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SIGMA/*GRANAT* SOFT GAMMA-RAY OBSERVATIONS OF THE X-RAY NOVA IN MUSCA: DISCOVERY OF POSITRON ANNIHILATION EMISSION LINE

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ABSTRACT

The day after its discovery by the Watch instrument, the X-ray nova GRS 1124−684 in Musca was detected by the soft γ-ray telescope SIGMA at the limit of its field of view. SIGMA pointed the source seven other times between 1991 January and February, and GRS 1124−684 has always been detected up to 300 keV, showing it was one of the hardest objects of the sky. After the flare of January 9 the average spectrum is well fitted by a power law of index 2.38, and the light curve shows a slower decrease than observed at low energy with superposed variability on time scales of several hours. However, the most remarkable result is the discovery of an emission feature around 500 keV in the source spectrum during one postflare observation. The line was detected in the images at a level of 5.1 σ; it had a width compatible with the detector spectral resolution and a flux of 6.0×10^{-3} photons cm^{-2} s^{-1}. This is first clear evidence of γ-ray line emission from soft X-ray transients, and, if interpreted as a positron annihilation line, it strongly suggests the X-ray nova in Musca to be a new black hole candidate.

Subject headings: binaries: close — gamma rays: observations — X-rays: general

1. INTRODUCTION

A new soft X-ray transient has been discovered in Musca by the Watch detector aboard the *GRANAT* satellite and by the *Ginga* ASM instrument (IAU Circ., No. 5161). Watch detected the new source (called GRS 1124−684) on 1991 January 8 at a level of 0.7 Crab in the 6–15 keV band, then at 1.5 Crab on the 10th and again at 2 Crab on the 13th, while it was below the Watch detection sensitivity on January 5 (Brandt 1991). *Ginga* detected the source on January 8 but recorded the maximum a few days later. The X-ray peak at low energies (< 15 keV) was therefore attained by the source between January 12 and 16 and was followed by a smooth exponential decay with $\tau \approx 30$ days (Tanaka et al. 1991). *ESO* optical observations carried out at La Silla (Chile) led to the discovery of the optical counterpart which showed an increase of 8–9 V at R.A.(1950) = $11^h24^m18^s.49$, decl.(1950) = $-68°24'0''.17$ (IAU Circ., No. 5165; Della Valle 1991).

On January 9 the γ-ray telescope SIGMA on board *GRANAT* detected Nova Muscae at the very edge of its field of view (FOV). Follow-up observations took place during the same month and again in February. Results obtained from the whole set of the SIGMA imaging observations of Nova Muscae (Table 1), including three later ones carried out in April, May, and August, are presented here and in a companion *Letter* (Sunyaev et al. 1992).

2. IMAGE ANALYSIS AND TIME VARIABILITY

The French coded aperture telescope SIGMA provides high-resolution ($\approx 15'$) images of the sky in the 35–1300 keV band (see Paul et al. 1991). An observation lasts ≈ 1 day and is divided into five or six subsessions during which four fine resolution images in wide energy bands (40–70, 70–150, 150–280, 280–620 keV) are recorded along with three sets of 95 images of coarser resolution in 95 channels between 35 and 1300 keV. After corrections to remove spurious nonuniform structures, sky images are reconstructed by standard decoding procedures (e.g., Fenimore & Cannon 1981).

Figure 1 shows the sum of the SIGMA fine images of the last three January observations of GRS 1124−684 in the 40–150 keV band. The source is detected at a level of 55 σ. The peak shape is fully compatible with the SIGMA point-spread function (PSF) at the best-fit position of R.A.(1950) = $11^h24^m08^s$, decl.(1950) = $-68°23'06''$ with a square error box of $3'.3$ size (statistical errors at 90% confidence level in four parameters plus incertitude on the satellite attitude), compatible with the optical position.

Figure 2 shows the source light curve in three bands during winter. The flux (40–150 keV) dropped rapidly from 0.97 Crab[1] at the beginning of January 9 to 0.36 Crab 6 days later. Since then, the decay slowed down and the 40–150 keV intensity decreased to only 0.22 Crab in 24 days, but with strong (up to 60%) and irregular superposed variability on time scales of several hours. In April the source was not detected (3 σ upper limit of 0.08 Crab in 40–150 keV), while in May and August

[1] One Crab is the intensity detected by a given detector in a given energy band from the Crab Nebula. For SIGMA 1 Crab in the 40–150 keV band corresponds to 4.74 counts s^{-1}, i.e., 1.15×10^{-8} ergs cm^{-2} s^{-1}.

TABLE 1

SIGMA Observations and Power-Law Spectral Parameters of Nova Muscae

Observation Date (1991)	Exposure Time (s)	Photon Spectral Index	Energy Flux (40–300 keV) (10^{-9} ergs cm^{-2} s^{-1})	χ^2_ν d.o.f. $\nu = 23$
Jan 9	61,131	2.73 ± 0.12	14.46 ± 0.75	1.22
Jan 16	72,651	2.30 ± 0.09	5.46 ± 0.22	1.56
Jan 17	61,211	2.35 ± 0.11	4.56 ± 0.23	0.99
Jan 20	73,631	2.30 ± 0.09	5.21 ± 0.22	1.76
Feb 1	64,387	2.31 ± 0.14	3.25 ± 0.24	1.65
Feb 3	66,164	2.53 ± 0.11	4.20 ± 0.22	0.92
Feb 5	77,175	2.53 ± 0.11	3.73 ± 0.20	1.50
Feb 10	70,427	2.35 ± 0.14	3.14 ± 0.22	1.48
Apr 12	22,655		Not detected	
May 31	63,232	2.61 ± 0.78	0.92 ± 0.30	1.04[a]
Aug 15	47,148	2.01 ± 0.44	1.29 ± 0.23	0.87[a]

[a] Number of degrees of freedom $\nu = 13$.

(more than 100 days after the flare) positive signals at 6 and 6.5 σ in the first band and at 3 and 4.6 σ in the second were, respectively, detected (0.08 and 0.1 Crab in 40–150 keV, respectively).

3. SPECTRAL ANALYSIS

After correction and deconvolution of the 95 spectral images of each observation, the count rate at the source position is estimated and the resulting pulse-height spectrum is compared to models of incident spectra modified by the detector response matrix (Barret & Laurent 1991). In all winter observations, the nova was detected up to 300 keV with a spectrum generally well fitted by a power-law model. The best-fit parameters (photon index and integrated energy flux) are given in Table 1 (errors are at confidence level of 70% in two parameters). A clear hardening of the source is observed after the flare (see also Fig. 3). Then the power-law slope remained comprised between 2.3 and 2.6, with a possible harder slope during August. The averaged spectrum of all the afterflare winter observations is well fitted by a power law with an index of 2.38 ± 0.05 and an integrated energy flux in 40–300 keV of (4.15 ± 0.08) × 10^{-9} ergs cm^{-2} s^{-1} ($\chi^2_\nu = 1.47$ for $\nu = 43$ d.o.f.). Different spectral shapes can also fit the data. For an unsaturated Comptonization model with disk geometry (Sunyaev & Titarchuk 1980) we obtained the best fit for a temperature of $kT_e = 74 \; +48/-16$ keV and half-disk optical thickness of $\tau = 0.37 \pm 0.19$ ($\chi^2_\nu = 1.35$ for $\nu = 42$ d.o.f.).

4. DISCOVERY OF AN EMISSION FEATURE AROUND 500 keV

A feature around 500 keV is present in the spectrum of the last 13 hr of the January 20 observation. Figure 4 shows two images of part of the SIGMA FOV around the nova in the 430–530 keV band, for the first 7.1 hr of data of the observation (*left*) and for the last 13 hr (*right*). The images have been obtained by first deconvolving by delta decoding (Fenimore & Cannon 1981) and then convolving with the corresponding PSF in order to optimize the signal-to-noise ratio. A 5.1 σ excess is located close (≈3′) to the position of GRS 1124−684

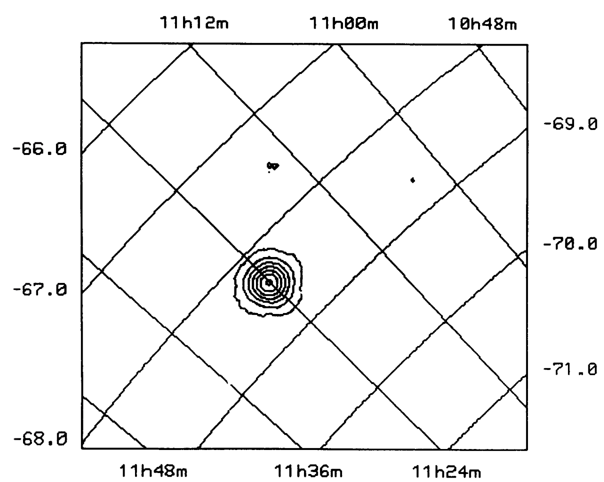

FIG. 1.—Contour plot image of the sum of the fully coded FOV of the observations performed on 1991 January 16, 17, and 20 in the range 40–150 keV. The contour levels are in units of standard deviations (σ) over the background mean, starting from 4 σ and spaced by 6.5 σ. GRS 1124−684 is here detected at 55 σ.

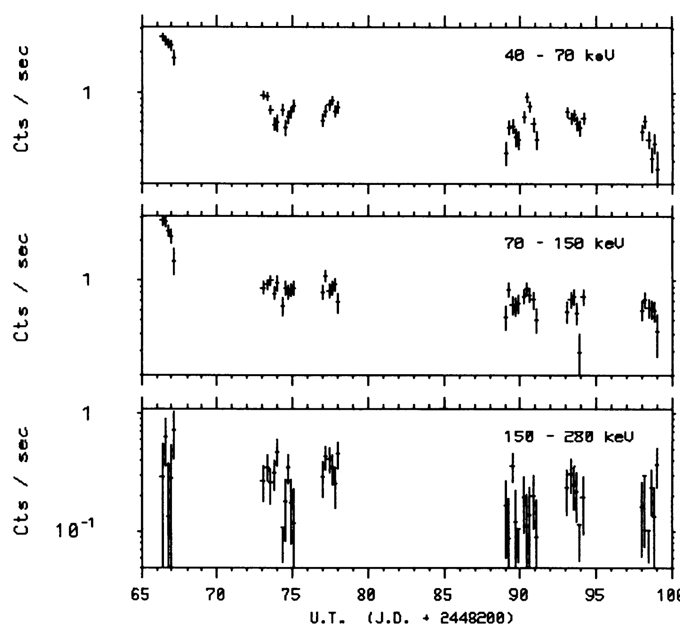

FIG. 2.—Light curve of GRS 1124−684: the detected count rate in the three fine image energy bands for the different subsessions of each winter observation is plotted vs. the universal time (U.T.).

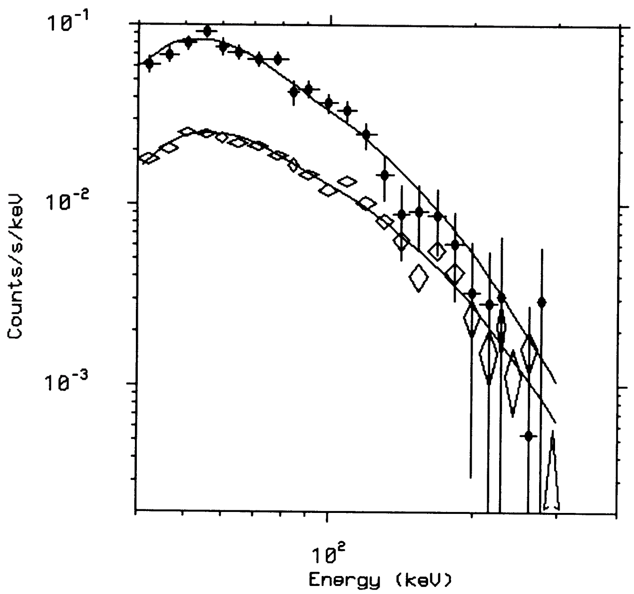

FIG. 3.—Count spectrum of GRS 1124−684 during the flare of January 9 (*circles*) and after the flare (averaged spectrum of January 16, 17, and 20 data) (*diamonds*). The continuum lines are the best-fit power-law models.

in the second part of the observation while no excess ($<1.5\ \sigma$) is present in the first part. Figure 5 shows the source spectrum of the last 13 hr of the observation where can be noted the significant excess around 500 keV and the absence of emission between 350 and 430 keV as well as after 550 keV. The 40–1000 keV count spectrum has been fitted with a model of a power-law plus a Gaussian function. The best fit ($\chi^2_\nu = 1.25$ for 35 d.o.f.), the solid line in Figure 5, was obtained for a power-law index of 2.42 with an integrated flux of 6.76×10^{-9} ergs cm^{-2} s^{-1}, a line flux of $(6.01\ +2.95/-2.76) \times 10^{-3}$ photons cm^{-2} s^{-1} at a centroid of 481 ± 22 keV, and an intrinsic line width (σ) of 23 ± 23 keV (errors are at 68% confidence level in the three line parameters with power law fixed at the best fit). The observed line width could be compatible with the instrumental spectral resolution (9.1% FWHM at the 513 keV; Mandrou et al. 1991). The best fit of a power law alone to the same data gave $\chi^2_\nu = 1.62$ for 38 d.o.f. for an index of 2.36 ± 0.11 and a flux of $(7.15 \pm 0.60) \times 10^{-9}$ ergs cm^{-2} s^{-1}. Therefore the emission feature is significant at a confidence level >99.95%.

Including, as the third component in the model, the ortho-positronium (ortho-Ps) spectrum we obtained a best-fit line flux of $(5.50\ +1.9/-3.7) \times 10^{-3}$ photons cm^{-2} s^{-1} at about the same energy centroid, and an integrated ortho-Ps flux upper limit of 5.1×10^{-3} photons cm^{-2} s^{-1} at 68% confidence level in four parameters (power law fixed at the best fit), that is more than a factor of 4.8 less than the expected flux when all pairs annihilate through Ps formation. Another feature seems to be present in the spectrum around 200 keV, suggestively close to the 511 keV backscattering energy (≈ 170 keV). Its flux is $\approx 1.8 \times 10^{-3}$ photons cm^{-2} s^{-1} and cannot be attributed to the 511 keV backscattered photons in the instrument, indicating the possible presence of a 511 keV reflection feature in the incident source spectrum (Lingenfelter & Hua 1991). The 500 keV feature was not detected in other observations. For a line width of 20 keV, we obtained a 3 σ upper limit of 3.2×10^{-3} photons cm^{-2} s^{-1} on February 1.

5. DISCUSSION AND CONCLUSIONS

The Nova Muscae progenitor was probably a faint K5–M0 late-type star at a distance of <3 kpc (Della Valle et al. 1991; Gonzales & Shrader 1991). At 1 kpc the X-ray luminosity in the 40–300 keV is $(1.73 \pm 0.09) \times 10^{36}$ ergs s^{-1} at the peak and $(6.53 \pm 0.26) \times 10^{35}$ ergs s^{-1} after the flare. The 3–300 keV luminosity is at least 10 times higher because the power law extends down to ≈ 3 keV with similar slope or steeper (Sunyaev et al. 1992). Therefore GRS 1124−684 must be a low-mass close binary system whose accreting object is a neutron star or a black hole (BH). The slow decay of the X-ray light curve and all other observed properties identify this source with a soft X-ray transient (SXRT) (White et al. 1984). A distinct subclass of SXRT has been recognized to have properties similar to those of the BH candidate Cyg X-1 (White et al. 1984; Tanaka 1989). One of their distinct features is a single power-law X-ray spectrum with a hard tail extending up to ≥ 200 keV. The prototype A0620−00 is now considered one of the best BH candidates (McClintock & Remillard 1986).

Our results show that also Nova Muscae has a strong hard power-law component which extends up to 300 keV with a relatively constant slope similar to other A0620−00-like SXRTs. Moreover its <15 keV light curve is strikingly similar to those of A0620−00 and GS 2000−25 (Tanaka et al. 1991),

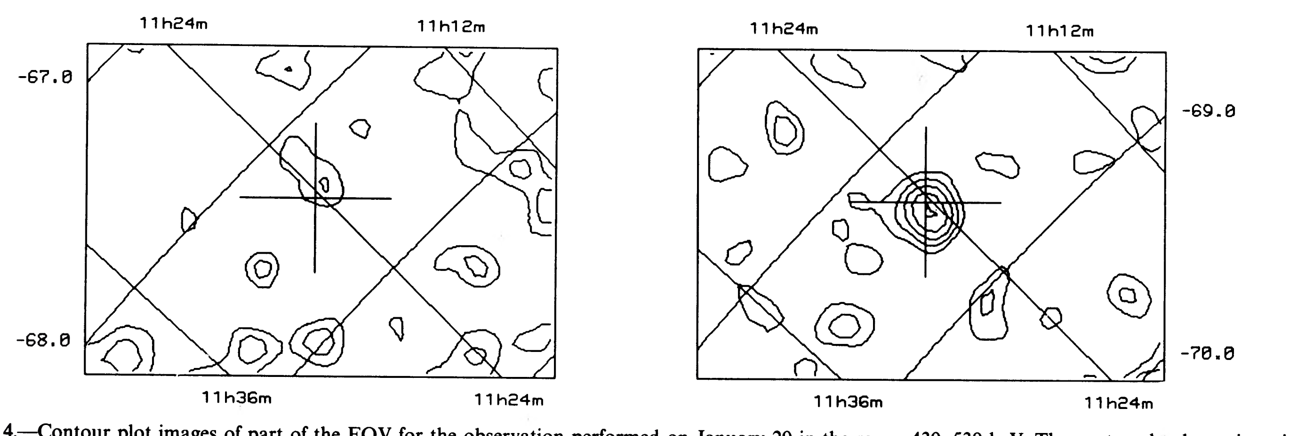

FIG. 4.—Contour plot images of part of the FOV for the observation performed on January 20 in the range 430–530 keV. The contour levels are in units of statistical standard deviations (σ) over the background mean starting from 1 σ and separated by 1 σ. The GRS 1124−684 optical position is indicated by a cross. *Left:* first 7.1 hr of the observation. *Right:* last 13.3 hr of the observation.

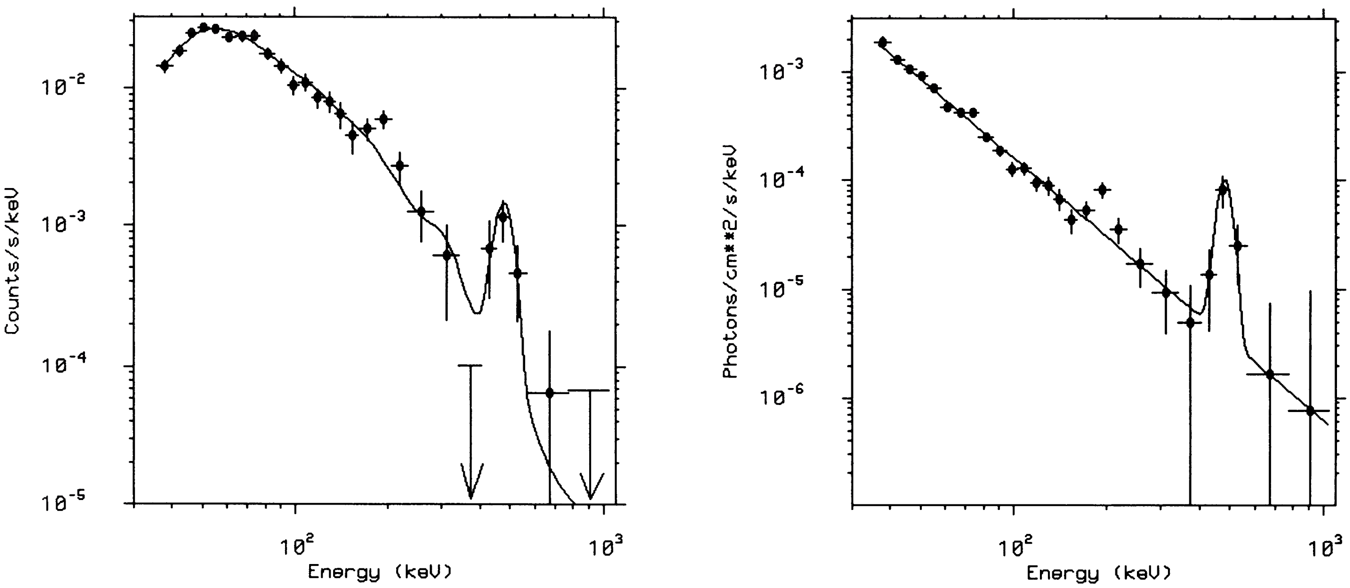

FIG. 5.—Spectrum of GRS 1124−684 for the last 13.3 hr of the January 20 observation: count spectrum (*left*) and photon spectrum (*right*). The solid line is the best-fit model of a power-law plus a Gaussian line.

although at high energy (> 40 keV) we observed a much slower and irregular decay.

If the observed emission line at 480 keV is interpreted as a positron annihilation line, the BH hypothesis is further supported. Nucleosynthesis origin is unlikely since the feature suddenly rose up 10 days after the flare and because of the lack of evidence of such processes in SXRT. Both thermal (Liang & Dermer 1988) and nonthermal (Aharonian & Vardanian 1985) models predict important production of pairs in the hot plasma of the innermost region of a BH accretion disk, the same hot plasma which could produce the hard power-law tail through unsaturated Comptonization of soft photons (Shapiro et al. 1976). In thermal models episodic heating of this plasma to $T > 10^9$ K (suppressed in neutron star systems by the Compton cooling due to the intense soft radiation emitted by the hot surface) gives rise to the production of positrons via photon-photon interactions and their annihilation in a colder medium would then produce a narrow 511 keV line. This model was proposed to explain the ≈1 MeV bump (Liang & Dermer 1988) and the weak detection of the 511 keV line in Cyg X-1 during its γ_1 state (Ling & Wheaton 1989; Ling 1991). In the case of Nova Muscae, however, the ratio L_{511} to > 500 keV continuum is certainly higher than expected from this model and observed in Cyg X-1 (Ling & Wheaton 1989). In fact the line was very intense with a flux of 6×10^{-3} photons cm^{-2} s^{-1} (i.e., at 1 kpc a luminosity of $L_{511} \approx 5.8 \times 10^{35}$ ergs s^{-1}), variable (rise time < 7 hr and decay within 10 days), not too broad (1 σ line width upper limit ≈107 keV) with no sign of ortho-Ps emission. The line width limit constrains the temperature of the annihilation region to be $T < 10^8$ K while the lack of ortho-Ps indicates that either $T > 8 \times 10^5$ K, so that annihilation occurs mainly without formation of Ps, or the density is $> 10^{14}$ cm^{-3} so that the ortho-Ps is dissociated by collisions (Crannell et al. 1976). The line variability sets an upper limit of only 7×10^{14} cm to the size of the emitting region. We also measured a redshift of the line centroid of ≈6%–7% from 511 keV, although, due to the large errors, its statistical significance is not very high.

In conclusion, Nova Muscae strongly resembles to the A0620−00-like SXRTs thought to contain a BH. The BH hypothesis is further supported by the SIGMA detection of a variable emission line at ≈500 keV which suggests that physical conditions in GRS 1124−684 are similar to those of the black hole candidates Cyg X-1 and 1E 1740.7−2942, for which episodic excesses at ≈500 keV have also been detected (Ling et al. 1987; Bouchet et al. 1991; Sunyaev et al. 1991; Ling 1991).

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