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Chandra observation of the fast X-ray transient IGR J17544-2619: evidence for a neutron star?

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Abstract. IGR J17544-2619 belongs to a distinct group of at least seven fast X-ray transients that cannot readily be associated with nearby flare stars or pre-main sequence stars and most probably are X-ray binaries with wind accretion. Sofar, the nature of the accretor has been determined in only one case (SAX J1819.3-2525/V4641 Sgr). We carried out a 20 ks Chandra ACIS-S observation of IGR J17544-2619 which shows the source in quiescence going into outburst. The Chandra position confirms the previous tentative identification of the optical counterpart, a blue O9Ib supergiant at 3 to 4 kpc (Pellizza, Chaty & Negueruela, in prep.). This is the first detection of a fast X-ray transient in quiescence. The quiescent spectrum is very soft. The photon index of 5.9 ± 1.2 (90% confidence error margin) is much softer than 6 quiescent black hole candidates that were observed with Chandra ACIS-S (Kong et al. 2002, ApJ, 570, 277; Tomsick et al. 2003, ApJ, 599, L133). Assuming that a significant fraction of the quiescent photons comes from the accretor and not the donor star, we infer that the accretor probably is a neutron star. A fit to the quiescent spectrum of the neutron star atmosphere model developed by Pavlov et al. (1994, A&A, 289, 837) and Zavlin et al. (1996, A&A, 315, 141) implies an unabsorbed quiescent 0.5–10 keV luminosity of $(5.2 \pm 1.3) \times 10^{32}$ erg s^{-1}. We speculate on the nature of the brief outbursts.

Key words. X-rays: binaries – X-rays: transients – X-rays: individual: IGR J17544-2619

1. Introduction

It has recently become clear that there is a distinct group of fast X-ray transients with outburst durations of order a few hours and peak fluxes of order 10^{-9} erg cm^{-2} s^{-1} (2–10 keV) that are not readily identifiable with other similarly active X-ray sources: magnetically active nearby stars (i.e., DY Dra, RS CVn or pre-main sequence stars) or superbursters (e.g., Kuulkers 2004; time profiles, luminosities and spectra are inconsistent). The high fluxes and the lack of nearby counterparts suggest high luminosities which would indicate an X-ray binary origin. The first case, XTE J1739–302, was discovered by Smith et al. (1998). Accurate Chandra localization yielded an identification with a highly reddened probably supergiant O star (Smith et al. 2003). The list has been steadily growing and now consists of at least seven objects: XTE J1739–302, SAX J1818.6–1703 (In 't Zand et al. 1998), V4641 Sgr (In 't Zand et al. 2000; Orosz et al. 2001), XTE J1901+014 (Remillard & Smith 2002), AX J1749.1–2733 (Grebenev 2004), IGR J16465-4507 (Lutovinov et al. 2005; Negueruela et al. 2005) and IGR J17544-2619 which is the subject of this paper. For the first two systems there is suggestive evidence that the strong variability is due to a high-mass companion star feeding the compact object through a wind instead of an accretion disk, like in many high-mass X-ray binaries (Smith 2004).

IGR J17544-2619 was first reported from INTEGRAL detections on Sep. 17, 2003, when it exhibited two flares (Sunyaev et al. 2003; Grebenev et al. 2003) and a second time on Mar. 8, 2004 (Grebenev et al. 2004). Three XMM-Newton observations (Gonzalez-Riestra et al. 2003, 2004) show that even outside large flares, the flux appears to vary violently, with fluxes between an upper limit of 5×10^{-14} erg cm^{-2} s^{-1} and 4×10^{-11} erg cm^{-2} s^{-1} (0.5–10 keV). The first detection of IGR J17544-2619 was with the BeppoSAX Wide Field Cameras that detected hours-long flares in 1996, 1999 and 2000 with 0.5–10 keV peak fluxes of a few times 10^{-9} erg cm^{-2} s^{-1} (In 't Zand et al. 2004). Semi-weekly flux measurements since 1999 with the RXTE Proportional Counter Array (Swank & Markwardt 2001) point to a duty cycle of about 5% above $\sim10^{-11}$ erg cm^{-2} s^{-1} (2–10 keV; In 't Zand et al. 2004).

Rodriguez (2003) tentatively identified a counterpart in the 2MASS catalog, 2MASS J17542527-2619526, which is also in the USNO B1.0 catalog. Its brightness is $B2 = 13.9$, $R2 = 12.0$ and $K_s = 8.02$. Pellizza, Chaty & Negueruela (in prep.) identify the optical counterpart as a blue supergiant of spectral type O9Ib at 3 to 4 kpc distance. The nature of the accretor is thus far undetermined. Rodriguez-Riestra et al. (2004) noted the similarity with SAX J1819.3–2525/V4641 Sgr which is also a fast transient that at one time revealed a giant flare of approximately 10^{-7} erg cm^{-2} s^{-1} (Smith et al. 1999; Hjellming et al. 2000). Orosz et al. (2001; 2003) and Orosz (2002) determined
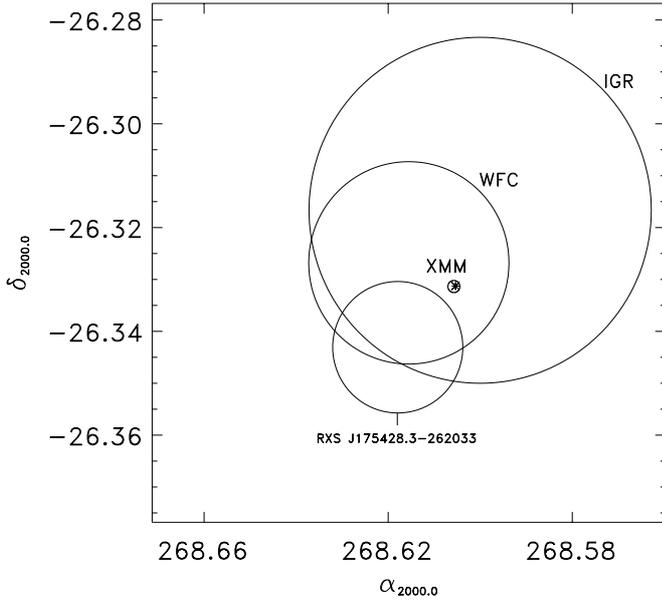
Fig. 1. Map showing source detections around IGR J17544–2619. All error circles are for a confidence level in excess of 90% (the radius of the 68%-confident ROSAT error circle was multiplied by two). The Chandra position is indicated by an asterisk inside the XMM-Newton error circle. Technically, since the Chandra and XMM-Newton positions are so close to the ROSAT error circle an association to the ROSAT cannot be completely ruled out.

a mass between 6.8 and 7.4 $M_\odot$ (1σ confidence) from optical spectroscopy, revealing that it is a black hole (BH) candidate. This similarity prompts the question whether the accretor in IGR J17544-2619 is also a BH.

In this paper we present a 20 ks Chandra observation of IGR J17544-2619. Thanks to its higher angular resolution and, therefore, smaller background level, Chandra is able to probe deeper than XMM-Newton which improves the signal-to-noise ratio of the quiescent emission. Such a study may yield constraints on the nature of the compact object. If the luminosity would be above 10^{32} erg cm^{-2} s^{-1} and the spectrum a black body with a temperature of order a few tens to hundreds of eV, this would represent strong evidence for a neutron star (NS; Rutledge et al. 1999; Garcia et al. 2001). Furthermore, the Chandra observations provide an improvement in the positional accuracy by an order of magnitude. Thus, the optical counterpart can be identified unambiguously. This is not the first Chandra observation of a fast X-ray transient. XTE J1739–302 was observed for 5 ks (Smith et al. 2003; Smith & Heindl 2003). However, inspection of those data shows that the source was not in quiescence.

2. Chandra observation

Chandra observed IGR J17544-2619 on July 3rd, 2004 (obsid 4550), with the ACIS-S CCD array (Garmire et al. 2001) in the focal plane and no grating. The CCD frame time is 3.2 s, the exposure time 19.06 ks. We analyzed these data with CIAO version 3.2.1. The source is clearly detected. The point source image shows a heavily piled-up source with a characteristic hole at the center and readout trails. The average
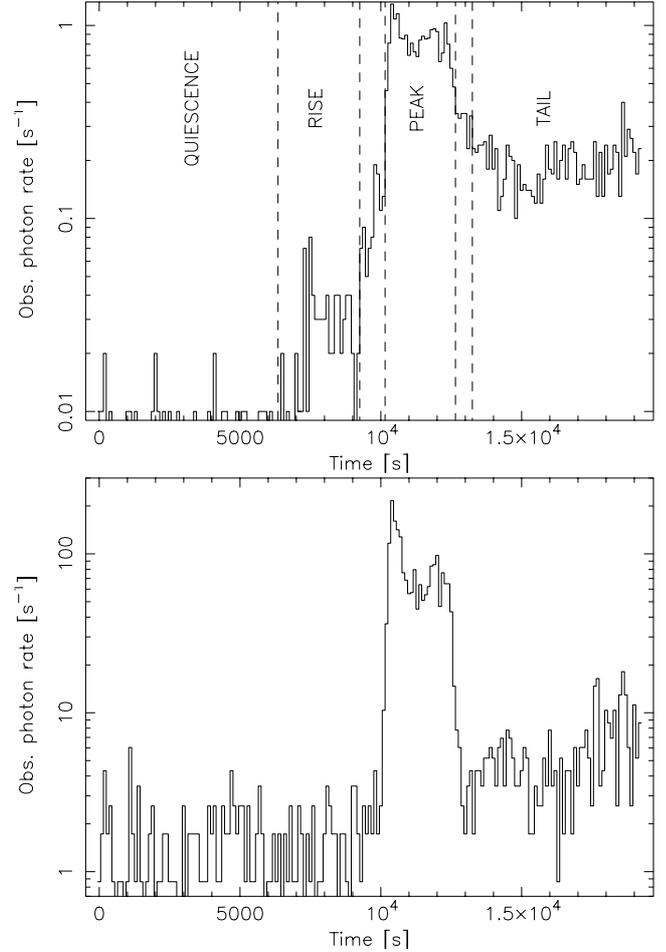
Fig. 2. *Top*: Chandra light curve of IGR J17544-2619 from all photons extracted from 4.''5 from the centroid. The photon rate is not corrected for pile up. The background count rate is 2.5×10^{-4} phot s^{-1}. *Bottom*: light curve from trailed image. No background subtraction was applied. The photon rate during the first 6300 s, 1.55 ± 0.01 s^{-1}, is due to the background.

photon position according to the Mexican Hat wavelet method employed in CIAO tool `wavdetect` is $\alpha_{2000.0} = 17^h54^m25^s284$, $\delta_{2000.0} = -26°19'52.''62$ ($l^{II} = 3°23$, $b^{II} = +0°33$). The nominal uncertainty is 0.''6. This position is 1.''2 from the XMM-Newton position (see Fig. 1) and 0.''2 from the previously identified optical counterpart (Rodriguez 2003).

Figure 2 (top) shows the time profile at 100 s resolution of the rate of all 4191 observed photons within a 4.''5 accumulation radius from the centroid. Interestingly, the source shows two markedly different states. During the first 6300 s the source is very faint with a mere 26 detected photons. Subsequently, it rises in two steps over 3700 s to a level that is approximately 250 times brighter. Thereafter it decays down to a level 4 times fainter at which it remains for the 5000 s remainder of the observation. To assess the true dynamic range (corrected for pile up), we made a light curve of all 2934 photons in the readout trails that are at least 25'' from the centroid, employing CIAO tool `acisreadcorr`. Such counting rates are not subject to pile up for photon rates below a few thousand s^{-1}, because in the readout mode the CCD pixels have an effective readout time of only 40 μs. The result is provided in the bottom panel of Fig. 2.

Table 1. Power law spectral fits to the 4 different states indicated in Fig. 2. Errors are for 90% confidence.

State	$N_{\rm H}$ (10^{22} cm^{-2})	Γ	Obs. flux[‡]	Unabs. flux[‡]	χ^2_ν
quiescence[★]	1.36[†]	5.9 ± 1.2	$1.4^{+0.3}_{-0.2} \times 10^{-14}$	$9.3^{+15.4}_{-5.8} \times 10^{-13}$	38%[+]
rise[★]	$\downarrow$	$\downarrow$	$8.4^{+2.1}_{-2.1} \times 10^{-13}$	$9.8^{+2.4}_{-2.4} \times 10^{-13}$	$\downarrow$
peak[×]	1.36 ± 0.22	0.73 ± 0.13	$2.31^{+0.09}_{-0.09} \times 10^{-9}$	$2.69^{+0.11}_{-0.11} \times 10^{-9}$	0.839 (144 d.o.f.)
postflare[×]	$\uparrow$	$\uparrow$	$1.35^{+0.13}_{-0.13} \times 10^{-10}$	$1.57^{+0.15}_{-0.15} \times 10^{-10}$	$\uparrow$

[†] Fixed; [‡] average flux in 0.5–10 keV (erg cm^{-2} s^{-1}); [★] these spectra were extracted from the point spread function with extraction radii of $1''.5$ and $5''.0$ for the quiescence and rise data, respectively; [×] these spectra were extracted from the readout trails; [+] this is the goodness of fit as determined through 10^4 Monte Carlo simulations. It is the percentage of simulations with a goodness of fit parameter better than measured, based on the best fit model.

The peak rate is 214.5 ± 2.1 s^{-1} (background subtracted). This is 6.5×10^4 times larger than during quiescence.

We used the 40 μs resolved trail data to search for a ms pulsar signal by constructing Fourier spectra for every CCD frame with a net exposure time of 41 ms, and averaging the spectra. We followed this procedure for all data as well as for only those pertaining to the peak and postflare intervals. No periodic signal was found. The 3σ upper limit on the amplitude of a sinusoidal signal is ~10%.

We extracted spectra for four characteristic flux levels which are indicated by dashed lines in Fig. 2 (top): quiescence, rise, peak and tail. The first two spectra were taken from within circles centered on the source position with different accumulation radii. The extraction radius for the quiescent spectrum was chosen to be $1''.5$, which is small in order to minimize the background (0.7 background photons are expected in this region). For a soft quiescent spectrum (see below) the encircled energy is still 90 to 95% for such a radius. The spectra for the latter two time intervals, where pile up is heavy, were taken from the readout trails. Quick inspection of the spectra reveals that there is an obvious change in the hardness of the spectrum between quiescence and thereafter. All photons of the former spectrum are detected between 1.0 and 2.2 keV while for the rising part and the peak part the fraction of photons above 2.2 keV is 72% and 74%, respectively.

We modeled all spectra with an absorbed power law, using XSPEC vs. 11.3.1 (Arnaud et al. 1996). For the quiescent spectrum we applied the Cash statistic (Cash 1979) because of the low number of photons; for the remaining spectra the chi-squared statistic was used, after rebinning energy channels so that each channel contains at least 15 photons. The three non-quiescence spectra were fitted simultaneously, employing a single free hydrogen column density, which parametrizes the low-energy absorption (Morrison & McCammon 1983), and a single photon index Γ. The results are provided in Table 1. The fitted value for $N_{\rm H}$ is, within errors, identical to the interstellar value of $(1.4 \pm 0.2) \times 10^{22}$ H-atoms cm^{-2} (Dickey & Lockman 1990). When leaving free $N_{\rm H}$ or Γ, the fit did not improve (i.e., χ^2_ν did not decrease).

The quiescent spectrum could also be satisfactorily fitted with a NS hydrogen atmosphere model following Pavlov et al. (1994) and Zavlin (1996), with $N_{\rm H}$ fixed to 1.36×10^{22} H-atoms cm^{-2}. The fit was similar in quality: 37% of 10^4 Monte Carlo

simulations based on the best-fit model had a smaller C statistic than observed. We find for a NS at 3.5 kpc with $M = 1.4\,M_\odot$, $R = 10$ km and $B = 0$ G a temperature of 90 ± 10 eV. The unabsorbed 0.5–10 keV flux is $(1.9 \pm 0.4) \times 10^{-13}$ erg cm^{-2} s^{-1}.

3. Discussion

The observation was fortunately timed catching the source both in quiescence and outburst. The outburst phase provides an unambiguous identification and the quiescence phase a constraint for the nature of the accretor as follows. Kong et al. (2002) reports Chandra ACIS-S spectra of four quiescent BH systems and find that these can all be best modeled with an (absorbed) power law with Γ between $1.70^{+0.88}_{-0.78}$ and $2.28^{+0.47}_{-0.64}$ (90% confidence level error margins). Other simple models also fit the data, except the black body model. The power law model is consistent with an advection-dominated accretion flow according to Kong et al. Similar results were obtained on other BH candidates (Tomsick et al. 2003). The quiescent spectrum of IGR J17544-2619 does not adhere to this rule. That suggests that IGR J17544-2619 is *not* a BH candidate, but a NS. The quiescent flux corrected for absorption and extrapolated to 0.01–10 keV is $(3.5 \pm 0.9) \times 10^{-13}$ erg cm^{-2} s^{-1}, based on the NS model spectrum. This translates to a luminosity at 3.5 kpc of $(5.2 \pm 1.3) \times 10^{32}$ erg s^{-1}, a reasonable value for a NS.

However, OB stars also emit X-rays with similarly soft spectra. In a list of optically bright OB-type stars observed with ROSAT (Berghhöfer et al. 1997a,b) there are 14 O9I/II supergiants. Six were detected with luminosities between 1.7 and 7.1×10^{32} erg s^{-1} and eight were not detected with upper limits from 0.4 to 1.7×10^{32} erg s^{-1}. Thus, a considerable portion of the observed luminosity may be explained by radiation from the donor star. Given the statistics, though, it is more likely that most comes from the accretor.

We speculate on the origin of the outbursts, that are so brief compared to typical transient X-ray binary outbursts of at least a week. Our study shows that this is probably unrelated to the nature of the compact object, given that IGR J17544-2619 probably contains a NS while V4641 Sgr contains a BH (Orosz et al. 2001). Rather, it must be related to the donor star. As already noted by In 't Zand et al. (2004) and Smith (2004), optical counterparts for three fast X-ray transients have been identified and all are of early spectral type (O9Ib for

Letter to the Editor

IGR J17544-2619, O8 for XTE J1739–302 and B9 for V4641 Sgr). Many early-type stars are suspected to have massive winds driven by resonance line scattering that are highly structured and variable (e.g., review by Owocki 1997; see also Lamers & Cassinelli 1999). A star that is particularly interesting in the present context is the B0 main sequence star τ Sco whose otherwise homogeneous wind is thought to contain at any time 10^3 clumps with masses of order 10^{19-20} g (Howk et al. 2000). A sizeable fraction of these may fall back to the star, giving rise to shock X-ray emission and redshifted spectral features, while others may flow with the wind. Thus, it is fairly well established that clumpy winds can exist in early-type stars and clump capture by a nearby compact object may explain the time scale of the X-ray flares. Surprisingly, the masses of the clumps in τ Sco are a good match to the fluence of the transient outburst within an order of magnitude, assuming that all gravitational energy provided by the fall of the clump on a NS is liberated in the form of radiation. Modeling of this effect for a supergiant rather than main sequence star and for an earlier spectral class than for τ Sco should be carried out to verify whether the outburst duration and recurrence time make sense in this scenario.

Our improved positional accuracy (by a factor of 6 in one axis) confirms the identification with 2MASS J17542527-2619526. An initial spectroscopic study of that star is being carried out by Pellizza et al. (in prep.). As a follow-up it is important to carry out time-resolved spectroscopy of this star. Measurements of Doppler-shifted spectral lines may provide constraints on key parameters such as the orbital period and the mass of the compact object. The shape of the lines is instrumental in determining the outburst mechanism: it may show signs of the clumpiness of the wind (e.g., Howk et al. 2000) or of strong variability in wind speed and/or density (e.g., Lindstrøm et al. 2005). Preferably, there should be simultaneous optical and X-ray observations.

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