THE ASTROPHYSICAL JOURNAL, 394:615–618, 1992 August 1

SIGMA DETECTION OF HARD X-RAY EMISSION FROM THE SOFT TRANSIENT TYPE I X-RAY BURSTER KS 1731−260

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Received 1992 January 2; accepted 1992 February 4

ABSTRACT

During the observations of the Galactic center region performed by the French hard X-ray/soft γ-ray telescope SIGMA, several transient sources were detected. One of them was the soft transient type I X-ray burster KS 1731−260 recently discovered by the TTM experiment aboard the Soviet *MIR-KVANT* observatory. The SIGMA observations of KS 1731−260 reveal the existence of a hard state for which the spectrum extends up to 150 keV, with a power-law shape having a photon spectral index of ≈ 2.9 (± 0.8). Consequently KS 1731−260 can be added to the list of hard X-ray sources recently discovered by SIGMA in the vicinity of the Galactic center. Furthermore, this result indicates that the high-energy tail commonly observed among the ultra-soft transient sources, which are thought to be black holes, may also be an attribute of transient systems where the compact object is a weakly magnetized neutron star.

Subject headings: stars: individual (KS 1731−260) — X-rays: bursts — X-rays: stars

1. INTRODUCTION

The discovery of KS 1731−260 by the coded mask imaging spectrometer TTM on the *MIR-KVANT* observatory, in the X-ray energy range ($E < 30$ keV), was first reported by Sunyaev (1989). The position of KS 1731 − 260 derived by TTM was $\alpha = 262^\circ.78$, $\delta = -26^\circ.053$ (1950 equinox, error circle radius 1′). The source, which was in a high state from 1989 August 16 to 31, displayed intensity variations in the 2–27 keV energy band ranging from 50 to 100 millicrab with a corresponding mean value of 83 millicrab. Averaged over the whole outburst, the spectrum is well fitted by a thermal bremsstrahlung model with a temperature of about 5.7 keV, and a corresponding 3–20 keV X-ray luminosity of 1.5×10^{37} ergs s^{-1} for an assumed distance of 8.5 kpc (Sunyaev 1989, Sunyaev et al. 1990a). In addition, during the same observations, at least 13 type I X-ray bursts per day with durations of 10–20 s and peak fluxes up to 0.6 crab were recorded from KS 1731−260. In 1990 the source was detected on two occasions, April 4 and August 23, by the ART-P imaging instrument ($E < 30$ keV) aboard the *GRANAT* spacecraft. The 3–20 keV X-ray luminosities inferred from these two observations were 2.1×10^{37} ergs s^{-1} and 1.2×10^{37} ergs s^{-1}, respectively (Sunyaev et al. 1990a, b).

Following the classification of transient X-ray sources made by White, Kaluziensky, & Swank (1984) on the basis of their spectral signatures in the soft X-ray range ($E < 10$ keV), KS 1731−260 belongs unambiguously to the soft X-ray transient class (hereafter SFXT), containing the well-studied sources Aql X-1, Cen X-4, and 4U 1608−522. Often referred to as X-ray novae, these sources undergo outbursts, reaching luminosities of 10^{37}–10^{38} ergs s^{-1}, for a few weeks to a few months with a recurrence time on the order of a few years. Moreover, they are characterized by (1) the absence of observable pulsations, indicating a weak magnetic field, and (2) a faint blue optical counterpart, attesting to the presence of a low-mass late-type companion. Another feature of SFXTs is the emission, during the decay phase or during the maximum, of type I X-ray bursts widely believed to result from the thermonuclear burning of hydrogen and/or helium on the neutron star surface (Lewin & Joss 1983). All these similarities with the bright persistent bursting X-ray sources located in the galactic bulge immediately suggest that SFXTs are accreting neutron stars in low-mass binary systems (LMXRBs) with the mass transfer caused by a late-type star filling its Roche lobe (White et al. 1984). This is supported by the determination of the orbital period in Cen X-4 by Chevalier et al. (1989).

While there are many observations in the classical X-ray energy range ($E < 20$ keV), only a few reliable measurements at high energy exist. However, the few data available suggest that high-energy emission ($E > 10$ keV) is present at least at some stages of the outburst (Bouchacourt et al. 1984 for Cen X-4; Mitsuda et al. 1989 and Gottwald et al. 1987 for 4U 1608−522). In this paper we report the observations of KS 1731−260 at hard X-ray energies (above 35 keV), revealing the existence of a hard state, for which the energy spectrum extends up to 150 keV. The observations were achieved by the French hard X-ray/soft γ-ray coded-mask imaging telescope SIGMA on the *GRANAT* observatory. With the two new black hole candidates 1E 1740.7−2942 and the newly discovered GRS 1758−258 (Sunyaev et al. 1991), the hard X-ray source probably located in the globular cluster Terzan 2 (Barret et al. 1991), and the binary pulsar GX 1+4 (Denis et al. 1991), KS 1731−260 is the fifth hard X-ray source reported by SIGMA in the vicinity of the Galactic center. We note that, as in the case of the soft X-ray source GX 5−1 which was incorrectly associated with the nearby *GRANAT* hard X-ray source

GRS 1758−258, KS 1731−260, which is located only ≈1° away from GX 1+4, may have caused confusion to previous nonimaging experiments. Furthermore the high variability of these objects in the SIGMA energy band clearly demonstrates the need for imaging instruments when observing sky regions containing numerous time-variable X-ray sources.

2. OBSERVATIONS AND RESULTS

The SIGMA telescope, operating in the 35–1300 keV energy range, was successfully launched from the Baïkonour Space Center (USSR) on 1989, December 1. It was designed to provide arcminute resolution images over a field of view of 4°.7 × 4°.3 for the first time in this energy range. This full sensitivity field of view is surrounded by a so-called partially coded field of view of decreasing sensitivity (the half-sensitivity boundary is an 10°.9 × 11°.5 rectangle). Due to its wide field of view and its good angular resolution, SIGMA is well suited for observations in confused regions like the Galactic center. The telescope consists mainly of a NaI position-sensitive detector based on the Anger camera principle, associated with a tungsten-coded mask, whose basic pattern is a uniformly redundant array (URA; Fenimore & Cannon 1978). During a typical 1 day long observation (≈20 hr), the telescope operating in the "spectral imaging" mode records six series of four high-resolution images (248 × 232 1'.6 pixels) in four adjacent energy intervals and three series of 95 low-resolution images ("spectral images" with 124 × 116 3'.2 pixels) in 95 fixed energy channels covering the whole energy range with a width varying with the energy resolution of the instrument. For a full description of the SIGMA experiment, as well as its various operating modes, see Paul et al. (1990); for its in-flight performance, the reader is referred to Mandrou et al. (1990).

The Galactic center region was observed by the SIGMA telescope more than 25 times in 1990 spring and fall, and in 1991 winter and spring. In 20 of these observations, KS 1731−260 was located either in the fully or partially coded field of view. A source located in the full sensitivity field of view casts a shadow of the complete pattern of the mask onto the detector. Its flux is totally modulated by the mask before being recorded by the detector. On the other hand, when the source is in the partially coded field of view, the detector is shadowed by an incomplete mask pattern. However, it is still possible to reconstruct the position of the source with the nominal angular resolution of 15' (several arcminute positioning accuracy depending on the strength of the source), but the sensitivity is decreased according to the fraction of the mask pattern projected on the detector. To take into account the partial modulation of the flux, we compute an average sensitivity factor during the pointing.

To search for the source, all 20 observations were analyzed following standard techniques: the images were "flat-fielded" to remove spatial nonuniformities intrinsic to the detector or due to the background and then cross-correlated with the mask pattern. The signal-to-noise ratio is computed as the ratio of the net source counts to the statistical error, defined as the square root of the total counts in the image before the deconvolution procedure. KS 1731−260 was detected only once during the 20 observations, on 1991 March 14. Operating in the spectral imaging mode, SIGMA was pointed for ≈20 hr (duration corrected for the instrumental dead time) in the direction of the well-known γ-ray source 1E 1740.7−2942. KS 1731−260, which is located about 4°.5 from this source, was then in the partially coded field of view with a corresponding sensitivity factor of about 0.66. In the high-resolution image, integrated over the whole session and corresponding to the 40–130 keV energy range, a clear excess is present at $\alpha = 262°.8$, $\delta = -26°.09$ (1950 equinox). The associated error radius is ≈0°.07 at a 90% confidence level. The size of the error box takes into account both the SIGMA positioning accuracy for weak sources and the uncertainty in the satellite attitude. The SIGMA position of KS 1731−260 is fully compatible with the TTM position reported in Sunyaev et al. (1989). The day after the March 14 session, a strong solar flare occurred, prematurely interrupting the observation once again devoted to the Galactic center. These perturbations lasted ≈17 days, and for the first nominal observation the source was not detected, indicating that it had returned to its quiescent state in the hard X-ray range.

The observed spectrum is obtained by taking the counts in each of the 95 spectral images, integrated over the whole session, in the pixel corresponding to the SIGMA source position. KS 1731−260 is detected in the 40–150 keV energy range at a significance level of 5.8 σ. We have evaluated the probability of detecting a peak at 5.8 σ significance assuming that the peak results from a background fluctuation. The probability of finding such an excess within the SIGMA error box of KS 1731−260, has been found to be of the order of 10^{-4}.

The observed spectrum has been fitted in the counts space folding an incident power law with the complete energy response of the telescope (Barret & Laurent 1991). A more complicated model than a simple power law is not justified by the statistical quality of the data. The power-law parameters are adjusted until the minimum χ^2 value is reached by a standard gradient search method. The best-fit power-law spectrum obtained in this way is

$$\Phi(E) = 10^{-4}(1.0 \pm 0.28)\left(\frac{E}{70\ \mathrm{keV}}\right)^{-(2.9 \pm 0.8)} \quad \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}\,,$$

with a reduced χ^2 of 0.8 for 11 degrees of freedom. The errors given are at the 68% confidence level for joint variation of the two fitting parameters. Figure 1 shows the SIGMA data points together with the best-fit power-law model. This best-fit power-law spectrum corresponds to an integrated flux of $\approx 10^{-2}$ photons cm^{-2} s^{-1} and an associated luminosity of ≈9 (±3) × 10^{36} $(d_{\mathrm{kpc}}/8.5)^2$ ergs s^{-1} in the 40–150 keV energy range.

Using all the observations (≈200 hr), from 1989 March to 1991 April, for which KS 1731−260 was not detected above the 2 σ level, we have computed 2 σ upper limits to its quiescent emission. The 200 hours correspond to the sum of the effective exposure time of each session multiplied by the sensitivity factor if the source was in the partially coded field of view. Assuming a Crab-like spectrum (spectral index of 2), this gives the following limits: 3.8 × 10^{-5} and 9.4 × 10^{-6} photons cm^{-2} s^{-1} keV^{-1}, respectively, in the 40–60 and in the 60–100 keV energy ranges.

3. DISCUSSION

The type I X-ray bursts recorded by TTM leave no doubt about the presence of a neutron star in KS 1731−260. Therefore the SIGMA result provides strong evidence of hard X-ray emission (up to 150 keV) from a system containing a clearly identified neutron star. Since the SIGMA positioning accuracy

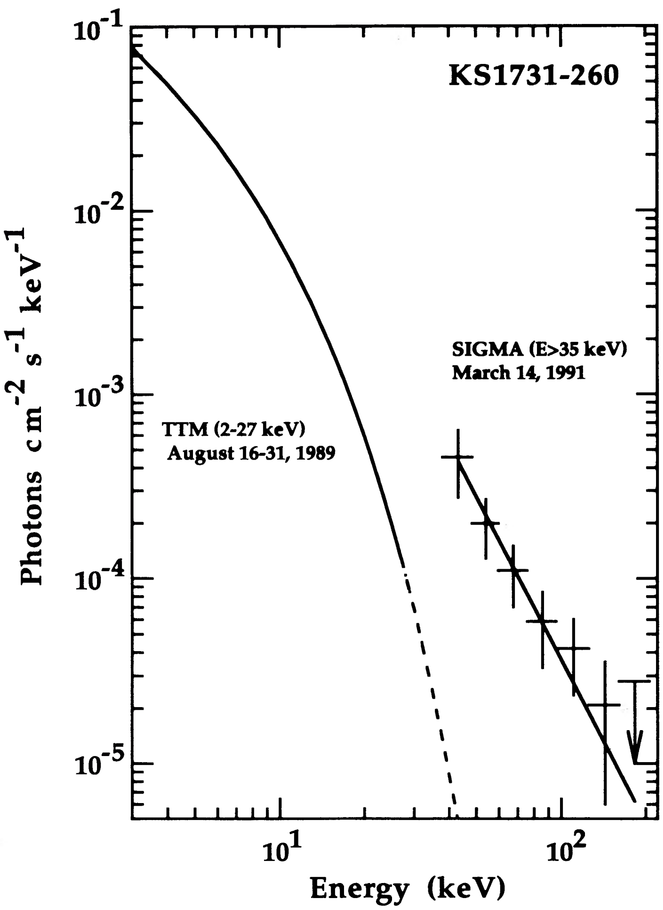

FIG. 1.—The incident photon spectrum of KS 1731−260 measured by SIGMA for the 1991 March 14 observation. Above 40 keV, the solid line represents the best-fit power-law model (photon index of ≈2.9). The SIGMA upper limit is at the 2 σ confidence level. The best thermal bremsstrahlung fit ($kT \approx 5.7$ keV) obtained by the TTM experiment during the 1989 August outburst of the source is also shown for comparison at lower energy.

allows one to avoid contamination from other hard X-ray sources in confused regions like the Galactic center, this result constitutes one of the strongest pieces of evidence obtained so far.

In contrast with the black hole candidate case, Comptonized hard tail emission is not naturally expected from LMXRBs containing neutron stars. (For a review of X-ray spectral properties of black hole candidates, see Tanaka 1989.) In fact, as long as the flux of primary photons is low, the Compton cooling of the hot electrons is expected to be a small effect compared to other energy-loss mechanisms. However, at higher fluxes, Compton cooling becomes sufficiently effective to quench the hot electrons. By lowering the electron temperature, this process removes the possibility of hard X-ray emission. If the central object is a weakly magnetized neutron star, such that the disk may extend down to the neutron star surface, the energy released in the optically thick boundary layer, and (or) the energy deposited onto the neutron star surface, is reradiated in the form of a blackbody radiation (Fujimoto & Hoshi 1985; White, Stella, & Parmar 1988; Mitsuda et al. 1984). In the classical scenario, this cool ambient radiation is believed to be intense enough, at least for the bright sources, to not allow the electron temperature to be high in the neighborhood of a neutron star. Incidentally, this is widely accepted as a reliable explanation of the large discrepancy existing between systems containing black holes and neutron stars, with respect to the hard X-ray emission (Sunyaev et al. 1991).

However, the SIGMA result, taken together with previous observations, for example, Cen X-4 (Bouchacourt et al. 1984) and 4U 1608−52 (Mitsuda et al. 1989; Gottwald et al. 1987), indicates the presence of hard tails in SFXTs. In the last two cases the hard tail appeared anticorrelated with the soft X-ray emission. Furthermore the spectrum hardened, as the overall X-ray luminosity decreased. In particular, Mitsuda et al. (1989) using extensive observations of 4U 1608−522 found that the up-Comptonization effect on the spectral formation increased significantly when the source intensity dropped below 10^{37} ergs s^{-1} and may well account for the power-law excess above 10 keV. This would suggest that at low accretion rate, the cool radiation intensity is not strong enough for the cooling mechanism to be effective. This effect may be amplified by the fact that at low accretion rate, both the boundary layer (Hoshi 1984; Fujimoto & Hoshi 1985) and the inner parts of the accretion disk (Ichimaru 1977) are expected to be hot and optically thin, the hot electron population being thereby continuously fed. Although limited to the high-energy range and with relatively poor statistics, we note that the KS 1731−260 spectrum we observed requires electron temperatures in excess of 15 keV in the framework of the Comptonization model (Sunyaev & Titarchuk 1980).

The fact that the Compton cooling may preclude the existence of very hot regions, and accordingly hard X-ray emission from neutron stars, has triggered theoretical work on alternative scenarios accounting for this emission (Kluzniak & Wilson 1991; Hanawa 1990, 1991). Following Hanawa (1990, 1991), the soft X-rays produced at the neutron star surface are scattered by the semirelativistic electrons of the infalling plasma accreting onto the neutron star. Some photons are scattered repeatedly in an optically thin boundary layer and are observed as high-energy X-rays. This nonthermal model, developed to account for the high-energy tail observed in 4U 1608−522, should therefore be relevant chiefly when the accretion rate, and by inference the X-ray luminosity, are low.

Finally, the all-sky X-ray monitor WATCH also on board the *GRANAT* satellite did not detect any bright X-ray burst (3 σ upper limit of about 100 millicrab) from KS 1731−260 both before and during the SIGMA observation (N. Lund 1991, private communication). This would indicate that the hard X-ray emission detected by SIGMA is not associated with a bursting phase of the source. Assuming that the SIGMA observation corresponds to a low-intensity state of the source, this would constitute a difference between KS 1731−260 and 4U 1608−522 for which a type I X-ray burst (intensity of 2 crab in the 1.5–20 keV energy range) was recorded during its low state (Gottwald et al. 1987).

4. CONCLUSION

We have reported hard X-ray emission from the bursting soft X-ray transient KS 1731−260 and by inference from an accreting neutron star. Consequently KS 1731−260 must be added to the list of the hard X-ray sources located within the 100 deg^2 around the Galactic center. Furthermore, the SIGMA result strengthens considerably the idea that power-law tails are not an exclusive property of the ultrasoft transients, which are black hole candidates, but may also be a temporary characteristic of weakly magnetized neutron stars. Our knowledge of X-ray transient sources is strongly dependent on future observations, which should be achieved over a wide X-ray energy band, ranging from a few to a few hundred keV. This would allow us to study precisely the spectral shape as well as the intensity variations of both the soft and hard X-ray components, which are essential for a better understanding of the emission mechanisms.

We acknowledge the outstanding contributions of the SIGMA project group of the CNES, as well as the laboratory staffs, to the overall success of the mission. We also thank the staffs of the Baïkonour Space Center, the Lavotchkine Space Company, the Babakin Space Center, and the Evpatoria ground station for their unfailing support throughout the conception, integration, and operational phases. The authors are grateful to L. Bassani and G. Vedrenne for their useful comments on this paper.

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