THE ASTROPHYSICAL JOURNAL, 383: L49–L52, 1991 December 20

THREE SPECTRAL STATES OF 1E 1740.7−2942: FROM STANDARD CYGNUS X-1 TYPE SPECTRUM TO THE EVIDENCE OF ELECTRON-POSITRON ANNIHILATION FEATURE

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Received 1991 July 24; accepted 1991 September 30

ABSTRACT

The source 1E 1740.7−2942 is known to be the brightest hard X-ray source close to the dynamic center of our Galaxy. Three apparently different spectral states of this source were detected by the *GRANAT* observatory during 1990–1991 observations of the Galactic Center (GC) region. In almost all 1990 observations the source had Cyg X-1—like spectrum with nearly constant flux. The hardest of the states (observed on 1990 October 13–14) exhibits a prominent high-energy bump on the spectrum at 300–600 keV, probably related to the annihilation processes in relatively cold electron-positron plasma. In the most recent measurements on 1991 February–March a long-term low state of 1E 1740.7−2942 was discovered with the source flux on the level of 15%–20% of its 1990 value.

Subject headings: black holes — galaxies: The Galaxy — gamma rays: general — X-rays: sources

1. INTRODUCTION

The numerous balloon flights during the 1970's and 1980's have discovered extremely hard X-ray and gamma-ray emission from the direction to GC (Matteson 1982). This emission with a power-law spectrum similar to AGN spectra was tentatively attributed to the supermassive black hole with a mass of $10^6\ M_\odot$ which was supposed to be in the dynamic center of our Galaxy (Lacy et al. 1980). Observations with high-resolution germanium detectors (see Leventhal et al. 1989; Lingenfelter & Ramaty 1989) have discovered strong variable emission in the narrow 511 keV line with hard continuum, similar to one observed in earlier balloon flights.

The first imaging observations of the GC region at 3–30 keV with XRT coded mask telescope (Skinner et al. 1987) have shown that at the energies ~20–30 keV the brightest source among the dozen of sources observed at lower energies in the vicinity of GC is 1E 1740.7−2942, discovered earlier by the *Einstein* observatory (Hertz & Grindlay 1984). The imaging hard X-ray observations of the GRIP telescope (Cook et al. 1991) and SIGMA telescope on board *GRANAT* on 1990 Spring (Mandrou 1990; Paul et al. 1990b; Sunyaev et al. 1990b, 1991c) have discovered that 1E 1740.7−2942 is the only bright source in the neighborhood of GC at the energies above 35 keV. The closest source with comparable flux at 100 keV was GRS 1758−258, discovered by *GRANAT* and located near GX5−1 and ~5° away from GC.

2. INSTRUMENTS AND OBSERVATIONS

The coded aperture telescopes ART-P and SIGMA are the major instruments of the *GRANAT* spacecraft, launched on 1989 December 1. The ART-P instrument is a coded-mask telescope with 3°.6 × 3°.4 field of view (FOV) and 5′ angular resolution, sensitive in the 4–30 keV energy band (Sunyaev et al. 1990a). The SIGMA telescope (Paul et al. 1990a) provides sky images in the energy range 35–1300 keV with an angular resolution of approximately 15′. Instrument FOV at the half-sensitivity boundary is a 11°.5 × 10°.9 rectangle.

Three sets of intensive observations of the GC region were performed by *GRANAT* so far: on 1990 Spring and Fall and 1991 Spring. Some of observational data possibly affected by systematic errors of image reconstruction (in particular some observations on 1991 Spring after tremendous solar flare, influenced the detector parameters) were omitted. For SIGMA spectra the energy/channel relation obtained from the analysis of the induced background lines was used.

Hard X-ray maps (in 40–110 keV band) of the region a few degrees around GC, obtained by SIGMA telescope in different sets of observations in 1990–1991, are shown in Figures 1*a* and 1*b*. During the first observations on 1990 March–April it was discovered that there are only two comparatively bright sources at energies above 35 keV in ±5° vicinity of GC: 1E 1740.7−2942 and the newly discovered very hard source GRS 1758−258, located 40′ apart from the well known QPO source GX 5 − 1. Observations of 1990 September–October confirmed this conclusion (Fig. 1*a*). During 1990 October 13–14, the SIGMA telescope has detected apparent hardening of the 1E 1740.7−2942 spectrum. Shown on Figure 1*c* is an image in 300–600 keV energy band obtained by SIGMA in these observations. Clearly seen on the image is 5.5 standard deviations peak close to the position of 1E 1740.7−2942. The new set of GC observations, performed in 1991 February–April, revealed that the source entered a low state with the averaged luminosity at the level of 15%–20% of the luminosity, observed in 1990. Two apparent peaks seen on Figure 1*b* correspond to GRS 1758−258 and GX 1 + 4. The latter was not detected in

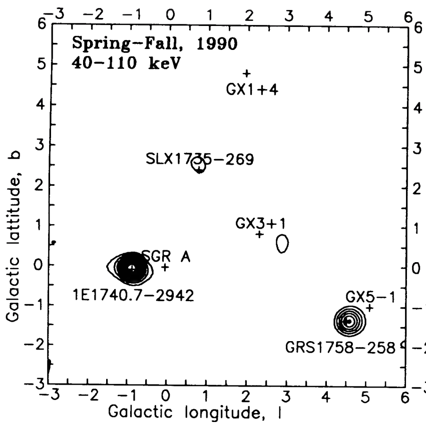

FIG. 1a

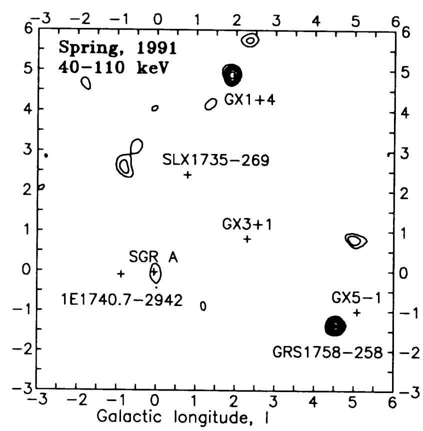

FIG. 1b

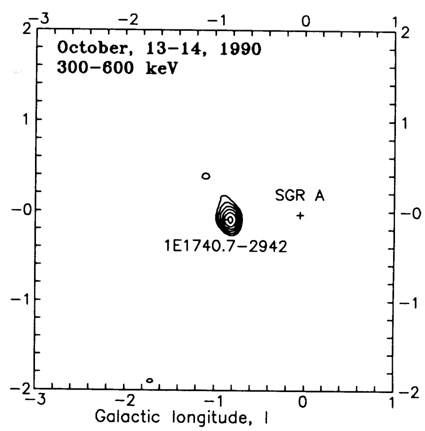

FIG. 1c

FIG. 1.—X-ray map of the several degrees region near GC, obtained by SIGMA during different periods of observations. (*a*) 1990 Spring–Fall, 40–110 keV, total exposure of 655×10^3 s (dead time corrected) (contours are 4, 7, 10 ... σ, 1 σ corresponds to 3.9 mCrab at the position of 1E 1740.7−2942 and 4.6 mCrab at the position of GRS 1758−258 and GX 1 + 4); (*b*) 1991 Spring, 40–110 keV, 242×10^3 s (contours are 4, 5, 6 ... σ, 1 σ − 4.9 and 6.3 mCrab); (*c*) October 13–14, 300–600 keV, 45.5×10^3 s (3, 3.5, 4 ... σ, 1 σ corresponds to 1.5×10^{-3} photons s^{-1} cm^{-2}). The crosses (+) mark the position of some known sources. Note that the scale for right figure differs from those of the left and center figures.

1990 (Fig. 1*a*), but during 1991 Spring observations, it was found to be the brightest source in GC field in the 40–110 keV energy band.

The pulse-height spectra of 1E 1740.7−2942 measured by SIGMA in different spectral states of the source are shown on Figure 2. The spectral fluxes and luminosities of the source are given in Table 1.

3. STANDARD STATE

The averaged spectrum of 1E 1740.7−2942, collected over 1990 Spring observations with the source being in normal state, is shown on Figure 3. The approximation of the data in 4–300 keV band by Comptonized disk model (Sunyaev & Titarchuk 1980) gives an electron temperature of 35 ± 2 keV, half-thickness of the disk $\tau = 1.5 \pm 0.1$, hydrogen column density $N_H = (1.9 \pm 1) \times 10^{23}$ cm^{-2}, and spectral flux at 100 keV $F_{100} = (9.0 \pm 0.5) \times 10^{-5}$ photons s^{-1} cm^{-2} keV^{-1} (Fig. 3). The averaged luminosity of the source in 4–300 keV energy range was $L = (3.2 \pm 0.2) \times 10^{37}$ ergs s^{-1} (assuming 8.5 kpc distance). The source spectrum clearly shows steepening above ~150 keV. It is much better described by thermal bremsstrahlung or Comptonized disk model (reduced χ^2 0.7 for 14 d.o.f.) than by simple power-law (reduced χ^2 2.4 for 15 d.o.f.).

Hardness of the source spectrum in normal state argues to consider this source as a black hole candidate. Moreover the shape of the spectrum is quite similar to the most reliable black hole candidate Cyg X-1 (see Fig. 3). It is important that during MIR-KVANT observations on 1989 March 20–21, the source was also found in standard state (Sunyaev et al. 1991a).

4. HARD STATE

The spectrum of 1E 1740.7−2942 obtained by SIGMA on 1990 October 13–14 differs strongly from the spectrum of the normal state. Most remarkable is the spectral feature in 300–600 keV range (Figs. 1*c* and 2), which was detected at the level of ~5.5 standard deviations. One can note that the X-ray luminosity (35–600 keV) of 1E 1740.7−2942 in the hard state increased by several times as compared with the normal state (see Table 1). Moreover, the hard energy feature itself contains about 60%–70% of the 35–600 keV luminosity of the source. It is important that the previous and following observations of this region, held on October 10–11 and 14–15 did not reveal any evidence for the flux from the source above 300 keV with an upper limit (2 σ) of 3.6×10^{-4} counts s^{-1} cm^{-2} (300–600 keV). Moreover, the analysis of the whole set of observations on 1990 Spring and Autumn gives the upper limit, on 300–600 keV flux from the source, at the level of 1×10^{-4} counts s^{-1} cm^{-2} (2 σ). For comparison the source flux on October 13–14

TABLE 1

FLUXES AND LUMINOSITIES OF 1E 1740.7−2942

STATE	ENERGY INTERVAL (keV)		
	35–100	100–300	300–600
Normal state (1990, Spring–Fall)			
F	$(2.20 \pm 0.05) \times 10^{-4}$	$(2.3 \pm 0.1) \times 10^{-5}$	$<3 \times 10^{-6}$
L	$(1.11 \pm 0.03) \times 10^{37}$	$(1.04 \pm 0.05) \times 10^{37}$	$<5 \times 10^{36}$
Hard state (1990, Oct 13–14)			
F	$(2.7 \pm 0.2) \times 10^{-4}$	$(2.4 \pm 0.4) \times 10^{-5}$	$(2.7 \pm 0.5) \times 10^{-5}$
L	$(1.4 \pm 0.1) \times 10^{37}$	$(1.1 \pm 0.2) \times 10^{37}$	$(4.5 \pm 0.8) \times 10^{37}$
Low state (1991, Feb 22–27)			
F	$(3.7 \pm 0.8) \times 10^{-5}$	$<4 \times 10^{-6}$	$<5 \times 10^{-6}$
L	$(1.9 \pm 0.4) \times 10^{36}$	$<2 \times 10^{36}$	$<8 \times 10^{36}$

NOTES.—(*F*) Spectral flux in photons cm^{-2} s^{-1} keV^{-1}; (*L*) luminosity in ergs s^{-1} (for 8.5 kpc distance). Upper limits are 2 σ values.

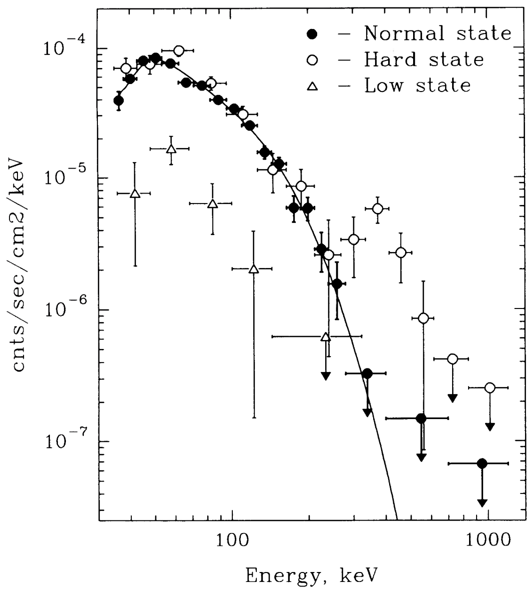

FIG. 2.—Pulse-height spectra of 1E 1740.7−2942 in normal, hard, and low states obtained by SIGMA.

was found to be $(10 \pm 1.8) \times 10^{-4}$ counts s^{-1} cm^{-2} (300–600 keV).

The characteristic feature of the spectrum, observed by SIGMA on October 13–14, is the change of the slope above 200 keV, maximum at 400–500 keV and the cutoff at higher energies.

The simplest explanation for the appearance of this feature is to suppose the existence of hot region in the accretion disk with large enough optical depth (producing a Wien-like component), so that the maximum of the emission from this region comes at about 400–500 keV. Detector response to Wien spectrum with temperature 100 keV is shown on Figure 4.

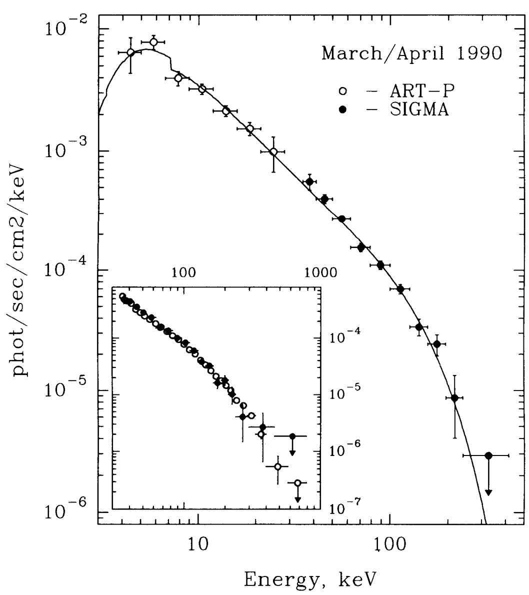

FIG. 3.—Spectrum of 1E 1740.7−2942, obtained by ART-P and SIGMA telescopes during observations in 1990 March/April. Solid line corresponds to the best-fit Comptonized disk spectrum. Spectra of 1E 1740.7−2942 (*filled circles*) and Cyg X-1, scaled to a distance of 8.5 kpc (*open circles*) above 30 keV, obtained by SIGMA, are shown in the lower left corner.

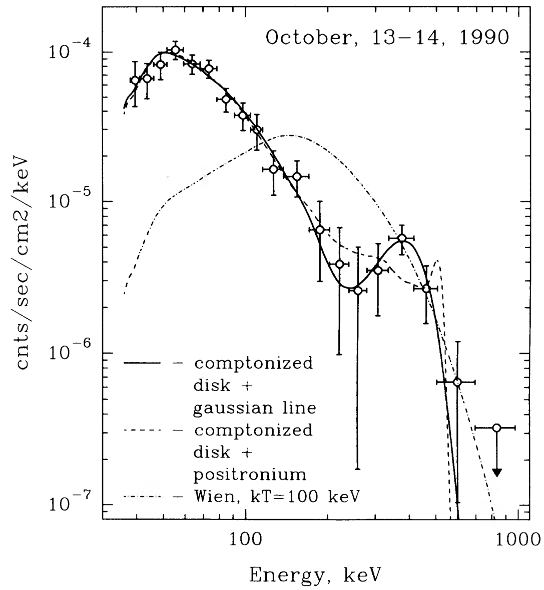

FIG. 4.—Pulse-height spectrum of 1E 1740.7−2942 during hard state. Detector responses to different model spectra are shown: Comptonized disk + Gaussian line, Wien spectrum with $kT = 100$ keV and Comptonized disk + positronium two- and three-photon annihilation components.

One can see that Wien spectrum is much broader than the high-energy feature observed.

More acceptable agreement can be achieved under the assumption that the feature is related to electron-positron annihilation. The calculations of Aharonian, Atoyan, & Sunyaev (1983) and Ramaty & Meszaros (1981) have shown that the maximum of the "in-flight" annihilation radiation is shifted to the higher energies (due to kinetic energy of annihilating particles) and the feature is broadened due to the Doppler effect. Fitting of the feature observed by the Gaussian gives the center at 410 (340–500—1 σ limits) keV and the width (FWHM) of ~ 180 keV and total flux $(9.5 \pm 4.5) \times 10^{-3}$ photons s^{-1} cm^{-2} (Fig. 4). The width of the feature indicates that the temperature of annihilating particles should be below $\sim 5 \times 10^8$ K. On the other hand, it is unlikely that the positrons were born with such a low kinetic energy: $T_e/m_e c^2 < 0.1$. It is more likely that the originally hot e^+e^- pairs are cooled down to comparatively low temperatures before annihilation. A molecular cloud, discovered recently (Bally & Leventhal 1991) at the position of 1E 1740.7−2942, can be a suitable site for deceleration of the pairs. In the extreme case of cooling below 10^6 K, the positronium formation might give rise to the high-energy spectrum, consisting of a broad component, corresponding to three-photon annihilation, and a narrow line resulting from two-photon annihilation of positronium (Leventhal 1973). The best-fit value for flux in narrow 511 keV line is $(1.9 \pm 0.9) \times 10^{-3}$ photons s^{-1} cm^{-2} in this case (positronium fraction was fixed to 1). This model gives a larger value of χ^2 (11.9 for 8 d.o.f.) than the Gaussian line model (8.7 for 8 d.o.f.). A crucial test for positronium model is the presence of narrow 511 keV line. Unfortunately our observation gave relatively weak constraints on the emission in the narrow 511 keV line itself ($\sim 3 \times 10^{-3}$ photons s^{-1} cm^{-2}—3 σ upper limit).

The centroid of the hard feature (with a used value of detector gain) observed by SIGMA seems to be shifted with respect to 511 keV to lower energies. If it is not related to the gravitational redshift, it might be evidence of the continuum at the energies below 511 keV (like in the case of positronium annihilation spectrum). Of course, a variety of shapes could be explained in terms of cold material of complicated geometry which scatters the line radiation. Taking into account statistical significance of the feature it is difficult to derive more definite conclusions about its nature.

5. LOW STATE

1991 Spring observations of this region gave a new, unexpected result: 1E 1740.7−2942 weakened at least several times. These observations discovered a new "low" state of the source which was never observed for the well-known black hole candidate Cyg X-1.

Recently, Bally & Leventhal (1991) reported the discovery of the molecular cloud at the position of 1E 1740.7−2942. Provided that the source is situated inside the cloud and Thomson optical depth of cloud is ~ 0.2 (which corresponds to the total $N_H \sim 3 \times 10^{23}$ cm^{-2} quoted in Bally & Leventhal 1991), the source flux at each moment of time should not drop below 0.2 of the flux averaged over past year (or years). Surprisingly, the low state of the source (averaged over the 1991 February 22–27 period) is characterized by a $\sim$5–6 times drop of intensity. Possibly, in a low state we are observing radiation scattered in the surrounding cloud. This scattered radiation should not disappear simultaneously with switch off of compact source. The duration of the low state might give the estimate of the size of the cloud (if the source was completely turned off).

6. DISCUSSION

The source 1E 1740.7−2942 is becoming of interest due to the following:

1. Discovery of the strong bump on the spectrum at high energies, which is probably related to electron-positron annihilation. This fact implies that the source should be included into the list of possible candidates for identification of the narrow 511 keV line observed by germanium nonimaging experiments.

2. Strong variability of the source flux indicates that this is most likely an accreting object, but not a Crab-like source (rotation-powered emitter).

3. Hardness of the source spectrum in the normal state, which is similar to the spectra of Cyg X-1 type sources, is characterized by anomalously hard spectra and considered to be black hole candidates. Luminosities of both Cyg X-1 and 1E 1740.7−2942 in their normal states are close to 2–4 $\times 10^{37}$ ergs s^{-1}, i.e., are tens of times below the Eddington luminosity for the stellar mass black hole. It is worth mentioning that in Cyg X-1 the "MeV bump" is accompanied by the decrease of the flux at lower energies (Ling et al. 1987). The high-energy bump in 1E 1740.7−2942 followed the increase of the flux in ART-P band as well as in the 40–200 keV SIGMA data, i.e., the luminosity and accretion rate increased.

4. The high-energy bump in the spectrum of 1E 1740.7−2942 was variable: it was absent $\sim$2 days before detection (observations on October 10–11) and few hours after (observations on October 14–15). This variability does not give us information concerning the physical processes inside the disk, since this time scale is eight or nine orders of magnitude larger than any characteristic time related to the maximum energy release region of disk [$t_{\rm disk} \sim 1/\omega$, where $\omega =$ the Keplerian frequency for $r \sim (5\text{–}15)r_g$]. Therefore we can consider this state with the high-energy bump as quasi-stationary. On the other hand, supposing that this bump is related to the positrons annihilation, which are decelerating and losing their kinetic energy in the region much larger than the zone of main energy release in the disk, one can restrict the size of this region to $\Delta l \leq c\Delta t \sim$ few 10^{15} cm. The deceleration of the positrons from thermal energies to the energies $\leq 0.1 m_e c^2$ should lead to the heating of ambient cold matter and the appearance of a comparatively short-lived source, most likely in a submillimeter spectral band.

5. In the context of the recent discovery of narrow spectral feature near 500 keV in the spectrum of Musca Nova (Sunyaev et al. 1991b) and earlier observations of the "MeV bump" in the spectrum of Cyg X-1 (Ling et al. 1987), the detection of the hard state of 1E 1740.7−2942 shows that the electron-positron annihilation processes might be common but rarely appearing signatures of the accretion onto stellar mass black holes.

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