High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Prospecting the wind structure of IGR J16320–4751 with XMM-*Newton* and *Swift*

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Abstract. The *INTEGRAL* satellite has revealed a previously hidden population of absorbed High Mass X-ray Binaries (HMXBs) hosting supergiant (SG) stars. Among them, IGR J16320–4751 is a classical system intrinsically obscured by its environment, with a column density of $\sim 10^{23}$ cm^{-2}, more than an order of magnitude higher than the interstellar absorption along the line of sight. It is composed of a neutron star (NS) rotating with a spin period of $\sim$1300 s, accreting matter from the stellar wind of an O8I SG, with an orbital period of $\sim$9 days. We analyzed all existing archival XMM-*Newton* and *Swift*/BAT observations of the obscured HMXB IGR J16320–4751 performing a detailed temporal and spectral analysis of the source along its orbit. Using a typical model for the supergiant wind profile, we simultaneously fitted the evolution of the hard X-ray emission and intrinsic column density along the full orbit of the NS around the SG, which allowed us to constrain physical and geometrical parameters of the binary system.

Keywords. X-ray: individual objects (IGR J16320–4751), stars: supergiants, stars: neutron, X-ray: binaries

1. IGR J16320–4751 as an obscured sgHMXB

For more than 15 years, the *INTEGRAL* mission has discovered several obscured low luminosity X-ray sources which are difficult to observe in the soft X-rays, below 3 keV. Follow-up observations with *Chandra* or *XMM-Newton* brought arc-second level astrometric accuracy allowing for subsequent optical/IR identification of their companions (Chaty *et al.* 2008; Coleiro *et al.* 2013). Many of these sources were found to be obscured high-mass X-ray binaries (HMXB) with early-type companion stars (see Chaty (2013), Walter *et al.* (2015) and Martínez-Núñez *et al.* (2017)). In some cases, even a periodicity could be detected in the hard X-rays, attributed to their orbital motions (Corbet 1986).

IGR J16320–4751 is one these highly absorbed binary systems. The source was discovered on Feb 1, 2003, with the *INTEGRAL* observatory showing a significant variability in the 15−40 keV energy range (Tomsick *et al.* 2003). Follow-up XMM-*Newton* observations on Mar 4, 2003 showed several flares without significant hardness variations (Rodriguez *et al.* 2003) and allowed Lutovinov *et al.* (2005) to identify a pulsation period of $P = 1309 \pm 40$ sec, confirming that the system is a HMXB with an accreting neutron star (NS). Later on, using a *Swift*/BAT light curve extending from Dec 21, 2004, to Sep 17, 2005 (Corbet *et al.* 2005), an orbital period of 8.96±0.01 days was also found. An infrared counterpart was identified by Chaty *et al.* (2008) and, in a recent study, Coleiro *et al.* (2013) performed NIR spectroscopy and classified the stellar component as an BN0.5 Ia supergiant (SG).

Table 1. XMM-*Newton* PN observations used along this work.

OBSID	Name	Start date [UTC]	End date [UTC]	Phase	Exp. [ks]	GTI [ks]	ER ["]
0128531101	1285	2003-03-04 20:58	2003-03-05 03:12	–	4.78	4.47	0
0201700301	2017	2004-08-19 13:28	2004-08-20 03:20	–	38.0	33.9	10
0556140101	101	2008-08-14 22:41	2008-08-15 01:12	0.408 ± 0.006	5.33	4.64	4
0556150201	201	2008-08-16 17:38	2008-08-16 19:52	0.606 ± 0.005	1.63	1.42	0
0556140301	301	2008-08-18 13:33	2008-08-18 15:31	0.809 ± 0.005	1.23	1.07	4
0556140401	401	2008-08-20 07:34	2008-08-20 10:41	0.006 ± 0.007	11.2	9.78	4
0556140501	501	2008-08-21 07:02	2008-08-21 07:39	0.109 ± 0.001	1.34	1.16	6
0556140601	601	2008-08-22 03:54	2008-08-22 07:20	0.212 ± 0.008	12.4	10.8	10
0556140701	701	2008-08-24 18:28	2008-08-24 20:59	0.500 ± 0.006	6.03	5.21	4
0556140801	801	2008-08-26 13:33	2008-08-26 16:13	0.700 ± 0.006	9.63	8.37	8
0556141001	1001	2008-09-17 01:25	2008-09-17 03:31	0.090 ± 0.005	4.33	3.77	0

Here we report a temporal and spectral study arising from an XMM-*Newton* and *Swift*/BAT monitoring of the source. In Sect. 2 we provide details about the observations and data analysis. On Sect. 3 we describe the our main results and on Sect. 4 we analyze them using a simple model for the supergiant wind binary modulation. Finally, on Sect. 5 we summarize our conclusions.

2. XMM-*Newton* and *Swift*/BAT monitoring

XMM-*Newton* observed IGR J16320–4751 twice in Mar 2003 and Aug 2004, and nine times between Aug 14 and Sep 17, 2008 (Zurita Heras *et al.* 2009). As the PN camera effective area is larger than the MOS CCDs, and the latter have long integration times, heavily affected by pile-up, we concentrate on the analysis of the PN data set. We reduced the XMM-*Newton* data using Science Analysis System (SAS) version 16.0.0. In order to exclude high-background periods we produced background light curves for events with energies above 10 keV and Good time intervals (GTI) were obtained. We found that eight of the eleven observations were affected by pile-up and we followed the standard procedures suggested by the XMM-*Newton* calibration team to determine the excision radii (ER) necessary to mitigate the pile-up effects in each of the observations. The set of observations with their corresponding dates, exposure times, GTIs and ERs are presented on Table 1. Shortened ObsIDs are shown in the "Name" column. Phases correspond to an orbital period of 8.99 days and a central epoch corresponding to the middle of the 0556140701 exposure (phase=0.5). We also used the full *Swift*/BAT data available up to September 26, 2017 of daily and orbital light curves to obtain a refined period of 8.99±0.01 days, consistent with Corbet *et al.* (2005) for the first year of BAT data.

3. Results

We extracted background-corrected light curves using the annular regions determined by the pile-up analysis with an outer radius of 35". Considering an average count rate of 3.56 cts s^{-1}, we chose a binning time of 20 s to analyze the X-ray variability and flaring activity of the source. Based on the spectral shape, we defined two bands (*soft:* 0.5–6.0 keV and *hard:* 6.0–12.0 keV energy ranges) and we generated *soft*, *hard*, and *soft/hard* or color ratio curves that we used to search for long-term variability, short flaring, and possible spectral changes of the source.

Our visual inspection of the light curves indicated high variability on several timescales but keeping the hardness ratio almost constant between flaring and non-flaring periods. In some of them a clear modulation can be seen on a timescale of ∼1300 s, as was first pointed out by Lutovinov *et al.* (2005), a period that was attributed to the spin of the NS in the system. In ObsID 0556140801, two short and bright flares were detected when the source increases its rate by a factor of ∼10 for ∼ 300 s, keeping a constant color ratio,

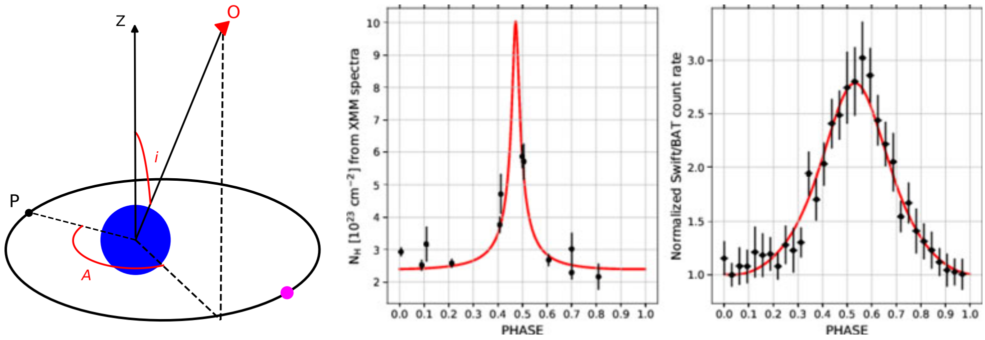

Figure 1. *Left panel:* Schematic view of our model. The NS describes an ellipse around the SG. Inclination, i, and azimuth, A, with respect to the orbital plane and the periastron, P, define the observer O. *Center and right panels:* N_H fitted to XMM-*Newton* spectra and normalized *Swift*/BAT count rate as a function of the orbital phase. Red lines represent our fitted model.

which points to a broadband flux increase and not to variations in the absorption. For subsequent spectral analysis, we separated the flaring intervals from the rest of the observation. In turn, two strong variations in hardness were detected in ObsIDs 0556140101 and 0556140701, which we thus splited into two A and B intervals for spectral analysis. In this case, the soft band is more affected and suggests a possible change in the absorption.

We extracted spectra under the same regions indicated above. We generated redistribution response matrices (RMF) and ancillary response files (ARF) using RMFGEN and ARFGEN tasks, respectively. The spectra were binned to 25 counts per bin and fitted with XSPEC v12.9.1 (Arnaud 1996) in the full 0.5–12.0 keV energy range. The spectra of IGR J16320–4751 are characterized by a highly-absorbed continuum at soft energies with a clear Fe-edge at ~7 keV as well as prominent Fe-Kα line. In the best-quality spectra also fainter Fe-Kβ and Fe XXV can be detected. We fitted the spectra with a thermally Comptonized COMPTT model and three narrow Gaussian lines. We used two TBABS absorption components to model the interstellar medium (ISM) and the intrinsic absorption. We fixed the hydrogen column density of the ISM absorption model to 2.1×10^{22} cm^{-2} as in Rodriguez *et al.* (2003) and we only fitted the second $N_{\rm H}$ column.

For the majority of the spectra, we obtained $N_{\rm H} \sim 20 - 30 \times 10^{22}$ cm^{-2}, compatible with previously reported values (Rodriguez *et al.* 2003). However, in Obs 101A, 101B, 701A, and 701B, we found significantly higher values of $N_{\rm H} \sim 35 - 60 \times 10^{22}$ cm^{-2} without noticing strong changes in the continuum emission parameters, which favours a geometrical effect over a local sudden change in the accretion process. Moreover, as previously noted in Giménez-García *et al.* (2015), we recover a correlation between the Fe Kα flux and the continuum level, which is expected for fluorescence emission from a small region of matter in the very close vicinity of the accreting NS. We also confirm a Baldwin effect given by the correlation between the X-ray flux and the Fe Kα EW.

4. A simple wind model for the orbital modulation

Using the whole set of observations, we found a clear modulation of $N_{\rm H}$ with the orbital phase (Fig. 1), and correlations with the flux of the Fe Kα line, suggesting a physical link between absorbing and fluorescent matter. These evidence points towards the stellar wind being the main contributor to both continuum absorption and Fe Kα line emission.

To better understand the orbital modulations found in the $N_{\rm H}$ and the BAT hard X-ray light curve we propose a simple model consisting of a NS orbiting embedded in the dense wind of a SG companion (Fig. 1). We model the SG wind profile by means of a typical CAK model (Castor *et al.* 1975) with $\dot{M} = 3 \times 10^{-6}$ M$_\odot$ yr^{-1}, $\beta = 0.85$ and

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$v_\infty = 1300$ km s^{-1}. In a close orbit, the NS accretes matter from this wind as it moves along its elliptical orbit, being able to produce a persistent X-ray emission exhibiting flux variability associated to the local density and to the integrated $N_{\rm H}$ column along the line of sight. We compute the $N_{\rm H}$, for each orbital phase (or time), integrating the wind density profile along the line of sight. We assume that the *Swift*/BAT count rate is proportional to the local wind density at the position of the accreting NS.

Under these assumptions, we simultaneously fitted the *Swift*/BAT folded light-curve and the $N_{\rm H}$ phase evolution obtaining an optimal solution given by $e = 0.20 \pm 0.01$, $A = 146.3^\circ\ ^{+3.7}_{-2.9}$ and $i = 62.1^\circ\ ^{+0.3}_{-1.5}$ (90% confidence intervals). Here, we note that e is mainly constrained by the BAT amplitude, i depends strongly on the $N_{\rm H}$ increase profile and the phase difference between the maxima of both modulations ($\sim$0.47 vs 0.53) arises as a consequence of the observer azimuth A.

5. Conclusions

Assuming a simple model for the supergiant stellar wind we were able to explain the orbital modulation of the absorption column density and the high-energy *Swift*/BAT flux of IGR J16320–4751. The model simultaneously reproduces both the sudden change in absorption column density, measured with XMM-*Newton*, and the smooth evolution of hard X-ray *Swift*/BAT lightcurve, as well as the phase shift of their maxima. Furthermore, given the correlations found for the Fe Kα line with the $N_{\rm H}$ column density and total continuum flux, we unambiguously show that the orbital modulation of this three physical quantities is driven by intrinsic absorption of matter surrounding the NS, modulated by the stellar wind density profile, as viewed by a distant observer.

Similar spectral evolution analysis sampled along the orbit of other obscured sgHMXB sources, both in the infrared and soft/hard X-ray bands, will be of high value to better constrain the physical and geometrical properties of the sgHMXB class.

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