A puzzling event during the X-ray emission of the binary system GX 1+4

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Abstract

We report on a long X-ray observation of the slow-rotating binary pulsar GX 1+4. BeppoSAX observed, in the 0.1–200 keV energy range, an event in which the source flux dropped for almost a day, and then recovered. During this event only the high-energy emission was found to be pulsed and the pulsations were shifted in phase of ∼ 0.2. The spectrum during the event was well fitted by a Compton-reflection model. A broad iron line at ∼ 6.55 keV was present outside of the event, where instead two narrow emission lines at ∼ 6.47 keV and ∼ 7.05 keV were detected. The pulse profile was highly variable as a function of both energy and time. We interpret this low-flux event as an occultation of the direct X-ray emission, due to the increase of a torus-like accretion disk; we then discuss similarities between this source and the recently discovered highly absorbed INTEGRAL sources.

Key words: Neutron star, pulsar, binary system, GX 1+4, Compton reflection
GX 1+4 is an X-ray binary system harboring a $\sim 130$ s pulsar ([13, 10, 8]) accreting mass from a red giant companion of class M5 III (V2116 Ophiuchi; [6,2,4,18]). Among the large X-ray binary zoo, we know so far only another system hosting a neutron star (NS) with a red giant companion: 4U 1700+24 ([16,9]). GX 1+4 shows an unpredictably variable X-ray flux on timescales from hours to decades. At the time of its discovery ([13]) it was one of the brightest object in the X-ray sky and it had the largest spin-up rate recorded for any pulsar at that time. The average spin-up trend reversed inexplicably in 1983 switching to spin-down at approximately the same rate. So far a remarkable number of changes in the sign of the torque has been observed for this source ([3]).

This is somehow a peculiar object among the X-ray binaries not only because of its red giant companion, but also because of the high magnetic field that the NS is believed to have ($\sim 2 - 3 \times 10^{13} \text{G}$; [7,11,5]). In fact, the presence of a such high magnetic field in a slowly rotating NS with a red giant companion is an intriguing puzzle for the evolutionary scenario of this system.

Here we report on the timing and spectral X-ray properties of GX 1+4, in particular on a strange drop in the flux occurred in 2000 November 1st during a BeppoSAX observation.
2 Timing and spectral analysis

The BeppoSAX observatory covered more than three decades of energy, from 0.1–200 keV. The payload was composed by four co-aligned instruments: the Narrow Field Instruments ([1]: LECS, 0.1–10 keV; MECS, 1–10 keV; HPGSPC, 4–100 keV; PDS, 15–200 keV) and the Wide Field Cameras ([12]). All the four NFI instruments were on during the ∼3.5 days BeppoSAX observation carried out around 2000 November 1st.

The lightcurve of the X-ray source, in the 0.1–200 keV energy range, showed a large flux variability (see Fig. 1). We searched for coherent pulsations performing a power spectrum analysis followed by a phase-fitting analysis, and we found the spin period value of $P_s = 134.925 \pm 0.001$ s (phase zero calculated at TJD 11785.000781; errors in the text are at 1σ confidence level). In order to study the possible evolution or changes of the timing properties of the source, we divided the observation in 10 time intervals and looked for pulsations all over each interval in different energy bands. Making this division we noticed that outside of the low X-ray flux event, all instruments showed pulsations at the same spin period $P_s = 134.925 \pm 0.001$ s in the whole BeppoSAX energy range (see Fig. 2), while in interval D no pulsed emission was detected below ∼7 keV. As we can see from Fig. 2, the pulse shape was highly variable either in time or in energy. Comparing the phase at which the minimum of the pulse occurs among the HPGSPC profiles, we found shifts in phase between all curves: e.g. the folded lightcurve in the interval L is shifted in phase by 0.22±0.05 with respect to that in the interval D. Along with the pulse profile
changes, the pulsed fraction also varies. During the event the pulsed fraction below 7 keV was consistent with zero (6% upper limit), while it increases until 20 ± 4% in the 7–35 keV energy range.

In order to fit the spectra of the source in all the intervals, we first tried several simple models such as a bremsstrahlung emission, as a blackbody plus a power-law, or as a multicolour blackbody, but all these models gave a bad chi-square value. Noticing then that the source spectrum in the low-flux state was exactly what is expected for a Compton-reflection dominated spectrum, we tried to fit all the spectra with an absorbed cut-off power law with a reflection component (pexrav model in Xspec; [15]). This was actually the best model for all the time resolved spectra ($\chi^2_\nu \sim 0.98 - 1.1$) with a very small relative reflection strength (refl ≃ 0–0.3) outside the event and being 42 ± 3 during the low-flux event (see Fig. 3). The $N_H$ ranged between 7–48×10^{22} cm$^{-2}$, reaching the maximum values just before and after the event, while at higher energies, the spectrum showed a hardening when the Compton scattering component started to dominate, soon after the flux dropped.

All time-resolved spectra showed at least one emission line. Only one broad ($\sigma \sim 0.3$ keV) Fe emission line was present at $E \sim 6.55$ keV outside of the low-flux event, while in the intervals D and E, the reduced persistent flux revealed the presence of two narrow lines at $\sim 6.45$ keV and $\sim 7.05$ keV, with very high equivalent widths ($\sim 2.1$ and 0.5 keV, respectively). The interpretation of all these lines is very difficult and uncertain considering the limited energy resolution of the MECS. Thus, we can only speculate on the origin of the lines. Our idea is that the broad line at 6.55 keV might be the blend of the neutral Fe $K_\alpha$ around 6.4 keV and the ionized Fe XXV at 6.7 keV, while during the event only the neutral Fe components are present, the $K_\alpha$ and the $K_\beta$. 

Fig. 3. Comparison of the spectrum out and during the low-flux event (the spectra of intervals A and D are the top and bottom data, respectively). Both continuum spectra are fitted with the Xspec model: wabs*pexrav, but with largely different spectral parameters (see text for details).
3 Discussion

We report here on the longest uninterrupted observation of the X-ray binary system GX 1+4. The most important results of this analysis are: i) a Compton-reflection component dominates the source spectrum during a low-flux emission event, ii) the discovery of the line at \(\sim 7.05\) keV during such low-intensity event, iii) during the latter, a pulsed X-ray emission was detected only at energies \(> 7\) keV, vi) the detection of a highly variable pulse profile and v) the detection of a shift in phase of the minimum of the high-energy pulse profile during the low-flux event.

Hereafter we consider a few models for this event taking in account the results of our analysis. Our first idea was that the X-ray source entered in a different emission status (as happen for some X-ray binaries), where the flux diminishes and the spectrum changes. However, since one spectral model was able to describe all the spectra and that the spectrum during the low-flux event was Compton-reflection dominated, we ruled out this first hypothesis.

In fact, the reflection component should be produced by a Compton thick material that reprocesses the source photons. This reprocessing occurs through the Compton-reflection process, where X-rays and \(\gamma\)-rays emitted by a source impinge upon a slab of material (e.g. accretion disk) and re-emerge with a spectrum altered by the Compton scattering and the bound-free absorption. This process cause a characteristic hardening in the X-ray spectrum which is due to the onset of the reflected component, which appears at energies \(>10\) keV, as a result of the increased importance of the Compton scattering in comparison with the bound-free absorption, which instead dominates at low-energies ([21, 14]). At this point, we were then interested to figure out the geometry and the nature of the material responsible for the reflection.

Concerning the geometry, one possibility is that the NS was simply hidden in a partial eclipse caused by the giant companion. The partial covering might be due to part of the giant star (a spherical cap) which temporarily occults the NS direct X-ray emission from our line of sight. Although this eclipse scenario is consistent with the source variability, however, a wide solid angle of Compton thick material around the source is needed in order to produce such highly reflection dominated spectrum, and this large solide angle cannot be produced by the stellar companion wind only. Moreover, taking into account the large size of the companion star compared with the \(10\) km radius of the NS, the occurrence of a \(\sim 90\) ks eclipse, requires an ad hoc fine tuning of the line of sight inclination with respect to the orbital plane.

Another possible geometry might be a torus-like accretion disk around the compact source, due to matter coming from the giant companion. The lobes
of the torus become thicker and increase in volume with increasing of the accretion rate. The direct emission of the NS would had been hidden by one side of the torus while the other side of the torus reflected it, causing the drop of the flux and the Compton reflected spectrum.

This model can explain as well the lack of detection of the low-energy pulsations, as they are too weak to keep their coherence through the scattering in the thick torus material. Moreover, during the low-emission event the photons make a different path before reaching the observer, compared to the direct emission phases, and this can be the cause of the shift in the spin-phases revealed in the high-energy pulsations (see Fig. 2 right panel).

This scenario requires an highly variable mass accretion rate, possibly due to a variable mass loss from the red giant companion, which is expected from these stars. Thus, note that the accretion rate variability of this source, is well supported by the detections of spin-torque variations in the source timing history ([3]).

This latter model we propose in order to explain the low-flux event, is in analogy with what was proposed for some AGN sources and for some of the highly absorbed INTEGRAL sources ([20,19,17]). If this scenario is correct we can imagine that the highly absorbed INTEGRAL sources are compact binary systems of this type for which our unlucky line of sight, hides the direct emission of the compact object behind the accretion torus lobes. Note that the absorption value reached by GX 1+4 in some part of the observation is similar of the $N_H$ found for some of this highly absorbed INTEGRAL sources, although a Compton-reflection component was never unambiguously revealed in these sources so far.

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