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ART-P/GRANAT Observations of the X-ray Source KS 1731−260

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Abstract—The results of observations of the transient X-ray burster KS 1731−260 with the ART-P telescope onboard the GRANAT observatory are presented. The observations were performed in 1990–1991 at the initial stage of the source's 12-yr activity period when no studies were conducted by other X-ray observatories. The flux from KS 1731−260 is shown to have systematically decreased, forming a separate initial "minioutburst" of the source with a duration of ∼2.5 yr. The decrease in flux was accompanied by an increase in the spectral hardness of KS 1731−260 and an enhancement of its burst activity; two X-ray bursts were detected in the last observing sessions when the flux decreased by 40–60%. Their analysis showed that they occurred in a medium with an appreciable hydrogen abundance; i.e., the enrichment efficiency of the material in the lower atmospheric layers of the neutron star during quasi-steady hydrogen burning was low. The BDLE model that was suggested by Grebenev et al. (2006) to describe the radiation spectra of weakly magnetized accreting neutron stars has been used for the first time to analyze the continuum radiation spectrum of the source. This model incorporates two spectral components associated with the radiation from the boundary layer formed at the place of contact between the accretion disk and the neutron star surface and with the radiation from the accretion disk proper. The model satisfactorily fits the observed radiation spectra of the source and allow such parameters of the binary system as the accretion disk inclination, the bolometric luminosity (accretion rate), and the temperature of the outer boundary layer to be estimated. The boundary layer radiation for KS 1731−260 is shown to have originated in an exponential atmosphere of moderate optical depth for Thomson scattering under conditions where comptonization had no time to form the Wien spectrum, but only modified the thermal plasma radiation spectrum.

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INTRODUCTION

The X-ray transient KS 1731−260 was discovered in 1989 during a survey of the Galactic center region by the TTM telescope of the Rentgen observatory onboard the KVANT module of the Mir orbiting station (Sunyaev 1989). After the detection of X-ray bursts from KS 1731−260 (Sunyaev et al. 1990b), it became clear that this is a binary system containing an accreting neutron star with a weak magnetic field. Coherent flux oscillations in the source at a frequency of ∼524 Hz, which are probably related to the rotation of the neutron star, were found in 1996 when the RXTE observatory studied its X-ray bursts (Smith et al. 1997). In quiescence (between bursts), quasi-periodic oscillations were found in the radiation from the source at frequencies of ∼900 and ∼1150 Hz (Wijnands and van der Klis 1997). The RXTE observatory succeeded in detecting several intense X-ray bursts that were accompanied by photospheric expansion of the neutron star, which allowed the distance to the binary to be estimated, $d \simeq 7$ kpc (Muno et al. 2000). An even more interesting burst was detected by the BeppoSAX satellite; it became a kind of a record-holder in duration (∼12 h) among all of the bursts ever observed from bursters (Kuulkers et al. 2002).

KS 1731−260 is located in a densely populated region of the sky and is observed through the Galactic disk. Although its optical (more precisely, infrared) identification has been attempted repeatedly (see, e.g., Barret et al. 1998; Revnivtsev and Sunyaev 2002), certain progress here has been achieved only recently (Wijnands et al. 2001a; Orosz et al. 2001; Mignani et al. 2002). The infrared companion is a strongly evolved star with an apparent magnitude of $J \simeq 19^m$ and an absolute magnitude of $J = 2\overset{m}{.}4 \pm 0\overset{m}{.}4$ or a main-sequence early F or G star (Orosz et al. 2001). Using RXTE data, Revnivtsev and Sunyaev (2003) showed that the flux from KS 1731−

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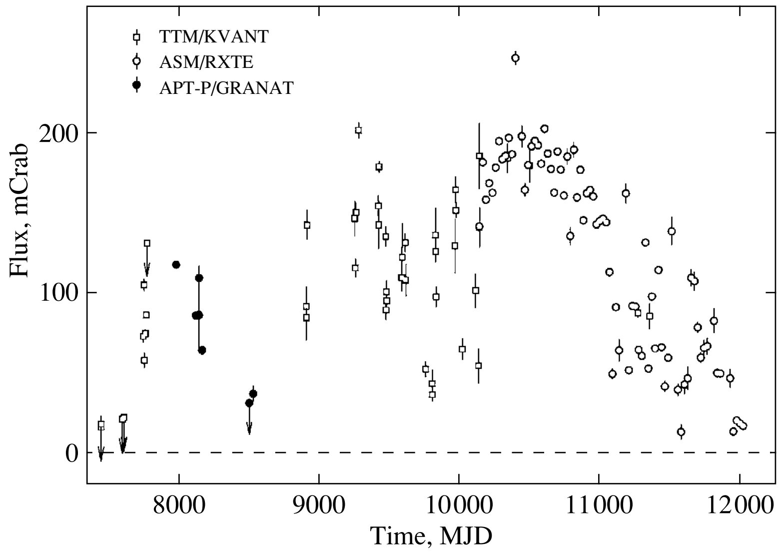

Fig. 1. Light curve for KS 1731−260 constructed from TTM/KVANT (2–27 keV), ASM/RXTE (2–12 keV), and ART-P/GRANAT (3–20 keV) data. The TTM/KVANT and ASM/RXTE observational data were averaged on a time scale of 2 days (provided by Aleksandrovich et al. (2002)).

260 varies with an (orbital or precession) period of ∼38 days.

The source belongs to the group of long-period transients with a characteristic X-ray activity time scale from 1– or 2–10 years and with a very long recurrence period (Aleksandrovich et al. 2002). KS 1731−260 had been bright for 12 yr (Fig. 1). The flux in the standard X-ray energy range, on average, increased (from ∼40 mCrab at the detection time to ∼200–250 mCrab at maximum light) during the first 7–8 yr and then began to decrease (it was recorded at a level of ∼20 mCrab in the last successful observations). On a time scale of several weeks and months, the flux from the source exhibited a strong variability, which was larger in the periods of a relatively low mean flux. Although the source mainly had a thermal radiation spectrum with a temperature of $kT \sim 5$–7 keV (when fitted by the bremsstrahlung model of an optically thin thermal plasma) typical of low-mass X-ray binaries, a very hard spectrum with a temperature of $kT \gtrsim 40$ keV was recorded in several observations (Barret et al. 1992; Aleksandrovich et al. 2002).

Before the discovery of KS 1731−260 in 1989, the X-ray observatories had been repeatedly pointed in this direction, but they found no evidence of the source. The CHANDRA observatory observed this region several months after the turn-off of the source in 2001 (Wijnands et al. 2001b) and revealed a weak object with an X-ray (0.5–10 keV) luminosity of $\sim 10^{33}$ erg s^{-1} (at $d = 7$ kpc) at the location of KS 1731−260. This value agrees well with the luminosities of other similar transients (accreting neutron stars in low-mass X-ray binaries) observed during their off state. Estimates (Menou et al. 1999) show that this luminosity can be produced by residual accretion related to the natural evolution of the binary system (the loss of angular momentum due to the gravitational radiation and evolutionary expansion of the donor star).

In 1990–1991, at the initial stage of its outburst, KS 1731−260 was within the ART-P/GRANAT field of view several times. In this period, the ART-P telescope was the only in-orbit instrument that performed observations in the standard X-ray energy range. Grebenev et al. (1997) and Lutovinov et al. (2003) included preliminary results of these observations in their review article (2003). In this paper, we present the results of the observations of KS 1731−260 in full.

OBSERVATIONS

The GRANAT orbiting astrophysical observatory was placed in orbit on December 1, 1989, and had operated for almost nine years. The ART-P telescope onboard the observatory was designed to image the sky in X rays in a $3^\circ\!.6 \times 3^\circ\!.4$ field of view with an angular resolution of 5 arcmin. This telescope made it possible to localize compact sources (with an accuracy of 4 arcsec), to measure their X-ray spectra (with an energy resolution of ∼22% in the 5.9-keV iron calibration line), and to analyze their variability (with a time resolution up to 3.9 ms and a dead time of ∼580 μm). The operation of the telescope was based on the principle of a coded aperture.

Table 1. ART-P observations of KS 1731−260

Session number	ART-P module	Start−end session date, UT	Exposure time,[a] s	Photon flux,[b] mCrab	Luminosity,[b,c] 10^{37} erg s^{-1}
1	1	Apr. 4.550−4.796, 1990	14140	117.5 ± 1.7	1.67 ± 0.02
2	1	Aug. 23.699−23.996, 1990	16770	85.8 ± 2.3	1.22 ± 0.03
3	4	Sep. 15.408−15.416, 1990	530	86 ± 22	1.22 ± 0.31
4	4	Sep. 15.561−15.604, 1990	2790	109.1 ± 7.7	1.55 ± 0.11
5	4	Oct. 7.485−7.975, 1990	32750	64.1 ± 1.6	0.91 ± 0.02
6	3	Sep. 8.572−8.854, 1991	16470	≤ 31[d]	≤ 0.45[d]
7	3	Oct. 6.526−6.836, 1991	17870	36.8 ± 4.6	0.53 ± 0.07

[a] Corrected for the dead time.
[b] In the energy range 3−20 keV.
[c] At a distance of $d = 7$ kpc.
[d] The 3σ upper limit.

Each of the four independent onboard ART-P modules consisted of a position-sensitive detector, a coded mask, and a collimator. The detectors were multiwire proportional chambers with a geometric area of 625 cm^2 and a factor of 2 smaller effective area (due to the shadowing by opaque mask elements). The original design of the telescope provided a full coding in the entire field of view, allowing the distortions related to the shadowing by the collimator walls to be compensated for. The telescope operated in the energy range 2−60 keV; the sensitivity reached its maximum in the energy range 3−30 keV. The sensitivity of the third ART-P module at energies below 6 keV was reduced because of voltage problems on one of the anode grids. This prevented us from performing a spectral analysis of the data from this module in full. The telescope was described in more detail by Sunyaev et al. (1990a).

One of the highest priority objectives of the GRANAT observatory was a deep survey of the Galactic center region in the X-ray and soft gamma-ray energy ranges. The observations were performed each time the technical conditions permitted. Unfortunately, the observatory was pointed directly at the Galactic center (the source Sgr A*) in most cases, and KS 1731−260 was outside the ART-P field of view. The cases where the source was observable are listed in Table 1. In all these cases, only one of the ART-P modules was switched on. Note that the SIGMA telescope onboard the GRANAT observatory was sensitive to hard ($h\nu \gtrsim 35$ keV) photons, had a wider field of view, and could observe KS 1731−260 during almost the entire survey (Barret et al. 1992).

In general, the X-ray pulsar GX1+4 (see, however, Grebenev et al. 1997) was the target for the observations presented in Table 1. Figure 2 shows the 3−20 keV image obtained by the ART-P telescope on September 15, 1990, during session 4. Both sources are clearly seen in this image. The position of the transient IGR J17331−2406 that was recently discovered in this field at $\sim 40'$ from GX1+4 by the INTEGRAL observatory (Lutovinov et al. 2004) is also marked. The ART-P telescope detected no radiation from IGR J17331−2406 (the 3σ upper limit on the 3−20 keV photon flux was 16 mCrab in this session and below 4 mCrab in other sessions). The photon flux and luminosity measured in different observing sessions from KS 1731−260 are given in Table 1. We see that the flux in sessions 3 and 6 was determined with large statistical errors; this is attributable to the short duration of the session in the former case and to the unsuccessful pointing in the latter case (KS 1731−260 was at the very edge of the field of view). The situation in the latter case was also deteriorated by the fact that the observations were performed by module 3 of the ART-P telescope with a reduced sensitivity at soft energies.

In the light curve of KS 1731−260 presented in Fig. 1, the ART-P X-ray flux measurements are indicated by filled circles and the RXTE and Rentgen measurements are indicated by open circles and squares, respectively. The latter were taken from Aleksandrovich et al. (2002) and were averaged on a time scale of 2 days for the convenience of perception. We see that the flux from the source, on average, decreased during its ART-P observations. Since the decrease in flux was preceded by its increase observed since the discovery of KS 1731−260, a separate initial outburst of the source with a duration of 2.5−3 yr may be said to have occurred. We may even assert with a certain degree of confidence that the source experienced another outburst with approximately the same duration, but with a larger amplitude after

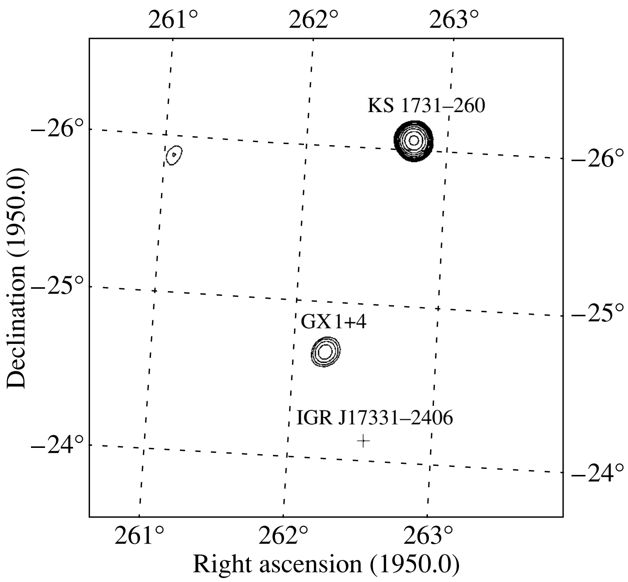

Fig. 2. X-ray image of the KS 1731−260 field obtained by the ART-P telescope on September 15, 1990 (session 4, an exposure time of 2790 s). The contours indicate the region of statistically significant detection of the sources in the energy range 3−20 keV and are given at signal-to-noise ratios of 3, 3.9, 5.1, 6.6, ..., 32 (on a logarithmic scale).

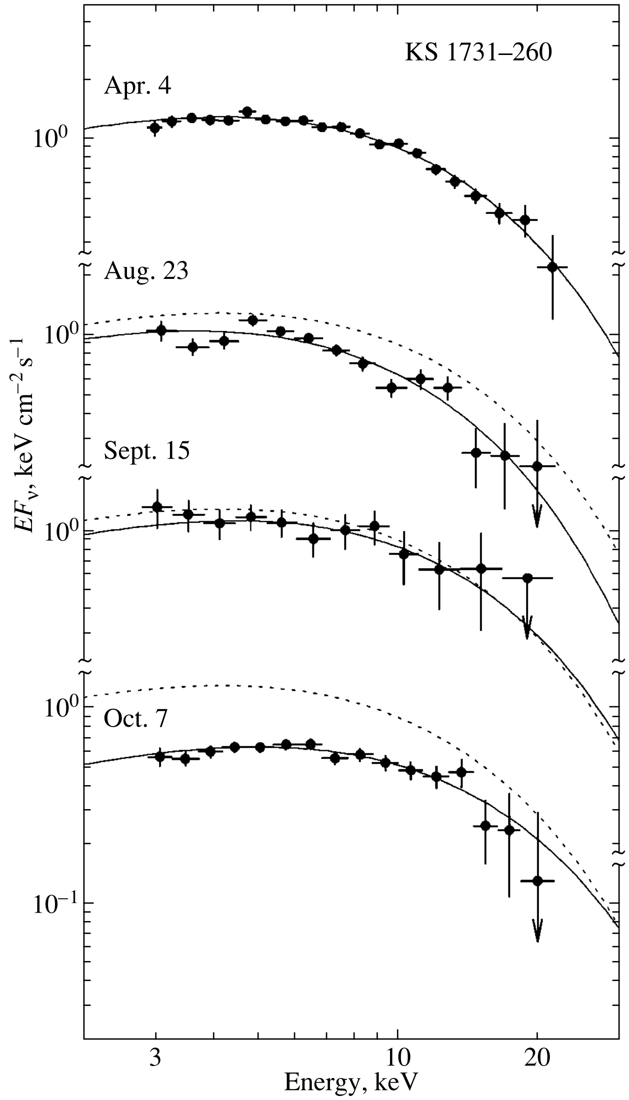

Fig. 3. Persistent radiation spectra for KS 1731−260 taken by the ART-P telescope in 1990 during the observing sessions 1, 2, 4, and 5. The solid lines indicate the fits to the spectra by the bremsstrahlung model of an optically thin thermal plasma. For spectra 2−5, the dotted line also indicates the fit to spectrum 1 (for comparison).

the first outburst and before the primary brightness maximum was reached.

THE PERSISTENT RADIATION SPECTRUM

We used data from the observing sessions 1, 2, 4, and 5 to analyze the X-ray spectrum of KS 1731−260 and its evolution under conditions of the observed decrease in flux. The corresponding spectra are shown in Fig. 3. At the first step of their analysis, we tested three simple models: a power law with a high-energy exponential cutoff (cutoffpl in the standard XSPEC/HEASOFT package), the bremsstrahlung spectrum of an optically thin thermal plasma (bremss), and the spectrum formed when low-frequency radiation is Comptonized in a cloud of high-temperature electron plasma (compst, Sunyaev and Titarchuk 1980). The best-fit parameters for these models in the energy range 3−20 keV are given in Table 2, and the corresponding spectra obtained with the bremss model are indicated in Fig. 3 by solid curves. When fitting the spectra, we applied a correction for the photoabsorption in the interstellar gas at the level corresponding to a hydrogen column density of $N_{\rm H} \simeq 1.1 \times 10^{22}$ cm^{-2} (Barret et al. 1998).

The χ^2 values given in Table 2 suggest that the observed radiation spectra of the source are satisfactorily fitted by these one-component models. Unfortunately, all of them bear almost no relation to describing the actual physical conditions in the region where the X-ray radiation originates. A realistic model must contain two components: a soft component that describes the radiation spectrum of the inner accretion disk and a hard component that describes the radiation from the hot boundary layer formed at the place of contact between the disk and the neutron star surface. The first component can be fitted, to a first approximation, by the radiation spectrum of a multicolor blackbody disk (Shakura and Sunyaev 1973; Mitsuda et al. 1984). The second component, which is generally difficult to model, can be fitted

Table 2. Best-fit parameters for the radiation spectra of KS 1731−260 taken during its ART-P observations in 1990

Session number	Model[a]	kT, keV	$\alpha^{\rm b}$	$\tau^{\rm c}$	$\chi^2_N(N)^{\rm d}$
1	bremss	6.14 ± 0.15			1.06(17)
	compst	2.98 ± 0.17		10.50 ± 0.67	1.21(16)
	cutoffpl	6.05 ± 0.75	1.36 ± 0.16		1.12(16)
2	bremss	5.40 ± 0.28			1.23(17)
	compst	2.52 ± 0.29		11.78 ± 1.64	1.35(16)
	cutoffpl	4.22 ± 0.96	0.99 ± 0.39		1.27(16)
4	bremss	6.14 ± 1.07			0.42(17)
	compst	2.99 ± 0.28		10.50[e]	0.41(17)
	cutoffpl	6.09 ± 1.07	1.36[e]		0.42(17)
5	bremss	7.57 ± 0.50			0.59(17)
	compst	3.13 ± 0.43		11.18 ± 1.60	0.65(16)
	cutoffpl	6.67 ± 2.42	1.23 ± 0.36		0.62(16)

[a] The spectral model used: bremss—bremsstrahlung of an optically thin thermal plasma; compst—comptonization of Sunyaev and Titarchuk (1980); cutoffpl—a power law with an exponential cutoff, $E^{-\alpha}\exp(-E/kT)$.
[b] The photon index.
[c] The radial Thomson depth of the cloud of electron plasma.
[d] The χ^2 value normalized to N (N is the number of degrees of freedom).
[e] The parameter is fixed at the value obtained in session 1.

at high luminosities, $L_{\rm X} \gtrsim 5 \times 10^{37}$ erg s^{-1}, by the Wien radiation law (Grebenev and Sunyaev 2002). At such luminosities, the plasma in the boundary layer is optically thick and tenuous due to the radiation pressure. The observed spectrum is formed when the low-frequency bremsstrahlung photons emitted deep in the boundary layer are Comptonized. At lower luminosities, $L_{\rm X} \lesssim 1 \times 10^{37}$ erg s^{-1}, the plasma in the boundary layer is more transparent. The Comptonization parameter $y = (kT_{\rm b}/m_e c^2)\tau_{\rm T}^2$ decreases to unity, and the spectrum ceases to be the Wien one. The photon scattering by electrons (without any change in frequency) still plays a crucial role in its formation, leading to the so-called modified radiation spectrum of an exponential atmosphere (Zel'dovich and Shakura 1969).

Directly using the two-component model consisting of the Wien spectrum (or the spectrum of an exponential atmosphere) and the spectrum of a multicolor disk leads to an unreasonably large number of independent parameters for describing the relatively simple observed spectra of accreting neutron stars. Grebenev et al. (2006) suggested a new model, BDLE (Boundary Layer—Disk Luminosity Equality), in which the equality between the intrinsic luminosities of the two spectral components is used to reduce the number of parameters,

$$L_{\rm d} = L_{\rm b} = \frac{GM_*\dot{M}}{2\,R_*}.$$

The latter is valid for a nonrotating neutron star with a weak magnetic field in the limit of Newtonian gravity.[1] Here, $L_{\rm b}$ and $L_{\rm d}$ are the boundary layer and disk luminosities, respectively; M_* and R_* are the mass and radius of the neutron star; and $\dot{M}$ is the accretion rate. The radius of the star is assumed to be $R_* \gtrsim R_0$, where $R_0 = 6GM_*/c^2$ is the radius of its marginally stable orbit, so the inner edge of the accretion disk almost touches the stellar surface. In the simplest case of the approximate equality $R_* \simeq R_0$, the luminosity of the components is $L_{\rm d} = L_{\rm b} \simeq 1/12\dot{M}c^2$.

At a known distance to the binary system ($d \simeq$ 7 kpc), the total spectral flux F_t in the BDLE model depends on four parameters: $L_{\rm d}$, $T_{\rm d}$, $T_{\rm b}$, and i. Here, $T_{\rm d} = \left(3L_{\rm d}/4\pi\sigma_{\rm B}R_*^2\right)^{1/4}$ is the surface temperature of the central disk regions, $T_{\rm b}$ is the temperature of the outer boundary layer, i is the disk inclination, and $\sigma_{\rm B}$ is the Stefan—Boltzmann constant. Given $L_{\rm d}$ and $T_{\rm d}$, we can determine the neutron star radius R_* and,

[1] Including the stellar rotation (with a rate of $\nu_* \simeq 524$ Hz for KS 1731−260) distorts only slightly this equality $L_{\rm b}/L_{\rm d} \simeq 1 - (2\pi\nu_*/\Omega_{\rm K})^2 \simeq 0.89$, where $\Omega_{\rm K} = (GM_*/R_*^3)^{1/2}$ is the Keplerian angular velocity of the material at the inner disk edge. In general relativity, $L_{\rm b}$ can exceed appreciably $L_{\rm d}$; in particular, in the Schwarzschild metric, $L_{\rm b}/L_{\rm d} \simeq 2.2$ if the radius of the star is equal to the radius of its marginally stable orbit $R_* = R_0$ and $L_{\rm b}/L_{\rm d} \simeq 1 + 0.5R_0/R_*$ if $R_* \gg R_0$ (Sunyaev and Shakura 1986; Sibgatullin and Sunyaev 1998).

Table 3. Best-fit parameters for the radiation spectra of KS 1731−260 with the BDLE model[a]

Session number	kT_b,[b] keV	kT_d,[b] keV	μ[c]	$\dot{M}$,[d] $10^{-9}M_\odot$ yr^{-1}	L_t,[e] 10^{37} erg s^{-1}	L_X/L_t,[f] %	χ^2_N [g]
1	2.07 ± 0.03	1.46 ± 0.01	0.87 ± 0.01	6.33	5.99	28.9	1.7
2	1.82 ± 0.07	1.35 ± 0.03	0.84 ± 0.04	4.69	4.43	28.2	1.7
4	2.15 ± 0.28	1.44 ± 0.05	0.89 ± 0.05	6.07	5.74	27.5	0.4
5	2.04 ± 0.07	1.26 ± 0.02	0.84 ± 0.03	3.47	3.28	27.2	1.2
1	2.73 ± 0.06	1.41 ± 0.01	0.71 ± 0.03	5.54	5.24	32.8	1.0
2	2.33 ± 0.11	1.30 ± 0.02	0.58 ± 0.13	4.00	3.78	32.7	1.4
4	2.93 ± 0.52	1.41 ± 0.06	0.79 ± 0.13	5.46	5.17	30.6	0.4
5	2.79 ± 0.13	1.21 ± 0.02	0.66 ± 0.08	2.99	2.83	31.7	0.8

[a] At given distance $d = 7$ kpc, mass $M_* = 1.4M_\odot$, and radius $R_* = R_0$ of the neutron star and under the assumption of two different boundary layer radiation laws: the Wien one (the upper part of the table) or the radiation of an exponential atmosphere (the lower part).
[b] The plasma temperature in the outer regions of the boundary layer kT_b and the inner disk kT_d.
[c] The cosine of the disk inclination to the line of sight.
[d] The accretion rate.
[e] The bolometric luminosity $L_t = L_b + L_d$.
[f] The ratio of the X-ray, L_X (3–20 keV), and bolometric, L_t, luminosities.
[g] The χ^2 value normalized to the number of degrees of freedom $N = 16$.

assuming the neutron star mass to be $M_* = 1.4M_\odot$, the accretion rate $\dot{M}$. For KS 1731−260, the ART-P telescope measured the spectra in an overly hard energy range, which makes it impossible to accurately determine the radiation parameters of the accretion disk. Therefore, we simplified the model to an even greater extent by setting $R_* = R_0$. The other model parameters obtained by fitting the above four radiation spectra of the source are given in Table 3. This table also gives the accretion rate, the bolometric luminosity of the binary system $L_t = L_b + L_d$, and the ratio L_X/L_b, where L_X is the X-ray (3–20 keV) luminosity. The upper and lower parts of the table contain the parameters obtained by fitting the radiation spectrum of the boundary layer by the Wien law and the radiation law of an exponential scattering atmosphere, respectively. We see that, in general, the latter law describes better the measured spectra of the source. Both models suggest that only ∼30% of the energy released during accretion is emitted in the X-ray range.

The BDLE model fit to the radiation spectrum of the source observed on October 7, 1990 (session 5) is shown in Fig. 4. The solid and dashed lines in Fig. 4a correspond to the assumptions about the Wien radiation spectrum of the boundary layer and the radiation spectrum of an exponential atmosphere, respectively; for comparison, the dotted line indicates the bremsstrahlung spectrum of an optically thin thermal plasma. The solid, dashed, and dotted lines in Fig. 4b correspond to the total radiation spectrum in the BDLE model (with an exponential atmosphere) and to the individual radiation spectra of the boundary layer and the accretion disk. We see that the accretion disk and the boundary layer dominate in the source's spectrum at low and high energies, respectively. The sum of these two components satisfactorily describes the X-ray spectrum of the binary system in quiescence.

X-RAY BURSTS

During the observations under discussion, two X-ray bursts were detected in the ART-P field of view. The first burst was observed on October 7, 1990, during session 5 (the flux was at a maximum at $14^h48^m29^s$ UT); the second burst was observed on October 6, 1991, during session 7 (the flux was at a maximum at $12^h59^m10^s$ UT). KS 1731−260 was the only known burster in the ART-P field of view and, hence, a likely burst source. We managed to identify the burst observed on October 7, 1990, with KS 1731−260 with a higher degree of confidence.

For the identification, we used the X-ray images of the sky in the field of view obtained during ∼13 s immediately before the burst onset (Fig. 5a) and ∼13 s during the burst (Fig. 5b). The first image revealed no statistically significant sources (for which the signal-to-noise ratio would exceed S/N = 4.5). The second image revealed one statistically significant source (with S/N ≃ 9.5), KS 1731−260. In a similar analysis for the burst observed on October 6, 1991, KS 1731−260 was also the only source in the second image, but its detection significance was low (S/N ≃ 4.0).

The burst time histories (the detector count rates recorded with a time resolution of 1 s in three different

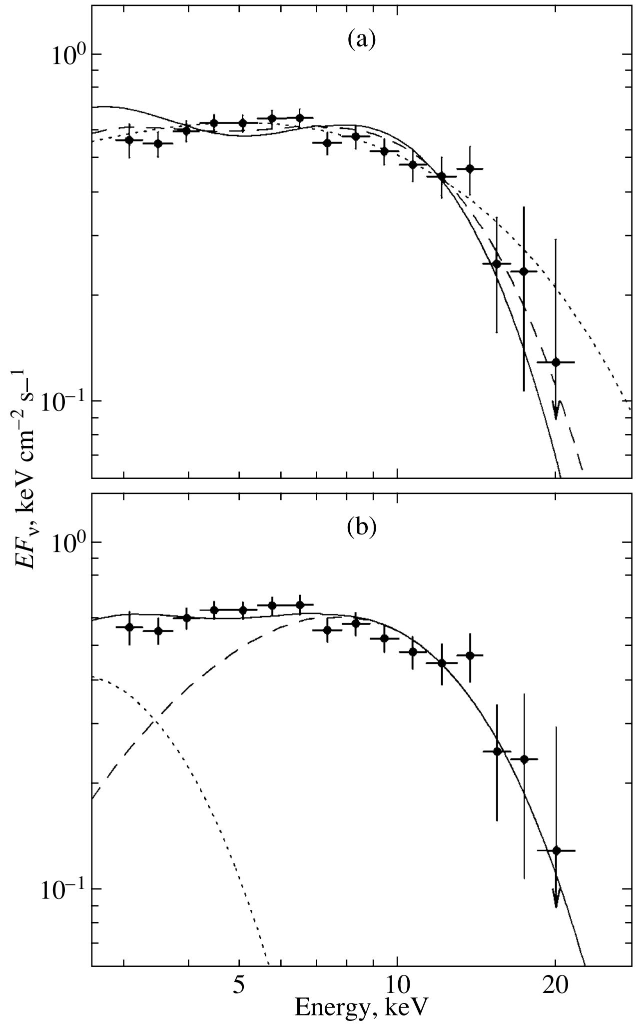

Fig. 4. BDLE model fit to the persistent radiation spectrum of KS 1731−260 measured on October 7, 1990 (session 5). The solid and dashed lines in panel (a) were obtained under the assumption of two boundary layer radiation spectra: the Wien one and the spectrum of an exponential atmosphere; the dotted line indicates the bremsstrahlung spectrum of an optically thin thermal plasma. The solid, dashed, and dotted lines in panel (b) correspond to the total radiation spectrum in the BDLE model with an exponential atmosphere and to the individual radiation spectra of the boundary layer and the accretion disk.

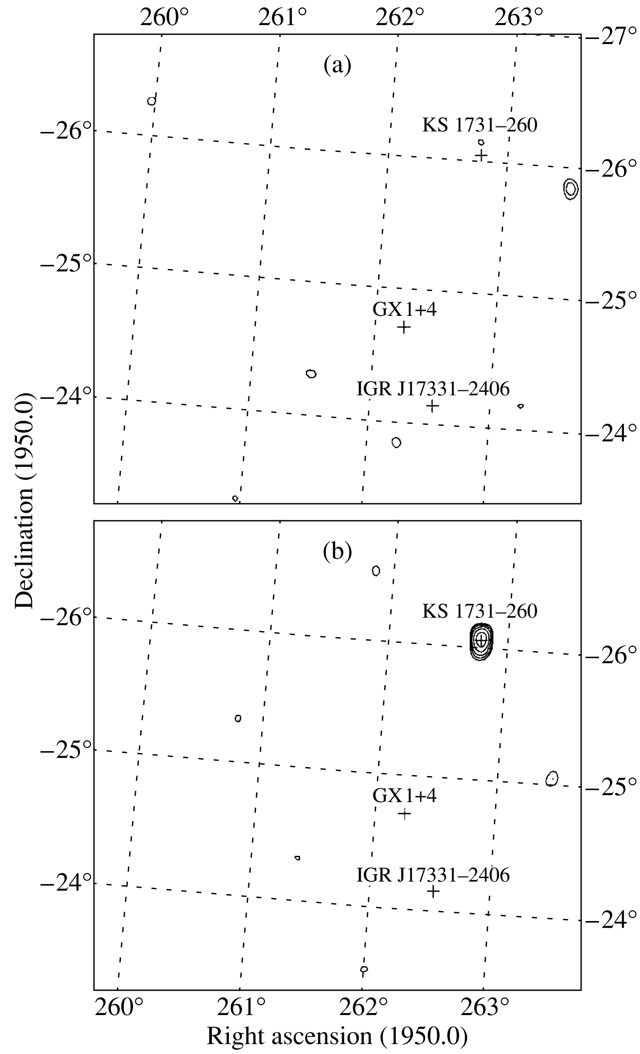

Fig. 5. Images of the sky regions in the ART-P field of view obtained during session 5 (on October 7, 1990) immediately before (a) and during (b) its X-ray burst. The contours indicate the region of statistically significant detection of the source in the energy range 3–20 keV and are given at signal-to-noise ratios of 3, 3.9, 5.1, 6.6, and 8.6 (on a logarithmic scale). In both cases, the exposure time is 13 s.

energy ranges) are presented in Fig. 6. The light curve of the first burst was cut off due to the ART-P memory buffer overflow and the switch-on of data transmission to the GRANAT onboard memory. As follows from this figure, the interval between the burst onset and the maximum light was 3–4 s; the subsequent period of the gradual decrease in flux was 5–10 s (depending on the energy range); the exponential decay time was ∼4.5 s for the first burst and ∼4.6 s for the second burst. Thus, the total burst duration was ∼15 s in the energy range 3–20 keV.

During the bursts, the hard flux decayed faster than the slow one; i.e., the radiation spectrum gradually softened. According to Hoffman et al. (1978), this suggests that these events belong to the type I X-ray bursts triggered by a thermonuclear explosion of the matter accreted onto the neutron star surface. Note the fairly complex shape of the second burst indicative of a double-peaked structure. The low relative amplitude of this burst in the energy range 3–10 keV is attributable to the reduced sensitivity of the ART-P module 3 to soft photons mentioned above.

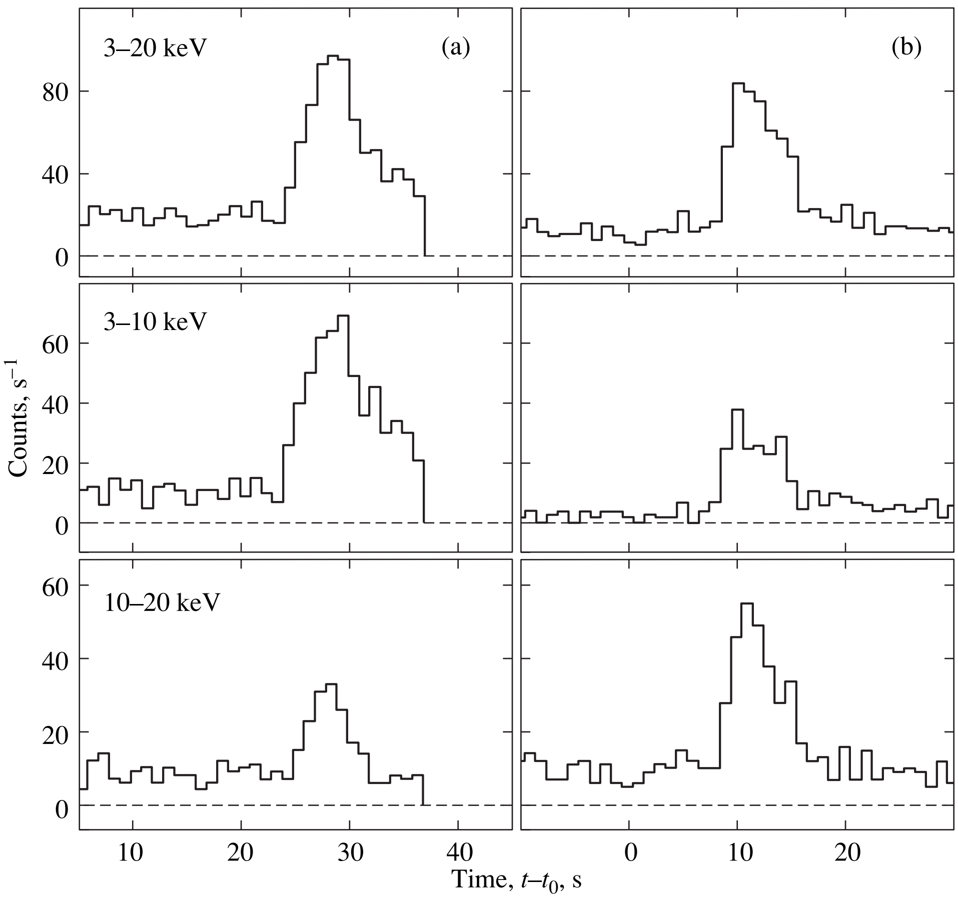

Fig. 6. Photon count rates in three energy ranges recorded by the ART-P telescope on October 7, 1990 (column a), and October 6, 1991 (column b), when the X-ray bursts were detected from KS 1731−260. The time along the Y axis is measured from $t_0 = 14^{\rm h}48^{\rm m}$ UT for the first burst and $t_0 = 12^{\rm h}59^{\rm m}$ UT for the second burst; the time resolution is 1 s.

The radiation spectrum measured during the October 7, 1990, burst is shown in Fig. 7 (after the subtraction of the persistent radiation from the source). The blackbody fit to the spectrum (the solid line in the figure) yielded a blackbody temperature of $kT_{\rm bb} \simeq 2.16 \pm 0.11$ keV and a bolometric luminosity of $L_{\rm bb} = (1.05 \pm 0.06) \times 10^{38}$ erg s^{-1} (for the assumed distance of $d = 7$ kpc). The corresponding blackbody radius is $R_{\rm bb} \simeq 6.1 \pm 0.7$ km. As above, we assumed that the original radiation spectrum was distorted by photoabsorption in a medium with a hydrogen column density of $N_{\rm H} \simeq 1.1 \times 10^{22}$ cm^{-2}. The blackbody model satisfactorily describes the observational data: the χ^2 value normalized to $N = 7$ degrees of freedom is 0.65. However, the derived blackbody radius, which is half the radius of the marginally stable orbit $R_0 = 12.6$ km for a neutron star with a mass of $M = 1.4M_\odot$, shows that comptonization played a prominent role in shaping the radiation spectrum. Comptonization is known (see, e.g., Kompaneets 1956) to more likely lead to the Wien spectral shape than to the blackbody one. Fitting the spectrum by the Wien law using the formula

$$F_W \simeq \left(\frac{L_W}{\sigma_{\rm B} T_W^4\, d^2}\right) \frac{h\nu^3}{2\,c^2} \exp\left(-\frac{h\nu}{kT_W}\right)$$

(Grebenev et al. 2002) yielded the following parameters: $kT_W \simeq 2.09 \pm 0.10$ keV and the bolometric luminosity $L_W = (1.09 \pm 0.06) \times 10^{38}$ erg s^{-1} ($\chi^2_N \simeq 0.58$). The fit is indicated by the dashed line in Fig. 7.

The maximum 3–20 keV luminosity determined using a 3-s interval near the burst peak reached $L_p = (2.06 \pm 0.49) \times 10^{38}$ erg s^{-1} (the photon flux reached 1.45 ± 0.34 Crab). This value closely corresponds to the critical Eddington luminosity for a neutron star with a mass of $1.4M_\odot$, provided that its atmospheric elemental abundances are normal (i.e., if it contains mainly hydrogen). That the outer stellar atmosphere during the burst was radiation-dominated and tenuous (the direct consequences of the Eddington luminosity) also follows from the above conclusion about a prominent role of comptonization in shaping the observed radiation spectrum.

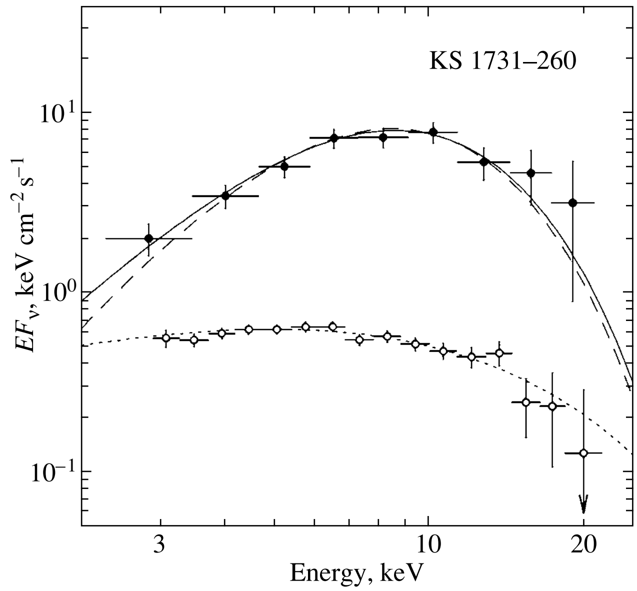

Fig. 7. Spectrum of the X-ray burst detected by the ART-P telescope from KS 1731−260 on October 7, 1990 (filled circles). The exposure time is 13 s. The persistent radiation from the source was subtracted (its spectrum averaged over this observing session is indicated by open circles for comparison). The solid and dashed curves indicate the best fits to the spectrum by the blackbody and Wien radiation laws, respectively. The best-fit parameters are given in the text.

At the base of the atmosphere where a thermonuclear explosion occurs, the composition of the material may differ from the normal one due to its helium enrichment during slow hydrogen burning. An indirect constraint on the helium abundance here can be obtained from the absence of other X-ray bursts during this fairly long ($T \sim 42\,300$ s) observing session. Indeed, the energy released during the burst is $E_{\rm b} = \tau L_W \simeq 1.4 \times 10^{39}$ erg, where $\tau \simeq 13$ s is the burst duration. The gravitational energy released between the burst and the end of the session[2] is $E_a = \Delta T L_{\rm X} \simeq 2.8 \times 10^{41}$ erg. The value of $\alpha = E_a/E_b \simeq 200$ is a lower limit on the ratio of the gravitational energy released when 1 g of material fell to the neutron star surface to the energy released during its thermonuclear burning. It is well known (see, e.g., Lewin et al. 1993) that $\alpha \sim 100$ for bursts in an atmosphere of pure helium and $\alpha \sim 1000$ in an atmosphere with normal elemental abundances. Even if we take into account the uncertainty due to the dependence of the efficiency of gravitational energy release on the neutron star radius, it is clear that the hydrogen abundance in the explosion region for KS 1731−260 was appreciable.

[2]We are interested in the maximum time of quiescent radiation from the source. The postburst period used $\Delta T = 30\,930$ s is longer than the preburst period.

DISCUSSION

The ART-P observations of KS 1731−260 were performed at the initial stage of its 12-yr activity period when no studies were conducted by other X-ray observatories. The results presented in this paper suggest that the flux from KS 1731−260 at this time systematically decreased, forming a separate initial minioutburst of the source with a duration of ~2.5 yr. A reanalysis of the more recent TTM/Rentgen observations of KS 1731−260 performed in light of this result suggests that the source experienced another minioutburst of approximately the same duration before its X-ray flux reached a maximum in 1996−1997. This behavior should be taken into account when explaining the activity of long-lived X-ray transients; at present, there is essentially no such explanation. Note that the outbursts of some of the X-ray novae (transients containing a black hole) also last for 0.5−2 yr and, in some cases (GX339−4, 4U 1630−47), also have a close recurrence period, 1.5−4 yr.

The decrease in the flux from the source recorded by the ART-P telescope was accompanied by an increase in its spectral hardness (Table 2). Curiously, both X-ray bursts were detected from KS 1731−260 precisely in the last observing sessions, when the persistent flux was 40−60% below the flux in the remaining sessions. Such an anticorrelation between burst activity and flux was previously observed in several other bursters (Lewin et al. 1993). On the other hand, the burst recurrence time proved to be unexpectedly long, $\Delta T \gtrsim 8.6$ h (30 930 s). During the RXTE observations of the source, bursts occurred appreciably more frequently, with a characteristic recurrence time scale of ~4 h (Muno et al. 2000), while, during its observations by the Rentgen observatory, two bursts were detected with an interval of ~ 1.5 h (Sunyaev et al. 1990a). Nevertheless, the mean accretion rate in the binary during these observations was probably higher, and, hence, the critical mass of the accreting material required for an explosion had time to accumulate faster than during the ART-P observations. At a higher accretion rate, the enrichment of the accreting material with helium during quasi-steady hydrogen burning in the lower atmosphere of the neutron star could also be more efficient. As we showed here, the burst detected by the ART-P telescope on October 7, 1990, occurred in a medium with an appreciable hydrogen abundance.

The shape of the continuum radiation spectrum for KS 1731−260 was typical of low-mass X-ray binaries with a high ($L_{\rm X} \gtrsim 0.1 L_{\rm ed}$) luminosity and a weakly magnetized neutron star as the compact object. We used the BDLE spectral model suggested for such binaries by Grebenev et al. (2006) for the first time to fit the spectrum. This model described satisfactorily the observed spectra of the source under the assumption that the boundary-layer radiation originated in an exponential atmosphere of moderate optical depth for Thomson scattering when comptonization had no time to form the Wien radiation spectrum, but only modified the thermal plasma spectrum by lengthening the photon paths at scatterings. The model allowed the inclination of the accretion disk and the bolometric luminosity (accretion rate) of the binary to be estimated.

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