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A SEARCH FOR THE 2.223 MeV NEUTRON CAPTURE GAMMA-RAY LINE FROM THE DIRECTIONS OF CYGNUS AND THE GALACTIC CENTER

MICHAEL J. HARRIS[1]
S M Systems and Research Corporation, Suite 510, 8401 Corporate Drive, Landover, MD 20785
AND
GERALD H. SHARE
E. O. Hulburt Center for Space Research, Mail Code 4150, Naval Research Laboratory, Washington, DC 20375–5000
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ABSTRACT

Free neutrons produced by nuclear reactions in high-temperature plasmas may undergo proton capture in ambient material, giving rise to γ-ray emission in a line at 2.223 MeV. Plausible settings for this process include accretion disks around black holes, material accreting onto neutron stars, and the binary companions of TeV γ-ray sources. Data accumulated by the *Solar Maximum Mission* Gamma Ray Spectrometer (GRS) between 1980 and 1989 have been searched for evidence of this line, during periods when the black hole candidates Cygnus X-1 and the Galactic center were in transit across the GRS aperture. During these periods the neutron-star X-ray binaries Cygnus X-3 and Scorpius X-1 were also in the respective GRS fields of view. A 3 σ upper limit of $1.0 \times 10^{-4} \gamma$ (cm^2 s)$^{-1}$ has been placed on the *steady* emission in the 2.223 MeV line from the Galactic center and Scorpius X-1. Upper limits in the range 1.2–2.2 $\times 10^{-4} \gamma$ (cm^2 s)$^{-1}$ have been set for Cygnus X-1 according to different models of the origin of the emission. The 3 σ upper limit to the phase-averaged steady emission from Cygnus X-3 was found to be $1.2 \times 10^{-4} \gamma$ (cm^2 s)$^{-1}$.

Subject headings: gamma rays: general — galaxies: nuclei — galaxies: the Galaxy — X-rays: binaries

1. INTRODUCTION

In two-temperature plasmas with high enough ion temperature ($T_i > 10^{10}$ K or 1 MeV) nuclei heavier than ^{1}H are subjected to breakup by spallation reactions. A substantial population of free neutrons is produced by these breakups, which themselves may undergo radiative capture by the reaction ^{1}H(n, γ)^{2}H. Aharonian & Sunyaev (1984) showed that the resulting direct-capture 2.223 MeV γ-ray line from the plasma is blueshifted and broadened to such an extent that it would be difficult to detect above the continuum. However, they also pointed out that in general the neutrons would be able to escape from the plasma and undergo capture in cooler ambient material, from which a narrow line at 2.223 MeV might be detectable. Calculations by Guessoum and coworkers have confirmed these results; they find very little emission of the line from neutron captures in somewhat cooler plasmas (Guessoum 1988, 1989) and intense continua at higher temperatures masking the line (Guessoum & Dermer 1988). Other γ-ray lines arising promptly from the breakup reactions themselves are weak due to the rapid decline in abundance of the heavy nuclei at high temperatures. The prospects for detecting γ-ray line emission from two-temperature plasmas are thus promising only if neutrons can escape from the plasma and encounter a cooler, denser medium.

The inner regions of accretion disks around black holes are plausible astrophysical sites for such plasmas (Shapiro, Lightman, & Eardley 1976). In the case of the suspected black hole Cygnus X-1, the B-type companion star HDE 226868 provides a cool medium in which the ^{1}H(n, γ) reaction could occur (Aharonian & Sunyaev 1984; Guessoum & Dermer 1988). Brecher and Burrows (1980) postulated a similar process occurring in the "atmospheres" of neutron stars under the impact of accreting material. Finally, Vestrand (1990) proposed a different mechanism for 2.223 MeV line emission, based on the production of TeV γ-rays in systems such as Cygnus X-3 by the impact on a companion star of energetic protons accelerated by a neutron star. In this scenario the protons produce free neutrons by spallation reactions in the companion's atmosphere, which in turn are thermalized and captured in situ.

In this paper a search for the 2.223 MeV line from the Cygnus direction using data from the Gamma Ray Spectrometer (GRS) on the *Solar Maximum Mission* (*SMM*) satellite is described. It has been argued (Lingenfelter & Ramaty 1989) that the Galactic center (GC) contains a black hole of mass comparable to Cyg X-1 with similar γ-ray–emitting properties (see § 3.2 below). Our analysis was therefore also applied to a point source of 2.223 MeV line radiation at the GC. The neutron-star X-ray binary Scorpius X-1 is also within the broad aperture of the GRS (FWHM ~ 170° at 2.223 MeV) together with the GC.

The basis of the method (cf. Share et al. 1988) was to search for increases in the count rate in the GRS channels around 2.223 MeV during the annual periods ("transits") during which the pairs Cyg X-1 plus Cyg X-3 and the GC plus Sco X-1 were each within the GRS field of view. Our analysis therefore leads to upper limits on the time-averaged *steady* line flux from these sources during the 9 yr mission, whereas previous observations of the γ-ray continuum in Cyg X-1 and the GC report considerable variability (Ling & Wheaton 1989). It should also be noted that, if HDE 226868 is the source of a 2.223 MeV line from Cyg X-1, the emission will be periodically occulted even when the object is in the GRS field of view. The Cyg X-1 analysis has therefore been performed for models in which the emission either is, or is not, occulted with the system's 5.6 day orbital period (see § 2.1 below).

[1] Postal Address: USRA, 409 Third Street S.W., Suite 330, Washington, DC 20024.

2. ANALYSIS AND RESULTS

2.1. *Analysis*

Our method of analysis is very similar to that used by Harris, Leising, & Share (1991) to set limits on the 478 keV line from β-decay of ^{7}Be from novae in the direction of the GC. The GRS was pointed at the Sun during the entire mission (1980 Feb.–1989 Dec.), accumulating data continuously except for a gap between 1983 November and 1984 April. Due to the GRS's broad aperture the GC and Sco X-1 (being close to the ecliptic) transited the aperture slowly once every year during a period of several months centered on the Sun's passage through Scorpius and Sagittarius in December, while Cyg X-1 and Cyg X-3 (ecliptic latitude $\sim 55°$) made an off-axis transit of the field of view centered around mid-January.

During the transits of the GC, increases have been measured by the GRS in the count rates in the well-known γ-ray lines at 0.511 and 1.809 MeV (Share et al. 1985, 1988) and in the 0.3–8.5 MeV continuum (Harris et al. 1990), which are believed to be due to emission at these energies from an extended source in the direction of the GC. In the present work similar evidence was sought for a line at 2.223 MeV. Data accumulated between 1980 February and 1989 March were summed over 1 minute intervals in 476 energy channels between 0.3 and 8.5 MeV. Data contaminated by solar flares, γ-ray bursts and other transient backgrounds, and by radioactive instrumental lines produced in orbits traversing the South Atlantic Anomaly, were rejected. The 1 minute spectra were summed over 3 day intervals into two bins according to the value of the Sun-Earth-satellite angle θ: "Earth-viewing" with $108° \leq \theta \leq 252°$ and "sky-viewing" with $288° \leq \theta \leq 360°$, $0° < \theta \leq 72°$. By subtracting "sky-viewing" from "Earth-viewing" spectra the strong background due to long-lived instrumental radioactivities was almost entirely eliminated (Harris et al. 1990), leaving an Earth-albedo spectrum with the much weaker celestial source spectrum superposed "in negative."

In the region around 2 MeV the Earth-albedo spectrum is dominated by a continuum which may be approximated locally by a power law of index ~ -1, plus two lines close to 2.223 MeV—one at 2.135 MeV of width 74 keV (FWHM), and one at 2.310 MeV of width 58 keV (Letaw et al. 1989; J. R. Letaw 1988, private communication). These two lines are believed to originate from de-excitation of nuclei produced in the spallation of atmospheric ^{14}N and ^{16}O by cosmic rays. Each 3 day "Earth minus sky-view" spectrum was therefore fitted between 1.85 and 2.65 MeV by a four-component spectral model containing a power law plus three lines at 2.135, 2.310, and 2.223 MeV. This model was folded with the GRS instrument response, iterating the strengths of the lines and power law and the power-law index to obtain the best agreement with the 3 day count spectrum. The fit for one such 3 day period is shown in Figure 1.

The contributions of the celestial sources (GC and/or Sco X-1, and Cyg X-1 and/or Cyg X-3) to the strengths of each of the four features were separated from that of the Earth's atmosphere by means of their distinctive annually transiting time signatures, which are plotted in Figure 2 for Cyg X-1 and the GC. After calculating the GRS angular response by Monte Carlo simulations at 1.8–3.0 MeV (S. M. Matz & G. V. Jung 1988, private communication), the exposures of point sources at the positions of Cyg X-1, Cyg X-3, Sco X-1, and the GC to the GRS aperture were calculated. Note that, after the subtraction of "sky-viewing" from "Earth-viewing" spectra, any actual increase in count rate from these sources will follow the *negative* of these transiting time signatures.

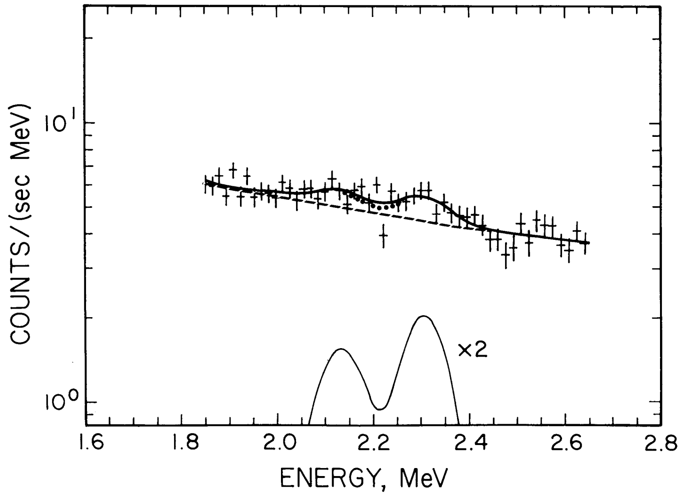

FIG. 1.—"Earth minus sky view" count spectrum accumulated over the 3 day interval 1987 January 5–8. A four-component model (see text) fitted to it after propagation through the instrument response function is also shown. Bold line represents the best-fitting model; three of the four components are also shown (*full line:* lines at 2.135 and 2.310 MeV, scaled up by a factor 2; *dashed line:* power law). Although no 2.223 MeV line is required in this fit, the dotted line shows the effect of a Galactic line at 2.223 MeV of intensity $5.0 \times 10^{-4}\ \gamma\ (\text{cm}^2\ \text{s})^{-1}$ added to the model.

In the case of Cyg X-1, exposures were calculated for two models of the origin of the 2.223 MeV line. In the simplest, a steady *unocculted* source, the emission arises in some region (e.g., the cool outer accretion disk, or circumstellar material around HDE 226868) which is always visible from Earth; this yields the dashed curve in Figure 2*a*, i.e., simple annual off-axis transits. In the second model, the emission arises from neutrons uniformly illuminating the disk-facing side of HDE 226868, which radiates isotropically in the 2.223 MeV line. The ephemeris of Aslanov & Cherepashchuk (1982) was used to calculate the exposure of this face to Earth. It is *occulted* with a period of $5^d\!.59998 \pm 0^d\!.00001$, and the annually transiting exposure of Figure 2*a* is assumed to be modulated by this $5^d\!.6$ exposure, as shown in Figure 2*b* for part of the mission.

The exposure of *SMM* to the position of Cyg X-3 is virtually identical to its exposure to the position of Cyg X-1. The 2.223 MeV line emission from Cyg X-3 in Vestrand's (1990) model also arises from the disk-facing side of a companion star and is thus necessarily occulted. In this case, however, the orbital period of the binary (4.8 hr) is much shorter than the 3 day interval over which GRS data was accumulated. Therefore, the *average* emission over the whole orbital cycle follows the unocculted exposure calculated for Cyg X-1 (the dashed line in Fig. 2*a*). A search for emission following the 4.8 hr cycle from Cyg X-3 is in progress (Matz 1990). Similarly the exposure of the GRS to Sco X-1 was found to be very similar to the exposure to the GC (full line in Fig. 2*a*); this similarity is illustrated in Figure 2*c* for part of the mission.

The time variability of the Earth-albedo emission was modeled by that of the 4.4 MeV line observed in GRS spectra, which is due to proton impacts on atmospheric ^{14}N and ^{12}C. As in previous studies of this kind (Harris et al. 1990, 1991), this procedure was found to reduce the systematic errors in the fitted values of 2.223 MeV line intensities due to the presence of the nearby 2.135 and 2.310 MeV lines.

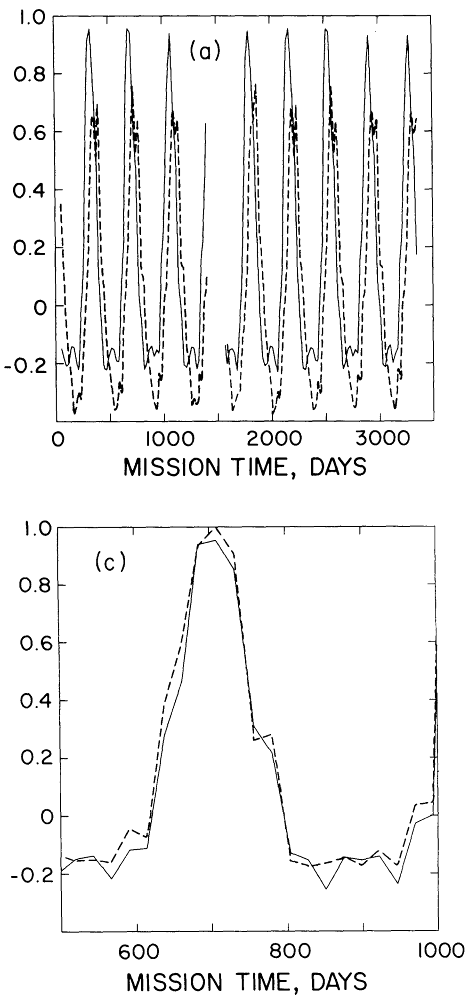

FIG. 2.—(*a*) Exposure of the GRS aperture at 2.223 MeV to point sources at the positions of the Galactic center and Sco X-1 (*full line*) and Cyg X-1 and Cyg X-3 (*dashed line*). (*b*) Exposure of the GRS aperture between 1984 April and 1985 June to the disk-facing hemisphere of HDE 226868 in the Cyg X-1 system. (*c*) Exposure of the GRS aperture to Sco X-1 (*dashed line*), compared with exposure to the GC (*full line*) between 1981 May and 1982 September. The abscissas are all expressed in days after 1980 January 0.

The time series of the strength of each spectral component (i.e., three lines and a power law) was fitted by each individual source exposure time series in Figure 2 plus the time series of 4.4 MeV line strengths (Share et al. 1991). As Harris et al. (1990) showed, this procedure separates the components in the time series of line and power-law strengths which vary with the temporal behaviors of source and atmospheric background. The fitting procedure yields the amplitude of the source time series which gives the best agreement with the time series of each spectral component. This best-fitting amplitude is the intensity of that spectral component from the direction of that source (see Fig. 2 of Harris et al. 1990). For example, when the time series of power-law strengths is fitted to the GC exposure time series plus the 4.4 MeV line time series, both of the amplitudes returned by the fitting would be expected to be statistically significant—they are the intensities of the continuum emission between 1.85 and 2.65 MeV from the GC region and from Earth's atmosphere, respectively. However, the quantity of greatest interest in the context of this paper is the amplitude which best fits each cosmic source's exposure time series to the 2.223 MeV line strength time series. The fitting was performed

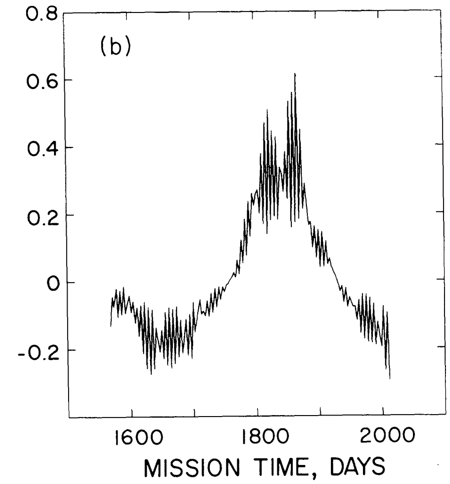

FIG. 2—*Continued*

by a standard method, and the uncertainties in the amplitudes were derived by the usual method of varying χ^2 (Press et al. 1986).

2.2. *Results*

A weak amplitude following the transiting behavior of the GC (the full line in Fig. 2*a*) was found in the time series of the amplitudes of the power-law component of the spectrum. The continuum flux from a GC point source implied by these annual increases was in good agreement with the flux found between 1.85 and 2.65 MeV by Harris et al. (1990). No transiting behavior was found in the time series of strengths of the 2.135 and 2.310 MeV lines. Their amplitudes following the atmospheric background time series were significant at the levels of 17 σ and 27 σ, respectively, in agreement with their origin in the Earth's atmosphere.

The 2.223 MeV line strength time series is shown in Figure 3. When the GC and Cyg X-1 transiting time series are compared with these data, no sign of long-term transiting behavior is evident (see, e.g., the dashed line in Fig. 3 for the case of the GC). The data have been summed over 48 day intervals for convenience of presentation. The 3 σ upper limit on the steady flux from the GC direction is $1.0 \times 10^{-4} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$, and that from the unocculted Cyg X-1 model is $1.2 \times 10^{-4} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$. These results are also applicable to Sco X-1 and the phase-averaged emission from Cyg X-3, respectively. No tendency of the 2.223 MeV line strengths to follow the occulted model behavior of Cyg X-1 (Fig. 2*b*) was found either; an upper limit of $2.2 \times 10^{-4} \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ was derived for the occulted Cyg X-1 source. The observed steady fluxes and upper limits are summarized in Table 1.

There are residual systematic errors in the 2.223 MeV line strength measurements which are not completely removed by

TABLE 1

2.223 MeV LINE FLUX UPPER LIMITS

Source	2.223 MeV Line Flux, $\gamma/(\mathrm{cm}^2\ \mathrm{s})$[a]	3 σ Upper Limit, $\gamma/(\mathrm{cm}^2\ \mathrm{s})$
GC[b]	$0.4 \pm 3.1 \times 10^{-5}$	1.0×10^{-4}
Cyg X-1 (unocculted)[c]	$2.1 \pm 3.4 \times 10^{-5}$	1.2×10^{-4}
Cyg X-1 (occulted)	$3.3 \pm 6.2 \times 10^{-5}$	2.2×10^{-4}

[a] Uncertainties represent 67% confidence limits.
[b] Results also applicable to Sco X-1.
[c] Results also applicable to the phase-averaged flux from Cyg X-3.

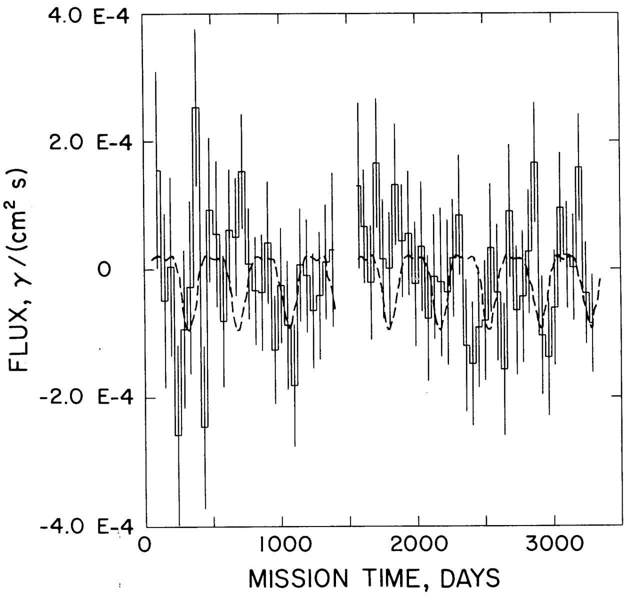

FIG. 3.—Intensities of the 2.223 MeV line from fits to the 3 day "Earth minus sky view" spectra (cf. Fig. 1) throughout the mission. The fitted background varying as the 4.4 MeV line has been subtracted (see text), and the intensities have been summed to 48 days for illustrative purposes. The error bars are 1 σ. The dashed line represents the variation expected from a point source at the GC with intensity $1.0 \times 10^{-4} \gamma$ (cm^2 s)$^{-1}$. The abscissa is expressed in days after 1980 January 0.

the use of the 4.4 MeV line as a correction factor. The values of χ^2 per degree of freedom for the fits of the transit functions to the data set of Figure 3 are around 1.2, corresponding to ~14% probability given 61 degrees of freedom. This indicates that the quality of the fits is limited by systematics in the data on $\sim 48^d$ time scales, rather than by statistics. Such systematics are visible in Figure 3, e.g., in 1981 January (around day 390). A conservative estimate of the total systematic and statistical uncertainty in the flux over any 48 day period would be typically $\sim 5 \times 10^{-4} \gamma$ (cm^2 s)$^{-1}$ for any of the sources [this was obtained by adding 3 times the characteristic 1 σ error $\sim 10^{-4} \gamma$ (cm^2 s)$^{-1}$ to the typical systematic error $\sim 2 \times 10^{-4} \gamma$ (cm^2 s)$^{-1}$].

3. DISCUSSION

3.1. *Cygnus X-1*

Guessoum & Dermer (1988) have calculated the production of free neutrons by nuclear breakup reactions in a typical two-temperature plasma around a compact object. Their model is a spherical plasma of radius 10^7 cm and proton density 1.5×10^{17} cm^{-3} which is impulsively heated to ion temperatures $5 \leq T_i \leq 50$ MeV. The free neutrons produced in nuclear reactions in this plasma may escape to be thermalized and radiatively captured on the surface of HDE 226868. Taking into account the escape probability of the neutrons and a distance of 2.5 kpc to Cyg X-1, they estimate a maximum flux at Earth for $T_i = 20$ MeV of $7.2 \times 10^{-5} f\gamma$ (cm^2 s)$^{-1}$, where f is the fraction of escaping neutrons which produce narrow-line 2.223 MeV photons. Given an uncertainty ~0.5 kpc in the distance, the most optimistic prediction ($f = 1$) of this model is $1.1 \times 10^{-4} \gamma$ (cm^2 s)$^{-1}$.

This prediction may be compared with our upper limits from § 2.2 if the emission from the Guessoum & Dermer (1988) model can be assumed to be steady in time. In the model the ultimate source of the free neutrons is the nucleus ^{4}He, via the ^{4}He(p, d)^{3}He or ^{4}He(p, pn)^{3}He reactions followed by $d(\gamma, n)p$ or ^{3}He(p, n)$3p$ (Guessoum & Gould 1989). The rate of the ^{4}He-destroying reactions is so large at the temperatures considered that the original ^{4}He is rapidly destroyed unless fresh ^{4}He can be supplied at a sufficient rate. It can be shown that an accretion rate $\sim 4 \times 10^{16}$ g s^{-1} of material containing 10% of ^{4}He atoms by number is necessary to balance the nuclear breakup of ^{4}He at $T_i = 20$ MeV, given the reaction rates calculated by Guessoum & Gould (1989). This is compatible with the accretion rate $\sim 2 \times 10^{17}$ g s^{-1} estimated for Cyg X-1 by Liang (1990) from the *HEAO 3* γ-ray luminosity above 0.511 MeV (the mechanism of which is discussed in § 3.2 below).

Our upper limits may thus properly be compared with the Guessoum & Dermer (1988) prediction, with the result that with the most optimistic model assumptions the prediction is about equal to our upper limit for an unocculted source, and about 50% of the upper limit for an occulted source. A more reasonable estimate of the neutron capture efficiency is $f \sim 0.1$ (Aharonian & Sunyaev 1984); this value is consistent with the assumptions underlying our occulted-source hypothesis, given the parameters adopted for HDE 226868 by Sokolov (1987). The Guessoum & Dermer (1988) model then predicts a flux $\leq 10^{-5} \gamma$ (cm^2 s)$^{-1}$ in the 2.223 MeV line. This more realistic prediction is about a factor of 20 less than our upper limit for an occulted source. It is also below the 3 σ sensitivity, $\sim 3 \times 10^{-5} \gamma$ (cm^2 s)$^{-1}$, of the oriented scintillation spectrometer experiment (OSSE) on the *Gamma Ray Observatory* (Johnson et al. 1989).

3.2. *The Galactic Center*

The main ground for believing that the γ-ray emission from the GC point source arises by the same mechanism as that from Cyg X-1 is the reported presence in both sources of a transient broad spectral feature around 1 MeV (Ling et al. 1987; Riegler et al. 1985; Ling & Wheaton 1989), which is interpreted in Cyg X-1 as a blueshifted thermally broadened 511 keV electron-positron annihilation line arising in a hot pair-dominated plasma (Liang & Dermer 1988). Guessoum & Dermer (1988) suggest, as a link between their hot-ion model described above and the Liang & Dermer model, that for $T_i \sim 50$ MeV the ions provide the heating for the electron-positron component via Coulomb coupling.

If the observed 1 MeV feature is real, and if the interpretation is correct, the argument may be inverted to imply the presence around the putative GC black hole of a hot ion component with $T_i \sim 50$ MeV, and hence of a possible source of the 2.223 MeV neutron capture line. However, the emission of this line depends critically on two factors which are ill-defined for the case of the GC: the strength of the gravitational field from which the neutrons must escape (i.e., the mass of the black hole), and the presence of cool material in which neutron capture can occur before the neutrons decay after about 10^3 s. While the black hole's mass can be estimated to be less than or equal to 1000 $M_\odot$ from its luminosity at 511 keV (Lingenfelter & Ramaty 1989), the nature and distribution of the cool material (if any) is obscure.

A crude estimate of the maximum expected 2.223 MeV line flux from the GC can be obtained by simply scaling the Guessoum & Dermer (1988) model for Cyg X-1. This is equivalent to assuming a low-mass ($\leq 10\ M_\odot$) black hole with ion temperature $T_i \sim 20$ MeV in the inner accretion disk (rising to $T_i \sim 50$ MeV during episodes of emission of the 1 MeV feature). Neutrons then escape easily from the black hole's gravitational field, and neutron production is limited by the ^{4}He abundance in the accreted material (if a sufficient accretion rate is assumed). The fluxes observed in the 1 MeV feature from Cyg X-1 and from the GC are very similar (Lingenfelter & Ramaty 1989), so that the GC source must be ~ 10 times more luminous in this feature than Cyg X-1, given the relative distances (8.5 vs. 2.5 kpc). If this enhanced luminosity is due to an enhancement of a factor 10 in the number of electron-positron pairs, and thus in the number of ions,[2] then the expected neutron flux escaping from the GC accretion disk would also be enhanced by a factor of 10. However, the 10-fold enhanced luminosity in the 2.223 MeV line of the GC source over Cyg X-1 which this neutron flux implies will be reduced by a factor of 10 due to the GC's greater distance. In other words, the expected flux from the GC is approximately the same as that from Cyg X-1, i.e., $7 \times 10^{-5} f\gamma$ (cm^2 s)$^{-1}$, where f is the efficiency with which neutrons are converted into 2.223 MeV photons. Our upper limit of $1.0 \times 10^{-4}\gamma$ (cm^2 s)$^{-1}$ is about 40% higher than the most optimistic ($f = 1$) value. There is at present no way of evaluating the quantity f. If f is close to 1, the 2.223 MeV line emission from the GC could be detected by OSSE at a level up to 6 σ.

3.3. *Cygnus X-3*

Vestrand (1990) has estimated the peak 2.223 MeV line flux from the Cyg X-3 system to be

$$\sim 1.5 \times 10^{-4} \frac{f_{2.2}}{0.4} \frac{\Omega}{2\pi} \frac{10 \text{ MeV}}{E_n} \times \frac{\epsilon_n}{0.1} \frac{L_p}{10^{39} \text{ ergs s}^{-1}} \frac{135}{D^2} \gamma \, (\text{cm}^2 \text{ s})^{-1} ,$$

where $f_{2.2}$ is the probability of neutron capture on thermal protons, E_n is the median neutron energy, ϵ_n is the neutron production efficiency, Ω is the solid angle subtended to the proton beam by the companion, L_p is the proton luminosity, and D is the distance to Cyg X-3 in kpc. The phase-averaged flux is ~ 0.4 of this value. The implied estimates of the various parameters are rather optimistic; hence an optimistic value for the predicted flux is $\sim 6 \times 10^{-5}\gamma$ (cm^2 s)$^{-1}$. Our measured upper limit $1.2 \times 10^{-4}\gamma$ (cm^{-2} s^{-1}) is a factor of 2 higher than the prediction, and perhaps rules out extremely optimistic estimates of the parameters. The predicted flux would be readily detectable by OSSE given the duty cycle of ~ 40% postulated by Vestrand (1990).

3.4. *Scorpius X-1*

Brecher & Burrows (1980) predicted fluxes in the 2.223 MeV line in the range 1.4–3 $\times 10^{-5}\gamma$ (cm^2 s)$^{-1}$ for energies in the range $200 \leq E_p \leq 600$ MeV of the accreting protons. However, this prediction assumes that the ^{1}H(n, γ) reaction takes place in the neutron star's atmosphere, in which case the 2.223 MeV line will be strongly redshifted. This line would not be detected by our analysis. The free neutron abundance is also probably an overestimate, since the decline in the abundance of the heavy nuclei (from which the neutrons are liberated by spallation) due to breakup reactions is not taken into account (Bildsten, Wasserman, & Salpeter 1991). However, escape of the neutrons to undergo capture on the surface of the companion star is a plausible source of the 2.223 MeV line which remains to be investigated theoretically.

Bhattacharya et al. (1991) obtained an upper limit on the 2.223 MeV line flux in Sco X-1 from data taken by *HEAO 3*. Their value $9.1 \times 10^{-4}\gamma$ (cm^2 s)$^{-1}$ is nearly an order of magnitude larger than the 3 σ upper limit $1.0 \times 10^{-4}\gamma$ (cm^2 s)$^{-1}$ obtained in the present work.

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[2] This explanation is suggested by the fact that the spectral shapes of the 1 MeV feature in the two sources are so alike that the temperatures of the electron-positron pairs must be very similar (cf. Liang 1991). A higher temperature in the GC pair-dominated plasma cannot therefore be argued as the cause of the enhanced luminosity. It follows that the charge balance in the two plasmas (i.e., the ratio of ions to electrons) must also be much alike.

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