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X-RAY NOVA IN MUSCA (GRS 1124−68): HARD X-RAY SOURCE WITH NARROW ANNIHILATION LINE

R. SUNYAEV, E. CHURAZOV, M. GILFANOV, A. DYACHKOV, N. KHAVENSON, S. GREBENEV, R. KREMNEV, AND K. SUKHANOV
Space Research Institute, Russian Academy of Sciences, Profsouznaya 84/32, 117810 Moscow, Russia
A. GOLDWURM, J. BALLET, B. CORDIER, AND J. PAUL
Service d'Astrophysique, Centre d'Etude Nucleaire de Saclay, 91191 Gif-sur-Yvette Cedex, France
AND
M. DENIS, G. VEDRENNE, M. NIEL, AND E. JOURDAIN
Centre d'Etude Spatiale des Rayonnements, 9, avenue du Colonel Roche, BP 4346, 31029 Toulouse Cedex, France
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ABSTRACT

On 1991 January 20–21, the SIGMA telescope on board *GRANAT* detected a relatively narrow variable emission line near 500 keV with net flux ~6 × 10^{-3} photons s^{-1} cm^{-2} in the spectrum of the X-ray Nova Muscae. During 1991 January 9–August 14, the spectrum had a strong hard component extending up to ~300 keV with average power-law photon index ~2.5. This component varies by a factor ~2 on time scales of hours. The hard component was absent only once, on April 12, but it reappeared during subsequent observations on May 31 and August 14. In contrast to the soft component, the light curve of the hard X-ray component does not decay exponentially, and so its relative contribution to the luminosity increased with time.

Subject headings: black hole physics — gamma rays: observations — X-rays: general — X-rays: stars

1. INSTRUMENT AND OBSERVATIONS

GRS 1124−684 (X-ray Nova Muscae) was discovered by all-sky monitors on board *GRANAT* (Lund & Brandt 1991) and *Ginga* (Makino 1991) on 1991 January 8. The source was localized by the ART-P and SIGMA telescopes on board *GRANAT* at R.A. = $11^h24^m10^s$, decl. = −68°24′ (1950 equinox) with 1′ accuracy, confirming the optical identification reported earlier by *ESO* (West 1991).

The SIGMA coded mask telescope provides sky images in the 35–1300 keV energy band with angular resolution of ~15′ and energy resolution ~9% at 500 keV (Paul et al. 1991). For spectral analysis of SIGMA data, the energy/channel relation, obtained from the positions of induced background lines, was used. The detector gain, obtained with uncertainty of a few percent, differs by ~8% from the preflight calibration and shifts the energy scale of the detector toward lower energies. The X-ray nova was observed by SIGMA on 1991 January 9.9–10.9, 16.6–17.7, 17.9–18.8, 20.5–21.7, February 1.6–2.6, 2.7–3.8, 5.6–6.8, 10.5–11.6, April 12.3–12.8, May 31.6–June 1.6, August 14.6–15.4, October 22.5–23.2, 26.5–27.2, and December 19.8–20.8, 22.5–23.7.

The main results of these observations are the broad-band spectrum of Figure 1, showing a clear emission line at ~500 keV that appeared on 1991 January 20–21, and an image (Fig. 2) that firmly identifies the line source with the X-ray nova in Muscae. Results of independent analysis of the same experimental data are presented in the companion *Letter* by Goldwurm et al. (1992).

2. HARD X-RAY LIGHT CURVE AND SPECTRA

The light curves of Nova Muscae in two hard X-ray bands are shown in Figure 3 along with the soft X-ray light curve observed by Tanaka et al. (1991). Each point corresponds to an individual observation with duration 3–6 hr. One can note the following:

1. The hard X-rays reached maximum significantly earlier than the soft X-rays.
2. The hard component declined more slowly than the softer component.
3. The soft X-ray light curve exhibits a secondary rise or "kick" (also found for A0620+00 and GS 2000+25) around 60–80 days after the main outburst. A short observation on April 12 (the only *GRANAT* data near the "kick," ~90 days after outburst), restricts the 40–70 keV flux to a value 2–3 times less than that observed before and after the "kick" (2 σ upper limit ~35 mCrab, where 1 mCrab unit corresponds roughly to 5.8 × 10^{-12} ergs s^{-1} cm^{-2} in the 40–70 keV band). This behavior of the hard component near the "kick," detected also by ART-P (Grebenev et al. 1992), resembles the transitions between hard and soft states observed for the well-known black hole candidates Cyg X-1 and GX 339−4.
4. The hard X-ray flux is highly variable, by factors up to 2 on time scales of ~3–6 hr (the minimal variability time scale that can be measured in the imaging mode). This behavior contrasts with the smooth decay of the 1–6 keV light curve (Tanaka et al. 1991; Grebenev et al. 1992), i.e., the soft and hard components are completely uncorrelated.

The flux from Nova Muscae had declined below the SIGMA detection limit, i.e., below 18 mCrab (2 σ upper limit, 40–70 keV band) in the observations of 1991 October and December.

Spectra of Nova Muscae obtained by SIGMA at different times are shown in Figure 4. The 35–300 keV spectrum averaged over the period January 16–February 11 (excluding the observation of January 20–21, to be discussed below) can be approximated by a power law with photon index $\alpha = 2.46 \pm 0.03$ (all errors quoted are one parameter estimates) and the flux at 100 keV $F_{100} = (1.57 \pm 0.03) \times 10^{-4}$ photons

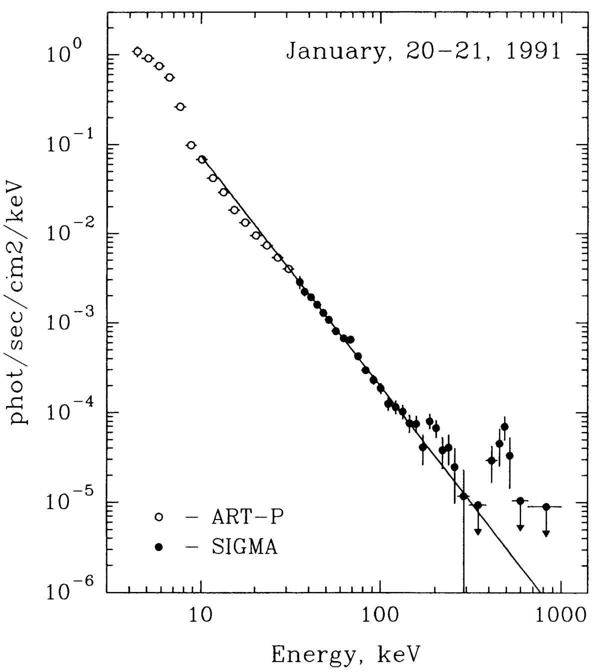

FIG. 1.—The spectrum of Nova Muscae with 500 keV spectral feature. The spectrum above 35 keV (SIGMA data) was collected over the last 13 hr of the January 20–21 observations (UT 20.8–21.6). Points below 30 keV (ART-P data, from Grebenev et al. 1992) were obtained several hours before (UT 20.4–20.9). A power-law spectrum with photon index 2.54 is shown by the solid line. Points below 1 σ are replaced by 1 σ upper limits.

cm^{-2} s^{-1} keV^{-1} ($\chi^2 = 75.8$ for 49 dof). The Comptonized disk model (Sunyaev & Titarchuk 1980) requires $T_e = 62 \pm 13$ keV and $\alpha = 1.29 \pm 0.05$ ($\chi^2 = 64.5$ for 48 dof). Although the source luminosity changed a factor >10 during the *GRANAT* observations, power-law approximations to individual spectra obtained between January 9 and August 14 give 35–300 keV photon indices in the relatively narrow range 2.2–2.6 (Fig. 4, *inset graph*).

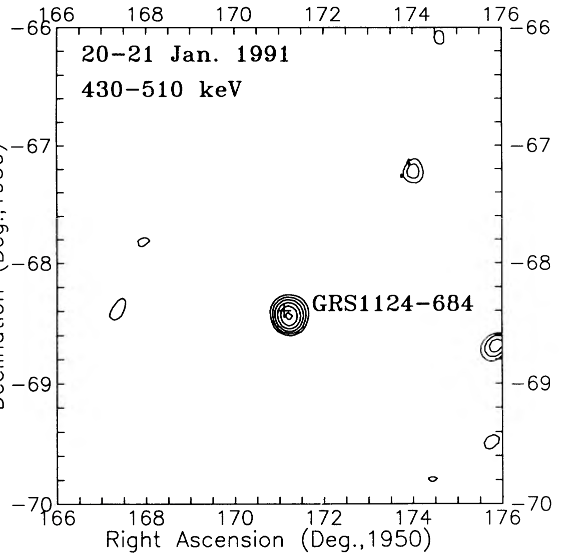

FIG. 2.—The SIGMA telescope image of the Nova Muscae region in the 430–510 keV band during last 13 hr of the January 20–21 observation (UT 20.8–21.6). Contour levels are 2.5, 3.0, 3.5, ... standard deviations.

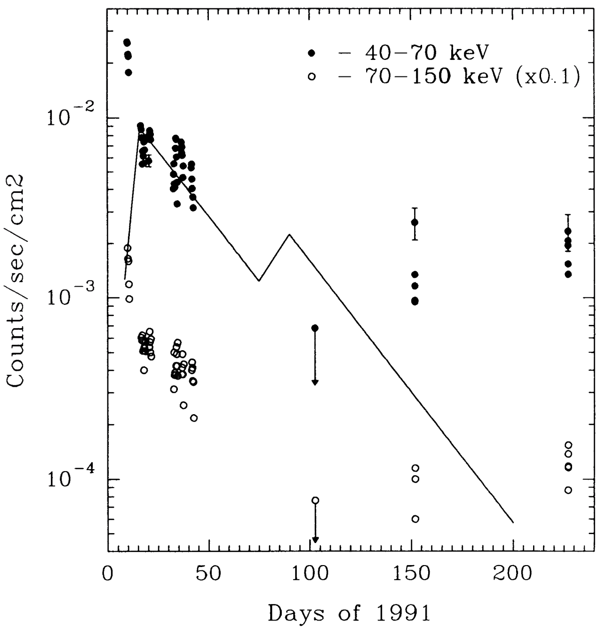

FIG. 3.—Hard X-ray light curves of Nova Muscae obtained by SIGMA telescope. The 70–150 keV flux was multiplied by 0.1 for clarity. One Crab unit corresponds to 1.9×10^{-2} and 1.8×10^{-2} counts s^{-1} cm^{-2} in 40–70 and 70–150 keV bands, respectively. Behavior of the light curve in the 1–20 keV X-ray band (Tanaka et al. 1991) is schematically shown. Upper limits are 2 σ values.

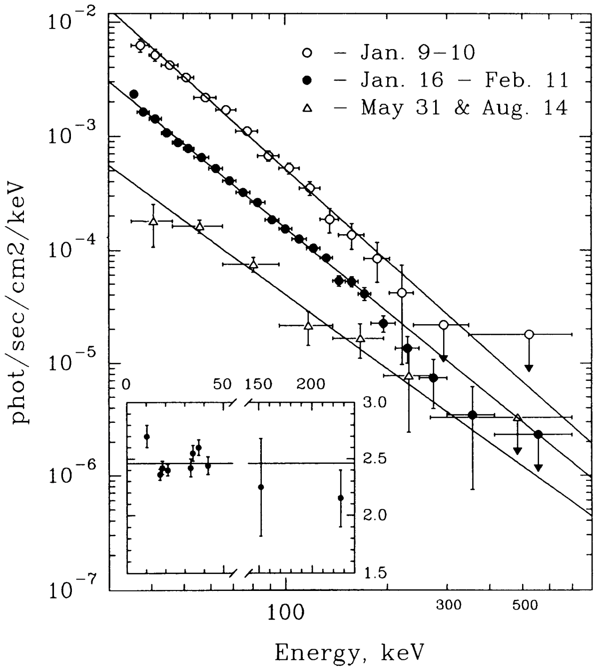

FIG. 4.—Hard X-ray spectra of Nova Muscae, obtained in different periods of observations: on January 9–10, during the initial hard outburst; the spectrum averaged over the period January 16–February 11 excluding January 20–21; and the spectrum averaged over the May 31–June 1 and August 14–15 observations. Best-fit power-law spectra (photon index α = 2.70, 2.46 and 2.18, respectively) are shown by solid lines. All points below 1 σ are replaced by 1 σ upper limits. Power-law photon indexes (35–300 keV), obtained in individual observations (~20 hr duration each) are shown on inset graph (horizontal axis is marked in days of 1991).

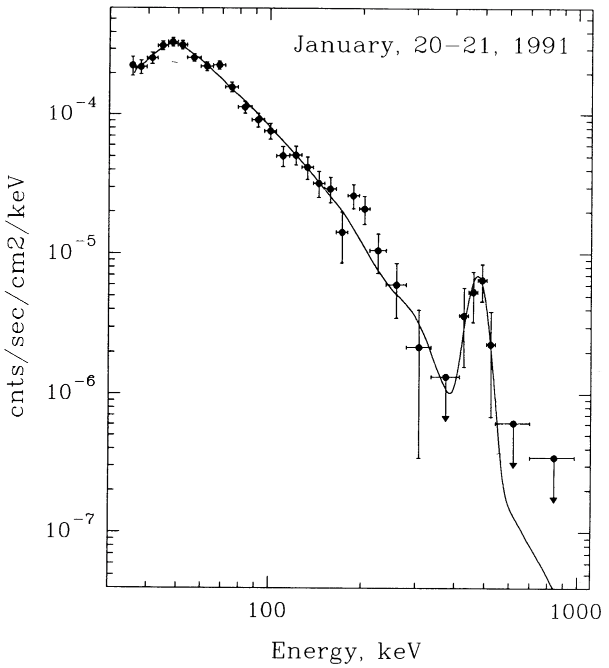

FIG. 5.—Pulse-height spectrum of Nova Muscae obtained during last 13 hr of the January 20–21 observation (UT 20.8–21.6). Points below 1 σ are replaced by 1 σ upper limits. The best-fit model spectrum, including power-law and Gaussian line (see text), is shown by a solid line.

3. DISCOVERY OF HARD SPECTRAL FEATURES

During the last 13 hr of a 21 hr observation on January 20–21, an emission feature near 500 keV was found in the source spectrum (Figs. 1 and 5). A peak at 5.1 σ significance level is clearly seen on 430–510 keV image at a position well compatible (within 3′) with that of Nova Muscae (Fig. 2). In contrast to the spectrum of the hard state of 1E 1740.7−2942 (Sunyaev et al. 1991b), the 500 keV feature contains (Table 1) only a small fraction (~6%–7%) of the 3–600 keV luminosity (but ~30% of the 35–600 keV luminosity).

The observed pulse-height spectrum in 35–700 keV band can be fitted with a power-law component with $\alpha = 2.54 \pm 0.07$, $F_{100} = (1.98 \pm 0.08) \times 10^{-4}$ photons s^{-1} cm^{-2} keV^{-1} plus Gaussian line with $E_{\rm line} = 476 \pm 15$ keV, $F_{\rm line} = (6.3 \pm 1.5) \times 10^{-3}$ photons s^{-1} cm^{-2}, FWHM = 58 ± 34 keV. The fit has reduced $\chi_r^2 = 1.04$ for 33 dof (Fig. 5). For a source at distance 1 kpc, this flux corresponds to annihilation of 7×10^{41} positrons s^{-1} and a net production of 3×10^{46} positrons!

Note also the excess above the power-law spectrum in the range 180–210 keV, that appeared simultaneously with the feature near 500 keV (Fig. 1). This excess has statistical significance (above power law) 3.8 σ and estimated net flux $\sim 1.5 \times 10^{-3}$ photons s^{-1} cm^{-2}.

The first 8 hr of the January 20–21 observations did not give a positive detection of flux from the source in the 430–510 keV band, although a constant line flux would have been seen with statistical significance 4 σ. The inferred rise time, less than or equal to several hours, restricts the emitting region to a size less than or equal to a few times 10^{14} cm. Subsequent observations, held on February 1–2, did not detect this feature with upper limit of 3×10^{-3} photons s^{-1} cm^{-2} (3 σ), thus restricting the decay time to ~10 days. The same upper limit on the line flux applies to any individual observation between January 9 and February 11 (except, of course, January 20–21). Analysis of all observations made in this period gave a (3 σ) upper limit of 1×10^{-3} photons s^{-1} cm^{-2} for the time-averaged line flux, 6 times less than the flux observed during January 20–21.

4. DISCUSSION

During the last two decades, at least five very bright X-ray novae (A0620−00, Nova Ophiuchi, GS 2000+25 = Nova Vul X, GS 2023+338 = V404 Cygni, and GRS 1124−68 = Nova Muscae) have been observed from radio to hard X-rays (Coe et al. 1976; Wilson & Rothschild 1983; White et al. 1984; Tanaka 1989; Sunyaev et al. 1988, 1991a). These objects are related by episodic accretion onto compact objects in low-mass binaries, and in fact two of these sources, A0620−00 (McClintock & Remillard 1986) and GS 2023+338 (Casares, Charles, & Naylor 1992), have high-mass functions strongly suggesting black holes. They all have anomalously hard X-ray spectra, detected up to several hundred keV, but the particular spectral

TABLE 1

FLUXES AND LUMINOSITIES OF NOVA MUSCAE

		BAND			
DATE (1991)	PARAMETER[a]	35–100 keV	100–300 keV	180–210 keV[b]	430–510 keV[b]
Jan 9–10	F	$(14.5 \pm 0.53) \times 10^{-2}$	$(2.12 \pm 0.28) \times 10^{-2}$	$(-1.2 \pm 1.0) \times 10^{-3}$	$(2.4 \pm 3.0) \times 10^{-3}$
	L	$(14.9 \pm 0.47) \times 10^{35}$	$(5.39 \pm 1.14) \times 10^{35}$	$(-4.3 \pm 3.9) \times 10^{34}$	$(2.1 \pm 2.7) \times 10^{35}$
Jan 16–Feb 11 (excluding Jan 20–21)	F	$(3.95 \pm 0.05) \times 10^{-2}$	$(0.78 \pm 0.03) \times 10^{-2}$	$(-0.3 \pm 0.1) \times 10^{-3}$	$(-0.5 \pm 0.3) \times 10^{-3}$
	L	$(4.08 \pm 0.05) \times 10^{35}$	$(2.21 \pm 0.13) \times 10^{35}$	$(-1.4 \pm 0.5) \times 10^{34}$	$(-0.5 \pm 0.3) \times 10^{35}$
Jan 20.4–20.8 (UT)	F	$(4.49 \pm 0.21) \times 10^{-2}$	$(1.22 \pm 0.13) \times 10^{-2}$	$(0.3 \pm 0.5) \times 10^{-3}$	$(2.5 \pm 1.4) \times 10^{-3}$
	L	$(4.71 \pm 0.19) \times 10^{35}$	$(3.58 \pm 0.51) \times 10^{35}$	$(1.1 \pm 1.8) \times 10^{34}$	$(2.2 \pm 1.2) \times 10^{35}$
Jan 20.8–21.6 (UT)	F	$(5.28 \pm 0.15) \times 10^{-2}$	$(1.18 \pm 0.09) \times 10^{-2}$	$(1.2 \pm 0.3) \times 10^{-3}$	$(5.1 \pm 1.0) \times 10^{-3}$
	L	$(5.40 \pm 0.14) \times 10^{35}$	$(3.69 \pm 0.37) \times 10^{35}$	$(4.6 \pm 1.3) \times 10^{34}$	$(4.5 \pm 0.9) \times 10^{35}$
May 31–Jun 1	F	$(0.50 \pm 0.14) \times 10^{-2}$	$(0.13 \pm 0.09) \times 10^{-2}$	$(0.1 \pm 0.4) \times 10^{-3}$	$(-0.1 \pm 0.9) \times 10^{-3}$
	L	$(0.60 \pm 0.14) \times 10^{35}$	$(0.47 \pm 0.38) \times 10^{35}$	$(0.3 \pm 1.3) \times 10^{34}$	$(-0.0 \pm 0.8) \times 10^{35}$
Aug 14–15	F	$(1.01 \pm 0.14) \times 10^{-2}$	$(0.36 \pm 0.09) \times 10^{-2}$	$(0.4 \pm 0.4) \times 10^{-3}$	$(1.2 \pm 1.0) \times 10^{-3}$
	L	$(1.08 \pm 0.13) \times 10^{35}$	$(1.25 \pm 0.36) \times 10^{35}$	$(1.3 \pm 1.3) \times 10^{34}$	$(1.1 \pm 0.9) \times 10^{35}$

[a] F: flux in photons s^{-1} cm^{-2} (as measured at the source position); L: source luminosity in ergs s^{-1}, calculated for 1 kpc distance.

[b] Excess flux above 30–150 keV power law.

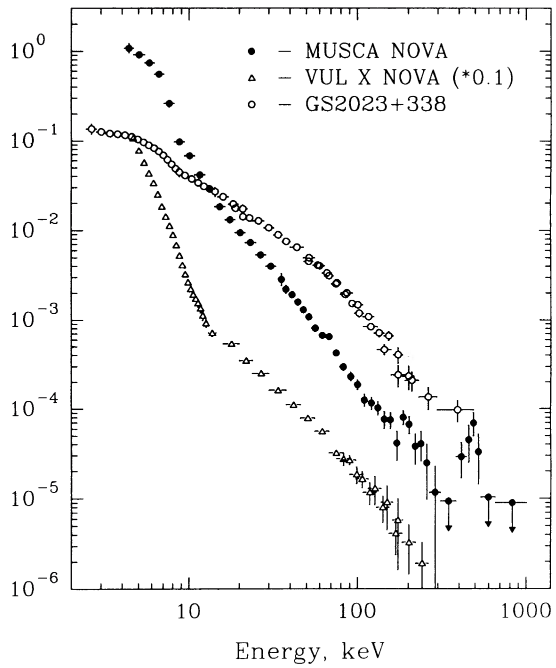

FIG. 6.—Spectra of three bright X-ray transients: Nova Vul X (observations of GSPC, HEXE, and PULSAR X-1 instruments on board *MIR-KVANT* in 1988, from Sunyaev et al. 1988), GS 2023+338 (TTM, HEXE, and PULSAR X-1 on board *MIR-KVANT*, 1989, from Sunyaev et al. 1991a), and Nova Muscae (this *Letter*). The spectrum of Nova Vul X was multiplied by 0.1 for clarity.

shape differs strongly from object to object (Fig. 6). Nova Muscae has the steepest spectrum among them, with slope ~2.5. The discovery of a variable narrow line near 500 keV (Figs. 1 and 2), in conjunction with the detection of similar high-energy excesses in the spectra of Cyg X-1 (Ling et al. 1987), 1E 1740.7−2942 (Sunyaev et al. 1991b; Bouchet et al. 1991), and GS 2023+338 (see Fig. 6), indicates that the appearance of rather narrow 400–500 keV features (possibly related to the production of electron-positron pairs) might be common (but rare) signature of "hard tail" sources, usually supposed to be black hole candidates (Tanaka 1989; Sunyaev et al. 1988, 1991a, 1991c).

4.1. *The e^+e^- Annihilation Region*

The relatively small line width (~60 keV or less) sets a firm upper limit, $kT < \sim 3$–4 keV, to the temperature of the annihilating particles (Ramaty & Mészáros 1981; Aharonian et al. 1983). Unless the inclination angle is extremely small, $i \leq 10°$, the line cannot originate from the rapidly rotating inner regions of an accretion disk. Therefore, the annihilation must occur beyond the zone of maximal energy release in the disk $\sim(5$–$15)r_g$ (Gilfanov et al. 1991). If the innermost part of the accretion disk generates hard radiation up to ~MeV, pairs could be produced above the disk via the $\gamma\gamma \rightarrow e^+e^-$ processes (Lingenfelter & Ramaty 1982). Since the proton density above the disk might be very low, and the Eddington luminosity for pairs is ~1000 times less than that for *e-p* plasma, the pairs will be blown away by radiation pressure. A mechanism (perhaps a magnetic field) to decelerate the pair wind would then be required for efficient annihilation. In this kind of model, the 180–210 keV spectral feature might result from scattering of the annihilation line by cool electrons in the outer disk (cf. Lingenfelter & Hua 1991).

4.2. *Cooling of Pairs*

The small value of low-frequency absorption observed in the spectrum of Nova Muscae, implying $N_{\rm H} \leq$ few 10^{21} cm^{-2} (Greiner et al. 1991), rules out a cloud of cold gas as a possible mechanism for cooling the pairs. However, at a distance of several tens of r_g above the disk surface, Comptonization (Levich & Sunyaev 1971) by the emergent radiation field (Fig. 1) may cool the pairs to an equilibrium temperature ~1 keV (Gilfanov et al. 1991).

4.3. *Absence of Orthopositronium Continuum*

If nearly all annihilations occur through positronium formation, a strong orthopositronium three-photon annihilation continuum is expected below line centroid energy with net flux exceeding that in the narrow line by a factor 4.5 at the level of $\sim 3 \times 10^{-2}$ photons s^{-1} cm^{-2}. No evidence of such a continuum is found in the SIGMA data (the best-fit value of positronium annihilation fraction is 0.1 with 1 σ interval 0.0–0.2). The absence of such a continuum could imply that the pair temperature never drops below $\sim 10^6$ K (and the pairs annihilate in flight) or, alternatively, that orthopositronium is destroyed rapidly by UV photons or due to the collisions of particles (Gilfanov et al. 1991).

4.4. *Possibility of Line Redshift*

According to inflight calibration of the SIGMA detector, the line is centered at ~476 keV, i.e., notably below 511 keV. If this redshift is real, a gravitational redshift interpretation provides an estimate $\sim 6r_g$ for the distance of the annihilation region from the central object. For accretion onto a black hole, typical flow velocities should result in a line much broader than observed. A narrow redshifted line might also be understood in the context of a model where annihilation occurs on a neutron star surface, as proposed for γ-ray bursts by Mazetz & Golenetsky (1981).

REFERENCES

Aharonian, F. A., et al. 1983, Ap&SS, 93, 229
Bouchet, L., et al. 1991, ApJ, 383, L45
Casares, J., Charles, P. A., & Naylor, T. 1992, Nature, 355, 614
Coe, M. J., et al. 1976, Nature, 259, 544
Goldwurm, A., et al. 1992, ApJ, 389, 79
Gilfanov, M., et al. 1991, Soviet Astron. Lett., 17 (12), 1059
Grebenev, S., et al. 1992, Soviet Astron. Lett., 18 (1), 7
Greiner, J., et al. 1991, in Proc. Workshop on Nova Muscae, Lyngby, in press
Levich, E. V., & Sunyaev, R. A. 1971, Soviet Astron., 48, 461
Ling, J. C., et al. 1987, ApJ, 321, L117
Lingenfelter, R. E., & Hua, X.-M. 1991, ApJ, 381, 426
Lingenfelter, R., & Ramaty, R. 1982, in The Galactic Center, ed. G. R. Riegler & R. D. Blandford (New York: AIP), 148
Lund, N., & Brandt, S. 1991, IAU Circ., No. 5161
Makino, F. 1991, IAU Circ., No. 5161
Mazetz, E. P., & Golenetsky, S. V. 1981, Ap. Space Phys. Rev., 1, 205
McClintock, J. E., & Remillard, R. A. 1986, ApJ, 308, 110
Paul, J., et al. 1991, Adv. Space Res., 11 (8), 289
Ramaty, R., & Mészáros, P. 1981, ApJ, 250, 384
Sunyaev, R., & Titarchuk, L. 1980, A&A, 86, 121
Sunyaev, R., et al. 1988, Soviet Astron. Lett., 14 (9), 771
Sunyaev, R., et al. 1991a, Soviet Astron. Lett., 17 (4), 291
Sunyaev, R., et al. 1991b, ApJ, 383, L49
Sunyaev, R., et al. 1991c, Soviet Astron. Lett., 17 (11), 975
Tanaka, Y. 1989, in Proc. 23rd ESLAB Symposium, ed. J. Hunt & B. Battrick (Noordwijk: ESA), 1, 3
Tanaka, Y., et al. 1991, in Proc. Workshop on Nova Muscae, Lyngby, in press
West, R. 1991, IAU Circ., No. 5165
White, N., et al. 1984, in High Energy Transients in Astrophysics (AIP Conf. Proc. 151), ed. S. E. Woosley (New York: AIP), 31
Wilson, C. K., & Rothschild, R. E. 1983, ApJ, 274, 717