were removed. For all fits, we took the Gaia distances found previously.

3.1 Diffuse interstellar bands

An attempt was made to find a value for the reddening of the spectra $E(B-V)$ using the diffuse interstellar bands (DIBs). Those bands are absorption features that can be found in many spectra independently of the nature of the source observed: indeed their origin is the interstellar medium. Several authors found a linear correlation between their equivalent width and the reddening of the type $EQW = a E(B-V) + b$ with $a$ and $b$ parameters depending on

MNRAS 517, 3034–3044 (2022)
Figure 2. Example of a shell profile of a Helium line, the absorption component falls below the continuum and is usually thinner than the emission.

Figure 3. Example of a double-peaked profile of a Hydrogen line, the depression in the centre is due to the shape of disc and its inclination.

the DIB used (Groh, Damineli & Jablonski 2007; Cox et al. 2014; Krelowski et al. 2019).

We only observed those DIBs for the 2 Be sources, and only 4 different DIBs were used. We fitted them with Gaussians (see Fig. 4) and evaluated their equivalent width to deduce the reddening (see Table 4). For the 3 DIBs at 1179 and 1317 nm, the uncertainties are too high (≥40 per cent) to be of interest, but the DIB at 1078 nm has lower uncertainties. For IGR J11435—6109 in particular, the reddening found with the DIB at 1078 nm, \([E(B - V) = 1.7 \pm 0.4]\) is compatible with the value found with the dust extinction map of Schlafly & Finkbeiner (2011) \([E(B - V) = 1.8]\). The reddening found with the 862 nm DIB (2.3 ± 0.7) is also compatible within the error margins.

This information could be useful in the future when the reddening cannot be properly estimated by other means and DIBs are observed in the spectrum. In the rest of this paper we used other methods to find the reddening, namely a dust extinction map and the Balmer decrement in the case of IGR J12489—6243.

3.2 The 3 accreting binaries

3.2.1 IGR J10101—5654

This source was discovered in 2006 by Kuiper et al. (2006). Its counterpart was found at visible wavelength by Masetti et al. (2006),
the same year and identified as an HMXB. According to the authors, the equivalent width of the H α line hints towards a giant or subgiant companion star. Tomisic et al. (2008) also found a variability in the X-ray flux, which could mean an eccentric orbit for the compact object. A study of the infrared spectrum then identified the source as an sgB[e] HMXB because of the presence of forbidden emission line (Coleiro et al. 2013). They could also fit the continuum with a 20,000 K B star and a second spherical blackbody at 1016 K to take into account the circumstellar dust.

3.2.3 Our results

In our X-Shooter spectra, we found hydrogen lines in emission: they are single peaked profile for the Balmer series but double peaks for the Paschen and Brackett series in infrared. The double peaked lines are well adjusted by the sum of two Lorentzians, which would mean they originate from a disc. Some single-ionized and neutral metals are also seen as double peaks or as simple emission lines, and a single Fe II line was detected in absorption. The value of the fit parameters are summarized in Tables 5 and 6.

We do not find any P-Cygni profile that would originate from the wind of the supergiant. We also found a single He I line at 1083 nm which presents a shell profile (a broad emission line combined with an absorption line) with an FWHM of 140 ± 2 km s⁻¹. The shape is compatible with a high-inclination (i > 70°).

In our spectrum, we do not detect the two forbidden emission lines of Fe II found by Coleiro et al. (2013) although we do observe what could be another [Fe II] line at 1676.8 nm. The inconsistencies between the supposed forbidden lines could be explained by a high time-variability of the source, but this seems highly unlikely, especially when the signal-to-noise ratio is measured at only 2.5 for our line, and estimated at around 3 for the lines of Coleiro et al. (2013). We therefore decided to exclude this feature from our analysis.

We then compared the emission lines present in the H band with a stellar atlas for Be star (Chojnowski et al. 2015), in particular fig. 7 and A22 of their article, and find the most likely stellar type to be a B0.5Vnpe. The ‘p’ (for peculiar) refers to the presence of a strong double-peaked neutral carbon line at 1689 nm, whose

Table 5. Double peaked emission lines of IGR J10101—5654.

| Line     | \(\lambda_0\) nm | \(\delta\nu_p\) km s⁻¹ | V/R | \(\nu_{rad}\) km s⁻¹ |
|----------|-------------------|-------------------------|-----|----------------------|
| Paschen  | 854.53            | 285                     | 1.4 | −21                  |
|          | 859.83            | 279                     | 1.1 | −4                   |
|          | 866.502           | 253                     | 1.7 | −27                  |
|          | 875.04            | 287.3                   | 1.0 | −9                   |
|          | 886.28            | 298.0                   | 1.1 | −22                  |
|          | 1004.98           | 243.5                   | 1.0 | −17                  |
|          | 1093.81           | 230                     | 0.8 | −2                   |
|          | 1281.80           | 223.4                   | 1.0 | −5                   |
| Brackett | 1534.17           | 285.1                   | 1.0 | −11                  |
|          | 1543.89           | 282.5                   | 1.0 | 0                    |
|          | 1555.64           | 285.1                   | 1.0 | −5                   |
|          | 1570.06           | 289.4                   | 1.1 | −5                   |
|          | 1588.05           | 275.6                   | 0.9 | −3                   |
|          | 1610.93           | 277.7                   | 1.0 | −3                   |
|          | 1640.68           | 265.3                   | 0.9 | 2                    |
|          | 1680.65           | 259.7                   | 1.0 | −3                   |
|          | 2165.529          | 223.5                   | 1.2 | −7                   |

Notes. V/R is the ratio of intensities of the bluished peak over the redshifted peak.

Table 6. Simple lines of IGR J10101—5654.

| Line     | \(\lambda_0\) nm | FWHM Å | EQW Å | Flux erg s⁻¹ cm⁻² | \(\nu_{rad}\) km s⁻¹ |
|----------|-------------------|--------|--------|-------------------|----------------------|
| Fe I     | 906.0             | 1.4    | −1.4   | 1.5e−16           | 25                   |
| Fe II    | 917.59            | 1.29   | 0.1    | −4.1e−16          | 4                    |
| C I      | 1068.30           | 6.9    | −0.17  | 1.0e−15           | 11                   |
| C I      | 1069.12           | 5.3    | −0.15  | 8e−16             | −20                  |
| Fe I     | 1232.02           | 9.2    | −0.4   | 4.4e−16           | 57                   |
| N I      | 1246.16           | 18.6   | −1.3   | 1.7e−15           | −29                  |
| N I      | 1246.96           | 13.6   | −0.6   | 5.2e−16           | 45                   |
| Mg II    | 2137.4            | 14     | −0.31  | 7.0e−16           | 73                   |

Note. A negative value of EQW indicates an emission feature, and a positive value indicates an absorption feature.

et al. (2013). We therefore decided to exclude this feature from our analysis.

We then compared the emission lines present in the H band with a stellar atlas for Be star (Chojnowski et al. 2015), in particular fig. 7 and A22 of their article, and find the most likely stellar type to be a B0.5Vnpe. The ‘p’ (for peculiar) refers to the presence of a strong double-peaked neutral carbon line at 1689 nm, whose

Table 4. Reddening from the EQW of several DIBs. The last line, given for comparison, corresponds to the value found with a dust extinction map.

| Wavelength | IGR J11435—6109 |              | IGR J10101—5654 |              |
|------------|-----------------|--------------|-----------------|--------------|
|            | EQW             | \(E(B − V)\) | EQW             | \(E(B − V)\) |
| 862 nm     | 1079 ± 116 mÅ  | 2.3 ± 0.7    | 1045 ± 253 mÅ  | 2.4 ± 0.4    |
| 1078 nm    | 253 ± 27 mÅ    | 1.7 ± 0.4    | 376 ± 42 mÅ    | 2.5 ± 0.6    |
| 1179 nm    | 266 ± 35 mÅ    | 3.4 ± 1.6    | 507 ± 174 mÅ   | 6.8 ± 4.4    |
| 1317 nm    | 903 ± 145 mÅ   | 2.8 ± 1.0    | 1214 ± 341 mÅ  | 3.8 ± 1.8    |
| Schlafly & Finkbeiner (2011) | | 1.8 | | 4.4 |
origin is yet unknown. Some of this peculiar feature is hidden by the telluric absorption, but it is clearly observed for the next source (IGR J11435–6109). Because this feature is uncertain, another analysis was done using lines between 1040 and 1090 nm and another spectral atlas (Groh et al. 2007), in particular fig. 5 of their article, gives a spectral type closer to a B1IVe. In both cases, the companion star seems to be a B0–B1 near the main sequence, and nothing indicates that it could be a supergiant.

Because of the temporal variation of the source (as discussed in Section 2.2), we only fitted the X-Shooter data. Therefore, we only had enough information to use a simple reddened blackbody to fit the companion star at a fixed temperature of 28000 K (corresponding to a B0.5). We find an extinction $A_V$ of $14.7 \pm 0.2$ mag and taking into account the uncertainty on the distance, a stellar radius of $13.6 \pm 3.6$ $R_\odot$. This value should be taken with care since the distance deduced by Bailer-Jones et al. (2021) is not necessarily reliable, due to the low S/N ratio associated with the Gaia measurements.

When we add the WISE data points above 2.4 $\mu$m for comparison, we clearly see a strong infrared excess (see Fig. 5), which is likely due to circumstellar matter in the form of a disc. We were not able to model the continuum with a full disc model, but the radius found with our simple fit at least gives a maximal radius for the star of $13.6$ $R_\odot$. This radius, as an upper limit, is more compatible with a main-sequence star than a supergiant, whose radii are typically above $30$ $R_\odot$ for B stars (Cox 2000).

The extinction we found with our model contains both the contribution of the interstellar medium and the circumstellar matter. Riquelme, Torrejón & Negueruela (2012) show that there is a correlation between the equivalent width of the H\(\alpha\) line and the extinction from circumstellar matter. After normalizing the spectrum, we found an EQW of $W_{\text{pec}} = -9.7$ Å for H\(\alpha\), and assuming a type B0.5 V companion star, we removed the stellar contribution from the EQW to find $W_{\text{env}} = -12.7$ Å. Using the correlation given by Riquelme et al. (2012), we find the reddening induced by the envelope to be $E(B-V) = 0.14 \pm 0.04$ mag, meaning an extinction of $0.4 \pm 0.1$ mag. After correcting for the presence of the envelope, the extinction from the interstellar medium is then $A_V = 14.3 \pm 0.3$ mag.

We conclude that this HMXB is most likely a BeHMXB rather than a supergiant B[e], since:

(i) we do not detect any forbidden line feature
(ii) the lines are compatible with a main-sequence star in two different catalogues
(iii) the maximum stellar radius found with a continuum fitting (although this measure is uncertain) is too small for a typical supergiant
(iv) no P-Cygni profiles are seen

The discrepancy between flux measurements, both in X-ray (between Chandra and INTEGRAL) and in optical (between our observations and Gaia) also hints towards a temporal variability of the source which is not compatible with a wind-fed system.

The companion star is found to be a B0.5V with a radius of at most $13.6 \pm 3.6$ $R_\odot$.

3.2.4 IGR J11435–6109

3.2.5 Previous results

This source was discovered by Grebenev et al. (2004) in 2004. It was then found at lower energy by the Chandra satellite and classified as an HMXB (Tomsick et al. 2007). The authors also detected the counterpart at infrared and visible wavelength. A more thorough study was done by Coleiro et al. (2013) on the near-infrared spectrum,
Table 7. Double peaked emission lines of IGR J11435−6109.

| Line      | $\lambda_0$ | $\delta v_p$ | $V/R$ | $v_{rad}$ |
|-----------|--------------|--------------|-------|-----------|
| Balmer    | 656.27       | 339.9        | 1.2   | 25        |
| Paschen   | 850.24       | 296.1        | 1.2   | −75       |
|           | 854.53       | 285.8        | 1.2   | −37       |
|           | 859.83       | 326.2        | 1.1   | 12        |
|           | 875.04       | 286.6        | 0.8   | −4        |
|           | 886.28       | 328.1        | 1.5   | 15        |
|           | 901.53       | 341.0        | 1.4   | 10        |
| Brackett  | 1281.80      | 321.1        | 1.4   | 22        |
|           | 1519.18      | 317.3        | 1.3   | 14        |
|           | 1526.05      | 353.9        | 1.9   | 32        |
|           | 1534.17      | 313.6        | 1.2   | 5         |
|           | 1543.89      | 315.3        | 1.3   | 13        |
|           | 1555.64      | 317.0        | 1.4   | 8         |
|           | 1588.054     | 311.2        | 1.28  | 6         |
|           | 1610.93      | 315.0        | 1.4   | 2         |
|           | 1640.68      | 303.0        | 1.5   | 10        |
|           | 1680.65      | 318.0        | 1.5   | 7         |

Note. $V/R$ is the ratio of intensities of the bluish peak over the redshifted peak.

and they classified the source as a BeHMXB with a companion star of type B0.5Ve, using the intensity ratio of He I at 2.05 μm and H I at 2.16 μm. The continuum was fitted in the same way as IGR J10101−5654, with a second blackbody at 925 K.

3.2.6 Results

We detect all the hydrogen lines in double peak emission (see Table 7), except H β which is in shell profile. Helium is only found in its atomic form, either as simple absorption lines or as shell profiles. The fits of the shell profile lines are summarized in Table 8 and indicates a high inclination for the system. The remaining fits for simple lines of the various metals found are summarized in Table 9.

As for the previous source, we focused on the H band and used the atlas of (Chojnowski et al. 2015) which gave us a spectral type of B0.5Vnep. This is confirmed by the fact that He I is seen in absorption at 587 and 667 nm and no He II lines are detected, typical of early B stars (Leone & Lanzafame 1997).

The fitting of the SED (see Fig. 6) is done with an isotropic blackbody representing the companion star and kept at a temperature of 28 000 K, to which we added a disc around the star, with a flux of

Table 8. Shell profile lines of IGR J11435−6109.

| Line | $\lambda_0$ | FWHM | Amplitude | $v_{rad}$ |
|------|--------------|------|-----------|-----------|
| H β | 486.13       | 257  | 0.2       | 7         |
| He I| 706.51       | 200  | 0.2       | 68        |
| He I| 1083.03      | 258  | 5.2       | 11        |
| He I| 1700.24      | 235  | 1.5       | 15        |

Note. The amplitudes are given in arbitrary units to compare the emission and absorption features.

Table 9. Simple lines of IGR J11435−6109.

| Line | $\lambda_0$ | FWHM | EQW | Flux | $v_{rad}$ |
|------|--------------|------|-----|------|-----------|
| He I | 587.56       | 2.1  | 0.65 | −5.5e | 14        |
| He I | 667.81       | 2.7  | 0.44 | −4.7e | 27        |
| Fe I | 890.59       | 2.6  | −0.05| 9e    | 17        |
| C I  | 1066         | 11   | −0.99| 1.7e  | 48        |
| N I  | 1246.12      | 15   | −0.09| 2.3e  | −110      |
| N I  | 1246.96      | 23   | −0.20| 2.1e  | 25        |
| Mg I | 1574.07      | Ø    | <0   | >0    | Ø         |
| Mg II| 1678.1       | Ø    | <0   | >0    | Ø         |
| Fe I | 1696.9       | 7.8  | −0.36| 3.7e  | −75       |
| Fe I | 2204.28      | 3.22 | −0.22| 1.47e | 6         |

Note. A negative value of EQW indicates an emission feature and a positive value an absorption feature.

the form:

$$F_e = \int_{R_{min}}^{R_{max}} B_i(T_d(R)) \frac{2 \pi R \cos i}{D^2} dR$$

where $B_i$ is the Planck function, $R$ the distance from the centre of the disc, $D$ the distance to the source, and $T_d(R)$ the temperature inside the thin disc, which depends on the radius as

$$T_d(r) = K T_{max} r^{-\frac{2}{3}} \left(1 - r^{-1}\right)^{-\frac{1}{2}}$$

where $K \approx 2.04, r = \frac{R}{R_{max}}$, and $T_{max}$ the maximum temperature inside the disk (Warner 2014).

This disc adds 3 parameters to the model related to the maximum temperature, the internal, and the external radius. The two dimensions of the disc are highly correlated, so they could not be constrained. We found a maximum disc temperature of 2070 ± 650 K, an extinction $A_V = 5.8 ± 0.3$ mag, and taking into account the distance uncertainty, we find a stellar radius between 7.3 and 11.7 $R_\odot$, typical of a main-sequence B0 star (Cox 2000).

For this source only, we also have access to the periods of the system. A period of 161.76 s which corresponds to the rotation of a neutron star (NS) was computed by in’t Zand & Heise (2004) using a Fourier transform. A longer period of 52.46 ± 0.06 d corresponding to the orbital period of the NS was found by Corbet & Remillard (2005) who fitted a sine wave to the light curve. Note that the variation of luminosity during the orbit is due to its eccentricity. Using a mass-luminosity relation of the type $L \propto M^{2/3}$ (Cassisi 2005), we can estimate a mass of $M = 15.5 ± 1.2 M_\odot$ (typical of an early B star). Along with the period and Kepler’s 3rd law, this mass gives an orbital separation of $a = 151 ± 3 R_\odot = 0.70 ± 0.01 AU$, where the NS mass is estimated around $1.4 ± 0.1 M_\odot$ (Kiziltan et al. 2013). From Corbet & Remillard (2005) and from the observation date of the X-Shooter spectrum, we also found the orbital phase $\phi_{obs} =$
0.072 ± 0.001, meaning that the spectrum was taken at peak X-ray luminosity, when the NS was interacting with the decretion disc of the Be.

Furthermore, we can estimate at which distance from the centre of the star each line is emitted. From our fits of the double peaked lines, we have $v_{a\sin i} = \delta v_p/2$ (where $v_d$ is the speed of the emission zone in the disc) and Kepler’s 3rd law can be rewritten as $R_d = \frac{GM}{v_d^2}$, assuming that the emission comes from a thin disc in Keplerian motion. Unfortunately, the inclination of the decretion disc is not known, so we can only estimate the maximal radius of emission:

$$R_{d,\text{max}} = \frac{GM}{v_d\sin i}.$$ 

We took the average value of $\delta v_p$ for each hydrogen series and computed the corresponding value of $R_{d,\text{max}}$. All the values were compatible with one another, so we took the overall average from all the hydrogen lines and found $R_{d,\text{max}} = 116 \pm 12 R_\odot = 0.53 \pm 0.05$ AU. This radius is smaller than the orbital separation by 25 per cent, which means that the NS can only interact with this portion of the disc when it comes close enough along its eccentric orbit.

In conclusion, this source is confirmed to be a BeHMXB with a companion star of type B0.5Ve. The compact object (NS) has an eccentric orbit that extends outside the hydrogen-emitting zone of the decretion disc.

### 3.2.7 IGR J12489—6243

### 3.2.8 Previous results

This source was discovered by Bird et al. (2009). Afterwards, 2 sources detected by *Chandra* were candidates as a possible counterpart, since the location given by *INTEGRAL* is not precise enough (Tommsick et al. 2012). The authors finally chose the source with the hardest X-ray emission as the true counterpart and concluded it was either a CV or an HMXB. A study by Fortin et al. (2018) was also done in infrared and the source was found to be a CV with K or M companion star, despite the lack of molecular absorption in the spectrum. They explained this peculiarity by saying that the white dwarf accreted a portion of the atmosphere of the low-mass star. The molecules that can usually be seen in the atmosphere of those stars have hence been depleted in large enough quantities so that they do not appear on the spectrum.

#### 3.2.9 Our results

Our X-Shooter spectrum is characterized by the presence of hydrogen lines in emission as well as 8 He I lines, which indicates a relatively helium-rich environment (see Table 10). We also found numerous neutral metal lines in absorption, which hints towards a low-mass star (see Table 11), but none of the CO absorption bands in the region 2.2–2.5 µm are detected in the spectrum, which could have been used to constrain the luminosity class by comparing their strength to other metallic lines. Instead, we focused on 3 absorption lines of Mg I and Al I in the H band and used their equivalent widths to determine the spectral type. According to Meyer et al. (1998), those lines are compatible with a subgiant between K0IV and K2IV.

We then tried to confirm this finding by fitting the continuum with a single blackbody. Unlike the 2 previous sources, the temperature of the star is not well constrained, so we made it a free parameter of the model. Unfortunately, during the fitting process, the interstellar absorption parameter is correlated to the temperature, so we had to keep $\lambda_V$ and $E(B - V)$ as fixed parameters. The reddening given by the dust reddening map of Schlafly & Finkbeiner (2011) is $E(B - V) = 12.8$, which seemed too high for a relatively nearby source (distance of 2.5 kpc). When applied to the spectrum, this reddening was also found to be inaccurate, since no blackbody could fit the unreddened spectrum. Therefore, we instead decided to use a method based on the Balmer decrement. Indeed, the intensity ratio between the H $\alpha$
Table 10. Emission lines of IGR J12489–6243.

| Line | λ0 (nm) | FWHM (Å) | EQW (Å) | Flux (erg s⁻¹ cm⁻²) | vrad (km s⁻¹) |
|------|---------|-----------|---------|---------------------|--------------|
| Balmer | 486.13 | 7.4 | −13 | 6.7e−16 | 77 |
|       | 656.27 | 10.5 | −39 | 4.86e−15 | 24 |
| Paschen | 850.24 | 7.0 | −3.2 | 3.5e−16 | −183 |
|       | 854.53 | 17 | −14 | 1.4e−15 | −56 |
|       | 859.83 | 15 | −7.8 | 7.6e−16 | 18 |
|       | 866.50 | 17.3 | −20.0 | 1.74e−15 | −17 |
|       | 875.04 | 17.5 | −14.6 | 1.32e−15 | −2 |
|       | 886.28 | 16.1 | −16.8 | 1.50e−15 | 6 |
|       | 901.53 | 14.6 | −15.1 | 1.27e−15 | −8 |
|       | 922.97 | 18.5 | −21.6 | 2.07e−15 | −50 |
|       | 954.62 | 6.3 | −8.0 | 7.0e−16 | 80 |
|       | 1093.81 | 12.0 | −7.8 | 1.26e−15 | 44 |
|       | 1281.80 | 13.0 | −10.1 | 1.41e−15 | 56 |
| Brackett | 1610.93 | 27.5 | −7.1 | 5.0e−16 | 48 |
|       | 1640.68 | 25.3 | −9.8 | 6.46e−16 | 62 |
|       | 1680.65 | 25.0 | −10.1 | 6.67e−16 | 34 |
|       | 1736.00 | 25.8 | −15.3 | 8.59e−16 | 77 |
|       | 2166.11 | 17.2 | −21 | 6.40e−16 | −40 |
| He I | 667.81 | 5.8 | −3.9 | 4.158e−16 | 70 |
|       | 706.51 | 6.06 | −3.0 | 3.36e−16 | 85 |
|       | 728.13 | 3.1 | −1.8 | 1.0e−15 | 100 |
|       | 1083.03 | 16.5 | −23.9 | 3.78e−15 | 11 |
|       | 1279.05 | 20.0 | −5 | 6e−16 | 8 |
|       | 1700.24 | 13 | −2 | 1e−16 | 83 |
|       | 2058.69 | 24 | −24 | 6e−16 | −39 |
| Ca II | 849.80 | 5.1 | −2.0 | 2.7e−16 | −56 |
|       | 854.20 | 2.8 | −1.2 | 1.5e−16 | −60 |
|       | 866.21 | 1.5 | −0.3 | 4.3e−17 | −59 |

Table 11. Absorption lines of IGR J12489–6243.

| Line | λ0 (nm) | FWHM (Å) | EQW (Å) | Flux (erg s⁻¹ cm⁻²) | vrad (km s⁻¹) |
|------|---------|-----------|---------|---------------------|--------------|
| Fe II | 942.84 | 2.1 | 2.0 | −3.5e−16 | −41 |
| Si II | 1060.34 | 2.7 | 2.6 | −3.6e−16 | −12 |
| Mg II | 1182.81 | 2.5 | 0.6 | Ø | −129 |
| Mn II | 1290.00 | 1.8 | 0.4 | −5e−17 | 17 |
| Mg II | 1502.49 | 5 | 0.8 | −7e−17 | −107 |
| Al II | 1576.58 | 7.5 | 1.9 | −1.5e−16 | −64 |
| Mg II | 1671.89 | 6 | 0.8 | −5e−17 | −54 |
| Al II | 1675.00 | 5.5 | 1.4 | −9.3e−17 | −65 |
| Mg II | 1710.86 | 5 | 1.5 | −8e−17 | −92 |
| Na I | 2205.32 | 6 | 3 | −6e−17 | −41 |

and H β emission lines can be linked directly to the reddening (see appendix), and for a ratio of 8.64, we found a reddening of E(B − V) = 2.79, which was used for the final SED fitting (see Fig. 7).

After taking this fixed value of the reddening, the star temperature fitting the continuum is found to be 5046 ± 206 K, which is coherent with an early K star in the atlas of Meyer et al. (1998). Taking into account the uncertainty on the distance of the source, the radius is 4.4±1.8 R⊙ and the corresponding luminosity is 11.1±5 L⊙, which is compatible with an evolved star of type subgiant or giant (Cox 2000). This confirms that the companion star is of type K0IV–K2IV, but further investigations could be done to constrain the luminosity if the distance is known more precisely.

Moreover, on the fit in Fig. 7, we clearly see a growing discrepancy between the data and the blackbody emission when going towards higher energy, especially between 380 and 500 nm. This excess in flux in the UV could be explained by another source of light at higher energy that adds up to the flux of the blackbody. Such a source could be the accretion disc or the white dwarf of the CV system that emits some of its light in UV. This contamination from another blackbody, as well as the weakness of some molecular lines was also observed by Harrison, Osborne & Howell (2004) and Southworth et al. (2009). Unfortunately, the fitting process does not converge when we add more parameters so the origin of this discrepancy remains unclear.

We also note the presence of 3 Ca II lines in emission, that we had to disentangle from the nearby Paschen lines. This single-ionized metal is usually present in absorption in K–M star, but we find it here in emission, which means that this element is in the accretion disc of the compact object, indicating that it was stripped from the stellar atmosphere. This Calcium triplet is sometimes observed in CV and is a marker of the cool outer regions of the accretion disc, similarly to what is observed in AGNs (Persson 1988). This corroborates the explanation of Fortin et al. (2018) concerning the lack of molecular absorption in the spectra: both the molecules usually present in the star and the Ca II were stripped from the atmosphere.

We can then confirm that this source is a Helium-rich CV and we constrain the companion star to a K0–K2 subgiant with an atmosphere which has been stripped of molecules and other elements like Ca. The source cannot be a polar since we observe emission lines coming from a disc, the source is then an Intermediate Polar (IP). This is confirmed by the X-ray luminosity of 4 × 10³² erg s⁻¹, which is typical of a high-luminosity IP (Byckling et al. 2010).

3.3 Peculiar C I emission in the Be stars

In both Be studied, we observed a double-peaked emission of neutral carbon at 1689 nm, although it is uncertain for IGR J10101−5654. The lines can be seen in Fig. 8 along with the fits, and look similar in terms of width, amplitude, and shape. The C I line of IGR J10101−5654 is strongly affected by sky absorption but becomes clearly visible after a median filter is applied to smooth the spectrum near the line.

Chojnowski et al. (2015) observed this line in 18 to 26 percent of the 238 Be studied, and our two sources have quite similar spectrum overall, which is why it would not be too surprising to find this peculiar emission in both. Numerous neutral metals were observed in emission, notably other C I emission lines around 1068 nm, and Fe I emissions. The presence of Fe I was also found by Chojnowski et al. 2015, to be associated with the C I 1689 nm emission, in particular Fe I 1529 nm, which is indeed observed for IGR J11435−6109.

4 CONCLUSIONS

Thanks to the X-Shooter spectra, we were able to constrain the nature of 3 sources and find many relevant physical parameters concerning their close environment:

(i) IGR J10101−5654 was previously thought to be a supergiant Be[e] but our investigation showed no real evidence for this source to be one, in particular because of the lack of reliable detection of forbidden lines (S/N ∼ 2.5). Using a star atlas, we found the companion star to be compatible with a B0.5Ve with peculiar carbon emission, thus a BeHMXB system. The double-peaked lines also confirm the presence of a decretion disc. The flux variation in both X-ray and optical over time could hint towards a variability of the source.

(ii) IGR J11435−6109 has many similarities to IGR J10101−5654, with which it shares the same companion star atlas compatible with a B0.5Ve with the presence of double-peaked lines.
Figure 7. Fitting of the SED of IGR J12489–6243, the data points are from the X-Shooter spectrum.

Figure 8. C\textsc{i} double-peaked emission with fit, the spectrum of IGR J10101–5654 is smoothed around this feature because of local atmospheric features.

We could also estimate the orbital separation between the NS and the companion star, as well as the maximal extension of the zone of hydrogen emission in the decretion disc.

(iii) IGR J12489–6243 was confirmed to be a CV. The companion star was also constrained to be a subgiant K0IV–K2IV by using a stellar atlas in the H band and a fit of the SED of the spectra. We did not find any molecular bands in the spectra so this companion star seems to have been stripped from some of its photosphere. This is confirmed by the presence of Ca\textsc{ii} in emission, i.e. in the outer accretion disc, which also indicates that the source is an IP.

A further study of the sources could be done in the future, for instance by comparing spectra of the same source taken at different orbital time. In the case of Be stars, this could help us to understand how the shape of the decretion disc changes with time by following the evolution of the double peaks in the spectrum, in particular the ratio in intensity between the two peaks ($V/R$) and the inter-peak distance ($\delta v_p$) which were already measured here.

**ACKNOWLEDGEMENTS**

Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under program ID 0102.D-0918(A). SC is grateful to the Centre National d’Etudes Spatiales (CNES) for the funding of MINE (Multi-wavelength INTEGRAL Network). This work has made use of data from the European Space Agency.
(ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. JAT acknowledges partial support from the National Aeronautics and Space Administration (NASA) through Chandra Award Number GO9-20045X issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astronomical Observatory under NASA contract NAS8-03060.

DATA AVAILABILITY

The data underlying this article are available in the article.

REFERENCES

Abbott B. P. et al., 2016, Phys. Rev. Lett., 116, 061102
Bailey-Jones C. A. L., Rybicki J., Fousneau M., Demleitner M., Andrae R., 2021, AJ, 161, 147
Bird A. J. et al., 2009, ApJS, 186, 1
Byckling K., Mukai K., Thorstensen J. R., Osborne J. P., 2010, MNRAS, 408, 2298
Calzetti D., Kinney A. L., Storchi-Bergmann T., 1994, ApJ, 429, 582
Cassisi S., Maurizio S., 2005, Evolution of stars and stellar populations : 5.7
The mass - Luminosity relations
Chaty S., 2013, Adv. Space Res., 52, 2132
Chaty S., Fortin F., García F., Fogantini F., 2018, Proc. Int. Astron. Union, 14, 161
Chojnowski S. D. et al., 2015, AJ, 149, 7
Clark I. S., Steele I. A., Fender R. P., Coe M. J., 1999, A&A, 348, 888
Coleiro A., Chaty S., Heras J. A. Z., Rahoui F., Tomskij J. A., 2013, A&A, 560, A108
Corbet R. H. D., Remillard R., 2005, Astron. Telegram, 377, 1
Cox A. N., 2000, Allen’s astrophys. quant. Fourth edition, p. 389
Cox N. L. J., Cami J., Kaper L., Ehrenfreund P., Foing B. H., Ochsendorf B. B., van Hooff S. H. M., Salama F., 2014, A&A, 569, A117
Fortin F., Chaty S., Coleiro A., Tomskij J. A., Nitschelm C. H. R., 2018, A&A, 618, A150
Gaia Collaboration et al., 2016, A&A, 595, 23
Gaia Collaboration et al., 2021, A&A, 649, 20
Giacconi R., Gursky H., Paoloni F. R., Rossi B. B., 1962, Phys. Rev. Lett., 9, 439
Grebenev S. A., Uberini P., Chenevez J., Mowlavi N., Roques J. P., Gehrels N., Kuijkers E., 2004, Astron. Telegram, 350, 1
Groh J. H., Damineli A., Jablonski F., 2007, A&A, 465, 993
Hanuschek R., Hammel H., Dierle O., Sutorius E., 1995, A&A, 300, 163
Harrison T. E., Osborne H. L., Howell S. B., 2004, AJ, 127, 3493
Kausch W. et al., 2015, A&A, 576, A78
Kiziltan B., Kottas A., Yorocc M. D., Thorsett S. E., 2013, ApJ, 778, 66
Krelowski J., Galazutdinov G. A., Godunova V. G., Bondar A., 2019, Acta Astron., 69, 159
Kretschmar P. et al., 2019, New Astronomy Reviews, 86
Kuiper L., Keek S., Hermsen W., Jonker P. G., Steeghs D., 2006, Astron. Telegram, 684, 1
Leone F., Lanzafame A. C., 1997, A&A, 320, 893
Martin R. G., Franchini A., 2021, ApJ, 922, L37
Masetti N. et al., 2006, A&A, 459, 21
Meyer M. R., Edwards S., Hinkle K. H., Strom S. E., 1998, ApJ, 508, 397
Okazaki A. T., Negueruela I., 2001, A&A, 377, 161
Osterbrock D. E., 1989, Astrophys. gaseous nebulae and active galactic nuclei
Persson S. E., 1988, PASP, 100, 710
Riquelme M. S., Torrèn J. M., Negueruela I., 2012, A&A, 539, A114
Schlafly E. F., Finkbeiner D. P., 2011, ApJ, 737, 103
Seaton M. J., 1979, MNRAS, 187, 73
Smette A. et al., 2015, A&A, 576, A77
Southworth J., Hickman R. D. G., Marsh T. R., Rebassa-Mansergas A., Gänside B. T., Copperwheat C. M., Rodríguez-Gil P., 2009, A&A, 507, 929
Tomskij J. A., Chaty S., Rodriguez J., Walter R., Kaaret P., 2007, Astron. Telegram, 1231, 1
Tomskij J. A., Chaty S., Rodriguez J., Walter R., Kaaret P., 2008, ApJ, 685, 1143
Tomskij J. A., Bodaghee A., Chaty S., Rodriguez J., Rahoui F., Halpern J., Kaleci E., Arabaci M. Ö., 2012, ApJ, 754, 145
Warner B., 2014, Accretion on to white dwarfs. Cambridge Univ. Press, Cambridge, p. 89
in’t Zand J., Heise J., 2004, Astron. Telegram, 362, 1

APPENDIX A: BALMER DECREMENT

The observed intensity of a line at a wavelength $\lambda$ depends on the optical depth $\tau$, and its intensity without interstellar absorption $I_0$ as:

$$I = I_0 e^{-\tau_\lambda}$$

In the UV, Calzetti, Kinney & Storchi-Bergmann (1994) found that the optical depth is linked to the reddening $E(B-V)$ with the relation:

$$k_\lambda = \frac{1.086 \tau_\lambda}{E(B-V)}$$

where $k_\lambda = \frac{\tau_\lambda}{E(B-V)}$, and $A_\lambda$ is the extinction. We can replace the optical depth in the first relation to get:

$$I = I_0 \exp \left(-k_\lambda E(B-V) \right)$$

which can be re-written as $I = I_0 10^{-0.4 k_\lambda E(B-V)}$. The absorbed intensity of H$\alpha$ and H$\beta$ are known, we can then invert the last relation to find $E(B-V)$:

$$E(B-V) = \log \left( \frac{I_\alpha}{I_\beta} \right)$$

The relative intensity of the lines without absorption are known physical parameters: $\frac{I_\alpha}{I_\beta} = 2.86$ (Osterbrock 1989), moreover Seaton (1979) found $k_\alpha - k_\beta = -1.25$ for our Galaxy. This gives us a direct relation between the intensity of H$\alpha$ and H$\beta$, and the reddening:

$$E(B-V) = 2 \log \left( \frac{I_\alpha}{2.86 I_\beta} \right)$$

This paper has been typeset from a TeX/ΛΠarticle file prepared by the author.