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Monitoring of the peculiar X-ray binary pulsar SAX J0635.2+0533

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The X-ray binary pulsar SAX J0635.2+0533

Discovered with *BeppoSAX* in 1997 (Kaaret et al. 1999):

- $f(2-10 \text{ keV}) = 1.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \Rightarrow L_X = 3.4 \times 10^{34} \text{ erg s}^{-1}$
- hard power-law spectrum ($\Gamma = 1.5$), extending up to 40 keV
- positionally coincident with a Be star ($V = 12.8$) $\Rightarrow$ HMXRBs
- X-ray pulsations with $P_{\text{spin}} = 33.8 \text{ ms}$ (Cusumano et al. 2000)

$B \sim 10^9 \text{ G}$ for accretion onto the NS surface

quite a peculiar object

Pulse frequencies measured with *RXTE* in September 1999 (Kaaret et al. 2000):

- discovery of a possible orbital modulation with $P_{\text{orb}} = 11.2 \text{ days}$
- lower limit ($\dot{P}_{\text{spin}} > 3.8 \times 10^{-13} \text{ s s}^{-1}$) on its long-term spin down

possible large rotational energy loss ($\dot{E}_{\text{rot}} > 4 \times 10^{38} \text{ erg s}^{-1} \gg L_X$)

possibility of a rotation-powered pulsar:

the X-ray emission is due to the shocks between the relativistic wind of the pulsar and that of the companion star

In-depth timing and spectral analysis of SAX J0635.2+0533

1) We investigated the long-term variability of SAX J0635.2+0533 through:

- a systematic reanalysis of all the *RXTE* observations performed between 1999 and 2001 (epochs A, B, and C)
- a systematic reanalysis of all the *XMM-Newton* observations performed between 2003 and 2004 (epochs D and E)
- a new long-term source monitoring performed with *Swift*/XRT between 2015 and 2016 (epochs F and G)

$\Downarrow$

- SAX J0635.2+0533 was clearly detected in most of the observations, although at very different flux levels (Fig. 1 and 2).
- The source is very variable, with a dynamic range of more than two orders of magnitude
- The source variability is rather fast: the source flux can increase/decrease of more than one order of magnitude over a timescale of a few days
- In most observations the source was detected with $f_X \sim 10^{-13} - 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \Rightarrow L_X \sim 10^{32} - 10^{33} \text{ erg s}^{-1}$ (assuming $d = 5 \text{ kpc}$)

2) We searched for the presence of pulsations in the data of epochs B and C, that were not analyzed by Kaaret et al. (2000): we took into account a possible spin-up or spin-down of the pulsar since the time of the previous period measurement ($P = 33.9 \text{ ms}$ in epoch A), but we could not confirm the pulsed emission

3) We investigated the possible spectral dependence on the source flux: we considered two separate spectra (with similar count statistics) for, respectively, the high and low flux states observed with *Swift*/XRT, but the simultaneous fit of the two spectra provided no evidence of spectral variability

4) We searched for long-term periodicities in the *Swift*/XRT data by applying the Lomb-Scargle method (Scargle 1982), but we could not confirm the proposed orbital period of 11.2 days (Kaaret et al. 2000)

$\Rightarrow$ See La Palombara & Mereghetti 2017, A&A 602, A114

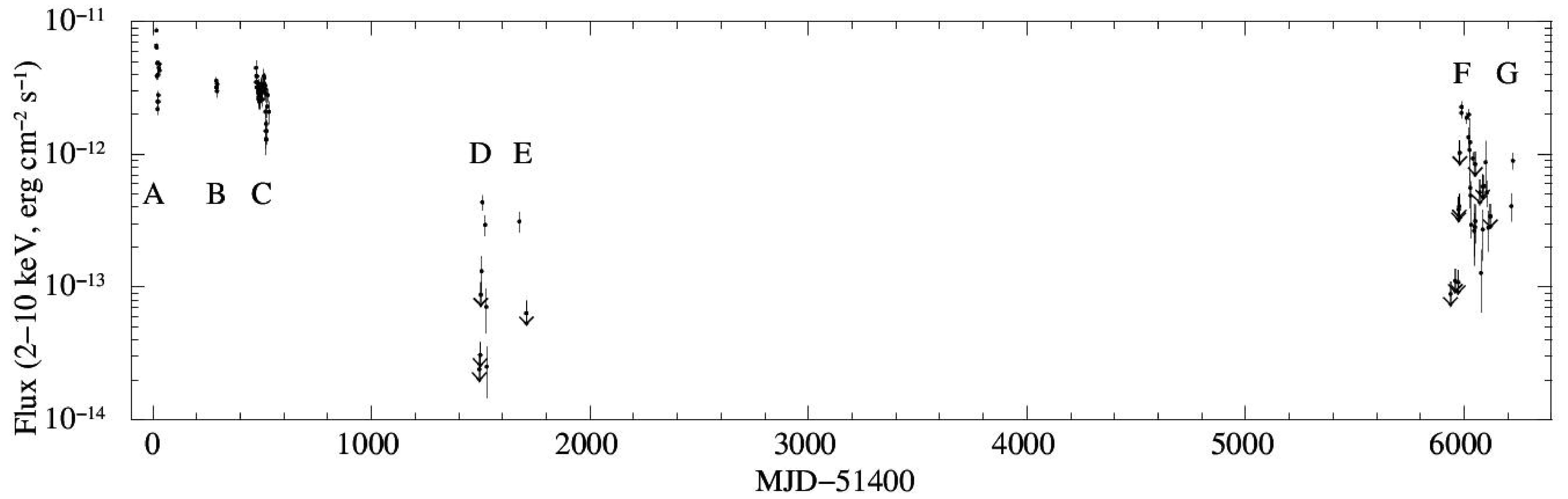


Fig. 1: long-term light curve of SAX J0635.2+0533 since MJD = 51400 (10 August 1999), with all the flux measurements (with different telescopes) obtained after the source discovery in 1997

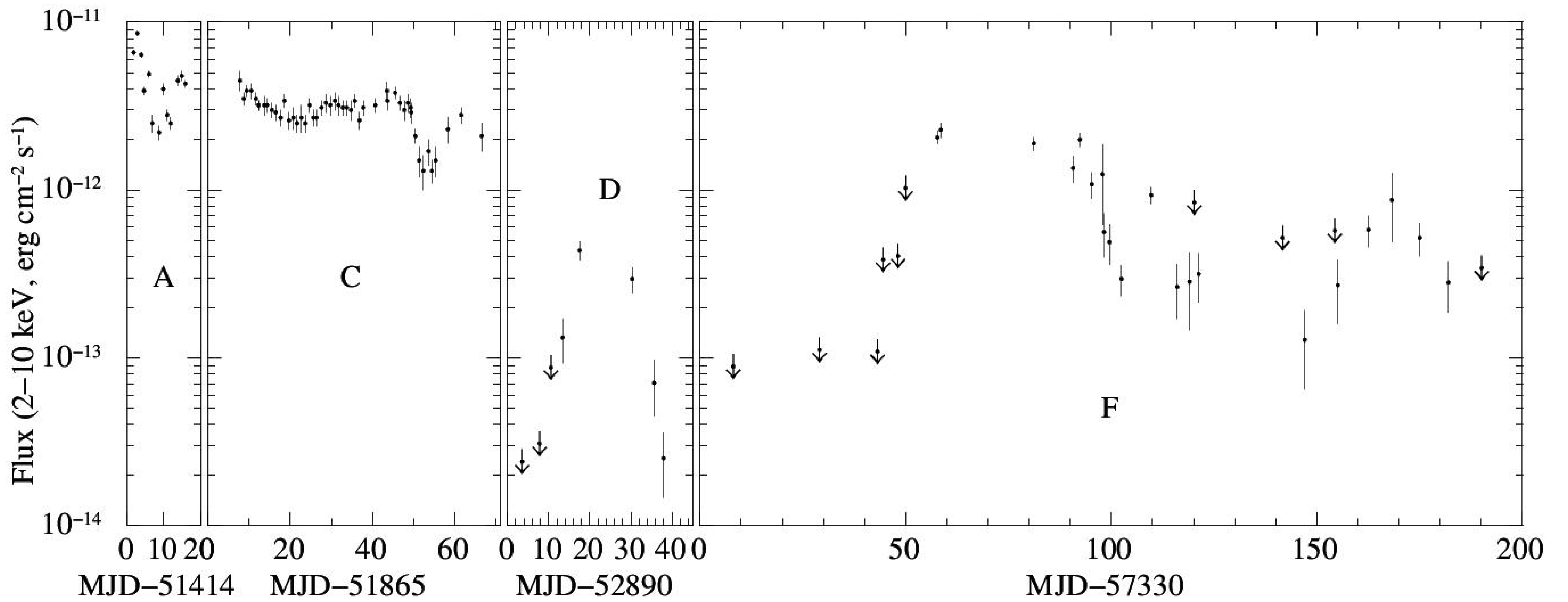


Fig. 2: zoom into the observations of epochs A, C, D, and F, respectively; for a better comparison of the flux variability among the different epochs, the same scale for the time and flux axes is used

The X-ray emission of SAX J0635.2+0533

In the latest years similar quiescent luminosities have been observed in several Be X-ray binaries, and various emission mechanisms have been proposed to explain them (see e.g. Tsygankov et al. 2017a). In the case of SAX J0635.2+0533, the high and fast variability implies that the emission is due neither to the companion Be star nor to the cooling of the NS crust

the source emission is most likely due to matter accretion

Very short pulse period $P_{\text{spin}} = 33.8 \text{ ms} \Rightarrow$ several constraints on the accretion regime:

- no possibility of accretion from a cold recombined disc, regardless of the magnetic field (Tsygankov et al. 2017b)
- very unlikely the subsonic accretion, even in the case of plasma radiative cooling (Shakura et al. 2013)

For a typical neutron-star magnetic field ($B = 10^{12} \text{ G}$)

the low source luminosity can be explained only with a propeller regime, where the accreting matter is stopped by the centrifugal barrier at the magnetosphere

Comparison with other BeXRBs

In Fig. 3 we report the $L_{\text{max}}/L_{\text{min}}$ ratio as a function of L_{max} for several known BeXRBs:

- open circles (o) = transient MW sources (Tsygankov et al. 2017a)
- crosses (x) = SMC sources (Haberl & Sturm 2016)
- filled circles (•) = persistent, long-spin-period and low-luminosity BeXRBs (see e.g. La Palombara et al. 2012)
- star (☆) = short-period ($P_{\text{spin}} = 69 \text{ ms}$) binary pulsar A0538-66 in the LMC (Skinner et al. 1982; Kretschmar et al. 2004)

- in both the MW and the MCs the source dynamic range increases with L_{max} , while the low-luminosity sources are also less variable
- lack of persistent high-luminosity sources (lower-right corner of the figure), due to the transient nature of the BeXRBs
- SAX J0635.2+0533 is clearly an outlier: it shows the largest dynamic range ($L_{\text{max}}/L_{\text{min}} \approx 400$) among the less luminous sources

SAX J0635.2+0533 has rather peculiar properties, at variance with those of the typical accretion-powered BeXRBs

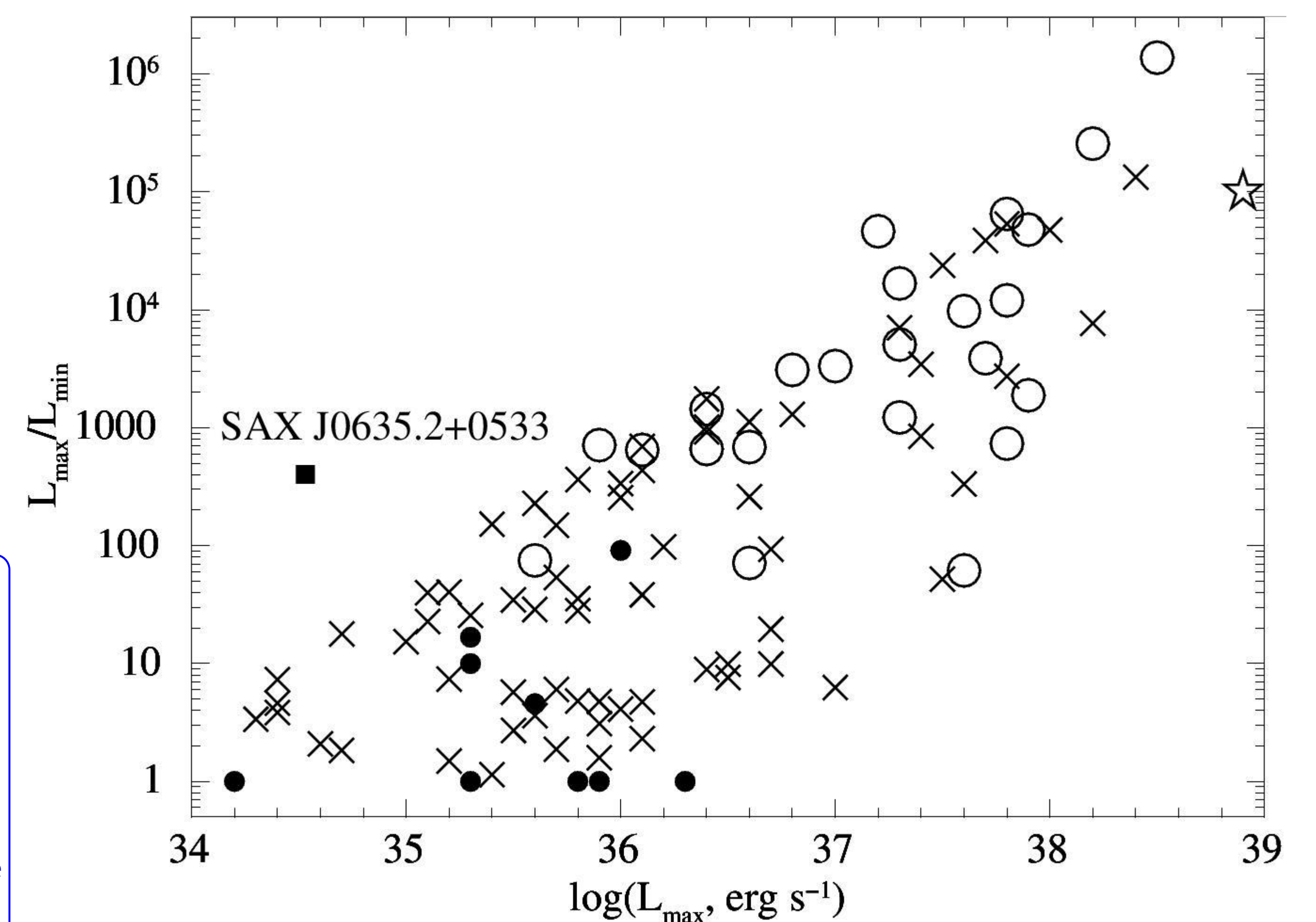


Fig. 3: X-ray luminosity ratio $L_{\text{max}}/L_{\text{min}}$ as a function of L_{max}