**XMM–Newton and INTEGRAL study of the SFXT IGR J18483–0311 in quiescence: hint of a cyclotron emission feature?**

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**ABSTRACT**

We report the results from archival XMM–Newton and INTEGRAL observations of the Supergiant Fast X-ray Transient (SFXT) IGR J18483–0311 in quiescence. The 18–60 keV hard X-ray behaviour of the source is presented here for the first time; it is characterized by a spectral shape ($\Gamma \sim 2.5$) similar to that during outburst activity, and the lowest measured luminosity level is $\sim 10^{34}$ erg s$^{-1}$. The 0.5–10 keV luminosity state, measured by XMM–Newton during the apastron passage, is about one order of magnitude lower and it is reasonably fitted by an absorbed blackbody model yielding parameters consistent with previous measurements. In addition, we find evidence ($\sim 3.5\sigma$ significance) of an emission-like feature at $\sim 3.3$ keV in the quiescent 0.5–10 keV source spectrum. The absence of any known or found systematic effects, which could artificially introduce the observed feature, gives us confidence about its non-instrumental nature. We show that its physical explanation in terms of atomic emission line appears unlikely, and conversely we attempt to ascribe it to an electron cyclotron emission line which would imply a neutron star magnetic field of the order of $\sim 3 \times 10^{11}$ G. Importantly, such direct estimation is in very good agreement with that independently inferred by us in the framework of accretion from a spherically symmetric stellar wind. If firmly confirmed by future longer X-ray observations, this would be the first detection ever of a cyclotron feature in the X-ray spectrum of an SFXT, with important implications on theoretical models.

**Key words:** X-rays: binaries – X-rays: individual: IGR J18483–0311.

1 INTRODUCTION

IGR J18483–0311 is a hard X-ray transient discovered in outburst with INTEGRAL in 2003 (Chernyakova et al. 2003). Other hard X-ray outbursts were observed showing fluxes and durations up to $\sim 120$ mCrab (20–100 keV) and $\sim 2$ d, respectively (Sguera et al. 2007). The X-ray emission shows two periodicities: a longer one at $\sim 18.55$ d which is interpreted as orbital (Levine & Corbet 2006; Sguera et al. 2007) and a shorter one at $\sim 21.0526$ s which was discovered with the X-ray monitor JEM-X (Sguera et al. 2007). Giunta et al. (2009) performed a study of the quiescent soft X-ray behaviour of the source (0.5–10 keV) and confirmed the pulse period through XMM–Newton data, providing a measurement of the spin-period derivative which is very likely due to light-travel time effects in the binary system. A complete monitoring of the X-ray emission from IGR J18483–0311 over an entire orbital period has been performed in 2009 with Swift/X-ray Telescope (XRT) (Romano et al. 2009).

The optical counterpart has been identified with a B0.5Ia supergiant star located at a distance of 3–4 kpc (Rahoui & Chaty 2008). This, together with the transient nature of the source, implies its classification as a Supergiant Fast X-ray Transient (SFXT; Sguera et al. 2005, 2006; Negueruela et al. 2006; Sidoli 2009).

2 XMM–NEWTON OBSERVATION AND RESULTS

2.1 Data reduction

We analysed an archival XMM–Newton European Photo Imaging Camera (EPIC) observation of IGR J18483–0311 collected on 2006 October 12 for a total exposure of $\sim 19$ ks. However, after rejecting time intervals affected by high background the net good exposure time reduced to 14.4 ks. XMM–Newton data were reprocessed using version 9.0 of the Science Analysis Software (SAS). Known hot, or flickering, pixels and electronic noise were rejected using the SAS. The ancillary and response matrices were generated using the SAS tasks ARFGEN and RMFGEN. Spectra were selected from single and double events only (pattern from 0 to 4) for the EPIC-pn full-frame...
mode while for both MOS cameras patterns from 0 to 12 were selected. Source counts were extracted from circular regions of 40 arcsec radius centred on the source for both pn and MOS. Backgrounds counts were obtained from similar regions offset from the source position. The backgrounds do not show any evidence for flaring activity, so that the entire nominal exposure times were considered. The source net count rates (1–10 keV) are the following: 0.097 ± 0.003 counts s⁻¹ (pn), 0.035 ± 0.002 counts s⁻¹ (MOS1) and 0.027 ± 0.001 counts s⁻¹ (MOS2). The source is too faint for a meaningful spectral analysis with the Reflection Grating Spectrometer. Also the spectroscopy with the MOS cameras does not provide any improvement with respect to the analysis of the pn spectrum alone; thus in the following, we will concentrate only on the source EPIC-pn results. In order to ensure applicability of the χ² statistic, the extracted spectra were rebinned such that at least 20 counts per bin were present and the energy resolution was not oversampled by more than a factor of 3. The spectral analysis was performed using XSPEC version 12.5; all quoted uncertainties are given at the 90 per cent confidence level for one single parameter of interest.

### 2.2 EPIC-pn spectral analysis

We first fit the 0.5–10 keV EPIC-pn spectrum of IGR J18483–0311 with an absorbed power-law model whose best-fitting parameters ($N_\text{H} = 7.8^{+1.3}_{-1.1} \times 10^{22}$ cm⁻², $\Gamma = 2.4 \pm 0.3$) are in fair agreement with those already reported by Giunta et al. (2009). However, we note that such model gives a statistically inadequate representation of the observed spectrum being the χ² = 1.46 for 52 d.o.f. (see also Giunta et al. 2009 where χ² = 1.3 for 39 d.o.f.). This motivates us to investigate alternative spectral models. An absorbed thermal bremsstrahlung is still a bad statistical description of the data (χ² = 1.3, 52 d.o.f.), on the contrary an absorbed thermal blackbody results in a much better fit (χ² = 1.17, 52 d.o.f.) and yields parameters ($N_\text{H} = 3.4^{+0.6}_{-0.5} \times 10^{23}$ cm⁻², $kT = 1.35 \pm 0.08$ keV) consistent with previous measurements by Romano et al. (2009) from a Swift/XRT monitoring campaign covering an entire orbital period. The upper and middle panels in Fig. 1 show the absorbed blackbody fit spectrum and the ratio of data to model, respectively. It is worth noting that such spectral fit resulted in a radius of the emitting blackbody region equal to ~0.14 km, i.e. consistent with a small portion of the neutron star surface such as its polar-cap region. The unabsorbed (observed) 0.5–10 keV flux is $1.24 \times 10^{-12}$ erg cm⁻² s⁻¹ (9.1 $\times 10^{-13}$ erg cm⁻² s⁻¹) which translates into an X-ray luminosity of $1.3 \times 10^{33}$ erg s⁻¹ by assuming a distance of the optical counterpart of 3 kpc. If we follow Sguera et al. (2007) and measure the source phase from the epoch of the brightest outburst observed with INTEGRAL at MJD 53844.2 (phase 0) then the XMM–Newton observation took place at orbital phase 0.52 (i.e. right during the apastron passage), and the above X-ray luminosity value represents the lowest quiescent X-ray state of the source ever reported in the literature. For the sake of clarity, here and in the following, we refer to ‘quiescence’ as to the lowest detectable level of X-ray activity from the source (i.e. ~$10^{33}$ erg s⁻¹) during which it is still accreting matter even if outside its bright outbursts activity (i.e. ~$10^{39}$ erg s⁻¹).

#### 2.2.1 An emission-like feature at ~3.3 keV?

As stated in the previous section, the absorbed blackbody model is a reasonable statistical description of the continuum; however, the ratio of data to model clearly shows an excess around ~3.3 keV (see Fig. 1, middle panel), suggesting the presence of a possible spectral line. To model such residuals we added a Gaussian emission line with energy, width and normalization free to vary. We obtained a significant improvement of the statistical quality of the fit (χ² = 0.97, 49 d.o.f) corresponding to a significance level of confidence of 99.4 per cent according to a simple F-test (≈3σ significance). We are aware that the F-test is not a good measure of the actual significance of such additional spectral line feature (see Protassov et al. 2002); however, it could give an indication. To this aim, we point out that the obtained low F-test probability value should make the detection of the line stable against mistakes in the calculation of its significance. Furthermore, we note that there are in the literature a few cases of cyclotron features reported with an F-test probability value very similar to ours (e.g. Ibrahim et al. 2002; Rea et al. 2003).
accreting X-ray pulsars in high-mass X-ray binaries (HMXBs) for which much higher signal-to-noise ratio X-ray spectra are available. Therefore, we explored an alternative physical explanation in terms of cyclotron line. In fact, depending on the physical condition of the emitting/absorbing material in the accretion column, cyclotron features from electrons or protons could be observed in the X-ray spectra of accreting magnetized pulsars (Heindl et al. 2004). They provide an important tool for a direct measurement of the neutron star magnetic field value, since the observed fundamental energy is related to the magnetic field value by \( E_{\text{cycl}} = 11.6(B/10^{14}\text{G}) \) in the case of electrons or by \( E_{\text{cycl}} = 0.63(B/10^{14}\text{G}) \) in the case of protons. If interpreted as an electron cyclotron emission feature, the putative line observed at \( \sim 3.3 \) keV implies a magnetic field of \( \sim 2.8 \times 10^{11} \) G (if the forming region is situated far above the pulsar’s polar cap) or alternatively of \( \sim 3.7 \times 10^{11} \) G (if it is situated close to the neutron star surface, i.e. at the base of the accretion column, and so affected by a gravitational redshift of \( z = 0.3 \)). For proton cyclotron feature, the magnetic field should be even higher by a factor of \( \sim 1836 \) (the proton to electron mass ratio) implying a value of \( \sim 5 \times 10^{14} \) G (i.e. a magnetar-type magnetic field).

### 3 INTEGRAL OBSERVATIONS AND RESULTS

The quiescent behaviour of IGR J18483–0311 in the soft X-ray band (0.5–10 keV) is fairly known and studied (Romano et al. 2009; Giunta et al. 2009) while above 20 keV is totally unknown. With the aim of investigating for the first time the hard X-ray quiescent state of the source, we collected INTEGRAL data with Imager on Board the INTEGRAL Satellite (IBIS) (Ubertini et al. 2003). INTEGRAL observations are typically divided into short pointings called Science Windows (ScWs) each of \( \sim 2000 \) s duration. The data reduction was carried out with the release 7.0 of the Offline Scientific Analysis software.

First, we searched the entire IBIS/ISGRI public data archive for pointings where IGR J18483–0311 was within the fully coded field of view of ISGRI. Subsequently, since our aim was to measure the quiescent hard X-ray emission, we intentionally excluded those individual ScWs during which the source was in outburst, i.e. significantly detected at \( \sim 5 \sigma \). By doing so, we collected a total of 401 ScWs which were used to generate a mosaic significance map in the 18–60 keV band for a total exposure of \( \sim 795 \) ks. IGR J18483–0311 was weakly detected at \( \sim 7 \sigma \) level with an average flux (luminosity) of \( 1.5 \) mCrab \( (1.3 \times 10^{34} \text{ erg s}^{-1}) \), likely representing the lowest quiescent hard X-ray state of the source. The relative spectrum (18–60 keV) is equally well fit using a power law \( (\Gamma = 2.5 \pm 0.8, \chi^2 = 0.8, 15 \text{ d.o.f.}) \) or alternatively a blackbody model \( (kT = 7 \pm 2 \text{ keV}, \chi^2 = 0.8, 15 \text{ d.o.f.}) \): such spectral shape is similar to that seen during the outburst activity (Sguera et al. 2007).

A joint spectral fit to the XMM–Newton and IBIS/ISGRI quiescent data, although non-simultaneous, was also attempted. A multiplicative factor for each instrument was included in the fit to take into account the uncertainty in the cross calibration of the instruments. We used spectral models usually adopted to describe the X-ray emission from accreting pulsars. First, we found that the 0.5–60 keV broad band spectrum can be adequately described \( (\chi^2 = 0.95, 64 \text{ d.o.f.}) \) by a phenomenological model such as absorbed power law together with a blackbody at low energies, to describe the continuum, plus a Gaussian line in emission at 3.3 keV (we left all parameters free to vary except for the absorption \( N_H \) which was fixed to its nominal value previously found from the XMM–Newton spectral analysis). The best-fitting parameters are \( \Gamma = 2.0^{+0.5}_{-0.6}, kT = 1.40^{+0.06}_{-0.09} \) and \( E_c = 3.28 \pm 0.05 \). Subsequently,
we used a more physical thermal Comptonization model, namely the bulk motion Comptonization (BMC) (Titarchuk et al. 1997). The spectral parameters of such model are the blackbody temperature \( kT_{bb} \), the spectral index \( \alpha \) which is related to the Comptonization efficiency (when \( \alpha \) is smaller then the efficiency of energy transfer from the hot electrons to the soft seed photons is higher) and finally \( \log A \) (where \( A \) is the illuminating factor) which gives an indication of the fraction of the upscattered blackbody photons with respect to the blackbody seed photons directly visible. The BMC model reproduced rather well the data (\( \chi^2 = 0.93, 64 \text{ d.o.f.} \)) both at high and low energies where it was only modified by photoelectric absorption and a Gaussian line (see Fig. 3). The best-fitting parameters are \( kT_{bb} = 1.40 \pm 0.07 \text{ keV}, \alpha = 1.37 \pm 0.9 \) and \( \log A = -1.04_{-0.3}^{+0.4} \). We note that although the intercalibration of XMM–Newton and IBIS is expected to be around 1, \( 0.01 \leq \chi^2 \leq 1.04 \) (where \( \chi^2 = -1.04_{-0.3}^{+0.4} \)).

**Figure 3.** Broad-band spectrum (0.5–60 keV) of IGR J18483–0311 fitted with a BMC model modified at low energies by photoelectric absorption and a Gaussian line. The lower panel shows the residuals from the fit.

**4 ALTERNATIVE ESTIMATION OF THE NEUTRON STAR MAGNETIC FIELD**

As previously reported in Sections 2 and 3, IGR J18483–0311 has been detected in quiescence by XMM–Newton and IBIS with a luminosity in the range \( 10^{33}–10^{34} \) erg s\(^{-1} \) and spectral shape similar to that during outburst activity. Such information could be used within the framework of accretion from a spherically symmetric stellar wind to obtain an alternative and independent estimation of the magnetic field. In fact, the material in the background wind will be accreted on to the neutron star only if the magnetospheric radius \( R_M \) is less than the corotation radius \( R_{Q}(R_{Q} > R_{M}) \), otherwise centrifugal forces will expel the matter (Davidson & Ostriker 1973; Stella, White & Rosner 1986). We are aware that the above-assumed model and propeller effect are based on various and strongly simplified assumptions; however, this is still a reasonable approach to obtain a rough and reliable estimate for the magnetic field strength and the eccentricity. The magnetospheric radius is obtained by balancing the matter pressure to the magnetic field pressure, i.e. \( \rho v^2 = B(R_{NS})/8\pi \) where \( B(R_{NS}) = B_{NS} R_{NS}/R_{NS}^2 \) (\( R_{NS} \) is the radius of the neutron star, \( M_{NS} \) is the mass and \( B_{NS} \) is its surface magnetic field). Although the measured \( M_{NS} \) in accreting X-ray systems is known to be roughly in the range \( 1–2.5 M_{\odot} \), neutron star masses determined at the highest accuracy display a normal distribution centred at the value of \( 1.35 M_{\odot} \) with a very small dispersion of \( \pm 0.04 M_{\odot} \) (Thorsett & Chakrabarty 1999). Bearing this in mind, here and in the following calculations, we assume the mass of the neutron star as a constant equal to its canonical value of \( 1.4 M_{\odot} \). The corotation radius is given by

\[
R_{Q} = \left( \frac{GM_{NS} P^2}{4\pi^2} \right)^{1/3},
\]

where \( P \) is the spin period. Assuming a typical neutron star mass of \( 1.4 M_{\odot} \) and \( P = 21.05 \) s, as measured for IGR J18483–0311, we get \( R_{Q} = 1.27 \times 10^{9} \) cm.

The observed quiescent X-ray luminosities could be produced only if the background wind material can reach the surface of the neutron star and impact on to it. However, the requirement of \( R_{Q} > R_{M} \) imposes important constraints.

We calculated the Bondi–Hoyle X-ray luminosity at orbital phases \( \phi = 0 \) and 0.52 assuming a supergiant mass \( M_{OB} = 33 M_{\odot} \) and a radius \( R_{OB} = 33.8 R_{\odot} \) (Searle et al. 2008), and \( M_{NS} = 1.4 M_{\odot}, R_{NS} = 10 \) km for the neutron star. Then we assumed the typical wind parameters for a star with same spectral type of the IGR J18483–0311 supergiant: a mass-loss rate \( M \) in the range \( 0.4 – 3 \times 10^{-6} M_{\odot} \) yr\(^{-1} \), the wind velocity law \( v(r) = v_{\infty}(1 - R_{OB}/r)^{\beta} \), where \( v_{\infty} = 1200–1900 \) km s\(^{-1} \), \( \beta = 0.8–1.6 \) and we leave the magnetic field (B) and the orbital eccentricity (e) as free parameters. We calculated the expected X-ray luminosity of the neutron star at periastron and at the orbital phase \( \phi = 0.52 \), assuming that the X-ray emission is due to accretion of matter from the spherically symmetric stellar wind emitted by the supergiant companion. The neutron star accretes only the fraction of the wind ejected by the OB star within a distance from the neutron star smaller than \( R_a = \frac{2GM_{NS}}{v_{\text{rel}}^2 + c_s^2} \).

\[
R_a = \frac{2GM_{NS}}{v_{\text{rel}}^2 + c_s^2},
\]

here \( R_a \) is called accretion radius and \( v_{\text{rel}} \) is given by

\[
v_{\text{rel}}^2(r) = [v_{\text{wind}}(r) - v_i]^2 + v_{\phi}^2(r)
\]

where \( v_{\text{rel}} \) is the relative velocity of the wind material \( v_{\text{wind}} \) with respect to the radial \( v_i \) and tangential \( v_{\phi} \) components of the neutron star orbital velocity, and \( c_s \) is the sound velocity. The fraction of stellar wind captured by the neutron star given by the mass flux, which goes through the area \( \pi R_a^2 \) and is given by

\[
M_{\text{acc}} = \rho_{\text{wind}}(r)v_{\text{rel}}(r)\pi R_a^2,
\]

where \( \rho_{\text{wind}}(r) \) is the wind density related to the rate of mass loss by the stellar wind (M) by means of the continuity equation. From equations (2), (3) and (4), we computed the X-ray luminosity \( L_X \) of a neutron star:

\[
L_{X,\text{wind}} = \frac{G M_{NS}}{R_{NS}} M_{\text{acc}} = \frac{(GM_{NS})^3}{R_{NS}} \left[ \frac{4\pi \rho_{\text{wind}}(r)}{v_{\phi}^2(r) + c_s^2} \right]^{3/2},
\]

where \( G \) is the gravitational constant.

The allowed range of parameters (\( e \) and \( B \)), which reproduce the X-ray luminosity at the periastron (\( \phi \approx 0 \)) and apastron (\( \phi \approx 0.52 \)), calculated according to equation (5), are \( B \lesssim 6 \times 10^{11} \) G and \( 0.39 \lesssim e \lesssim 0.62 \). We note that the above-estimated magnetic field is in very good agreement with the value independently inferred by us from the putative electron cyclotron line at \( \sim 3.3 \) keV (\( \sim 3–4 \times 10^{11} \) G).
5 SUMMARY AND CONCLUSIONS

In this work, we studied the SFXT IGR J18483−0311 in quiescence using archival INTEGRAL and XMM–Newton data. As results, we report for the first time the spectral properties ($\Gamma = 2.5 \pm 0.8$) and luminosity measurement ($1.32 \times 10^{34}$ erg s$^{-1}$) of the average quiescent hard X-ray emission above 18 keV, accumulated over a long time interval along the eccentric orbit. On the contrary, the 0.5–10 keV observation took place in coincidence with the apastron passage and allowed the measurements of the lowest quiescent state of the source ($1.3 \times 10^{33}$ erg s$^{-1}$); its spectrum is best-fitted by an absorbed blackbody with parameters consistent with those previously reported by Romano et al. (2009) from a Swift/XRT monitoring campaign.

One important point deserves further and deeper attention. An intriguing spectral emission line has been observed at $\sim 3.3$ keV in the XMM–Newton quiescent spectrum of IGR J18483−0311 at apastron passage, and we speculated about its physical origin. An explanation in terms of atomic emission lines (i.e. highly ionized argon) appears unlikely. We attempt to ascribe it to an electron cyclotron emission line from an X-ray pulsar accreting at a low rate, as predicted by Nelson et al. (1995, 1993). Specifically, these authors predicted the possible detection of electron cyclotron emission lines in the X-ray spectra of magnetized and transient X-ray pulsars during their low-luminosity quiescent state (i.e. $L_X \lesssim 10^{34}$ erg s$^{-1}$). The energy line centre is expected to peak at energies in the range $\sim 2–20$ keV and it should be superposed on the underlying soft thermal emission. Emission-like features, similar to the ones predicted, have been observed in the X-ray spectrum of a handful of transient X-ray pulsars in HMXB systems during low-luminosity states (Nelson et al. 1995). We point out that the emission feature observed from IGR J18483−0311 could be similar to the one predicted by Nelson et al. (1995, 1993). In our specific case, the lowest quiescent X-ray luminosity state achieved during the apastron passage as well as the sufficiently long XMM–Newton observation could have possibly favoured the detection of a putative cyclotron emission line. This interpretation would imply a neutron star magnetic field value in the range of $(3–4) \times 10^{11}$ G, which is in very good agreement with that independently inferred by us in the framework of accretion from a spherically symmetric stellar wind model for the source. It is also worth pointing out that the estimated magnetic field strength is of the order expected for neutron stars known to display X-ray pulsations in HMXBs, i.e. $(0.5–4) \times 10^{12}$ G. Consecutively, it is strong enough to affect the accretion flow within a few neutron star radii and cause the observed X-ray pulsations in IGR J18483−0311.

To date, IGR J18483−0311 is the only SFXT, among $\sim 10$ firm members of this class, which exhibits such intriguing emission feature with important implications on theoretical models. However, this could be explained with the lack of sufficiently long X-ray observations of SFXTs at apastron passage (i.e. during their lowest quiescent X-ray states) with appropriate and sensitive enough X-ray facilities.

Unfortunately, we can go no further on these issues because the available exposure time and statistics of the data prevent us from a more detailed investigation. Longer X-ray observations of IGR J18483−0311 using XMM–Newton, for example, are strongly needed in order to achieve a higher signal-to-noise ratio. This would allow us a much deeper investigation, in order to support or reject our proposed interpretation in terms of electron cyclotron emission line.

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