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,

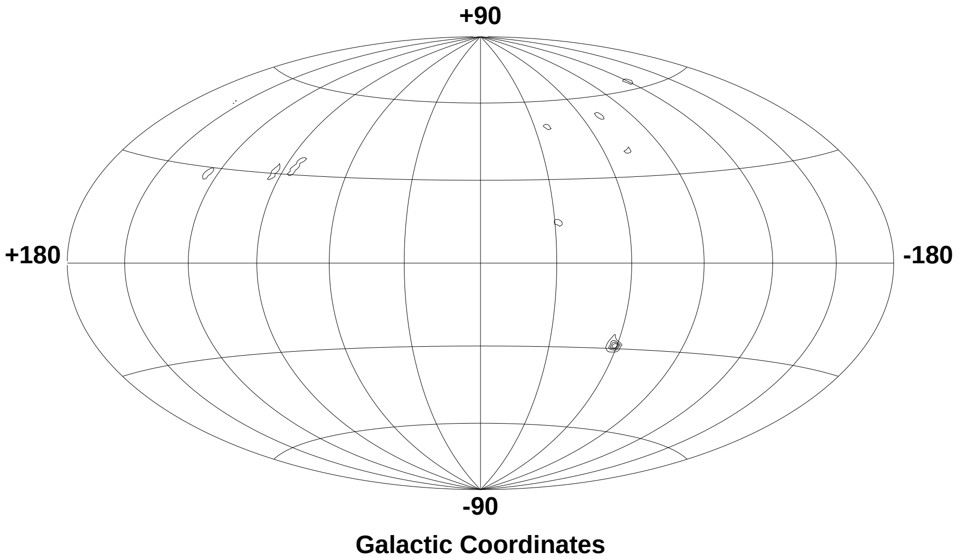

FIGURE 1. *COMPTEL* 2.2 MeV all-sky map derived using a maximum entropy imaging method. The only significant source is a point-like feature near $(\ell, b) = (300°, -30°)$, for which there is no obvious counterpart. This map appears nearly identical to a maximum likelihood map having a likelihood threshold 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 $(1-2)\times 10^{-5}$ 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.

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