DETECTION OF GAMMA-RAY LINES FROM THE DIRECTION OF THE CRAB NEBULA

A. Owens
Dept. of Physics, Case Western Reserve University, Cleveland Ohio 44016 U.S.A.

R.M. Myers and M.G. Thompson
Department of Physics, Durham University, South Road, Durham, DH1 3LE U.K.

ABSTRACT

The Crab Nebula and its associated pulsar NP0531+21 were observed during a balloon flight of the Durham MK1 high resolution spectrometer on June 6 1981. The data indicate two significant line features of energies of 404.7 and 1049.8 keV with intensities of $(7.2 \pm 2.1) \times 10^{-3}$ and $(2.0 \pm 0.5) \times 10^{-2} s^{-1}$. After subtracting instrumental resolution, the widths of these lines were determined to be (3.5 ± 1.4) keV and (6.3 ± 1.6) keV at 404.7 and 1049.8 keV respectively. A third line at 78.8 keV was detected as a transient event with a peak intensity of $(1.1 \pm 0.3) \times 10^{-2}$ photons $cm^{-2}s^{-1}$ and a width <1.5 keV. A cross correlation analysis of the data shows that all three line features are consistent with a point source located at the Crab.

1. Introduction During the past few years there have been several reports of gamma-ray line emission from the Crab. In a series of papers Jacobson and collaborators reported the detection of several lines from the Crab Nebula region. Four transient lines at energies 0.41, 1.79, 2.22, 5.95 MeV were observed without any detectable continuum (Jacobson et al. 1978). A possible line feature around 73 keV was also reported by Ling et al. (1979) from analysis of the same data. Confirmation of this line was provided by Stickman et al. (1982) and Manchanda et al. (1982) although the centre energy appears to be variable. This line is generally attributed to cyclotron emission in the intense magnetic field close to the pulsar.

Leventhal et al. (1977) report the detection of a line centred at 400 keV during a balloon flight in May 1976. They interpret the origin of this line to be gravitationally redshifted annihilation radiation. Apparent confirmation of this line was provided (albeit with small statistical significance) by Yoshimori et al. (1977) during a balloon flight in September 1979.

It should be pointed out that there have been many contemporary observations that have failed to detect line emission (Mahoney et al. 1984 and references therein).

2. Instrument and Observation The spectrometer consists of an 86 cm^3 Ge(HP) crystal, actively shielded from below and on the sides by 12.5 cm of NaI(Tℓ) (Ayre et al. 1983). The beam sensitivity pattern is defined by a 15 cm thick right-cylinderical NaI(Tℓ) collimator having a geometric FWHM angular aperture of 4.8°. The instrument has a spectral resolution of 1.5 keV FWHM at 400 keV and covers the energy range 50 keV to 10 MeV.

The Crab Nebula was observed from 17.01 to 21.52 UT during a balloon flight from Palestine texas on June 6 1981. A total source exposure of 54294.2 cm^2s was obtained at 400 keV.

3. Results After correcting for instrumental and atmospheric effects, the total Crab spectrum incident on the top of the atmosphere is shown in Figure 1. A best fit power law to the data points yielded $dN(E)/dE = (8.6 \pm 3.4) \times 10^{-4} (E/80)^{-2.5^{+2.7}_{-1.2}}$ photons $cm^{-2}s^{-1}keV^{-1}$ compatible with previous measurements. Also shown in Figure 1 is the spectrum of the associated pulsar NP0531+21 which was obtained from a superimposed epoch scan of all gamma-ray events in the energy range 50 keV to 2500 keV. The pulsation period derived from the present measurements was 33.258436 ms.

A computer search for spectral features in the total Crab gamma-ray spectrum located six lines having a significance in the detected flux of $> 3\sigma$ and a width commeasurable with the instrumental energy resolution. Of these six lines, three can be dismissed by confidence arguments which are described in detail in Ayre et al. (1983). The properties of the remaining lines, at energies 78.8, 404.7 and 1049.8 keV, are given in Table 1. The line at 78.8 keV was detected at the 4.1σ level only in the last third of the data corresponding to a confidence level of 99.5% for source variability at this energy. It is unfortunate that the observation ended before any conclusion could be drawn about the shape of the light curve or when it reached maximum intensity. Both the intensities of the 404.7 and 1049.8 keV lines are consistent with a constant mean rate throughout the 5 hour period of the observation. Figure 2 shows the count rate profile of each candidate line after background subtraction as a function of energy. The dashed line on each profile represents a best fit least squares function plus a Gaussian peak. The derived widths and centroid energies are given in Table 1. An attempt to determine if any of these lines were pulsed at the pulsar frequency was inconclusive due to timing uncertainties and poor statistics.

The observation employed a raster scan technique which covered right ascensions and declinations within ±5° of the target. The detected events for each orientation of the spectrometer axis were projected onto the celestial sphere and converted into 'on axis' counting rates. A cross correlation analysis was applied to the data. At each position r on the sky the correlation function C(r) and its associated standard deviation, σ, were calculated for an assumed source located at r. The results are shown in Figure 3. The contours represent those positions where the function $C(r)/\sigma$ has constant integer values. A best fit aperture response function indicated that all three lines are consistent with a point source located at the Crab. The dashed line on each contour corresonds to the FWHM aperture at that energy.

4. Discussion If the 405 keV line is interpreted as redshifted annihilation radiation then the present result indicates that $\sim 10^{42}$ positrons s^{-1} must be annihilating into 511 keV photons near the neutron stars surface assuming isotropic emission. The derived redshift of the line is 0.26 suggesting an implied mass for the pulsar of 1.4 to 2.1 M_o, depending on the equation of state. The apparent variability of the redshift from 0.28 in 1976 (Leventhal et al. 1977) to 0.26 in 1981 is regarded as significant, since constant monitoring of background lines in both experiments rule out systematic errors in energy calibration. It has been previously suggested (Lingenfelter et al. 1981) that the 400 keV feature detected by Leventhal et al. from the general direction of the Crab may be variable emission from the same source as the June 10 1974 transient event observed by Jacobson et al. (1978). The two experiments had overlapping fields of view and the indentification of the lines implied essentially the same neutron star mass. The cross correlation analysis of the present data strongly suggests that the transient event observed by Jacobson et al. cannot originate from the same source since the Crab was out of their field of view.

Assuming the 78.8 keV line is due to cyclotron emission, then the derived redshift would imply production in a magnetic field of strength 8.6×10^{12} gauss. A relativistic quantum mechanical treatment might enhance this value by a factor of two (Brecher and Ulmar, 1978). Since $\Delta E/E = \Delta B/B$, magnetic inhomogeneities must be $< 1.9\%$ which indicates that the emission cannot take place over an extended region. Further for a dipole field ($B \propto R^{-3}$) it follows that for R = 10km, the radial extent of the emission region is < 63 meters.

The 1049.8 keV line has not been seen before and there is no obvious mechanism for producing a line at this energy. If the effect is real then the narrow width and high luminosity would suggest production at the pulsar itself. One might at first thought invoke single photon annihilation (Daugherty and Bussard, 1980) but the narrow width and the relative intensity of the 405 keV line would rule out the possibility. Clearly confirmation of this feature is required.

References

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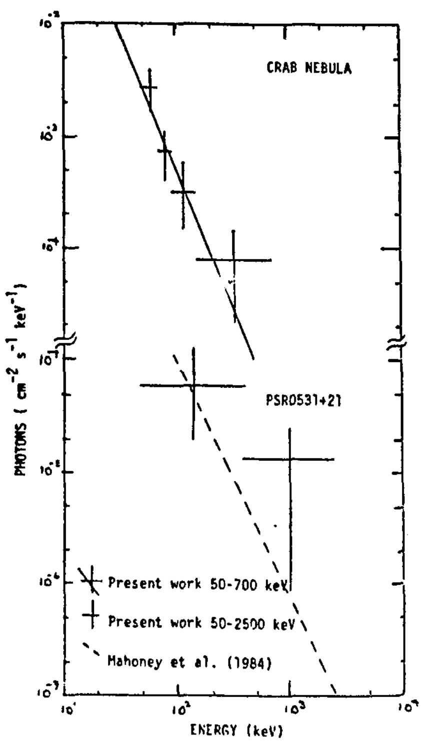

Figure 1. The total Crab and PSR0531+21 photon spectra measured on June 6 1981. The solid line through the Crab data points represents a best fit power law, i.e;

$$dN(E)/dE = (8.6 + 3.4) \times 10^{-4} (E/80)^{-2.5^{+2.7}_{-1.2}} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}.$$

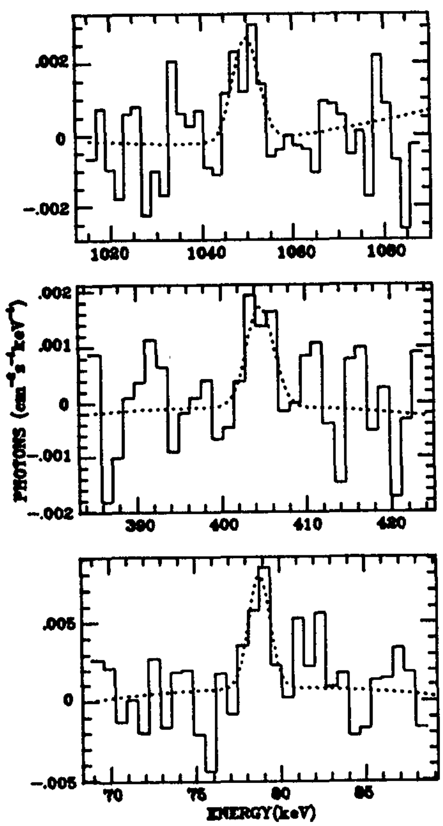

Figure 2. Line profiles of the three line features after correcting for the background. The dashed line on each profile is a best fit polynomial plus a Gaussian peak.

Centroid Energy* KeV	Position** RA	Position** Dec.	Error Radius Degrees	Flux Photons cm^{-2} s^{-1}	Width*** keV	Luminosity**** erg s^{-1}
50 - 350	83.5	20.7	0.4	0.12 ± 0.03	-	1.1×10^{37}
78.8 ± 0.2	85.3	20.8	0.4	$(1.1 \pm 0.3)^{+} \times 10^{-2}$	<1.5	6.5×10^{35}
404.7 ± 0.7	84.1	21.7	1.0	$(7.2 \pm 2.1) \times 10^{-3}$	3.5 ± 1.4	2.1×10^{36}
1049.8 ± 0.8	84.2	21.0	0.5	$(2.0 \pm 0.5) \times 10^{-2}$	6.3 ± 1.6	1.5×10^{37}

* Errors calculated by $\chi^2_{min} + 1$, i.e, single parameter determination

** Uncorrected for systematic errors in the orientation platform

*** Instrumental resolution subtracted

**** Assumed source distance 2 kpc

+ Peak flux observed in last subset of data with t_{on} = 1572 and t_{off} = 2020 sec.

Table 1. Properties of the significant line features detected on June 6 1981 from the direction of the Crab Nebula. The integral source flux 50 - 350 keV is shown for comparison.

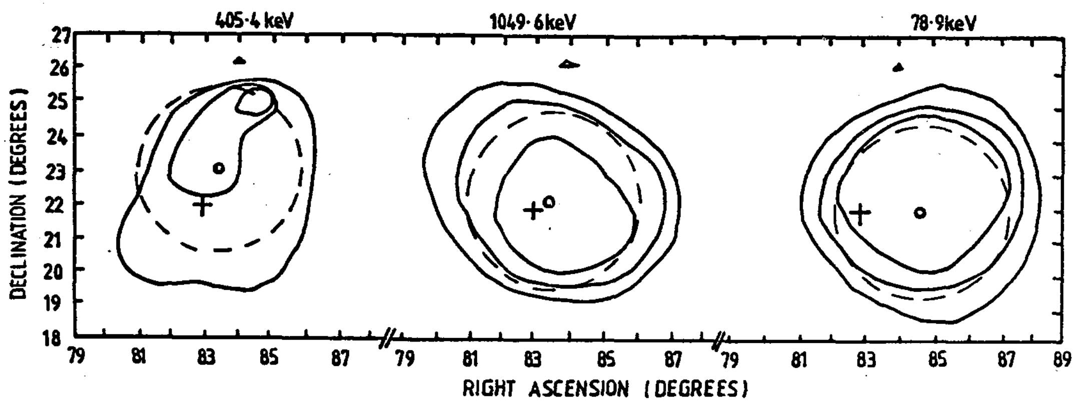

Figure 3. Results of a cross-correlation analysis of the significant line features detected on June 6 1981. The contours represent 1σ levels of the correlation function. The position of the Crab and the flaring x-ray source A0535+26 are shown by the crosses and triangles respectively. The circles represent the centroids of a best fit aperture response function to the data. The dashed circles represent the FWHM aperture at each energy. Note the positions of each of these contours have been corrected for the positional error in the orientation platform. This correction introduces an additional uncertainty in the position of the centroid of about 0.3°.