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SIGMA DISCOVERY OF VARIABLE e^+-e^- ANNIHILATION RADIATION FROM THE NEAR GALACTIC CENTER VARIABLE COMPACT SOURCE 1E 1740.7−2942

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ABSTRACT

A series of observations of the Galactic center have been performed by the hard X-ray and low-energy gamma-ray coded imaging telescope SIGMA, aboard the *GRANAT* space observatory, in 1990 March, April, September, and October, in the energy range 35 keV–1.3 MeV. The emission of the close nucleus center region above 35 keV was found to be dominated up to 300 keV by the previously observed X-ray source 1E 1740.7−2942, situated $\approx 48'$ away from the radio source Sgr A*.

During the 1990 October 13 observation, we discovered that the source was exhibiting a remarkable feature in its emission spectrum ($E > 300$ keV), which appears as a bump, reaching a maximum intensity around 500 keV, followed by a ≈ 700 keV cutoff. In an observation performed the day after, this feature was absent, showing that the source had recovered its nominal state in a very short time.

Subject headings: black holes — galaxies: nuclei — galaxies: The Galaxy — gamma rays: general

1. INTRODUCTION

The Galactic center (GC) region has been observed many times in the hard X-ray and low-energy gamma-ray domain during the last 26 years, both by balloon-borne telescopes and spacecraft experiments. The most prominent result obtained was the discovery of an e^+-e^- annihilation line emission associated with this region (Haymes et al. 1975).

High-energy–resolution telescopes, with a field of view $<20°$ (Leventhal, MacCallum, & Stang 1978; Riegler et al. 1985) provided evidence that the detected annihilation line was narrow (<3.2 keV) and centered at 511 keV. A significant continuum contribution interpreted as orthopositronium annihilation was also detected.

Further observations, performed by the Bell/Sandia group (Leventhal et al. 1980, 1982, 1986) with the same detector, as well as the *HEAO 3* observations (Riegler et al. 1985), have shown a variability of the line, leading to the idea that it originates from a variable compact object situated close to the GC.

At the same time, Share et al. (1990), using the 130° field of view detector aboard the *Solar Maximum Mission*, have clearly demonstrated that, since 1981, the e^+-e^- annihilation flux was quite stable and consistent with a value of 2×10^{-3} photons cm^{-2} s^{-1} over the 7 years of observation.

An extensive and comparative review of such different results accumulated during this long epoch was presented by Lingenfelter & Ramaty (1989 and references therein). These authors, considering the demonstrated time variations as well as the rather stable observations of *SMM*, conclude that the observations of the 511 keV line can be explained in a coherent way if they suppose that the contribution of a variable compact object situated close to the GC is, from time to time, superposed on a quite stable diffuse disk emission.

Recently, high-resolution imaging telescopes have observed the GC region in the high–X-ray and soft gamma-ray domain. They have demonstrated (Skinner et al. 1987, 1990; Kawai et al. 1990) that several hard X-ray point sources surrounded the geometric center located at the radio source Sgr A*. Using the 1°.1 resolution imaging balloon-borne telescope GRIP, Cook et al. (1989) have found that only one of them can account for a high-energy emission up to 200 keV, and they suspected that this source could be identified with 1E 1740.7−2942, discovered by the *Einstein* soft X-ray telescope (Hertz & Grindlay 1984).

Thanks to the precise images obtained by the French imaging telescope SIGMA, the first coded-aperture space telescope operating in the soft gamma-ray regime, a clarified picture of the GC is now emerging (Sunyaev et al. 1991). In this *Letter*, we report on the transient soft gamma-ray feature detected by SIGMA from 1E 1740.7−2942 on 1990 October 13, i.e., an intense emission of gamma-rays originating in the e^+-e^- annihilation radiation process.

2. OBSERVATION AND DATA ANALYSIS

The SIGMA telescope is a hard X-ray/soft gamma-ray instrument designed to obtain arcminute resolution images of the sky in the 35 keV–1.3 MeV energy range. The detector consists of a NaI(Tl) crystal optically coupled to an array of 61 hexagonal photomultiplier tubes. A tungsten-coded mask aperture, based on URA pattern, is placed 2.5 m in front of the detector plane. The fully coded field of view of the telescope is 4°.7 × 4°.3. A detailed description of SIGMA can be found in Paul et al. (1991); the first in-flight performances are presented in Mandrou et al. (1990).

Two series of observations of the GC region were carried out in the course of 1990 March/April and September/October. During all the GC observation sessions, the SIGMA telescope

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1991ApJ...383L..45B

was operating in the "spectral-imaging" mode. Two sets of images are recorded simultaneously by the instrument in this operating mode: the "high-resolution images," consisting of maps with pixel size of 1'.6 in four contiguous wide energy bands, and the "spectral images," a series of maps with pixel size of 3'.2 in 95 energy channels between 35 keV and 1.3 MeV. The recorded images have been corrected for the spatial non-uniformities intrinsic to the detector or due to the background, and then deconvolved using standard techniques (Laudet & Roques 1988). The energy calibration was checked on the basis of the in-flight control using known induced background lines.

The 95 channel electron spectra of a source are obtained from the deconvolution of the 95 "spectral images" by taking the counting rate in the sky pixel of the source for each energy interval image.

Then, in order to recover the incident photon spectrum, the appropriated response matrix has been constructed from a Monte Carlo simulation method, including an extensive geometrical representation of the telescope. The validity of the modelization has been tested by comparison with 12 spectral responses obtained with the whole telescope from calibrated radioactive sources, during ground calibrations (Barret & Laurent 1991). The photon spectra are deduced from the electron spectra, through a process based on the maximum entropy method.

3. RESULTS

During the 1990 GC observations, more than 150 hr of useful observing time were accumulated on this region. One of the first results obtained was to demonstrate unambiguously that the *Einstein* source 1E 1740.7−2942 is the most luminous object in the hard X-ray soft gamma-ray domain close to the Galactic nucleus (Mandrou 1990; Cordier et al. 1991; Paul et al. 1990; Sunyaev et al. 1990, 1991; Roques et al. 1991). The best position of the source was found by the SIGMA telescope to be at right ascension $\alpha = 265^\circ.18$ and declination $\delta = -29^\circ.73$ (in 1950 equinox coordinates) with a 90% confidence level error radius of 2' containing the *Einstein* source located $\alpha = 265^\circ.178$ and $\delta = -29^\circ.713$ (90% error radius of 0'.9).

The hard nature of the source was confirmed by its detection up to 300 keV. During seven different sessions performed on 1990 March 24, April 4, 8, 12, 17, September 19, 29, and October 10, the energy spectra of the source were found to be statistically consistent with the same law: all the spectra derived from the data are well explained in terms of disk accretion onto a black hole in the framework of the Comptonized disk model of Sunyaev & Titarchuk (1980) with an electron temperature of $kT_e = 31 \pm 4$ keV and an optical depth of $\tau = 1.8$ ($+0.5$, -0.4) for the March/April observations and $kT_e = 60$ ($+13$, -9) keV with $\tau = 1.0 \pm 0.2$ for the September and October 10–11 observations. Figure 1 (*diamonds*) shows the spectrum derived from March/April data. This series of detections where the source was found to be quite stable was suddenly interrupted by an important event in the course of October. In an observation performed between 1990 October 13 and 14, the source emission spectrum was found to exhibit a spectacular unexpected structure, above 200 keV up to 700 keV. This structure, observed during all the observation session (4.5×10^4 s useful time), is unambiguously apparent in the image, at 1E 1740.7−2942 position (Fig. 2), while nothing was revealed above 300 keV in the previous observations.

The photon spectrum resulting from this observation is shown in Figure 1 (*crosses*). The bump structure is well cen-

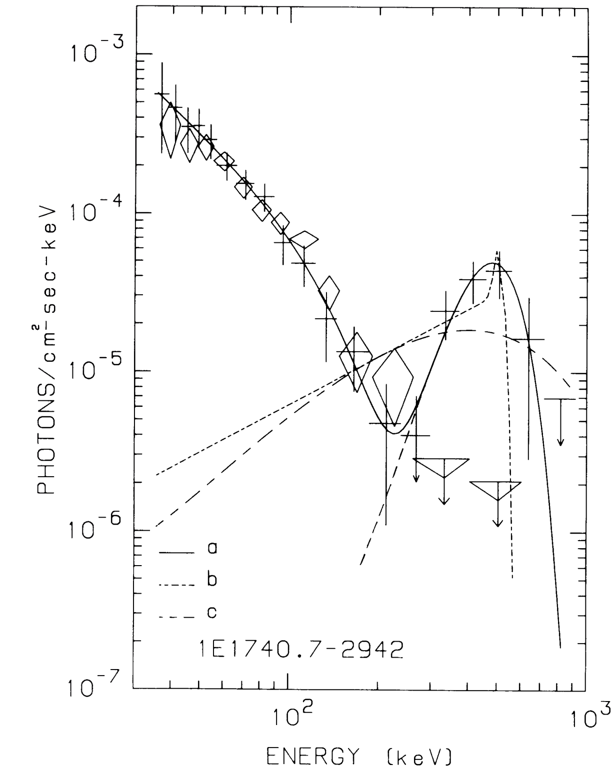

FIG. 1.—Energy spectrum of 1E 1740.7−2942 as obtained by SIGMA on 1990 October 13 (*crosses*); the spectrum derived from 1990 March/April (*diamonds*) is shown for comparison. Line a (*solid*) represents the best fit for the Comptonization law plus the Gaussian line. Line b (*short-dashed*) represents the positronium part of the Comptonized disk plus positronium model. Line c (*long-dashed*) represents the high-temperature part of the two-temperature Comptonization disk model.

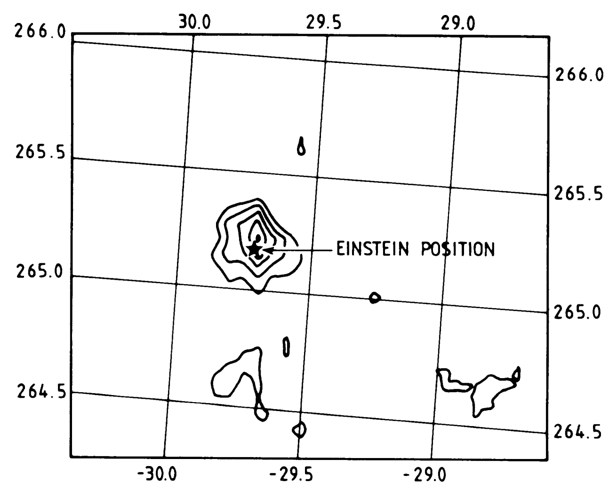

FIG. 2.—Contour map of the GC region, derived from the SIGMA data recorded during the October 13–14 observation session in the energy band 330–570 keV. Right ascension (*nearly vertical lines*) and declination (*nearly horizontal lines*) are indicated for epoch 1950.0. The contours indicate the number of excess counts in a given direction, calibrated in units of the statistical significance of the excess, with contours beginning at the 2 σ level and spaced by 1 σ (1 σ represents 3.8×10^{-2} counts s^{-1} in the deconvolved image). *Einstein* position of the X-ray source 1E 1740.7−2942 is indicated by a star.

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1991ApJ...383L..45B

tered around 500 keV, and a cutoff appears close to 700 keV. This shape suggests that this effect can be attributed to an electron-positron annihilation process in the vicinity of the source, coming from a massive production of a hot pair plasma.

The low-energy fraction (35–200 keV) of the spectrum derived from the data recorded by the SIGMA telescope during the 1990 October 13–14 observation does not differ significantly from its general behavior, as observed in 1990 March and April. The most straightforward modelization of the 1990 October 13–14 spectrum then simply consists of superposing a single "line" with a Gaussian profile to the Comptonized disk emission spectrum as derived from the combined 1990 March, April data.

In this context, the spectral feature observed by SIGMA during the 1990 October 13–14 session is represented by a Gaussian line centered at 480 keV with a FWHM of 240 keV (see Table 1B and Fig. 1). It should be stressed that such a feature is well resolved and cannot result simply from a narrow line convolved with the detector spectral resolution (the energy resolution $\Delta E/E$ is of the order of 8% in the 500 keV region).

It is worth noting that the spectrum derived from the data recorded during the session performed just prior to the high-energy event (between 1990 October 10 and 11) does not exhibit any spectral feature beyond 200 keV.

TABLE 1A

Model Fit Parameters for 1E 17420−2942: Two-Temperature Comptonized Disk (1990 October 13–14)

Parameter	Value
kT_1 (keV)	20 (+5, −4)
τ_1	2.5 (+2.7, −1.0)
kT_2 (keV)	201 (+139, −72)
τ_2	36 (+8, −11)
Reduced χ^2	0.90
Degrees of freedom	85

TABLE 1B

Model Fit Parameters for 1E 17420−2942: Comptonized Disk plus Gaussian Law (1990 October 13–14)

Parameter	Value
kT (keV)	27 (+8, −7)
τ	1.6 (+1.0, −0.5)
Line center (keV)	480 (+96, −72)
FWHM (keV)	240 (+101, −94)
Flux (photons cm^{-2} s^{-1})	1.3×10^{-2}
Reduced χ^2	0.78
Degrees of freedom	85

TABLE 1C

Model Fit Parameters for 1E 17420−2942: Comptonized Disk plus Positronium (1990 October 13–14)

Parameter	Value
kT (keV)	20 (±3)
τ	2.5 (±0.4)
Orthopositronium flux (photons cm^{-2} s^{-1})	0.9 (±0.3) $\times 10^{-2}$
Reduced χ^2	0.86
Degrees of freedom	87

Further observation sessions have been performed on the source, on October 14 and 15, a few hours after the bump was observed, as well as a second one during October 18, but they have demonstrated that the source had recovered its nominal state, quite consistent with the general spectra obtained during the March/April, September, and October sessions.

4. DISCUSSION

Although the hard source 1E 1740.7−2942 can be considered, on the basis of seven different observations performed during 1990 spring and September, as a quasi-stable object, observations carried out few days in October have revealed a peculiar behavior and have evidenced its randomly variable nature, particularly around the 500 keV energy domain.

In a period of a few days, two different states have been noted:

1. A quiet state so-called nominal in which the source exhibits, session by session, an emission spectrum, well fitted by a Comptonized disk model. This spectrum looks like the spectrum found for Cyg X-1 in the γ_2 and γ_3 states (Ling et al. 1987). Moreover, under the hypothesis of a 8.5 kpc distance for 1E 1740.7−2942, the luminosity in the range 30–200 keV is $L_{30-200} \approx 2 \times 10^{37}$ ergs s^{-1} which is also comparable to that of Cyg X-1.

2. A high state characterized by the discovery of a feature in the 300–700 keV domain, with a maximum around 500 keV. This feature contains almost 50% of the energy radiated by the source in the 35 keV–1 MeV interval.

The total duration of this state, taking into account the dead time and the nonoperative periods, can be estimated to be between a minimum of 18 hr and a maximum of about 70 hr. These values limit the dimension of the source to few 10^{15} cm.

Such an overall complex structure was also noticed in the Cyg X-1 high state (γ_1), but it must be pointed out that in the case of Cyg X-1, the structure appears to be centered at higher energies ($\approx$1 MeV). Also, this effect is accompanied in Cyg X-1 by a notable decrease of the continuum emission below 400 keV which is not found in the reported SIGMA observation of 1E 1740.7−2942. Nevertheless, the similarities in the behaviors of these two objects suggest that they might be of the same nature. The variable behavior of the hard emission of 1E 1740.7−2942 has been substantiated by a new series of observations of the GC region performed by SIGMA in 1991 February, March, and April, where the source intensity was found to be less than 20% of its 1990 March, April, and September value (Bouchet et al. 1991).

It is worth noting that the proposed modelization of the spectral feature as observed by SIGMA during the 1990 October 13–14 session can be explained in the framework of the hot pair plasma emission developed by Ramaty & Mészaros (1981) (see also Liang & Dermer 1988). Following these authors, the width of the line corresponds to a hot pair plasma temperature of $\approx 5 \times 10^8$ K. Other hypotheses, including positronium formation and subsequent annihilation, may account for the observed high-energy feature. In the light of this latter model, suggested by Leventhal et al. (1978), we have superposed a typical positronium spectrum to the Comptonized disk emission. The best fit (Table 1C and Fig. 1) is obtained for an electron temperature of $\approx$20 keV, an orthopositronium flux of $F_{ps} = 0.9 \times 10^{-2} \gamma_{ps}$ cm^{-2} s^{-1}. Nevertheless, this hypothesis leads to a difficulty: both the spectrum shape below 511 keV and the positive detection above 511 keV are in contradiction with a pure positronium emission.

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1991ApJ...383L..45B

In the context of the Sunyaev & Titartchuk (1980) Comptonization disk model, the spectrum may also be tentatively represented by two characteristic electron temperatures $kT_1 \approx$ 20 keV and $KT_2 \approx 201$ keV (see Table 1A). We should note that this model cannot fit the hard part of the spectrum.

However, it can be pointed out that it is difficult to deduce final conclusions on the basis of a single observation.

5. CONCLUSIONS

The first arcminute resolution images obtained with the SIGMA telescope aboard the *GRANAT* observatory, in the soft gamma-ray energy domain, have contributed to a better understanding of the region close to the Galactic nucleus of our Galaxy.

It is now quite clear that 1E 1740.7−2942 situated $\approx 48'$ away from the nucleus is the soft gamma-ray compact source imagined to explain all the observations performed during the last 20 years on the Galactic center region by several experiments. During the second *GRANAT* survey of the Galactic center in the course of 1990 autumn, 1E 1740.7−2942 was found to exhibit unexpected variations. During one session, a spectacular feature centered on 500 keV region was discovered in the emission spectrum, suggesting that this object can produce hot plasma of pairs in a short time. The general behavior of this object, with at least three observed states, as well as the general shapes of the spectra, suggests that it could be of the same nature as Cyg X-1 and thus could be also powered by a black hole.

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