NuSTAR and NICER reveal IGR J17591–2342 as a new accreting millisecond X-ray pulsar

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1051/0004-6361/201834160">http://dx.doi.org/10.1051/0004-6361/201834160</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>EDP Sciences</td>
</tr>
<tr>
<td>Version</td>
<td>Original manuscript</td>
</tr>
<tr>
<td>Accessed</td>
<td>Thu Mar 28 05:18:23 EDT 2019</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/121008">http://hdl.handle.net/1721.1/121008</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Creative Commons Attribution-Noncommercial-Share Alike</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td><a href="http://creativecommons.org/licenses/by-nc-sa/4.0/">http://creativecommons.org/licenses/by-nc-sa/4.0/</a></td>
</tr>
</tbody>
</table>
Letter to the Editor

**NuSTAR and NICER reveal IGR J17591−2342 as a new accreting millisecond X-ray pulsar**

A. Sanna¹, C. Ferrigno², P. S. Ray³, L. Ducci⁴, G. K. Jaisawal⁵, T. Enoto⁶,⁷, E. Bozzo², D. Altamirano⁸, T. Di Salvo⁹, T. E. Strohmayer¹⁰, A. Papitto¹¹, A. Riggio¹, L. Burderi¹, P. M. Bult¹⁰, S. Bogdanov¹², A. F. Gambino⁹, A. Marino¹³,¹⁴, R. Iaria⁹, Z. Arzoumanian¹⁰, D. Chakrabarty¹⁵, K. C. Gendreau¹⁰, S. Guillot¹⁶,¹⁷, C. Markwardt¹⁰, M. T. Wolff³

¹ Dipartimento di Fisica, Università degli Studi di Cagliari, SP Monserrato-Sestu km 0.7, 09042 Monserrato, Italy
e-mail: andrea.sanna@dsf.unica.it
² ISDC, Department of Astronomy, University of Geneva, Chemin d’Ecogia 16, CH-1290 Versoix, Switzerland
³ Space Science Division, Naval Research Laboratory, Washington, DC 20375-5552, USA
⁴ Institut für Astronomie und Astrophysik, Eberhard Karls Universität, Sand 1, 72076 Tübingen, Germany
⁵ National Space Institute, Technical University of Denmark, Elektrovej 327-328, DK-2800 Lyngby, Denmark
⁶ Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto, Kyoto 606-8502, Japan
⁷ The Hakubi Center for Advanced Research, Kyoto University, Yoshida-Ushinomiya-cho, Sakyo-ku, Kyoto, Kyoto 606-8302, Japan
⁸ Physics & Astronomy, University of Southampton, Southampton, Southampton, Hampshire SO17 1BJ, UK
⁹ Università degli Studi di Palermo, Dipartimento di Fisica e Chimica, via Archirafi 36, 90123 Palermo, Italy
¹⁰ Astrophysics Science Division, NASA’s Goddard Space Flight Center, Greenbelt, MD 20771, USA
¹¹ INAF, Osservatorio Astronomico di Roma, Via di Frascati 33, I-00044, Monteporzio Catone (Roma), Italy
¹² Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027, USA
¹³ INAF/IASF Palermo, via Ugo La Malfa 153, I-90146 - Palermo, Italy
¹⁴ IRAP, Université de Toulouse, CNRS, UPS, CNES, Toulouse, France
¹⁵ MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
¹⁶ CNRS, IRAP, 9 avenue du Colonel Roche, BP 44346, F-31028 Toulouse Cedex 4, France
¹⁷ Université de Toulouse, CNES, UPS-OMP, F-31028 Toulouse, France

Received -; accepted

**ABSTRACT**

We report on the discovery by the Nuclear Spectroscopic Telescope Array (NuSTAR) and the Neutron Star Interior Composition Explorer (NICER) of the accreting millisecond X-ray pulsar IGR J17591−2342, detecting coherent X-ray pulsations around 527.4 Hz (1.9 ms) with a clear Doppler modulation. This implies an orbital period of ∼ 8.8 hours and a projected semi-major axis of ∼ 1.23 lt-s. From the binary mass function, we estimate a minimum companion mass of 0.42 M⊙, obtained assuming a neutron star mass of 1.4 M⊙ and an inclination angle lower than 60 degrees, as suggested by the absence of eclipses or dips in the light-curve of the source. The broad-band energy spectrum is dominated by Comptonisation of soft thermal seed photons with a temperature of ∼ 0.7 keV by electrons heated to 21 keV. We also detect black-body-like thermal direct emission compatible with an emission region of a few kilometers and temperature compatible with the seed source of Comptonisation. A weak Gaussian line centered on the iron Kα complex can be interpreted as a signature of disc reflection. A similar spectrum characterises the NICER spectra, measured during the outburst fading.

**Key words.** X-rays: binaries; stars: neutron; accretion, accretion disc, IGR J17591−2342

1. Introduction

Accreting, rapidly-rotating neutron stars (NS) in low mass X-ray binaries have been extensively investigated for almost two decades. This class of objects, also known as accreting millisecond X-ray pulsars (AMXPs), includes at the moment 21 sources with spin periods ranging between 1.7 ms and 9.5 ms (see Burderi & Di Salvo 2013; Patruno & Watts 2012; Campana & Di Salvo 2018, for extensive reviews). The characteristic short spin periods observed in AMXPs are the result of long-lasting mass transfer from an evolved sub-Solar companion star via Roche-lobe overflow onto a slow-rotating NS (recycling scenario; Alpar et al. 1982), making them the progenitors of rotation-powered millisecond pulsars shining from the radio to the gamma-ray band. Almost a third of the AMXPs are ultra-compact binary systems (Porb < 1 hrs), while the rest show on average short orbital periods (Porb < 12 hrs), except for the intermittent pulsar Aql X−1 (Casella et al. 2008) with Porb ~ 18 hrs (Welsh et al. 2000). Short orbital periods suggest small low-mass companion stars, consistent with donor masses on average <0.2 M⊙.

Here, we report on the detection of millisecond X-ray pulsations from IGR J17591−2342, an X-ray transient first detected by the INTEGRAL Gamma-Ray Astrophysics Laboratory (INTEGRAL) during a Galactic Center scan on 2018 August 10 (Ducci et al. 2018). An archival search in the Neil Gehrels Swift Observatory (Swift) Burst Alert Telescope data revealed the source to be active since 2018 July 22 (Krimm et al. 2018). Pointed Swift/XRT observations of the source region, on 2018 August 12, revealed a point-like X-ray source and determined its precise X-ray position (Bozzo et al. 2018),
which was refined by a Chandra observation on 2018 August 23 to be R.A.=17\textdegree 59′′02.83′′ Decl.=-23′43′′10.2″ (J2000) with an astrometric uncertainty of 0.6″ (Nowak et al. 2018). On 2018 August 14, the Australia Telescope Compact Array (ATCA) detected IGR J17591–2342 with a flux density $S_{\nu} = 1.09 \pm 0.02 \mu$Jy and $S_{\nu} = 1.14 \pm 0.02 \mu$Jy (at 68% c.l.) at 5.5 GHz and 9.0 GHz, respectively, at a position R.A. = 17\textdegree 59′′02.86′′ ± 0.04′′ Decl.=-23′43′′08.3″ ± 0.1″, consistent with the X-ray determinations (Russell et al. 2018).

In this letter, we describe a coherent timing analysis of the NuSTAR and NICER observations that provided the pulsar spin period and binary ephemeris. We also report on the analysis of the X-ray spectral modelling obtained from NuSTAR, Swift, INTEGRAL, and NICER data.

2. Observations and data reduction

IGR J17591–2342 was observed by IBIS/ISGRI onboard the INTEGRAL satellite from 2018 August 10 at 15:50 to August 11 at 12:30 UT, for a total exposure time of 66 ks. We performed reduction and data analysis using the off-line science analysis (OSA) software provided by the INTEGRAL Science Data Centre. We produced a mosaic image from the combination of the individual images of the available data set, where the source was detected with a significance $>7\sigma$ in the 20–80 keV energy band. We extracted the average IBIS/ISGRI spectrum in 8 bins from 25 to 150 keV with equal logarithmic spacing. No JEM-X data were available due to the source location at the edge of its field of view.

NuSTAR observed IGR J17591–2342 (Obs.ID. 090401331002) on 2018 August 13 starting from 22:36 UT for a total exposure of ~ 30 ks. We performed standard screening and filtering of the events using the NuSTAR data analysis software (nustardas) from HEASOFT version 6.24. We extracted source events from a circular region of radius 80″ centered on the source position. Due to straylight we extracted the background with a similar extraction area but located in a region far from the source with similar degree of stray-light contamination. The average source count rate per instrument is ~ 9 counts/s in the energy range 3–80 keV. We did not detect any Type-I thermonuclear burst during the observation. We corrected for spacecraft clock drift applying the up-to-date clock correction file (version 84, valid up to 2018-08-14).

Swift observed IGR J17591–2342 (Obs.ID. 00010804002) on 2018 August 14 from 00:38 UT for a total of ~ 0.6 ks with Swift/XRT operated in photon counting mode. We reduced and processed the XRT data with xrtpipeline version 0.13.4, extracting source events from a circular region of radius 64″. We estimated a source count rate of ~ 1 cts/s above the pile-up threshold (see, e.g. Romano et al. 2006). Thus, we extracted the source spectrum using an annular region centered at the source position with inner and outer radius of 10″ and 64″, respectively. Similarly, we extracted the background spectrum from an annular region with inner and outer radius of 102″ and 230″, respectively.

NICER observed IGR J17591–2342 on 2018 August 15 from 00:00 to 14:08 UT for a total exposure of ~ 7.3 ks (Obs.ID. 1200310101, hereafter NICER-1), on August 18 from 02:08 to 03:56 UT (exposure of ~ 1.5 ks, Obs.ID. 1200310102, NICER-2), on August 23 from 00:58 to 22:57 UT (exposure of ~ 11.5 ks, Obs.ID. 1200310103, NICER-3) and on August 24 from 01:51 to 14:44 UT (exposure of ~ 7 ks, Obs.ID. 1200310104, NICER-4). We filtered events in the 1–12 keV band applying standard screening criteria with NICERDAS version 4.0. We removed short intervals showing background flaring in high geomagnetic

latitude regions. The spectral background was obtained from blank-sky exposures. We did not detect any Type-I thermonuclear burst during the observations.

3. Results

3.1. Timing analysis

To search for coherent signals, we first corrected the NICER and NuSTAR photon arrival times to the Solar System barycenter with the tool barycorr, using the DE-405 Solar planetary ephemeris, and adopting the source coordinates of Tab. 1. Power density spectra (PDS) obtained averaging either NuSTAR or NICER 150-s data segments showed a prominent (>4σ) excess at a frequency of 527.3 Hz. The feature exhibited a double-peaked structure characteristic of orbital Doppler broadening. Inspection of the NuSTAR PDS over short segments (500-s) revealed pulse frequency modulation typical for pulsars in binary systems (see Fig. 1). The best-fit is found for orbital period $P_{\text{orb}} = 31694(67)$ seconds, projected semi-major axis of $a = 3.1694 \times 10^7$ lt-s, time of passage through the ascending node $T_{\text{NOD}} = 58343.704(1)$ (MJD) and spin frequency $v_0 = 527.4253(6)$ Hz.

Starting from this provisional solution, we folded data segments of ~400-s and ~300-s for the NuSTAR and NICER observations, respectively, into 8 phase bins at the preliminary spin frequency $v_0$. We modelled each pulse profile with a constant plus two sinusoidal functions, representing the pulse frequency and its second harmonic. We retained only profiles for which the ratio between the pulse frequency amplitude and its 1 or 2 uncertainty was larger than three. Separately for NuSTAR and NICER, we modelled the pulse phase with a linearly varying frequency plus a circular Keplerian orbital model. A more detailed description of the procedure can be found in Sanna et al. (2016, and references therein).

The best-fit orbital and pulsar spin parameters for the NuSTAR and NICER data-sets are shown in the first and second column of Tab. 1, respectively. These are derived from the phase delays at the fundamental frequency; timing analysis using the second harmonic yields compatible results. The top panel of Fig. 2 shows the NuSTAR and NICER pulse phases after correcting for the best orbital solution and assuming a constant frequency. The NuSTAR pulse phases show a large distribution of residuals not
The *NICER* pulse phase residuals (top-panel right side) show a hint of positive spin frequency derivative (see Tab. 1 for the corresponding value and the bottom-panel right side of Fig. 2 for final residuals accounting for this component).

We improved the orbital parameter estimates (third column of Tab. 1) by orbitally phase-connecting the available data-sets (see, e.g. Sanna et al. 2017c,a, for more details on the procedure). We note that the uncertainty on the source localisation has an effect on the determination of the frequency and frequency derivative which is more than one order of magnitude smaller than the uncertainties reported in Tab. 1 for the corresponding parameters. Therefore, we ignore this effect. Finally, we created pulse profiles by epoch-folding the *NuSTAR* (3–80 keV) and *NICER* (1–12 keV) observations with the parameters reported in Tab. 1. We modelled them with a combination of three sinusoidal components (see Fig. 3). In *NuSTAR* data, the fundamental, the second and the third harmonics have fractional amplitudes of (16.1 ± 0.3)%, (5.1 ± 0.3)% and (1.5 ± 0.3)%, respectively. *NICER* pulse profiles are characterised by fractional amplitudes of (13.7 ± 0.2)%, (5.0 ± 0.2)% and (1.0 ± 0.2)% for fundamental, the second and the third harmonics, respectively.

### 3.2. Spectral analysis

We performed spectral analysis with Xspec 12.10.0c (Arnaud 1996) after applying an optimal binning (Kaastra & Bleeker 2016). For the first epoch, we used the 0.5–7.5 keV range for *Swift/XRT*, 3–70 keV for *NuSTAR* and 30–80 keV for *IBIS/ISGRI* and grouped the spectra to collect at least 20 counts per bin (Fig. 4). The broad-band (0.5–80 keV) spectrum is well-described by an absorbed thermal component (black-body) with temperature $kT_{BB}$ that provides also the seed photons for a thermally Comptonised continuum with electron energy $kT_e$ and a weak emission line centered on the iron Kα complex and width fixed to zero. In Xspec, this is implemented as $\text{TABS}^{*}[\text{cfux}\times\text{nthcomp}\times\text{bbodyrad}]+\text{gauss}$. For modelling, we left the flux of the Comptonisation component free to vary independently for each instrument, to account for cross-instrument.

### Table 1. Orbital parameters and spin frequency of IGR J17591–2342 with uncertainties on the last digit quoted at 1σ confidence level.

<table>
<thead>
<tr>
<th>Parameters</th>
<th><em>NuSTAR</em></th>
<th><em>NICER</em></th>
<th><em>NuSTAR+NICER</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>$1^h39^m02^s.86^s \pm 0.04^s$</td>
<td>$1^h39^m02^s.86^s \pm 0.04^s$</td>
<td>$1^h39^m02^s.86^s \pm 0.04^s$</td>
</tr>
<tr>
<td>Dec (J2000)</td>
<td>$23\degree43\arcmin08\arcsec.3 \pm 0.1^a$</td>
<td>$23\degree43\arcmin08\arcsec.3 \pm 0.1^a$</td>
<td>$23\degree43\arcmin08\arcsec.3 \pm 0.1^a$</td>
</tr>
<tr>
<td>$T_{\text{orb}}$ (MJD)</td>
<td>58345.171984 ± 0.003</td>
<td>58345.171984 ± 0.003</td>
<td>58345.171984 ± 0.003</td>
</tr>
<tr>
<td>$T_{\text{rad}}$ (MJD)</td>
<td>58344.0</td>
<td>58344.0</td>
<td>58344.0</td>
</tr>
</tbody>
</table>

Notes. (a) Localisation of the ATCA radio counterpart (Russell et al. 2018). (b) The spin frequency derivative likely originates from the time drift of the internal clock of the *NuSTAR* instrument, see Sec. 4 for more details. $T_0$ represents the reference epoch for these timing solutions. Frequencies and times reported here are referred to the TDB time scale.
calibration offsets and the possible source variations due to not strictly simultaneous observations.

The NICER observations were fitted independently by minimising the pgstat statistic in Xspec\(^1\). Due to uncertainties in the low-energy response, we ignored the NICER data below 1.4 keV. We adopted the same model, but we fixed the electron temperature at the value found from NuSTAR and checked that the result remained insensitive as long as \(kT_e > 12\) keV. After verifying the compatibility of single spectra, we performed a joint fit of NICER-1 and 2 observations, leaving only the flux to be independently determined between them. We applied the same procedure to NICER-3 and 4. The best-fit parameters are shown in Tab. 3.2 with uncertainties at the 90% confidence level. Regardless of the statistical test used to find the best-fit parameters, we reported the \(\chi^2_{\text{red}}\) value.

4. Discussion

We reported on the newly discovered AMXP IGR J17591−2342, for which we detected coherent X-ray pulsations at \(\sim 527\) Hz in the NuSTAR and NICER observations performed almost 25 days from the beginning of the outburst, with a pulse fraction of 15%. We modelled the NS spin frequency drift as the Doppler shift induced by the binary orbital motion, discovering the binary nature of the system, characterised by an orbital period of almost 8.8 hours, very similar to the intermittent AMXP SAX J1748.9−2021 (see, e.g. Altamirano et al. 2008; Sanna et al. 2016) and the eclipsing AMXP SWIFT J1749.4−2807 (see, e.g. Markwardt & Strohmayer 2010; Altamirano et al. 2011; Ferrigno et al. 2011).

The analysis of the NuSTAR pulse phase residuals revealed the presence of a large spin-up derivative (2.6 \(\times 10^{-10}\) Hz/s) and an oscillation close to twice the satellite orbital period. We suggest that both effects are associated with the time drift of the internal clock instrument (see, e.g. Madsen et al. 2015). Similar spurious frequency derivatives have been reported for NuSTAR observations of AMXPs such as MAXJ0911−655 (Sanna et al. 2017b), SAX J1808.4−3658 (Sanna et al. 2017a) and IGR J00291+5934 (Sanna et al. 2017c). Also the large discrepancy on the spin frequency (\(\sim 1 \times 10^{-4}\) Hz) between NuSTAR and NICER is a direct consequence of the NuSTAR clock issue. These considerations are reinforced by the analysis of NICER observations, which does not evidence any significant frequency drift.

A spin-up frequency derivative of \(2.0 \times 1.6 \times 10^{-13}\) Hz/s is observed from the phase-coherent timing analysis of the NICER observations. For a broad-band (0.1−100 keV) absorbed flux of \(\sim 7 \times 10^{-10}\) erg/s/cm\(^2\) and a source distance of 8.5 kpc (assumed near the Galactic Center, see, e.g. Kerr & Lynden-Bell 1986), we estimate an accretion rate of \(\dot{M} \approx 5.2 \times 10^{-7}\) M\(_{\odot}\)/yr (for a NS radius and mass of 1.4 M\(_{\odot}\) and 10 km, respectively). Assuming the accretion disc to be truncated at the co-rotation radius, the observed mass accretion rate yields a maximum spin-up derivative of a few \(10^{-13}\) Hz/s, fully consistent with the observed one.

A rough estimate of the NS dipolar magnetic field can be obtained by assuming the condition of spin equilibrium for the X-ray pulsar. The magnetic field can then be estimated as:

\[
B = 0.63 \zeta^{-7/6} \left( \frac{P_{\text{spin}}}{2 \pi} \right)^{7/6} \left( \frac{M}{1.4 M_{\odot}} \right)^{1/3} \left( \frac{\dot{M}}{10^{-10} M_{\odot}/\text{yr}} \right)^{1/2} 10^8 \text{G},
\]

where \(\zeta\) represents a model-dependent dimensionless factor (between 0.1−1) corresponding to the ratio between the magnetospheric radius and the Alfvén radius (see, e.g. Ghosh & Lamb

\[\text{Fig. 4. Upper panel: Swift (blue), NuSTAR FPMA and FPMB (black and red, respectively) and IBIS/ISGRI (green) unfolded spectra of IGR J17591−2342. The dashed and dash-dotted lines represent blackbody and Comptonisation components respectively. The sharp dotted line is a Gaussian with width set to zero. Additional rebinning is for displaying purposes. Lower panel: residuals from the best-fit model in units of standard deviations.}\]

\[\text{Table 2. Best-fit spectral parameters of IGR J17591−2342 with uncertainties at 90% confidence level.}\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>multiple</th>
<th>NICER-1</th>
<th>NICER-2</th>
<th>NICER-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_0) [10(^6) cm(^{-2})]</td>
<td>3.6±1.1</td>
<td>3.45(^{+0.15}_{-0.11})</td>
<td>3.59(^{+0.10}_{-0.09})</td>
<td></td>
</tr>
<tr>
<td>(\Gamma)</td>
<td>1.76±0.02</td>
<td>1.83±0.06</td>
<td>2.23±0.05</td>
<td></td>
</tr>
<tr>
<td>(kT_e) [keV]</td>
<td>22(^{+4}_{-5})</td>
<td>22 (fixed)</td>
<td>22 (fixed)</td>
<td></td>
</tr>
<tr>
<td>(kT_B) [keV]</td>
<td>0.79±0.09</td>
<td>0.58(^{+0.05}_{-0.07})</td>
<td>0.90(^{-0.06}_{+0.07})</td>
<td></td>
</tr>
<tr>
<td>(r_{\text{bb}}) [km / D(4kpc)(^2)]</td>
<td>2.6(^{+1.4}_{-0.6})</td>
<td>3.3(^{+0.8}_{-0.6})</td>
<td>&lt; 5\times 10(^3)</td>
<td></td>
</tr>
<tr>
<td>(E_{\text{bb}}) [keV]</td>
<td>6.8(^{+0.14}_{-0.19})</td>
<td>6.35±0.04</td>
<td>6.37±0.10</td>
<td></td>
</tr>
<tr>
<td>(N_0) [10(^{-3}) ph/s/cm(^2)]</td>
<td>5.2±1.8</td>
<td>3.8±0.9</td>
<td>2.9±1.6</td>
<td></td>
</tr>
<tr>
<td>Flux (1−10 keV)(^b)</td>
<td>2.0±0.3</td>
<td>1.85±0.09</td>
<td>2.35(^{+0.03}_{-0.04})</td>
<td></td>
</tr>
<tr>
<td>Flux (3−20 keV)(^b)</td>
<td>2.41±0.05</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Flux (20−100 keV)(^b)</td>
<td>3.8(^{+0.4}_{-0.3})</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Flux (0.1−10 keV)(^b)</td>
<td>1.73</td>
<td>1.31(^{+d}_{-d})</td>
<td>1.57(^{+e}_{-e})</td>
<td></td>
</tr>
<tr>
<td>(\chi^2_{\text{red}}/\text{d.o.f.})</td>
<td>1.09/473</td>
<td>1.11/377</td>
<td>1.13/1129</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) “multiple” indicated the combined fit of the NuSTAR, IBIS/ISGRI, and Swift/XRT observations. NICER-1 and NICER-2 are the observations of 2018, August 15 and 18, NICER-3, of August 23 and 24. \(^{b}\) The flux of the ncthrcp component in units of 10\(^{-9}\) erg s\(^{-1}\) cm\(^{-2}\). The 3−20 and 20−100 keV ncthrcp fluxes apply to NuSTAR and IBIS/ISGRI data, respectively. IBIS/ISGRI flux is higher than the others, since the data were obtained earlier, when the source was brighter. \(^{d}\) This flux applies to Swift/XRT data only. \(^{e}\) The upper and lower rows refer to the NICER-1 and 2 observations. \(^{f}\) The upper and lower rows refer to the NICER-3 and 4 observations. \(^{g}\) Extrapolated absorbed flux derived by the model in units of 10\(^{-9}\) erg s\(^{-1}\) cm\(^{-2}\). For the multiple observation, we extrapolate the NuSTAR spectrum.

---

\(^1\) pgstat is suited for Poisson distributed data with Gaussian distributed background; see https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixStatistics.html.
black-body like component ($kT \sim 0.8 \text{ keV}$) with relatively small emitting area compatible with emission from the neutron star surface (or part of it) plus a Comptonised component ($\Gamma \sim 1.8$) with a seed photon temperature compatible with the soft thermal component. The source spectral properties are consistent with other AMXPs observed in the hard state (see, e.g. Falanga et al. 2005; Gierliński & Poutanen 2005; Papitto et al. 2009, 2013; Sanna et al. 2017b,c). We found marginal evidence ($\sim 4\sigma$, based on an F-test) of a weak emission line compatible with the iron K-\(\alpha\) transition. Even if marginally significant, its introduction removes positive residuals around the expected energy and such lines are not unusual for this kind of sources (see, e.g. Papitto et al. 2009, 2013; Sanna et al. 2017b,c). From Tab. 3.2, we note that at later times, when the source has a re-brightening, the additional black body seems to disappear, while the asymptotic Comptonisation power-law index increases. This might be due to more effective cooling of the seed photons by a thicker accretion stream above the stellar surface.

The discovery of another transient by INTEGRAL and its characterisation as the 22nd accreting millisecond pulsar by NUSTAR and NICER enriches the census of these key objects in the understanding of the late stages of stellar evolution.

Acknowledgements. We thank Fiona Harrison for accepting a NuSTAR observation in the Director Discretionary Time. We thank the Swift, NuSTAR, and NICER teams for scheduling and performing these target of opportunity observations on a short notice. This work was supported by NASA through the NICER and NuSTAR missions, and the Astrophysics Explorers Program. It made use of data and software provided by the High Energy Astrophysics Science Archive Research Center (HEASARC). It is also based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain) and with the participation of Russia and the USA. DA acknowledges support from the Royal Society. LD acknowledges grant FZK 50 OG 1602.

References


Fig. 5. Radius–mass plane showing the size constraints on the companion star Roche-Lobe of IGR J17591–2342 (black solid line) obtained from the orbital parameters of the neutron star. The hatched region represents the constraints on the companion mass from the binary mass function, while the blue area defines the mass constraints for inclination angles between 60 and 90 degrees. The other curves represent theoretical mass-radius relations for Zero-Age Main Sequence stars (purple crosses) and isochrones for stars with age of 8 (red diamonds) and 12 Gyr (blue circles). The top x-axes represents the corresponding binary inclination angle in degrees assuming a 1.4 M⊙ NS.

1979; Wang 1996), $P_{\text{spin}}$ is the pulsar spin period in ms and $M$ is the NS mass. Assuming a 1.4 M⊙ NS and the value of $M$ reported above, we obtain a range for the dipolar magnetic field of $1.4 \times 10^{9} < B < 8 \times 10^{9}$ G, consistent with the average magnetic field of known AMXPs (see, e.g. Mukherjee et al. 2015).

From the NS mass function $f(m_2, m_1, i) \sim 1.5 \times 10^{-2} M_{\odot}$, we can constrain the mass of the companion star. Since neither total eclipses, nor dips, have been observed in the light curve, we can assume a binary inclination lower than 60 degrees (see, e.g. Frank et al. 2002). As shown in Fig. 5, the upper limit on the inclination angle (represented in blue) allows us to limit the companion star mass $m_2 \geq 0.42 M_{\odot}$ (for a 1.4 M⊙ NS), which increases up to $m_2 \geq 0.52 M_{\odot}$ if we consider a 2 M⊙ NS. Introducing the contact condition ($R_{\text{orb}} \approx R_{L2}$) required to activate Roche-Lobe overflow, we can express the donor radius as a function of its mass $R_{2} = 0.87 m_{2}^{1/3} P_{\text{orb}}^{1/3} R_{\odot}$, where $m_2$ is the companion mass in units of $M_{\odot}$ and $P_{\text{orb}}$ represents the binary orbital period in units of 9 hours. In Fig. 5, we report the companion mass-radius relation (black solid line) assuming a 1.4 M⊙ NS. For comparison, we show numerical simulated mass-radius relations for Zero-Age Main Sequence stars (ZAMS) (purple crosses; see, e.g. Tout et al. 1996), as well as isochrones for stars aged 8 (red diamonds) and 12 Gyr (blue circles; see, e.g. Girardi et al. 2000). From the intersections with the mass-radius companion curve, we can infer that the donor is compatible with either a ZAMS with mass ~ 1.1 M⊙ (corresponding to an inclination angle of $i \sim 24$ degrees) or an old main sequence star with mass 0.85–0.92 M⊙ ($i$ ranging between 28 and 30 degrees) for a star age between 8 and 12 Gyr. We note, however, that the a priori probability of observing a binary system with inclination $i \lesssim 30$ degrees is of the order of 13%. Mass values for which the main sequence radius is smaller than the companion Roche-lobe could still be acceptable if we consider the possibility of a bloated donor star. In that case, the thermal timescale ($GM_{2}^{2}/RL_{2}$) should be much larger than the evolutionary timescale ($M_{2}/M_{\odot}$).

Finally, the broad-band energy spectrum of IGR J17591–2342 is well described by an absorbed soft