

1.0 INTRODUCTION

We have recently generated the first all-sky map at 2.2 MeV using COMPTEL data from the first five years of the CGRO mission (McConnell et al. 1997a, 1997b). The purpose of this effort was to search for sources of unshifted neutron capture radiation, as one might expect in certain binary accretion scenarios. Although generally featureless, the maps do show one point-like feature (that we provisionally designate as GRO J0332-87) at a significance level of $\sim 4\sigma$. There is no obvious counterpart to this source, based on standard scenarios for 2.2 MeV emission, although X-ray coverage in this sky region is sparse. Even though the significance of this detection is limited, it is potentially an exciting result. *We therefore propose to obtain further observations to confirm the presence of this source using both OSSE and COMPTEL during cycle 7. In parallel with this effort, we also propose to continue work using archival COMPTEL data to refine our 2.2 MeV imaging methods and to incorporate additional data from later observations not included in the present analysis.*

Prior to CGRO, the most sensitive search for 2.2 MeV line emission was that carried out by Harris and Share (1991) using SMM data. Their survey was constrained (by the nature of the SMM mission) to a region along the ecliptic plane. They set 3σ upper limits in the range of $1\text{--}2 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ on the steady emission from the Galactic Center, Sco X-1, Cyg X-1 and Cyg X-3. COMPTEL, with its large FoV and excellent full-sky coverage, has provided the first-ever all-sky survey at this energy. Despite the presence of a strong background line at 2.2 MeV (resulting from neutron capture within the upper layer of liquid scintillators), COMPTEL maintains excellent 2.2 MeV line sensitivity and is thus an ideal tool for exploring the sky at 2.2 MeV.

2.0 SCIENTIFIC BACKGROUND

The possibility of observing γ -ray lines from the radiative capture of neutrons has been recognized for some time (e.g., Fichtel and Trombka 1981). Although several capture lines are possible, the most dominant line is expected to be that from neutron capture on hydrogen (with emission at 2.223 MeV). In what follows, we discuss several scenarios that might produce observable 2.2 MeV line emission in accreting compact sources.

2.1 Neutron Capture Within the Accretion Flow

The gravitational potential energy released from the accretion of matter onto a neutron star or black hole can lead to ion temperatures approaching 100 MeV. Even higher individual particle energies may be attained if the ion population is thermalized before reaching a critical radius (either the neutron star surface or the black hole event horizon). These temperatures are more than sufficient to subject heavier nuclei to breakup by spallation reactions. These breakup reactions liberate a large number of free neutrons. For solar abundances, the most dominant neutron-producing reactions are those that involve energetic protons interacting with ^4He . Some of the liberated neutrons might be captured on protons within the accretion flow itself, thus generating a 2.2 MeV line. This process requires that the proton density be at least 10^{16} cm^{-3} . However, even if this condition can be met, Guessom and Dermer (1988) have shown that the neutrons are more likely to escape the production region rather than be captured. Furthermore, neutron capture in the hot accreting plasma would lead to an extremely broad emission line (Aharonian and Sunyaev 1984), which might be difficult to observe. It therefore seems unlikely that any detectable 2.2 MeV line emission would be generated from *within* the accretion flow.

2.2 Neutron Capture in a Neutron Star Atmosphere

The possibility of nuclear line emission from the atmosphere of an accreting neutron star was first suggested by Shvartsman (1972), who noted that matter accreting onto a neutron star has large enough kinetic energy to excite or destroy nuclei. Neutrons liberated by these reactions (principally by the spallation of ^4He), once thermalized, will either recombine radiatively with a proton (to produce a 2.223 MeV photon) or non-radiatively with ^3He . The line flux expected from Sco X-1 was predicted by Reina, Treves and Tarengi (1974) to be $\sim 2 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$. Brecher and Burrows (1980) provided a more detailed treatment and predicted 2.2 MeV line fluxes exceeding $10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$ for Sco X-1. Most recently, this problem has been studied in detail by Bildsten, Salpeter and Wasserman (1993). They considered the spallation of both the infalling ^4He and the spallation which occurs once the ^4He thermalizes in the neutron star atmosphere. The predicted flux levels are as high as $\sim 2 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$, roughly equivalent to the sensitivity limit of COMPTEL for a 12-week (on-axis) observation. Enhanced levels of 2.2 MeV emission might be expected from sources where the accreting material contains an unusually high abundance of heavier elements. Bildsten (1991) has pointed out three cases where such heavy element enhancements may exist:

4U1916-05, 4U1626-67, and 4U1820-30. The line emission which we are discussing in this case is expected to be gravitationally redshifted. For production near the surface of a neutron star, the line energy is shifted to 1.76 MeV. COMPTEL maps of the 1.8 MeV emission may therefore be useful in searching for such sources of emission.

2.3 Neutron Capture in the Companion Star

Neutrons which are produced within the accretion flow are not confined by any magnetic fields which may be present. Consequently, they are free to leave the production region provided they can escape the gravitational well of the compact object. Some fraction of the escaping neutrons may then interact in the atmosphere of the companion star. The thermalization of the interacting neutrons, and the subsequent capture by ambient protons, would lead to line emission at 2.2 MeV. Various considerations (e.g., the neutron decay time, solid angle subtended by the companion, etc) suggest that close binaries are more probable sources of observable 2.2 MeV emission. In this scenario, the flux would originate on the side of the companion star irradiated by the neutrons. The flux would therefore be modulated by the binary period, peaking near the X-ray maximum. Guessom and Dermer (1988) have discussed this process in the context of Cyg X-1. They predict a flux level which may be as high as $\sim 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$.

2.4 Neutron Capture Resulting from a Beam Dump in the Companion Star

The detection of VHE photons ($E > 10^{12} \text{ eV}$) has been reported from various accreting sources, including Cyg X-3, Vel X-1 and Her X-1. These observations, coupled with the recent detection of Cen X-3 by EGRET (Vestrand et al. 1997) suggest the presence of very energetic protons. This may lead to a situation exactly analogous to a solar flare, in which an accelerated ion beam interacts in the solar atmosphere; subsequent neutron capture on ambient protons produces a strong line at 2.2 MeV. In the case of a binary system, the accelerated proton beam may interact in the companion star atmosphere or perhaps in some region of the accretion disk. In either case, we would expect some emergent flux of 2.2 MeV photons. For capture on the companion star, this would be an unshifted line at 2.2 MeV. As in the previous scenario, this line would also vary in intensity with orbital phase. Vestrand (1989) has estimated the resulting 2.2 MeV line flux, assuming that the protons are accelerated isotropically near the compact object. The peak flux predicted for Cyg X-3 ($\sim 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$) is within range of detection by COMPTEL.

3.0 ANALYSIS OF COMPTEL DATA

Each event in the COMPTEL datastream is defined by four fundamental parameters. The first is the total energy deposit, as determined by the sum of the energy deposits in both the D1 and D2 detector layers. The next two parameters (χ and ψ) define the direction of the scattered photon after it has undergone Compton scattering in the upper D1 detector layer; in particular, these two quantities refer to the back-projection of this vector onto the sky. Finally, an estimate of the Compton scatter angle ($\bar{\varphi}$) is made based on the D1 and D2 energy deposits applied to the standard Compton scattering formula. The COMPTEL image reconstruction is typically carried out starting from a 3-d dataspace defined by χ , ψ , and $\bar{\varphi}$, once some range of total energy deposit has been selected. (See Schönfelder et al. 1994 for a more complete description of COMPTEL). Image reconstruction requires some estimate of the background in this 3-dimensional dataspace. In this case, all-sky images have been generated using a procedure analogous to that which has been successfully employed in studies of the diffuse galactic 1.8 MeV emission (e.g., Diehl et al. 1995; Knödlseeder et al. 1996). This particular approach to background modeling is based on studies of the instrumental background, which show a strong energy-dependence in the $\bar{\varphi}$ -distribution and a lack of energy-dependence in the (χ, ψ) distribution. The background estimate therefore consists of independent empirical modeling of the distributions for χ and ψ (a 2-d distribution) and for $\bar{\varphi}$ (a 1-d distribution). A broad energy band (1–10 MeV) which excludes the line interval (2.110–2.336 MeV) provides information on the (χ, ψ) distribution. The $\bar{\varphi}$ distribution is derived directly from data in the line interval itself (2.110–2.336 MeV). Some smoothing is then applied in the χ and ψ directions to reduce statistical effects. Any structure in the dataspace which results from continuum source emissions is retained as part of the background model. Continuum sources will therefore be suppressed in the resulting image. Only sources of mono-energetic line emission (exhibiting a different distribution in χ and ψ) will remain in the images derived from such a background.

Using the background estimate described above, we have generated all-sky maps with both a maximum entropy algorithm (Figure 1) and a maximum likelihood algorithm (Figure 2). Note that, in both cases, there is no significant response from the Crab, confirming that continuum sources are indeed suppressed. At the sensitivity level of these maps (point source sensitivity of $\sim 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$), the 2.2 MeV sky is relatively featureless. For example, there is no evidence for any detectable level of diffuse galactic emission. We have used the X-ray binary

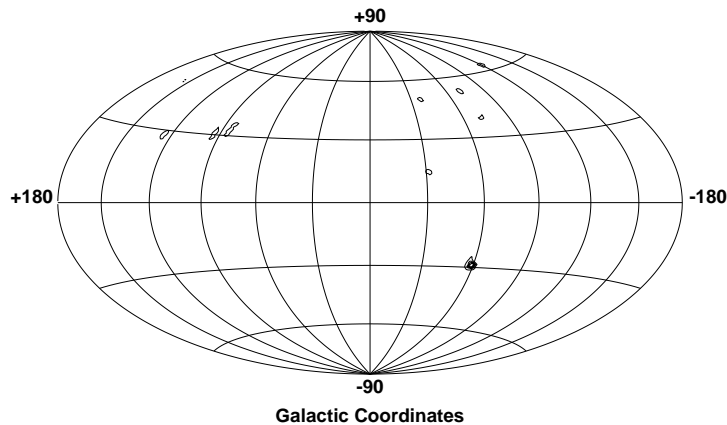


Figure 1. A maximum entropy map of the full sky at 2.2 MeV as derived from five years of COMPTEL data. Note the point-like feature at $(l,b) = (300.5^\circ, -29.6^\circ)$.

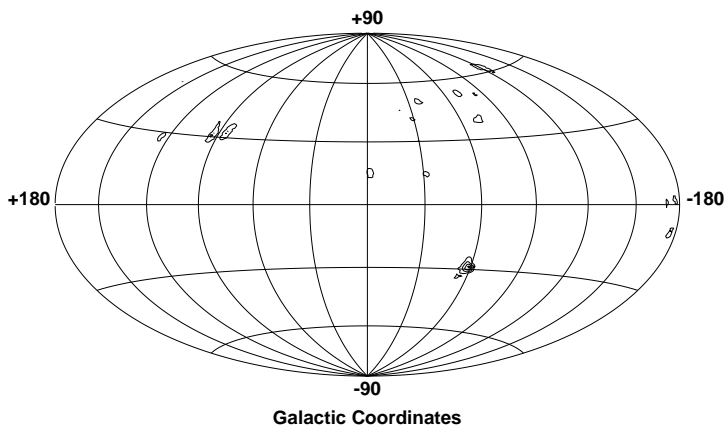


Figure 2. A maximum likelihood map of the full sky at 2.2 MeV as derived from five years of COMPTEL data. Note the similarities with the maximum entropy map of Figure 1. The point-like feature at $(l,b) = (300.5^\circ, -29.6^\circ)$ has a peak likelihood of 32.

catalog of van Paradijs (1995) to search for emission from particular source candidates. None of the catalogued sources show any sign of detectable emission. Flux limits (at the 3σ level) are typically in the range of $(1-2) \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$. Typical (3σ) upper limits include Cyg X-3 ($1.8 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$), Sco X-1 ($2.5 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$), 4U 1916-05 ($1.8 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$), 4U 1626-67 ($2.5 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$), and 4U 1820-30 ($1.6 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$). For Cygnus X-1, we set a 3σ upper limit of $2.3 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$, which is about one order-of-magnitude below the limit set by Harris and Share (1991). In the context of a two-temperature accretion disk model (Geussom and Dermer 1988), this result can be used to place a constraint on the fraction of escaping neutrons that are captured by the companion star. For an assumed ion temperature (T_i) of 20 MeV, the data imply that less than 25% of the escaping neutrons are captured by the companion star. Further insight may be provided by a phase-resolved analysis that is presently in progress.

Perhaps the most interesting result from these maps, however, is the evidence for emission from a point-like feature near $(l,b) = (300^\circ, -30^\circ)$. The maximum likelihood data indicates a peak likelihood value of 32 at $(l,b) = (300.5^\circ, -29.6^\circ)$. Given the number of trials associated with a full-sky survey, this amounts to a significance level of $\sim 4\sigma$. The corresponding flux level is $1.7(\pm 0.4) \times 10^{-4} \text{ cm}^{-2} \text{ sec}^{-1}$. The point source location contours, as derived from the maximum likelihood data, are shown in Figure 3. Images generated using data from individual phases of the CGRO mission are consistent with a constant

flux level, although there are independent detections only in phase 1 and (perhaps) phase 3 data. A search of the HEASARC databases indicates no obvious counterpart (such as an X-ray binary) corresponding to any of the emission models discussed above, although there is rather limited X-ray coverage in this region.

4.0 IMPROVEMENTS IN BACKGROUND MODELING

The COMPTEL team continues to make efforts to improve their understanding of the instrumental background. This leads naturally to potential improvements in the background modeling as applied, for example, to the 2.2 MeV analysis. Of particular interest are efforts to study the impact of various activation lines in the instrumental background (e.g., Oberlack et al. 1997; Varendorff et al. 1997). These lines, which result from cosmic ray interactions within COMPTEL and the surrounding spacecraft materials, include such species as ^{22}Na , ^{24}Na and ^{28}Si . In each case, the decay of these isotopes leads to the generation of two quasi-simultaneous photons (sometimes involving bremsstrahlung emission from an associated β particle). Due to geometry and event selection criteria, individual photons from these decays do not generate valid COMPTEL events. Valid events (so-called *cascade events*) can be generated, however, by the two photons interacting independently in the D1 and D2 detector layers. The identification of cascade events typically requires a detailed study of the D2 energy spectra. Such studies have

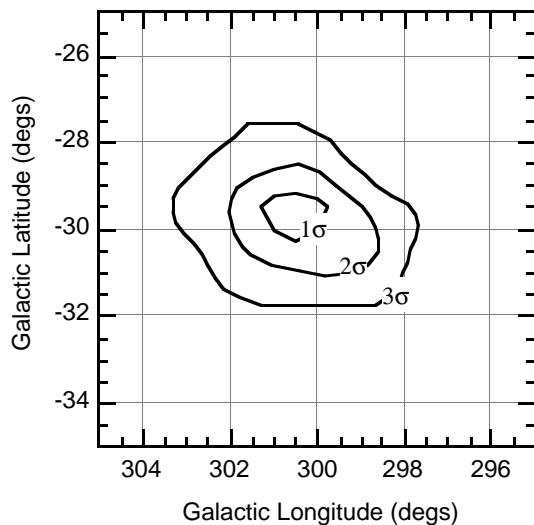


Figure 3. Location contours for GRO J0332-87 based on COMPTEL maximum likelihood imaging. The peak likelihood value of 32 at $(l,b) = (300.5^\circ, -29.6^\circ)$ corresponds to a source significance of $\sim 4\sigma$.

been included in the present analysis (viewing periods later than 523.0); 4) use the COMPTEL data from the 1.8 MeV all-sky survey to search for sources of *redshifted* 2.2 MeV emission (§2.2); and 5) perform a phase-resolved analysis of selected X-ray binaries (e.g., Cyg X-1 and Cyg X-3). The proposed observation of GRO J0332-87 is a 3-week exposure with both OSSE and COMPTEL. Even considering the increased background level, the OSSE sensitivity with such an exposure should be below the average flux level of $1.4 \times 10^{-4} \text{ cm}^{-2} \text{ sec}^{-1}$ as measured by COMPTEL. Due to the large size of the COMPTEL error box (Figure 3), the collimator offsets for OSSE should be $\pm 6^\circ$ from the nominal source location.

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also demonstrated long-term time variability in these lines, resulting from variations in the incident cosmic ray flux on CGRO. Recent improvements in the background modeling used for 1.8 MeV imaging (Oberlack et al. 1997) take into account the variability of these cascade events. The incorporation of these improvements in the 2.2 MeV analysis is part of the proposed program for Cycle 7. The COMPTEL simulation code (Stacy et al. 1996) allows for the simulation of some of these known background components (e.g., cascade events, neutron captures in D1, ^{40}K decays in D1 PMTs). Ultimately, we seek to develop a more physical approach to background modeling which can be used for a number of studies with COMPTEL data, including studies of celestial 2.2 MeV emission.

5.0 PROPOSED INVESTIGATIONS

For cycle 7, we propose to: 1) obtain additional observations of the candidate source GRO J0332-87 using both COMPTEL and (for the first time) OSSE; 2) continue our developments in background modeling, especially as applied to the 2.2 MeV data (§4); 3) incorporate additional data beyond that which has already