XMM-NEWTON OBSERVATIONS OF IGR J00291+5934: SIGNS OF A THERMAL SPECTRAL COMPONENT DURING QUISCENCE

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ABSTRACT

We present X-ray observations of the transient accretion-powered millisecond pulsar IGR J00291+5934 during quiescence. IGR J00291+5934 is the first source among accretion-powered millisecond pulsars to show signs of a thermal component in its quiescent spectrum. Fitting this component with a neutron star atmosphere or a blackbody model we obtain soft temperatures (∼64 and ∼110 eV, respectively). As in other sources of this class a hard spectral component is also present, comprising more than 60% of the unabsorbed 0.5–10 keV flux. Interpreting the soft component as cooling emission from the neutron star, we can conclude that the compact object can be spun up to millisecond periods by accreting only ≤0.2 $M_{\odot}$.

Subject headings: accretion, accretion disks — stars: individual (IGR J00291+5934) — stars: neutron

Online material: color figures

1. INTRODUCTION

IGR J00291+5934 (hereafter IGR J0029) is one of eight low-mass neutron star transients showing coherent pulsations during outbursts (see Wijnands 2005 for a review). Distinctive properties of these faint transients are weaker outburst peak luminosities [−(1−5) × 10$^{36}$ erg s$^{-1}$] with respect to classical neutron star transients (see Campana et al. 1998 for a review), very low mass companions (mass functions <2 × 10$^{-3}$ $M_{\odot}$), short orbital periods ($P_{orb}$ ≤ 4.3 hr), very faint quiescent X-ray luminosities (≤5 × 10$^{31}$ erg s$^{-1}$), and absence of a soft X-ray spectral component in quiescence (quiescent spectrum consisting of only a hard power-law component).

IGR J0029 was discovered while in outburst on 2004 December 2 during a routine monitoring of the Galactic plane with the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite (Eckert et al. 2004). Follow-up Rossi X-Ray Timing Explorer (RXTE) observations revealed 598.88 Hz (1.67 ms) coherent pulsations (Markwardt et al. 2004b), making it the fastest confirmed accretion-powered millisecond pulsar and a 2.46 hr orbital modulation (Markwardt et al. 2004a). In quiescence IGR J0029 was detected by Chandra at the beginning of 2005 (and historically by ROSAT; Jonker et al. 2005). The source quiescent 0.5–10 keV unabsorbed flux was ∼8 × 10$^{-14}$ erg cm$^{-2}$ s$^{-1}$ with a variability among different observations by a factor of 2 (Jonker et al. 2005). Chandra detected IGR J0029 also in 2005 November at a level of ∼7 × 10$^{-14}$ erg cm$^{-2}$ s$^{-1}$ (Torres et al. 2008). Finally, a short observation was carried out with Chandra in 2006 September with the source at a level of ∼1 × 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$ (Jonker et al. 2008). All of these Chandra observations collected a relatively low number of photons, and a detailed spectral analysis could not be carried out, with all spectra consistent with a single power law (photon index 2.4 ± 0.5, 90% confidence level).

The nondetection of X-ray bursts makes the estimate of the distance to IGR J0029 difficult. Shaw et al. (2005) gave an upper limit of 3.3 kpc considering the source position with respect to the Galactic center. Torres et al. (2008) estimated a distance of 2–4 kpc based on the critical X-ray luminosity needed to ionize the accretion disk and produce the observed X-ray light curve during outburst. We assume in the following a fiducial distance of 3 kpc.

In this Letter we report on the first study of IGR J0029 in quiescence with XMM-Newton. The larger throughput of the XMM-Newton instruments allowed us to study in detail the quiescent spectrum. In § 2 we discuss the XMM-Newton data analysis. Section 3 contains our discussion and conclusions.

2. DATA ANALYSIS

The XMM-Newton Observatory (Jansen et al. 2001) includes three 1500 cm$^2$ X-ray telescopes each with a European Photon Imaging Camera (EPIC; 0.1–15 keV) at the focus. Two of the EPIC imaging spectrometers use MOS CCDs (Turner et al. 2001) and one uses pn CCDs (Strüder et al. 2001).

XMM-Newton observed IGR J0029 on 2007 July 24 for 27 ks with the thin filter on all the EPIC instruments. Data were processed using SAS version 6.6.0. At the end of the observation, a strong soft proton flare occurred limiting the usable observing time to 17 and 24 for the pn and the MOS detectors, respectively (filtering out background flares for total 0.2–15 keV rates less than 5 and 20 counts s$^{-1}$ for the MOS and pn cameras, respectively). We extracted the pn source spectrum from a circular region with radius 22$''$ and the background spectrum from a larger region close to the source with radius 34$''$ within the same CCD. For the MOS cameras we used the same source extraction region and a 84$''$ background region. We obtained 466, 142, and 146 counts for pn, MOS1, and MOS2 cameras in the 0.2–10 keV range. The background contribution is at a level of 50% and 30% for the pn and MOS cameras, respectively (see Table 1).

We considered for timing analysis only the pn light curve in consideration of the higher signal-to-noise ratio. We subtracted the background light curve, and we did not find any evidence for variability down to 500 s, i.e., the shortest timescale that could be investigated (the fit with a constant provides a reduced $\chi^2 = 0.8$ with 43 degrees of freedom [ dof]). This is at variance with what was observed in the optical band, where strong flares (∼1 mag) were reported on a timescale of ≥500 s (Jonker et al. 2008).

The spectral analysis was carried out using the data from the three EPIC cameras together. Spectra were binned to at

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least 20 counts per spectral bin, resulting in 37 bins. A single power-law fit provides a good description of the data (reduced $\chi^2 = 0.9$, 34 dof) but the inferred column density (using the TBABS model in XSPEC12.4.0ai) is $N_H = 1.6^{+0.8}_{-0.8} \times 10^{21}$ cm$^{-2}$ (90% confidence level), which is much smaller than the column density observed in outburst of $N_H = 4.3^{+0.7}_{-0.5} \times 10^{21}$ cm$^{-2}$ obtained fitting together Chandra HETG and RXTE PCA data (Paizis et al. 2005). This value is also consistent with the Galactic value of $N_H = 4.6 \times 10^{21}$ cm$^{-2}$. Here we adopt this value (see Table 2).

Fitting the data with the column density fixed at the above value provides relatively poor fits (reduced $\chi^2$ = 1.35 in the case of a power law). Therefore, we tried double component models. Usually, spectra of neutron star transients in quiescence are fit with a two-component model: a neutron star atmosphere emission model (or a blackbody) plus a hard power-law component. These models provide a better description of the data. An $F$-test gives a 3.4 $\sigma$ probability for the significance in the fit improvement due to the extra model component (either blackbody or neutron star atmosphere; see Table 2). This indicates that, if $N_H$ is held fixed at the value measured in outburst, the addition of a soft spectral component is significant. Estimates of the column density during quiescence of transient accreting millisecond X-ray pulsars are available only for SAX J1808.4–3658. For this source the quiescent value of the column density is consistent with the one observed in outburst (Heinke et al. 2007; Campana et al. 2008).

### 3. DISCUSSION AND CONCLUSIONS

In recent years the quiescent properties of a handful of neutron star transients have been studied in some detail thanks to dedicated observations mainly carried out with XMM-Newton and Chandra. “Classical” (i.e., not showing pulsations during outbursts) neutron star transients have quiescent (0.5–10 keV) luminosities, below (and in some cases well below) $10^{35}$ erg s$^{-1}$. In these systems the quiescent spectrum is made just by a power-law component with no signs of a soft component. The best known system, SAX J1808.4–3658, shows a pure power-law spectrum, with an upper limit on the luminosity of the soft component of $\lesssim 23\%$ (Heinke et al. 2007).

Our XMM-Newton data on IGR J0029 in quiescence provides for the first time evidence for the presence of a soft component in the quiescent spectrum of a transient accreting millisecond X-ray pulsar (see Fig. 1). The temperature of this component ($kT \sim 70$ eV, when modeled with a neutron star atmosphere) is soft but in line with other classical neutron star transients (e.g., Heinke et al. 2007). The bolometric neutron star atmosphere luminosity is $1.4 \times 10^{35}$ erg s$^{-1}$. This luminosity is usually ascribed to the heat generated deep in the crust during outburst episodes (i.e., accretion onto the neutron star surface) that is then radiated away through the atmosphere while in quiescence producing the quiescent X-ray emission (Brown et al. 1998; Haensel & Zdunik 1990). The efficiency of the re-

### Table 1

| Instrument | Exposure Time (s) | Filtered Exposure Time (s) | Counts | Background-subtracted Counts |
|-----------|------------------|---------------------------|--------|-----------------------------|
| pn        | 26970            | 17305                     | 466    | 269                         |
| MOS1      | 28535            | 23920                     | 142    | 102                         |
| MOS2      | 28535            | 23877                     | 146    | 107                         |

### Table 2

| Model       | $N_H$ ($10^{21}$ cm$^{-2}$) | Photon Index | Temperature (keV/log $T$) | $\chi^2_{\nu}$ (dof) [nhp]$^*$ | Flux$^a$ (Luminosity) |
|-------------|-----------------------------|--------------|--------------------------|---------------------------------|----------------------|
| Power law   | $1.6^{+0.8}_{-0.8}$        | $1.7^{+0.2}_{-0.2}$ | ...                      | 0.89 (34) [66]                  | 7.2 (7.7)            |
| Blackbody   | <0.2                       | ...          | 0.56$^{+0.09}_{-0.07}$   | 1.55 (34) [2]                   | 3.4 (3.6)            |
| Power law   | 4.6                         | $2.5^{+0.3}_{-0.3}$ | ...                      | 1.35 (35) [8]                   | 8.5 (9.2)            |
| Blackbody   | 4.6                         | ...          | 0.38$^{+0.08}_{-0.07}$   | 2.86 (35) [0]                   | 4.4 (4.7)            |
| NSA         | 4.6                         | ...          | 5.91$^{+0.10}_{-0.10}$   | 3.46 (35) [0]                   | 7.1 (7.7)            |
| PL+BB$^d$   | 4.6                         | $1.8^{+0.1}_{-0.1}$  | 0.11$^{+0.04}_{-0.03}$   | 0.93 (33) [59]                  | 12.4 (13.3)          |
| PL+NSA$^a$  | 4.6                         | $1.5^{+0.2}_{-0.2}$  | 5.87$^{+0.03}_{-0.04}$   | 0.98 (34) [49]                  | 11.6 (12.4)          |

*Note.—All quoted errors are at 90% confidence level ($\Delta \chi = 2.71$).

$^a$ Null hypothesis probability.

$^b$ Unabsorbed 0.5–10 keV flux in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and luminosity in units of $10^{35}$ erg s$^{-1}$ at 3 kpc.

$^c$ NSA normalization fixed at $1.1 \times 10^{-7}$ as a source at 3 kpc. Neutron star mass, radius and magnetic field fixed to 1.4 $M_{\odot}$, 10 km, and 0 G, respectively.

$^d$ Blackbody radius $R = 2.9^{+3.3}_{-1.3}$ km at a distance of 3 kpc. The blackbody component comprises 36% of the 0.5–10 keV unabsorbed flux.

The NSA component comprises 38% of the 0.5–10 keV unabsorbed flux.
radiation process depends on which fraction of heat escapes the neutron star as neutrinos rather than photons and in turn on the physical conditions (i.e., composition, density, and pressure) of the neutron star interior.

The accretion history of IGR J0029 is relatively well known. IGR J0029 was discovered during an outburst in 2004 December. The bolometric fluence of this outburst has been estimated in $1.8 \times 10^{-3}$ erg cm$^{-2}$ using RXTE data (Galloway et al. 2005) or $1.37 \times 10^{-3}$ erg cm$^{-2}$ using INTEGRAL data (Falanga et al. 2005). Thanks to the RXTE all-sky monitor (ASM) two previous instances of activity, on 1998 November 26–8 and 2001 September 11–21, have been revealed (Remillard 2004). These results indicate that the transient appears regularly, roughly every 3 yr. Indeed, a new outburst started on 2008 August 13 (Chakrabarty et al. 2008), providing further evidence that the outbursts recur fairly regularly. Assuming that all the outbursts are due to accretion (since the spectrum at these low luminosities is expected to be soft; see, e.g., Zampieri et al. 1995).

Having estimated the quiescent cooling luminosity and the time-averaged flux (or mass inflow rate), we can put constraints on models for the neutron star interior (Yakovlev & Pethick 2004; Levenfish & Haensel 2007). As can be seen from Figure 2, IGR J0029 lies on the standard cooling curve for a low-mass neutron star. This is at variance with, for example, SAX J1808.4–3658 and Cen X-4, for which low cooling luminosities have been inferred, hinting at enhanced neutrino emission produced in the high-density core of a relatively high mass neutron star ($M > 1.6–1.7 M_{\odot}$; see, e.g., Colpi et al. 2001).

Our observation indicates that neutron stars showing coherent pulsation during their outbursts do not necessarily lack a soft component in their quiescent spectra. If the soft spectral component is due to deep crust heating emission, then the presence or lack of this component is a proxy of its mass, as massive neutron stars do not show it due to fast cooling. This would imply that light ($M \leq 1.6 M_{\odot}$) neutron stars too can show coherent pulsations at the millisecond level, having accepted only $\leq 0.2 M_{\odot}$ (Lavagetto et al. 2004).

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