GRANAT/ART-P OBSERVATIONS OF GX3+1: TYPE I X-RAY BURST AND PERSISTENT EMISSION

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ABSTRACT We present results of observations of the known LMXB source GX3+1 with the telescope ART-P on board GRANAT in the fall of 1990. A strong X-ray burst was detected from the source on Oct. 14 when it was in the low X-ray state with a luminosity $\sim 30\%$ smaller than the normal one. That was only the second case for the whole history of its study when it exhibited such type of activity. We describe results of the source spectroscopy during the burst and persistent state and discuss formation of its X-ray emission in the accretion disk boundary layer. It is noted that scattering on electrons plays the dominant role in the emission processes.

KEYWORDS: neutron star; accretion; boundary layer; X-ray burst; electron scattering

1. INTRODUCTION

The source GX3+1 is a typical representative of the group of bright Galactic X-ray binaries consisting of a neutron star with weak magnetic field and a low mass ($M_1 \lesssim M_\odot$) companion. Sources of this group radiate due to disk accretion and the bulk of the observed X-rays originates from the geometrically thin plasma layer at the boundary between the disk inner edge and the neutron star surface.

The coded-mask X-ray telescope ART-P, one of two major instruments on board GRANAT, was designed for imaging, timing and spectroscopy of compact sources in the 2.5-60 keV band. It has good angular (5$'$) and temporal (3.9 ms) but moderate energy (22$\%$ at 6 keV) resolution (Sunyaev et al. 1990). GX3+1 was observed with ART-P four times during the GRANAT Galactic center field survey in the fall of 1990. Each of the observations lasted several hours and the total exposure exceeded 18 hours. Already the quick-look analysis of the data led to one interesting finding – a strong X-ray burst was detected from GX3+1 on Oct. 14 (Pavlinsky et al. 1994).

2. X-RAY BURST

The 2.5-20 keV count rate recorded by ART-P on Oct. 14, 1990 is shown as a function of time in Fig. 1. The burst occurred $\sim 6000$ s after the session beginning (at 21$^h$49$^m$59$^s$ UT). In addition to GX3+1 there were three other persistent X-ray sources present that day within the telescope’s 3$\farcs4 \times 3\farcs6$ field of view (Fig. 2, left). One of them was the X-ray burster A1742-294. The ART-P image accumulated during a 17 s burst interval (Fig. 2, right) evidently shows that only GX3+1 can be
FIGURE 1. The 2.5-20 keV count rate history recorded by ART-P on Oct. 14, 1990 when a strong X-ray burst was detected from GX3+1. The insertion gives the burst profile in two different energy bands with the better temporal resolution (bars show ±1σ errors).

The source responsible for the detected burst event. The insertion in Fig. 1 shows that the burst duration Δt noticeably changed with energy being of about 12 s in the hard 10-20 keV band and reaching ∼18 s in the soft 2.5-6 keV band. Such behaviour is a characteristic of the type I X-ray bursts (Hoffman et al. 1978).

The source persistent luminosity $L_p$ was equal to $(5.4 \pm 0.2) \times 10^{37}$ erg s$^{-1}$ in the 2.5-20 keV band (assuming a distance of 8.5 kpc). This is ∼30% less than the luminosity measured in the other days. The luminosity during the burst interval $L_b \simeq 3 \times 10^{38}$ erg s$^{-1}$. The black-body approximation of the burst average spectrum gave the neutron star radius $R \simeq 7.2 \pm 1.2$ km and its surface temperature $kT_b \simeq 2.4 \pm 0.2$ keV. The burst recurrence time was estimated to be $t_r \sim \Delta t \nu L_b/L_p \simeq 2.0 \pm 0.2$ s.

FIGURE 2. Image of the field near GX3+1 obtained with ART-P in the 2.5-20 keV X-rays during the whole observation on Oct. 14, 1990 (left panel) and during the burst interval (right panel). Contours are given at the signal-to-noise levels of 3, 3.9, 5.0, 6.6, 8.6, 11.1, ..., 53.8σ.
FIGURE 3. The GX3+1 spectrum measured with ART-P on Sept. 13 and its best-fit approximation by Sunyaev-Titarchuk Comptonization model (left panel). Right panel shows results of the spectrum approximation by other models. Given are the $kT - \alpha$ confidence intervals (1, 2, 3$\sigma$ for model d and 3$\sigma$ for others) for black-body (a), exponential atmosphere (b), uniform isothermal half-space (c), Boltzmann law (d) and thermal bremsstrahlung (e) models.

$10^4$ s, where $\nu \simeq 100$ is the ratio of energy emitted during the accretion onto a neutron star and that released in thermonuclear reactions of helium burning. This time exceeds twice the duration of the source observation with ART-P on Oct. 14.

Although GX3+1 is one of the brightest X-ray sources on the sky, located near the Galactic center and thus regularly observed, that was only the second case for the whole history of its study when it exhibited bursting activity. First several bursts were detected by HAKUCHO in 1980 (Makishima et al. 1983). In both the cases the source was in the low X-ray state with the luminosity 30–50% smaller than the normal one. This supports the idea that bursting activity of many LMXB sources is suppressed due to their high accretion rates (Lewin et al. 1993).

3. PERSISTENT EMISSION AND PARAMETERS OF THE NEUTRON STAR

The accretion disk boundary layer gives the main contribution to the GX3+1 persistent emission, so the source spectra measured with ART-P can be used to investigate spectral formation in it. First, we applied to the spectra a few simple models, such as black-body emission, optically thin thermal bremsstrahlung, Sunyaev-Titarchuk Comptonization of soft photons on hot electrons and Boltzmann law in which photon flux $I_\nu \sim E^{-\alpha} \exp(-E/kT)$. The Comptonization model was most successful. The left panel in Fig. 3 illustrates this issue showing the spectrum measured on Sept. 13, 1990 (during the longest ART-P observation) and the result of its best-fit approximation. The obtained plasma cloud parameters, $kT \simeq 2.3\pm0.1$ keV and $\tau_T \simeq 14\pm1$, indicate however that the model may be physically invalid because it does not take into account effects of free-free absorption important in such a cool and optically thick plasma. Two other models more suitable for the description of boundary layer emission were considered – the model of exponential isothermal atmosphere and the
FIGURE 4. Radius \( R \) of a neutron star in GX3 +1 and parameters of its atmosphere, height \( h \) and density \( \rho \), estimated from the ART-P data of Sept. 13 on the basis of models of exponential atmosphere (left) and uniform isothermal half-space (right) and given as functions of the neutron star emitting surface area \( S \). In the left panel letters (a, b, c) mark cases with different luminosity levels \( L \ll L_{\text{cr}} \), \( L = 0.2 \) or \( 0.4 L_{\text{cr}} \), in the right panel – with different suggestions about the neutron star radius \( R = 4, 3 \) or \( 2 R_g \). Here \( L_{\text{cr}} \simeq 1.8 \times 10^{38} \text{ erg s}^{-1} \) and \( R_g \simeq 4.2 \text{ km} \) are the critical Eddington luminosity and the gravitational radius of a 1.4 \( M_\odot \) neutron star. Dashed line shows the dependence \( R \) on \( S \) for the black-body emission model.

model of uniform isothermal half-space. They take into account free-free absorption but still assume electron scattering to be dominant in opacity. In the first model \( I_\nu \sim h^{-1/3} E^{1/3} \exp(-E/kT) \), in the second \( I_\nu \sim \sqrt{E} E^{1/2} \exp(-E/kT) \) (Shakura, Sunyaev 1973). Here \( h \) and \( \rho \) are the atmosphere scale height and its density.

The models approximate the data quite successfully. In addition, they provide us with rather interesting estimates for the neutron star radius and the atmosphere parameters \( h \) and \( \rho \) (Fig. 4, see Molkov et al. 1999 for more details). Noticing that these two and some others of the considered models have the same spectral shape (Boltzmann law) we presented in Fig. 3 (right panel) confidence intervals for best-fit parameters (photon index \( \alpha \) and \( kT \)) of the models. The figure shows that the density distribution in the boundary layer is uniform rather than exponential and that the finite thickness of the layer can not be neglected in modeling of its spectrum.

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REFERENCES
Hoffman, J.A., Marshall, H.L., Lewin, W.H.G. 1978, Nature, 271, 630
Lewin, W.H.G., Van Paradijs, J., Taam, R.E. 1993, Space Science Rev., 62, 223
Makishima, K., Mitsuda, K., Inoue, H., et al. 1983, ApJ, 267, 310
Molkov, S.V., Grebenev, S.A., Pavlinsky, M.N., Sunyaev, R.A. 1999, Astron. Lett., in press
Pavlinsky, M.N., Grebenev, S.A., Sunyaev, R.A. 1994, ApJ, 425, 110
Shakura, N.I., Sunyaev, R.A. 1973, A&A, 24, 337