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Final Technical Report

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CGRO Guest Investigator Program – Cycle 7

1) Exploring the Gamma-Ray Sky at 2.2 MeV
2) COMPTEL Observations of Soft X-Ray Transients

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This grant covers two different projects that were funded under Cycle 7 of the CGRO Guest Investigator program. Each is treated separately in this report.

Part 1) *Exploring the Gamma-Ray Sky at 2.2 MeV*

Summary

The goal of this project was to search for a counterpart to an apparent point source of 2.2 MeV gamma-rays that had been detected using data from the COMPTEL experiment on CGRO (e.g., McConnell et al., AIP Conf. Proc. 410, 1099, 1997). The source detected by COMPTEL was of marginal significance (< 4σ) and a further, independent, confirmation by OSSE was highly desired. Unfortunately, the planned CGRO observations (with both COMPTEL and OSSE) during cycle 7 were superseded by ToO observations of SN 1998bu.

The COMPTEL Source

Data collected by the COMPTEL experiment on the Compton Gamma-Ray Observatory (CGRO) had been used to assemble an all-sky map in a narrow energy band centered at 2.2 MeV. The goal of this mapping exercise was to search for sources of 2.2 MeV line emission. Any such sources would indicate neutron capture processes, much like that which take place during solar flares. By this analogy, observations of 2.2 MeV radiation provide a tracer of particle acceleration. The COMPTEL map was found to be empty of any significant emissions, except for one marginal point source detection at (l,b) = (300.5°, -29.6°). This source was designated GRO J0332-87. The COMPTEL error box for this source was rather extended, with a 3σ radius of ~2.5°. The error box included only one unusual source – RE 0317-853, a hot, highly magnetized DA white dwarf at a distance of ~35 pc. Although speculative, we considered the association between the white dwarf and the 2.2 MeV γ-ray source to be an intriguing possibility.

Proposed CGRO Observations

Follow-up observations by OSSE were desired in order to confirm the COMPTEL point source detection and to perhaps reduce the size of the error box in an effort to associate the 2.2 MeV gamma-ray source with RE 0317-853. A two week observation of GRO J0332-87 was schedule for June of 1998, during Cycle 7 of the CGRO observing program. This observation was to include not only OSSE, but also additional exposure by COMPTEL. Unfortunately, these data were pre-empted by ToO observations of SN 1998bu.

Other Observations

During this same time frame, additional observations were obtained at both X-ray (RXTE) and radio (ATCA) wavelengths.

An RXTE scanning observation of the COMPTEL error box was carried out on 04-Feb-1998. A zig-zag scanning pattern was used to insure complete coverage of the error box. The total observation time was ~17ksec. The analysis of the PCA data from this observation yielded null results within the COMPTEL error box. A weak source was detected (at the 0.4 mCrab level) just outside of the COMPTEL error box.

Radio observations at the Australian Telescope Compact Array (ACTA) were carried out on 07-Jun-1998 at a wavelength of 6 cm (PI: Paul Barrett). This observation was dedicated to looking for radio flaring from the white dwarf candidate RE 0317-853. No emission from the white dwarf was detected during an 8 hour observation, down to a sensitivity level of 1 mJy.

Future Work

Although GRO J0332-87 was once again schedule for CGRO observations in June of 1999, that observation was also pre-empted by a ToO (Nova Vel 1999). Our goal remains to obtain observations with OSSE in an effort to confirm the source of 2.2 MeV radiation.

Related Publications

The work supported by this grant has so far led to the following conference presentations:

1) *A Search for 2.2 MeV Gamma-Ray Emission from X-Ray Binaries*
M. McConnell, J. Ryan, S. Fletcher, R. Diehl, V. Schönfelder, A. Strong, H. Bloemen, R. van Dijk, W. Hermsen, and K. Bennett. Poster presentation at a meeting of the High Energy Astrophysics Division of the American Astronomical Society, San Diego, CA, April 29 - May 4, 1996.

2) *A Map of the Gamma-Ray Sky at 2.223 MeV*
M.L. McConnell, J. Ryan, S. Fletcher, R. Diehl, V. Schönfelder, H. Bloemen, W. Hermsen, K. Bennett, and R. van Dijk. Poster presentation at the 189th Meeting of the American Astronomical Society, Toronto, Ontario, Canada, 12-16 January 1997. Published abstract: BAAS, 28, 1409 (1996).

3) *COMPTEL All-Sky Imaging at 2.2 MeV*
M.L. McConnell, J. Ryan, S. Fletcher, R. Diehl, V. Schönfelder, A. Strong, H. Bloemen, W. Hermsen, K. Bennett, and R. van Dijk. Poster presentation at the 4th Compton Symposium, Williamsburg, VA, 27-30 April 1997. Published in AIP Conf. Proc. 410, "Proceedings of the Fourth Compton Symposium", ed. C.D. Dermer, M.S. Strickman, & J.D. Kurfess (New York: AIP), p. 1099 (1997).

4) *COMPTEL All-Sky Imaging at 2.2 MeV*
M.L. McConnell, K. Bennett, H. Bloemen, R. Diehl, S. Fletcher, W. Hermsen, J. Ryan, V. Schönfelder, J.G. Stacy, A. Strong, and R. van Dijk. Poster presentation at the 25th International Cosmic Ray Conference, Durban, South Africa, 28 July - 8 August 1997. Published paper: Proc. 25th Internat. Cosmic Ray Conf., Durban (South Africa), 3, 393 (1997).

5) *A Possible Point Source of 2.2 MeV Gamma-Rays*

M. McConnell, J. Ryan, R. Diehl, V. Schönfelder, A. Strong, H. Bloemen, W. Hermsen, K. Bennett, R. van Dijk, and S. Fletcher. Oral presentation at the 191st Meeting of the American Astronomical Society, Washington, DC, 6-10 January 1998. Published abstract: BAAS, 29, 1370 (1997).

The work supported by this grant has so far led to the following conference publications, copies of which are attached to this report:

1) *COMPTEL All-Sky Imaging at 2.2 MeV*
M.L. McConnell, K. Bennett, H. Bloemen, R. Diehl, S. Fletcher, W. Hermsen, J. Ryan, V. Schönfelder, J.G. Stacy, A. Strong, and R. van Dijk, 1997, Proc. 25th Internat. Cosmic Ray Conf., Durban (South Africa), 3, 393.

2) *COMPTEL All-Sky Imaging at 2.2 MeV*
M. McConnell, J. Ryan, S. Fletcher, R. Diehl, V. Schönfelder, A. Strong, H. Bloemen, W. Hermsen, K. Bennett, and R. van Dijk, 1997, in AIP Conf. Proc. 410, "Proceedings of the Fourth Compton Symposium", ed. C.D. Dermer, M.S. Strickman & J.D. Kurfess (New York: AIP), p. 1099.

Part 2) *COMPTEL Observations of Soft X-Ray Transients*

Summary

The goal of this project was to provide COMPTEL observations of X-ray transient sources that, based on the observed spectrum by BATSE, were likely candidates for detection by COMPTEL. The observation of such a transient would then trigger a ToO observation by COMPTEL. A secondary goal of this program was to revisit some archival data for a few selected sources which were still considered as possible candidates for a COMPTEL detection.

Targets of Opportunity Declared During Cycle 7

Only one X-ray transient was declared as a COMPTEL ToO during Cycle 7. This was GRS 1915+105, declared as a ToO during VP 720.5 (May, 1998). Subsequent analysis of the COMPTEL data yielded no clear detection of this source.

Archival Studies of X-ray Transients

The COMPTEL team continues to make slow progress on various aspects of COMPTEL data analysis. The biggest problem with most of the X-ray transient sources is that they lie near the plane and in the general direction of the galactic center. The diffuse galactic emissions then present a background problem which complicates the search for faint sources. The one X-ray transient that has so far been detected by COMPTEL (GRO J0422+32) was in the direction of the galactic anticenter, where the background from such diffuse emissions is not as severe. Although some progress has been made by the COMPTEL team towards improving these studies, the search for point sources, especially near the galactic plane, is a difficult task. Although there have been some indications that certain X-ray transients have been detected by COMPTEL (in particular, GRO J1655-40), these detections are quite weak and remain a subject of discussion within the COMPTEL team.

Related Publications

Improving the Analysis of Gamma-Ray Data from CGRO-COMPTEL
M. McConnell, S. Kappadath, D. Morris, J. Ryan, W. Colmar, R. Diehl, V. Schönfelder, M. Varendorff, G. Weidenspointner, U. Wessolowski, H. Bloemen, W. Hermsen, K. Bennett, and R. van Dijk. Poster presentation at the 192nd Meeting of the American Astronomical Society, San Diego, CA, 7-11 June 1998. Published abstract: BAAS, 30, 1370 (1998).

25th ICRC, Durban, South Africa

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COMPTEL ALL-SKY IMAGING AT 2.2 MeV

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ABSTRACT

It is now generally accepted that accretion of matter onto a compact object (white dwarf, neutron star or black hole) is one of the most efficient processes in the universe for producing high energy radiations. The efficient conversion of gravitational potential enegy into kinetic energy is believed to be the primary source of power for X-ray binaries and for Active Galactic Nuclei (AGN). An understanding of these objects therefore requires an understanding of the accretion process itself. Measurements of the γ-ray emission provide a potentially valuable means for furthering our understanding of the accretion process. Here we focus on neutron capture processes, which can be expected in any situation where energetic neutrons may be produced and where the liberated neutrons will interact with matter before they decay (where they have a chance of undergoing some type of neutron capture). Line emission at 2.2 MeV, resulting from neutron capture on hydrogen, is believed to be the most important neutron capture emission. Observations of this line in particular would provide a probe of neutron production processes (i.e., the energetic particle interactions) within the accretion flow. Here we report on the results of our effort to image the full sky at 2.2 MeV using data from the *COMPTEL* experiment on the *Compton Gamma-Ray Observatory* (*CGRO*).

EMISSION MODELS

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, by far the most dominate line is expected to be that from neutron capture on hydrogen (producing a line at 2.223 MeV). There are several scenarios which might possibly produce 2.2 MeV line emission in accreting compact sources (neutron stars or black holes). These include: 1) neutron capture within the accretion flow; 2) neutron capture in the atmosphere of a neutron star; 3) neutron escape from the accretion flow followed by capture in the compact object's companion star; and 4) neutron capture in a situation where a beam of accelerated particles impinges on the companion star (in analogy to the production of a 2.2 MeV line in solar flares).

Neutron Capture Within the Accretion Flow

The gravitational potential energy released from accretion of matter onto the surface of a compact object can lead to ion temperatures approaching 100 MeV ($T_i \sim 10^{12} K$). 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). Ion temperatures approaching $kT \sim$ 100 MeV are more than sufficient to subject heavier nuclei to breakup by spallation reactions. These breakup reactions may liberate a large number of free neutrons. For solar abundances, the most dominant neutron-producing reactions are those that involve energetic protons interacting with ^{4}He. Some of the liberated neutrons might be captured on protons within the accretion flow itself, thus generating a 2.2 MeV line signature. 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), that 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.

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 ^{4}He), once thermalized, will either recombine radiatively with a proton (to produce a 2.223 MeV photon) or non-radiatively with ^{3}He. Most recently, this problem has been studied in detail by Bildsten, Salpeter and Wasserman (1993). They considered the spallation of both the infalling ^{4}He and the spallation that occurs once the ^{4}He thermalizes in the neutron star atmosphere. The predicted flux levels are as high as $\sim 2 \times 10^{-5}$ cm^{-2} s^{-1}. This level of emission is near 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. Bildtsten (1991) has pointed out three cases where such heavy element enhancements may exist: 4U1916-05, 4U1626-67, and 4U1820-30. The line emission that we are discussing in this case is expected to be gravitationally redshifted, since it is produced near the surface of the neutron star. Therefore, a 2.223 MeV neutron capture line would be shifted to an energy as low as 1.76 MeV.

Neutron Capture in the Companion Star

Neutrons that are produced within the accretion flow are not confined by any magnetic fields that 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 a γ-ray line at 2.223 MeV. Various considerations (e.g., the neutron decay time) suggest that close binaries are more probable sources of observable 2.2 MeV emission. Small binary separations are also preferred based on the need for the companion to subtend a relatively large solid angle so as to increase the capture probability. In this scenario, the 2.2 line flux will originate on the side of the companion star irradiated by the neutron flux, i.e., the side of the companion that faces the compact object. Therefore, the 2.2 MeV flux will most likely be modulated by the binary period, with the 2.2 MeV flux 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 that may be as high as $\sim 10^{-5}$ cm^{-2} s^{-1}.

Neutron Capture Resulting from a Beam Dump in the Companion Star

The detection of VHE photons ($E > 10^{12}$ eV) has been reported from various accreting sources, including Cyg X-3, Vel X-1 and Her X-1. These observations suggest that the acceleration of very energetic proton beams may be taking place within these systems. Such beams may interact in the companion star, in a situation exactly analogous to a solar flare. Following the solar flare analogy, we would expect some emergent flux of 2.2 MeV photons. Again, this would be a narrow, unshifted line at 2.223 MeV. As in the previous scenario, this line would also vary in intensity with orbital phase. Vestrand (1989) 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 ($\sim 10^{-4}$ cm^{-2} s^{-1}) is within the range of detectable emission with *COMPTEL*.

PREVIOUS RESULTS

To date, 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 a 3σ upper limit of 1.0×10^{-4} cm^{-2} s^{-1} on the *steady* emission from the Galactic center and from Sco X-1. Upper limits on the 2.2 MeV line emission from Cyg X-1 were in the range of $(1.2 - 2.2) \times 10^{-4}$ cm^{-2} s^{-1}, according to different models of the emission process. The 3σ upper limit to the phase-averaged steady emission from Cyg X-3 was set at 1.2×10^{-4} cm^{-2} s^{-1}.

OBSERVATIONS AND DATA ANALYSIS

The *COMPTEL* experiment is ideally suited for studies of the 2.2 MeV line from a variety of sources. The wide field-of-view imaging capability of *COMPTEL* provides for continuing exposure to a number of sources and provides the first-ever all-sky survey at these energies. Despite the presence of a major background line at 2.2 MeV (resulting from neutron capture within the upper layer of liquid scintillators), the *COMPTEL* experiment maintains excellent sensitivity at this energy. This analysis incorporates all available *COMPTEL* data from the first five years of the *CGRO* mission. Specifically, we have used data from *CGRO* viewing periods 1.0 through 523.0, with the exception of viewing 2.5, when *COMPTEL* was operated in a special solar mode.

The *COMPTEL* data analysis typically is carried out in a 3-d dataspace defined by the direction of the photon scatter vector, specified by the angles χ and ψ, and by the derived Compton scatter angle, specied by the angle $\bar{\phi}$ (Schönfelder et al. 1994). In this case, all-sky images were generated using a procedure analagous to that which has been successfully employed in studies of the diffuse galactic 1.8 MeV emission (e.g., Diehl et al. 1995). This approach is based on a background estimate that consists of separate empirical modeling of the distributions for χ and ψ (a 2-d distribution) and for $\bar{\phi}$ (a 1-d distribution). A broad energy band (1–10 MeV) that excludes the line interval (2.110–2.336 MeV) provides information on the (χ, ψ) distribution. The $\bar{\phi}$ distribution is derived directly from the data in the line interval (2.110–2.336 MeV). The resulting background model incorporates an estimate of the instrumental background along with the effect of any continuum sources within the FoV. Only sources of mono-energetic line emission (which exhibit a somewhat different scatter direction distribution) will remain in the resulting images.

RESULTS

Using the background estimate described above, we have generated all-sky maps with two different imaging algorithms. These include a maximum entropy algorithm and a maximum likelihood algorithm. The maps generated with these two different methods are similar in appearance. The all-sky map generated with the maximum entropy algorithm is shown in Figure 1. In general, the sky at 2.2 MeV is relatively featureless. For example, there is no evidence for any diffuse galactic emission at this energy. There is, however, evidence for significant ($\sim 4\sigma$) emission from a point-like feature near $(\ell, b) = (300°, -30°)$. There are no obvious counterparts (such as an X-ray binary) that are consistent with the emission models discussed above. We continue to search for a counterpart of this feature.

We used the X-ray binary catalog of van Paradijs (1995) to search for emission from particular source candidates. None of the catalogued sources showed any sign of detectable emission. Flux limts (at the 3σ level) are typically in the range of $(1 - 2) \times 10^{-5}$ cm^{-2} sec^{-1}. Typical (3σ) upper limits include Cyg X-3 ($< 1.8 \times 10^{-5}$ cm^{-2} sec^{-1}), Sco X-1 ($< 2.5 \times 10^{-5}$ cm^{-2} sec^{-1}), 4U 1916-05 ($< 1.8 \times 10^{-5}$ cm^{-2} sec^{-1}), 4U 1626-67 ($< 2.5 \times 10^{-5}$ cm^{-2} sec^{-1}), and 4U 1820-30 ($< 1.6 \times 10^{-5}$ cm^{-2} sec^{-1}). For Cygnus X-1, we set a 3σ upper limit of 2.3×10^{-5} cm^{-2} sec^{-1}, which is about one order-of-magnitude below the limit set by Harris and Share (1991). This result, in conjunction with the model of Geussom and Dermer (1988), can be used to place constraints in 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 come from a phase-resolved analysis in progress.

ACKNOWLEDGEMENTS

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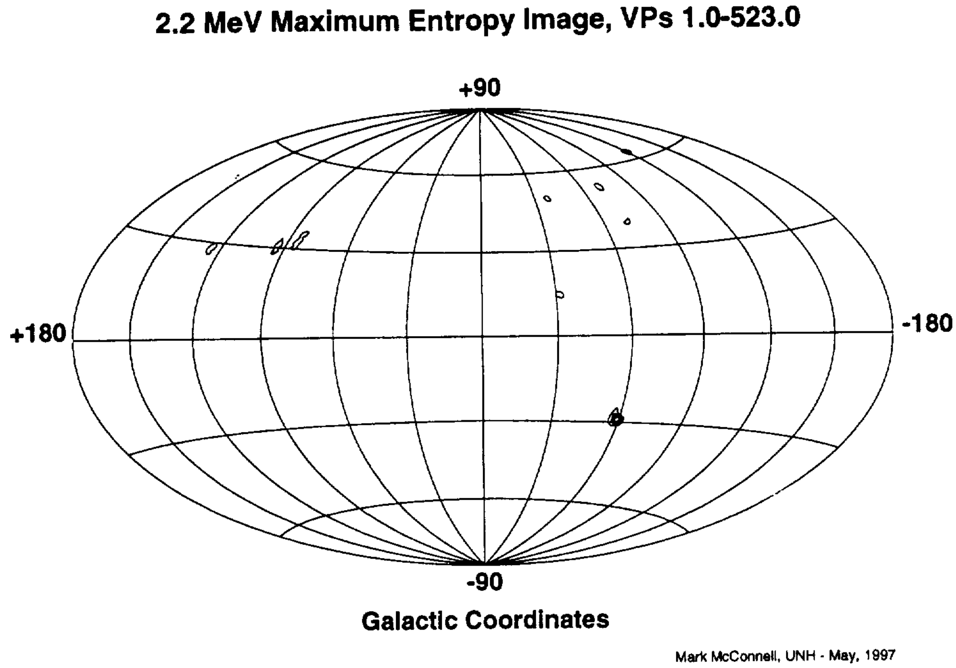

Fig. 1: COMPTEL *2.2 MeV all-sky map derived using a maximum entropy imaging method. The only significant source is a point-like feature near* $(\ell, b) = (300^\circ, -30^\circ)$*, for which there is no obvious counterpart.*

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REFERENCES

Bildsten, L. in *Gamma-Ray Line Astrophysics* (AIP Conf. Proc. 232), ed. P. Durouchoux & N. Prantzos (New York: AIP), p. 401.

Bildsten, L., Salpeter, E.E., & Wasserman, I. 1993, *ApJ*, **408**, 615.

Diehl, R., et al. 1995, *A&A*, **298**, 445.

Fichtel, C.E., and Trombka, J.I. 1981, *Gamma-Ray Astrophysics*, NASA SP-453.

Guessom, N. & Dermer, C.D. 1988, in *Nuclear Spectroscopy of Astrophysical Sources* (AIP Conf. Proc. 107), ed. N. Gehrels and G.H. Share (New York: AIP), p. 332.

Harris, M.J. & Share, G.H. 1991, *ApJ*, **381**, 439.

Schönfelder, V., et al. 1994, *ApJS*, **86**, 629.

Shvartsman, V.F. 1972, *Astrophysics*, **6**, 56.

Vestrand, W.T. 1989, in the *Proceedings of the Gamma Ray Observatory Workshop*, ed. N. Johnson, p. 4-274.

4th Compton Symposium
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COMPTEL All-Sky Imaging at 2.2 MeV

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Abstract. It is now generally accepted that accretion of matter onto a compact object (white dwarf, neutron star or black hole) is one of the most efficient processes in the universe for producing high energy radiations. Measurements of the γ-ray emission will provide a potentially valuable means for furthering our understanding of the accretion process. Here we focus on neutron capture processes, which can be expected in any situation where energetic neutrons may be produced and where the liberated neutrons will interact with matter before they decay (where they have a chance of undergoing some type of neutron capture). Line emission at 2.2 MeV, resulting from neutron capture on hydrogen, is believed to be the most important neutron capture emission. Observations of this line in particular would provide a probe of neutron production processes (i.e., the energetic particle interactions) within the accretion flow. Here we report on the results of our effort to image the full sky at 2.2 MeV using data from the *COMPTEL* experiment on the *Compton Gamma-Ray Observatory* (*CGRO*).

INTRODUCTION

The possibility of observing γ-ray lines from the radiative capture of neutrons has been recognized for some time [1]. Although several capture lines are possible, by far the most dominant line is expected to be that from neutron capture on hydrogen (producing a line at 2.223 MeV). There are several scenarios which might produce 2.2 MeV line emission in accreting compact sources (neutron stars or black holes). These include: 1) neutron capture within the accretion flow; 2) neutron capture in the atmosphere of a neutron star; 3) neutron escape from the accretion flow followed by capture in the compact object's companion star; and 4) neutron capture in a situation where a beam of accelerated particles impinges on the companion star (in analogy to solar flares).

The gravitational potential energy released from accretion of matter onto the surface of a compact object can lead to ion temperatures approaching 100 MeV ($T_i \sim 10^{12} K$), which subject heavier nuclei to breakup by spallation reactions. Some of the liberated neutrons might be captured on protons within the accretion flow itself, thus generating a 2.2 MeV line signature. It has been shown that, under most conditions, the neutrons are more likely to escape the production region rather than be captured [2]. Furthermore, neutron capture in the hot accreting plasma would lead to an extremely broad emission line [3] that 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.

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 ^{4}He), once thermalized, will either recombine radiatively with a proton (to produce a 2.223 MeV photon) or non-radiatively with ^{3}He. This problem has been studied in detail [4]. Predicted flux levels are as high as $\sim 2 \times 10^{-5}$ cm^{-2} s^{-1}. This level of emission is near the present all-sky sensitivity limit of *COMPTEL* observations collected over the first five years of the CGRO mission. Enhanced levels of 2.2 MeV emission might be expected from sources where the accreting material contains an unusually high abundance of heavier elements (as would be expected for a highly evolved massive companion). There are at least three cases where such heavy element enhancements may exist: 4U1916-05, 4U1626-67, and 4U1820-30 [5]. In this scenario, a 2.223 MeV neutron capture line would be gravitationally red-shifted to an energy as low as 1.76 MeV.

Neutrons that are produced within the accretion flow are not confined by any magnetic fields. 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 a γ-ray line at 2.223 MeV. Various considerations (e.g., the neutron decay time and the solid angle for interaction with the companion) suggest that close binaries are more probable sources of observable 2.2 MeV emission. In this scenario, the 2.2 line flux will originate on the side of the companion star irradiated by the neutron flux, i.e., the side of the companion that faces the compact object. Therefore, the 2.2 MeV flux will most likely be modulated by the binary period, with peak flux near the X-ray maximum. This process has been discussed in the context of Cyg X-1 [2], with predicted flux levels as high as $\sim 10^{-5}$ cm^{-2} s^{-1}.

The detection of VHE photons (E $> 10^{12}$ eV) has been reported from various accreting sources, including Cyg X-3, Vel X-1 and Her X-1, suggesting the presence of very energetic proton beams. If these beams interact with the companion star, we can, by direct analogy with solar flares, expect some emergent 2.2 MeV flux. Again, this would be a narrow, unshifted line at 2.223 MeV. As in the previous scenario, this line would also vary in intensity with orbital phase. The resulting 2.2 MeV line flux has been estimated, assuming that the protons are accelerated isotropically near the compact object [6]. The peak flux predicted for Cyg X-3 ($\sim 10^{-4}$ cm^{-2} s^{-1}) is well within the range of detectable emission with *COMPTEL*.

To date, the most sensitive search for 2.2 MeV line emission was that carried out using *SMM* data [7]. Their survey was constrained (by the nature of the *SMM* mission) to a region along the ecliptic plane. They set a 3σ upper limit of 1.0×10^{-4} cm^{-2} s^{-1} on the *steady* emission from the Galactic center and from Sco X-1. Upper limits on the 2.2 MeV line emission from Cyg X-1 were in the range of $(1.2-2.2) \times 10^{-4}$ cm^{-2} s^{-1}, according to different models of the emission process. The 3σ upper limit to the phase-averaged steady emission from Cyg X-3 was set at 1.2×10^{-4} cm^{-2} s^{-1}.

OBSERVATIONS AND DATA ANALYSIS

The *COMPTEL* experiment is ideally suited for studies of the 2.2 MeV line from a variety of sources. The wide field-of-view imaging capability of *COMPTEL* provides for continuing exposure to a number of sources and provides the first-ever all-sky survey at these energies. Despite the presence of a major background line at 2.2 MeV (resulting from neutron capture within the upper layer of liquid scintillators), the *COMPTEL* experiment maintains excellent sensitivity at this energy. This analysis incorporates all available *COMPTEL* data from the first five years of the *CGRO* mission. Specifically, we have used data from *CGRO* viewing periods 1.0 through 523.0, with the exception of viewing 2.5, when *COMPTEL* was operated in a special solar mode.

The *COMPTEL* data analysis typically is carried out in a 3-d dataspace defined by the direction of the photon scatter vector, specified by the angles χ and ψ, and by the derived Compton scatter angle, specified by the angle $\overline{\phi}$ [8]. In this case, all-sky images were generated using a procedure analagous to that which has been successfully employed in studies of the diffuse galactic 1.8 MeV emission [9,10]. This approach is based on independent background estimates at adajacent energies. More specifically, we rely on a background estimate that consists of separate empirical modeling of the distributions for χ and ψ (a 2-d distribution) and for $\overline{\phi}$ (a 1-d distribution). A broad energy band (1–10 MeV) that excludes the line interval (2.110–2.336 MeV) provides information on the (χ, ψ) distribution. The $\overline{\phi}$ distribution is derived directly from the data in the line interval (2.110–2.336 MeV). The resulting background model incorporates an estimate of the instrumental background along with the effect of any continuum sources within the FoV. Only sources of mono-energetic line emission (which exhibit a somewhat different scatter direction distribution) will remain in the resulting images. This approach has been validated for the 2.2 MeV line interval using data from the Crab (where we have no reason to expect such a line signature) and using solar flare data (where such a line signature is clearly present). The validation results were as expected. No signature from the Crab was detected, wheras a significant solar flare signature was detected at a level consistent with other, independent, measurements of the 2.2 MeV line flux.

RESULTS

Using the background estimate described above, we have generated all-sky maps with two different imaging algorithms. These include a maximum entropy algorithm and a maximum likelihood algorithm. The maps generated with these two different methods are similar in appearance. The all-sky map generated with the maximum entropy algorithm is shown in Figure 1. In general, the sky at 2.2 MeV is relatively featureless. For example, there is no evidence for any diffuse galactic emission at this energy. There is, however, evidence for emission at $(\ell, b) = (300°, -30°)$. With a peak likelihood value of 32.0, and given that the all-sky map represents about 500 independent trials,

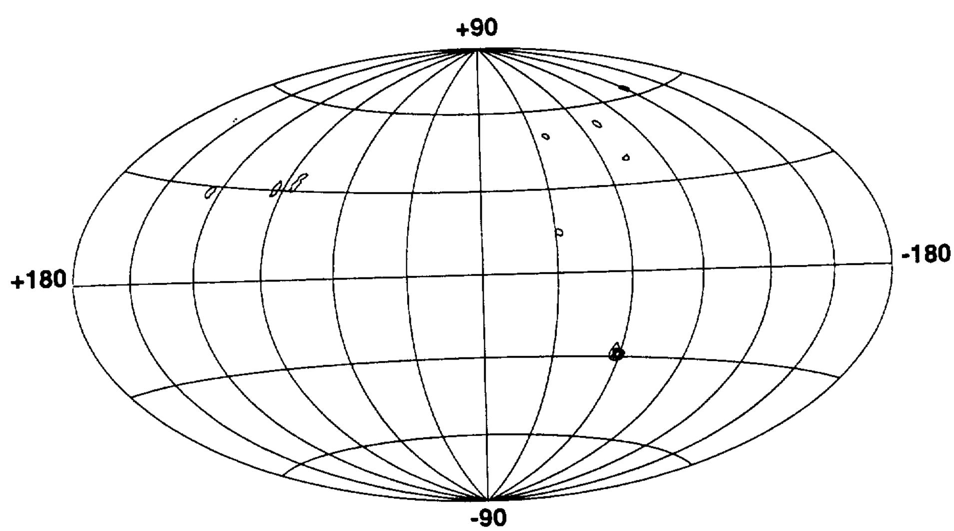

FIGURE 1. *COMPTEL* 2.2 MeV all-sky map derived using a maximum entropy imaging method. The only significant source is a point-like feature near $(\ell, b) = (300°, -30°)$, for which there is no obvious counterpart. This map appears nearly identical to a maximum likelihood map having a likelihood threshold value of 15.

this corresponds to a significance of $\sim 3.7\sigma$. There are no obvious counterparts (such as an X-ray binary) that are consistent with the emission models discussed above. We continue to search for a counterpart of this feature.

We used the X-ray binary catalog of van Paradijs [11] to search for emission from particular source candidates. None of the catalogued sources showed any sign of detectable emission. Flux limits (at the 3σ level) are typically in the range of $(1-2)\times10^{-5}$ cm^{-2} sec^{-1}. Typical (3σ) upper limits include Cyg X-3 ($< 1.8 \times 10^{-5}$ cm^{-2} sec^{-1}), Sco X-1 ($< 2.5 \times 10^{-5}$ cm^{-2} sec^{-1}), 4U 1916-05 ($< 1.8 \times 10^{-5}$ cm^{-2} sec^{-1}), 4U 1626-67 ($< 2.5 \times 10^{-5}$ cm^{-2} sec^{-1}), and 4U 1820-30 ($< 1.6 \times 10^{-5}$ cm^{-2} sec^{-1}). For Cygnus X-1, we set a 3σ upper limit of 2.3×10^{-5} cm^{-2} sec^{-1}, which is about one order-of-magnitude below the limit set by Harris and Share (1991). This result, in conjunction with the model of Geussom and Dermer (1988), can be used to place constraints in 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 come from a phase-resolved analysis in progress.

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REFERENCES

1. Fichtel, C.E., and Trombka, J.I. 1981, *Gamma-Ray Astrophysics*, NASA SP-453.
2. Guessom, N. & Dermer, C.D. 1988, in *Nuclear Spectroscopy of Astrophysical Sources* (AIP Conf. Proc. 107), ed. N. Gehrels and G.H. Share (New York: AIP), p. 332.
3. Aharonian, F.A. and Sunyaev, R.A., 1984, *MNRAS*, 210, 257.
4. Bildsten, L., Salpeter, E.E., & Wasserman, I. 1993, *ApJ*, **408**, 615.
5. Bildsten, L. 1991, in *Gamma-Ray Line Astrophysics* (AIP Conf. Proc. 232), ed. P. Durouchoux & N. Prantzos (New York: AIP), p. 401.
6. Vestrand, W.T. 1989, in the *Proceedings of the Gamma Ray Observatory Workshop*, ed. N. Johnson, p. 4-274.
7. Harris, M.J. & Share, G.H. 1991, *ApJ*, **381**, 439.
8. Schönfelder, V., et al. 1994, *ApJS*, **86**, 629.
9. Diehl, R., et al. 1995, *A&A*, **298**, 445.
10. Knödelseder, J., et al., 1996, *SPIE Conf. Proc.*, 2806, 386.
11. van Paradijs, J., 1995, in *X-Ray Binaries* (New York: Cambridge Univ. Press), p. 536.