A SEARCH FOR GAMMA-RAY LINES FROM THE CRAB, CYGNUS X-1 AND NGC 4151

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Abstract

The Crab Nebula, Cygnus X-1, and NGC 4151 were observed during a recent balloon flight of the University of New Hampshire's Directional Gamma-ray Telescope (DGT). This instrument employs the coded aperture mask techique to image γ-ray ray photons in the energy range 160 keV to 9.3 MeV over a field of view (FOV) of 15.2° × 22.8°. A total source exposure of approximately 340, 346 and 148 m^2 s respectively, was obtained for each of these sources near 511 keV. The results of a search for γ-ray line emission over the energy range 160 keV to 6.8 MeV are presented. From the analysis of the Crab data, we derive 3 σ upper flux limits of 3.2×10^{-3} and 1.9×10^{-3} photons $cm^{-2}s^{-1}$ for the unbroadened line features previously reported at 405 keV and 1050 keV, respectively [1].

1. Introduction. The detection of γ-ray lines provide a unique channel for studying the interactions of particles and fields expected to occur at many astrophysical sites [2]. Potential sources include novae, supernovae, neutron stars and black holes. Spatially extended emission may also be expected due to the interactions of cosmic rays with the ambient ISM and through ongoing nucleosynthesis within the Galaxy. To date, there have been numerous reports of line emision, primarily from a variety of galactic objects. In this paper we present preliminary results of a search for line emission from the Crab, the black hole candidate Cygnus X-1, and the active Galaxy NGC 4151.

During the past decade there have been several reports of line emission from the Crab. During a balloon flight in 1974 June, Ling *et al.* [3] detected a narrow line centered at 73 keV. Confirmation of this feature was subsequently provided by Strickman *et al.* [4] and Manchanda *et al.* [5], although the center energy appears to be variable. Most recently Ayre *et al.* [6] and Watanabe [7] report the detection of a transient feature at ~78 keV. The origin of this line is generally attributed to cyclotron emission in the intense magnetic field close to the pulsar.

Leventhal *et al.* [8] reported the detection of a narrow line centered at 400 keV during observations of the Crab in 1977 November. The authors attribute the feature to gravitationally redshifted annihilation radiation. Confirmation for this line has been provided (albeit with low statistical significance) by Yoshimori *et al.* [9] during a balloon flight in 1977 September, and most recently by Arye *et al.* [6] from a balloon flight in 1981 June. Ayre *et al.* [6] also reported the detection of a line feature at 1050 keV during the same balloon flight. No plausible explanation could be given for the origin of this feature [1].

There have been several reports of line emission from Cygnus X-1. Nolan and Matteson [10] observed the source during its low state in a series of observations between 1977 and 1978. They found an excess in the photon spectrum at energies > 300 keV which they interpret as being due to thermally broadened 511 keV positron annihilation radiation. Watanabe [7] reported a weak feature at 145 keV during the same flight that observed the Crab. It is assumed that the feature is due to redshifted photons arising from the thermal excitation of ^{56}Co within the accretion disc. Recently Ma *et al.* [11] provided tentative evidence for the presence of a weak feature at ~180 keV which they suggest may be due to the gravitational redshift and Comptonization of hard X-rays produced via pair annihilation in the hot inner region of the accretion disc.

At present there have been no reports of line emission from the Seyfert Galaxy NGC 4151 (see Dean and Ramsden [12] for a review of this source). Although no direct observational evidence exists for 511 keV annihilation radiation, there are a variety of reasons to suggest that the nuclei of active galaxies should be copious positron emitters, especially in view of their large luminosities at other wavelenghts [13].

2. Instrument. The observations described in this paper were carried out using a γ-ray imaging telescope which is described in detail in Dunphy *et al.* [14]. The instrument is shown schematically in Figure 1. and consists of coded aperture mask located above, and parallel to, a position sensitive detection plane. The mask is based on a cyclic repitition of a 5×7 URA pattern and defines a fully coded FOV of $15.2° \times 22.8°$. The intrinsic angular resolution within the FOV is $3.8° \times 3.8°$.

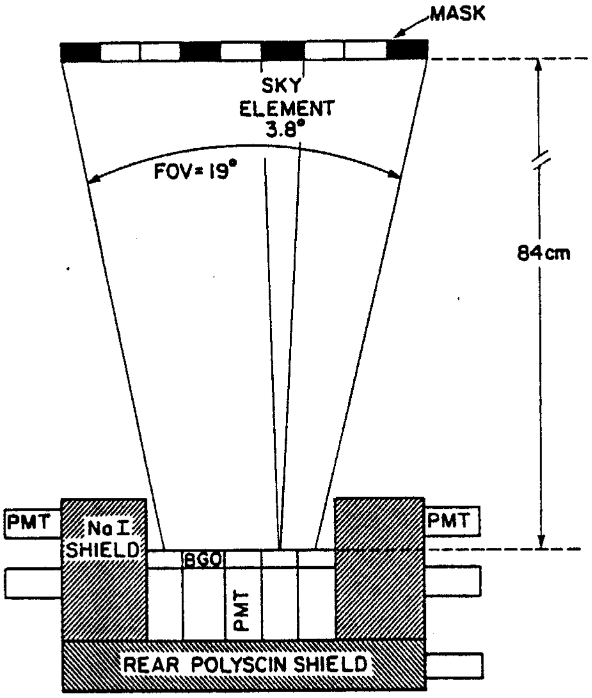

Figure 1

The detection plane is composed of an array of 35 bismuth germanate (BGO) detectors, actively shielded from below and on the sides by 10 cm of NaI(Tℓ). BGO events, in the energy range 160 keV to 6.8 MeV, which satisfy the anticoincidence condition, are pulse-height-analyzed by a 1024 channel ADC. An upper threshold discriminator ensures that the overflow channel of the ADC provides an integral measurement for the energy interval 6.8 MeV to 9.3 MeV. The instrument has an effective area of typically 600 cm^2 for energies < 500 keV. The FWHM spectral resolution to unbroadened lines is 19% at 662 keV and can be well described by the relationship $\Delta E/E = 5.33E_{(keV)}^{-0.51}$ over the entire energy range of the experiment.

3. Observations and Results. The telescope was succesfully launched from Palestine Texas at 1425 UT on 1984 October 1 and remained at a mean float altitude of 3 g cm^{-2} for ~30 hours, before termination at 2235 UT on October 2. During this time a number of imaging observations were carried out, including the regions of the

Crab, Cygnus and NGC 4151. Table 1 lists the observational parameters for each of these sources. Results from this flight have been presented elsewhere at this Conference [15,16,17].

TABLE 1

DGT Observational Parameters

Source	Exposure Time	Exposure @ 0.511 MeV cm^2 s
Crab	0730 UT–1000 UT (Oct. 1) 1230 UT–1500 UT (Oct. 2)	3.41×10^6
Cygnus X-1	2130 UT–0030 UT (Oct. 1–2) 0330 UT–0630 UT (Oct. 2)	3.46×10^6
NGC 4151	1900 UT–2100 UT (Oct. 1) 1530 UT–1630 UT (Oct. 2) 1900 UT–2100 UT (Oct. 2)	1.47×10^6

Because of the nature of the coded aperture technique, both source and background are accumulated simultaneously. The absorbing mask produces an intensity pattern at the detection plane, which for a point source within the fully coded FOV, spatially reproduces the pattern of apertures in the mask. The resulting pattern bears little resemblance to the actual source distribution and thus the image of the source must be recreated using a suitable post-processing technique [14].

The energy-loss spectrum due to the source is determined by fitting the known point-spread-function (PSF) to the imaging response and determining the number of counts within the peak as described in McConnell *et al.* [18]. The spectra are then automatically scanned for statistically significant excesses having a width comparable with the instrumental FWHM energy resolution. A measure of the significance is determined from the following relationship:

$$n_\sigma = \frac{N_T - N_b}{\sqrt{(N_T + \sigma_b^2)[1 + (1 + \frac{1}{m})\frac{T_{obs}}{T_{sys}}]}}$$

assuming a finite source hypothesis (note, the above formulation takes into account systematic errors due to the effects of background nonuniformities across the detection plane as described in McConnell *et al.* [19]). Here N_T is the total number of counts within the energy interval under consideration, T_{obs} is the source observation time, T_{sys} is the time spent accumulating the systematic correction factors [see reference 19], m is the number of elements in the detection plane, and N_b and σ_b are the number of background counts and its associated standard deviation.

To achieve the most realistic values for the significance, we have used the following approach to estimate N_b. At energies < 800 keV the flux of a particular line candidate was calculated as the source flux in a bin of width 1.2 ΔE centered on that line, minus the fitted source continuum flux determined from adjacent bins of the same width on either side of the central bin. The choice of this particular bin width is not arbitary, but was chosen so as to optimize the available statistics of a Gaussian line feature in the presence of a background [20]. At energies greater than ~ 800 keV there is no significant source flux in our data and therefore the significance of a particular candidate line was based on the statistical uncertainty of the central bin.

No lines $> 3\ \sigma$ were found in our data over the energy range 160 keV to 6.8 MeV and therefore we have examined a few specific energies of interest to γ-ray astronomy. For example, previous measurements of the Crab have suggested line emission at energies around 77 keV and 400 keV [3,4,5,7,8,9]. Most recently Owens *et al.* [1] report the detection of narrow line features at center energies 78 keV, 405 keV and 1050 keV, with intensities at the top of the atmosphere of $(1.0 \pm 0.2) \times 10^{-2}$, $(7.2 \pm 2.1) \times 10^{-3}$ and $(1.48 \pm 0.5) \times 10^{-2}$ photons $cm^{-2}\ s^{-1}$, respectively. We have examined the energy regions 404 keV and 1049 keV explicitly and place $3\ \sigma$ upper flux limits for narrow line emission at these energies of 3.2×10^{-3} and 1.9×10^{-3} photons $cm^{-2}\ s^{-1}$ respectively. Also, for the reported line features at 180 keV and 511 keV from Cygnus X-1 [11,10], we place $3\ \sigma$ upper limits on narrow line emission of 2.6×10^{-3} and 2.8×10^{-3}, respectively.

Finally, in order to obtain the lowest possible upper flux limits for each of the sources listed in Table 1, the sensitivities were calculated without regard to imaging properties of the instrument, following the approach of Jacobson *et al.* [20]. The results for narrow line emission (i.e. $\leq$ to the instrumental energy resolution) are shown in Figure 2 for the energy range 160 keV to 6.8 MeV. The limits were calculated at the $3\ \sigma$ level, corresponding to a confidence level of 99.7% (assuming Gaussian statistics).

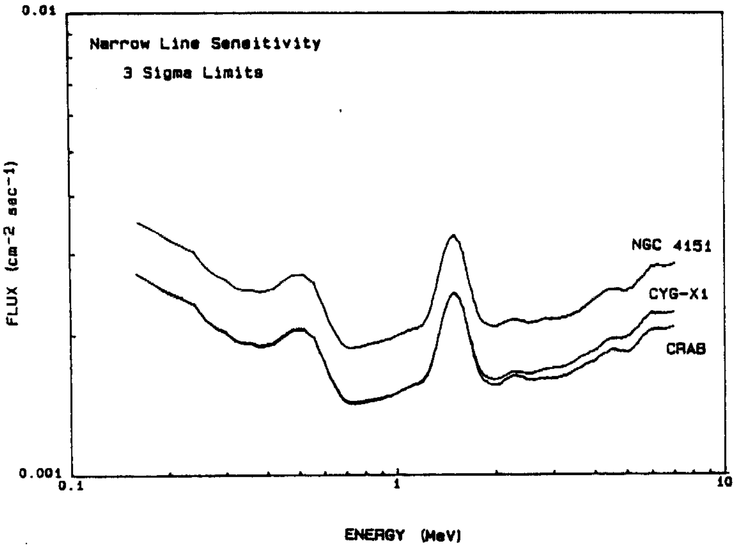

Figure 2

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