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LINE FEATURE AROUND 73 keV FROM THE CRAB NEBULA

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ABSTRACT

An observation of the Crab Nebula was made during a transmediterranean balloon flight launched on 1979 August 26. The data in the 20–150 keV energy region were obtained from a multiwire, high-pressure xenon, proportional counter. Our results indicate a line feature around 73 keV in the X-ray spectrum of the Crab Nebula. The continuum emission from the source fits a power law of $16.5E^{-2.3}$, while the line intensity is measured to be $(5 \pm 1.5) \times 10^{-3}$ photons cm^{-2} s^{-1} for an equivalent width of 3 keV. We briefly discuss the result in the context of cyclotron emission process as the possible mechanism for the observed line.

Subject headings: gamma rays: general — nebulae: Crab Nebula – radiation mechanisms — X-rays: sources

I. INTRODUCTION

Several observations of the X-ray source in the Crab Nebula in the energy region 20–250 keV have been made in the past, and spectral features have been reported (Peterson, and Jacobson 1970); Laros, Matteson, and Pelling 1973; Toor and Seward 1974; Gruber and Ling 1977; Dolan *et al.* 1977; Strickman, Johnson, and Kurfess 1979). The hard X-ray emission indicates a power-law spectrum of the source with spectral index $\alpha \sim 2$, which is consistent with the synchrotron origin of X-ray photons. The synchrotron nature of the X-ray photons is also demonstrated by the polarization measurements of Weisskopf *et al.* (1978).

A single power law seems to be a best fit right up to 4 MeV, above which the spectral shape is not so well determined because of experimental uncertainties (Baker *et al.* 1973; Schonfelder, Liehti, and Moyano 1975). The physical size of 34 (+17, −14) arcsec for the hard X-ray source and its positional coincidence with the optical wisps of the nebula were obtained with lunar occultation experiments (Fukada *et al.* 1975; Ricker *et al.* 1975; Ku *et al.* 1976). Many models using the generic relation between magnetic fields, electron spectrum, and synchrotron photon spectrum have been suggested in the past for the physical reconstruction of the X-ray emitting region (see Apparao 1973, and references therein).

Unlike other X-ray sources, a steady X-ray emission devoid of any line emission has been the unique feature of the Crab Nebula. An X-ray line at 400 keV in the photon spectrum of the Crab Nebula was first reported by Leventhal, MacCallum, and Watts (1977) with a large field of view instrument and with marginal statistical significance. However, no such feature was detected by Ling *et al.* (1977), even though it should have been seen at the 3.9 σ level.

A possible line feature at 73 keV in the Crab Nebula was later reported by Jacobson *et al.* (1978) and Ling *et al.* (1979) from the data obtained from a Ge(Li) detector on board a balloon flight. However, the recent measurements reported by Strickman, Johnson, and Kurfess (1979) do not confirm the earlier findings. The results obtained by a large area crystal spectrometer only show a spectral discontinuity at 80 ± 10 keV, while no clear line feature at 73 keV was seen in the data. The possible existence of an X-ray line brings in a new dimension to the Crab picture. A line component can be produced in nuclear processes or by the cyclotron emission in the intense magnetic field around the Crab pulsar. A high energy line at 58 keV has been observed in the case of Hercules X-1 (Trümper *et al* 1978) and is attributed to cyclotron emission.

In this paper we report the spectral measurement of the Crab Nebula between 20–150 keV made with a large area, high-pressure, multiwire proportional counter. Our data yield a line feature around 73 keV superposed on the continuum emission and confirm the earlier results obtained by Ling *et al.* (1979); while the total X-ray spectrum is in good agreement with other measurements. The preliminary data have been earlier reported by Ubertini *et al.* (1980) and Polcaro *et al.* (1980). We present here the detailed analysis of the data and discuss the possible origin of the line emission and its implications.

II. EXPERIMENTAL DETAILS

The balloon-borne X-ray experiment (HXR-79) was flown from Milo Base, Sicily (Italy), on 1979 August 26. The instrument was designed to study detailed spectral features of the known hard X-ray sources and to scan for hard X-ray emission of other sources visible in the northern sky around the 38th parallel.

Two high-pressure xenon-filled multiwire proportional chambers (MWPC) were used as the basic detectors. Each of these chambers has a sensitive area of 900 cm^2, a depth of 10.5 cm, and were made out of stainless steel containers. The window consisted of a laminated "Aeroweb" honeycomb material which is strong enough to withstand the high pressure. The sensitive volume was divided into a 21.5 × 21.5 mm cell arranged in four layers. The bottommost layer consisting of a 21.5 × 18.5 mm cell, and side cells were used as anticoincidence in a bucket-like arrangement. The detectors were surrounded with a complete passive shielding and were filled with 2.63 atm of gas mixture (2.37 xenon + 0.13 argon + 0.13 isobutane). The fields of view of the detectors were limited to 7°5 × 7°5 and 5° × 5° (FWHM), respectively, by means of passive collimators. The pulse output from the counters were pulse-height analysed into 256 channels of spectral information. The details of the payload design and fabrication have been discussed elsewhere (Ubertini *et al.* 1979).

The detectors and the associated electronics were mounted on an altazimuth stabilized gondole. The orientation of the payload is controlled by an on-board preprogrammed stepper-programmer. The aspect of the telescope was obtained from a set of triaxial flux gate magnetometers.

The payload was launched on August 26 at 0244 UT and reached a ceiling altitude of 2.9 mbars at 0515 UT. The pulse-height information along with the housekeeping data and the aspect information were transmitted via FM telemetry, and the data were received both at Milo (Italy) and Palma (Spain) receiving stations. Unfortunately, the 5° × 5° field of view detector developed a corona discharge soon after launch and therefore the power to the counter was switched off from ground command.

III. OBSERVATION AND DATA ANALYSIS

The X-ray source in the Crab Nebula was observed during the period 0524 UT to 0624 UT in a single transit scan soon after the balloon reached the ceiling altitude. Only 30 minutes of useful data were obtained from the 7°5 × 7°5 field of view detector, since we rejected the data during the telecommand slots in which we tried to reactivate the 5° × 5° counter and suspected interference. All the housekeeping data, such as power monitors, temperature, and pressure of the MWPC, showed a normal behavior. The aspect reconstruction from the magnetometer data indicated the positional accuracy of ±0°5 for the Crab pointing.

To determine the background count rate, we used the data obtained when the source was just outside the field of view of the collimator both preceding the observation and after. The result is shown in Figure 1*a*. The source contribution in different energy channels was obtained by simple subtraction. The X-ray source contributed about 20 counts s^{-1} at the peak projected area of 98% while the background level was 75 counts s^{-1} in the 22–150 keV energy region. The entire pulse-height data were grouped in 12 energy channels to minimize the statistical errors, as shown in Figure 1*b*. The energy loss spectrum as observed in the detector was simulated by using a Monte Carlo procedure taking into account the following steps:

1. Window absorption.
2. Physical interaction of X-ray photons with the detector window.

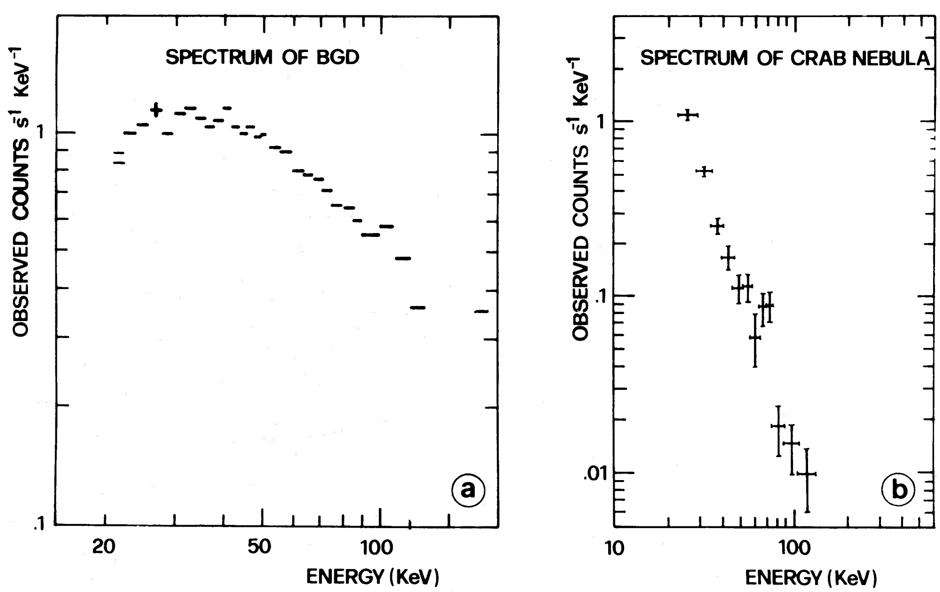

FIG. 1.—(*a*) Background as observed during the HXR-79 flight before and after the Crab transit. (*b*) Excess count rate from the Crab Nebula. One sigma error bars are shown.

3. Filling gas mixture: absorption coefficient, fluorescence emission, and the Auger effects.
4. Intrinsic resolution (obtained from ground calibration data).
5. Electronics effects which include the linearity of the system, thresholds, anticoincidence, and electronic deadtime.

The transfer functions computed for a line input showed very good agreement with the preflight calibration.

A similar method has also been used earlier by Brisken (1973) in the case of xenon-filled counters. The coefficients of the transfer function were inverted by using standard mathematical methods and were used to deconvolve the Crab data. The final spectral fit was arrived at by χ^2 analysis.

To determine the pulsed component in the Crab data, we have employed a simple data-folding technique with the PSR 0531+21 period corrected to our observation parameters. Data were folded in 12 phase lines and the pulse fraction calculated from the phase histogram.

IV. RESULTS

In Figure 2 we have plotted the deconvolved spectrum of the Crab Nebula reduced to the top of the atmosphere. The solid line represents the best line given by $dN/dE \approx 16.6E^{-2.3}$. It is quite evident from the figure that the observed flux in the energy range 67–79 keV lies well above the expected flux value, as indicated by the best-fit line. The best fit with a power law gives a minimum reduced χ^2 value of 2.7 for 10 degrees of freedom while 50% of the total is due to the excess in the 67–79 keV bins superposed on the continuum emission. The best-fit spectrum of the form:

$$\frac{dN}{dE} = AE^{-2.3\pm0.1} + \frac{B}{(2\pi\sigma)^{1/2}} \exp\left[\frac{-(E-73)^2}{45}\right].$$

$A = 16.6 \pm 4$ and $B = 1.5 \pm 0.5 \times 10^{-2}$ gives a reduced $\chi^2 = 1.7$ dof^{-1} for 8 degrees of freedom. We have also tried a 2 power-law fit to our data. However, the large value of χ^2 showed a very poor fit. The only way χ^2 could be lowered is by assuming a break around 80 keV along with an absorption feature around 60 keV. As is apparent from the data, any such fitting is arbitrary as the absorption feature has to be quite extended.

In order to bring out the line feature much more clearly, we have replotted the spectral data in Figure 3. The data points in the figure have been multiplied by $E^{2.3}$ to remove the intrinsic energy dependence of the flux values. The dotted line in the figure represents the spectral constant of a power-law fit as given in Figure 2. As can be seen from Figure 3, the line emission with combined statistical significance of 3.8 σ in the energy channel of 67–79 keV stands out quite clearly. We can use the Poisson statistics (Tananbaum *et al.* 1978; Rothschild *et al.* 1974) to determine the probability of obtaining the actual intensity observed in this bin by merely statistical fluctuations. Assuming the mean value for the distribution to be 21.7 (see Fig. 3), we found that the probability of having a bin with a flux higher than 30 is ~ 0.18, and higher than 40 is 1.4×10^{-3}, with 12 samples. Even though from the figure it appears that the increase around 140 keV may correspond to the second harmonic, the statistical significance of the data is too small to make such a guess. The dotted line Gaussian fit corresponds to the resolution spread of a narrow line in our detector. It is clear from the data that we cannot put a strict limit on the line width, except that $E < 4$ keV.

In Figure 4 we have plotted the results of the pulsar analysis of the Crab data. The X-ray data were folded into 12 time bins. The appropriate heliocentric pulsar period $t = 33.228798358$ ms was obtained from the *COS B* working group. The light curve obtained in this analysis is shown in the figure. Both the peaks, namely, the main peak and the interpulse, are quite evident from this figure, and their time separation matches the radio data (shown by arrow) within our timing uncertainties. Finer time resolution in our experiment was limited because of the uncertainties in time digitization of FM telemetrized data.

We determined the pulsed fraction by taking a ratio of the pulsed flux to that of steady emission. This ratio is plotted in Figure 5, along with the best-fit line for the world data as obtained from Boclet *et al.* (1972). It is evident from the figure that the pulse fraction obtained in our experiment (HXR-79) compares well with the other measurements.

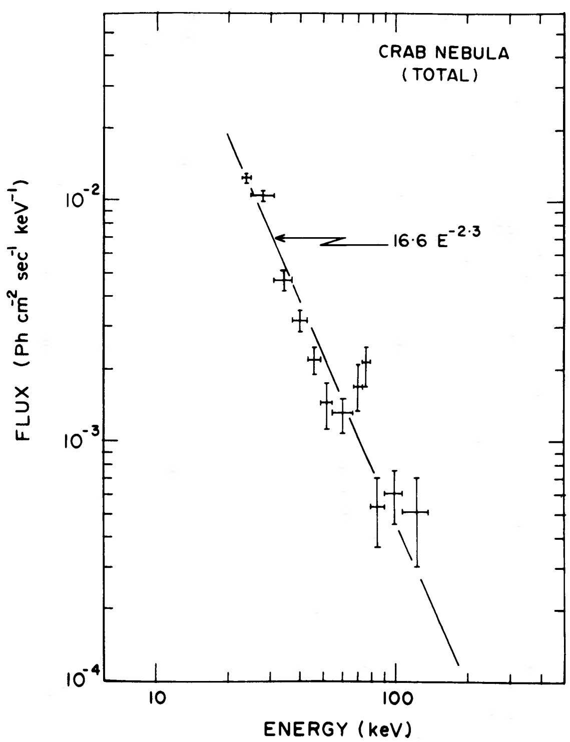

FIG. 2.—The hard X-ray spectrum of the Crab Nebula in the 22–150 keV range as obtained in the HXR-79 flight. The solid line represents the best-fit power-law spectrum.

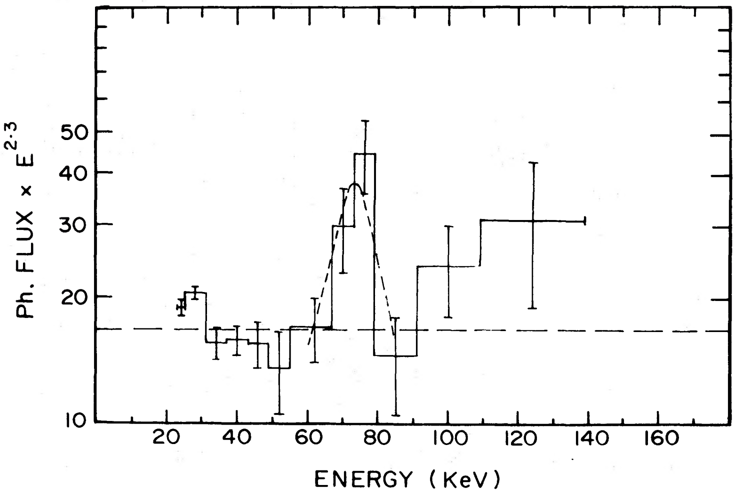

FIG. 3.—The hard X-ray spectrum shown in Fig. 1, in alternative units of flux times $E^{2.3}$ to remove the energy dependence. The dotted line corresponds to the constant of the fit 16.6, and the dotted Gaussian represents the line fitting.

V. DISCUSSION

The shape of the pulsar light curve as shown in Figure 4 and the consistency of the pulsed fraction with the world data (Fig. 5) establish beyond doubt that the object under study was indeed the Crab Nebula, and the analysis procedure developed by us is quite appropriate. In Figure 6 we have plotted our spectral measurement along with those obtained by other investigators. It is seen from the figure that our data points lie within the spectral spread of various measurements. In fact, our data points match more closely the recent measurement of Strickman, Johnson, and Kurfess (1979) and *HEAO* A-4 (Matteson 1979), but for the line feature, while the line feature reported by Ling *et al.* (1979) overlaps our data points. Thus the overall Crab spectrum seems to follow a power-law continuum with a superposed variable line feature around 73 keV. However, there does exist disparity among individual experiments.

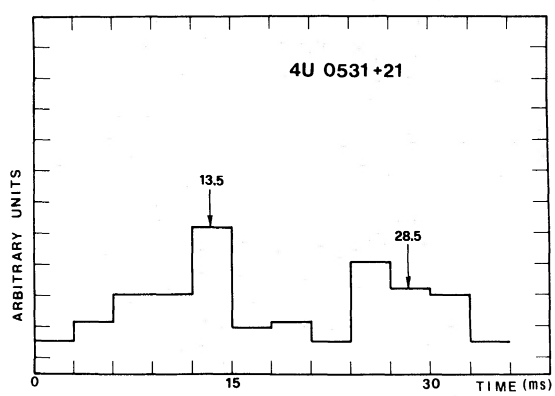

FIG. 4.—Pulsar light curve as obtained from the folding analysis of X-ray data with pulsar period $t = 33.228798358$ ms (obtained for *COS B* group). The position of the main pulse and subpulse are marked by arrows.

A comprehensive review of the earlier measurements of the Crab spectrum was made by Peterson and Jacobson (1970). It was shown that the spectrum in the energy region of 1–600 keV could be fitted with a single power law with spectral index $\alpha \sim 2.3$. In a later analysis, Laros, Matteson, and Pelling (1973) indicated the validity of the single power-law spectrum, even though their data did show lower flux values above 100 keV than those expected from the extrapolation. The differences in various measurements could be attributed to systematic effects in different measurements. All the recent results, in general, have confirmed the earlier observations. However, recently Strickman, Johnson, and Kurfess (1979) have reported a break in the Crab spectrum around 80 ± 10 keV. The best-fit spectrum shows a change in spectral index from 1.99 to 2.4. The spectrum can be fitted to a single power with a slightly higher value of χ^2. A similar result was obtained by the *HEAO* A-4 experiment. The reported spectrum shows a power-law index of 1.98 below 125 keV and 2.4 at higher energy. However, no clear line feature around 73 keV, as reported by Ling *et al.* (1979), was seen in the data of the two above reported experiments. The same indication comes from the results of the Germanium Array High Resolution Instrument of the University of California at Berkeley group, flown on 1979 October and 1980 June (G. U. Jung, private communication).

A synchrotron emission mechanism seems to account well for both the power-law nature of the observed X-ray spectrum and the polarized flux as measured by Weisskopf *et al.* (1978) and Silver *et al.* (1978).

The existence of an emission line around 73 keV as seen in our data and reported earlier by Ling *et al.* (1979) is quite important for determining the mechanism of X-ray production. If the line emission is produced by a nuclear process, the dominant mode will be the radioactive decay of various elements synthesized during the explosion of a supernova. Some of the isotopes which produce lines in

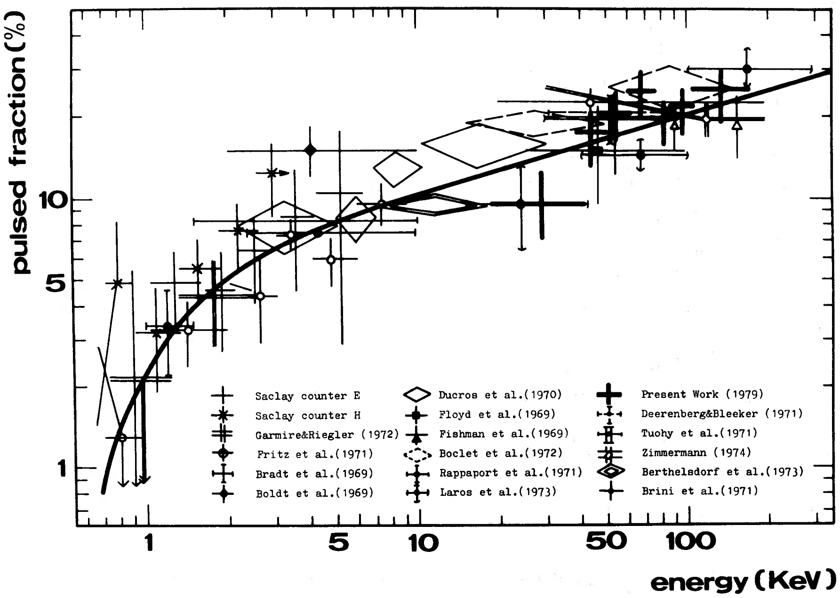

FIG. 5.—World data on the X-ray pulse fraction as a function of energy. The values obtained in our data are also shown

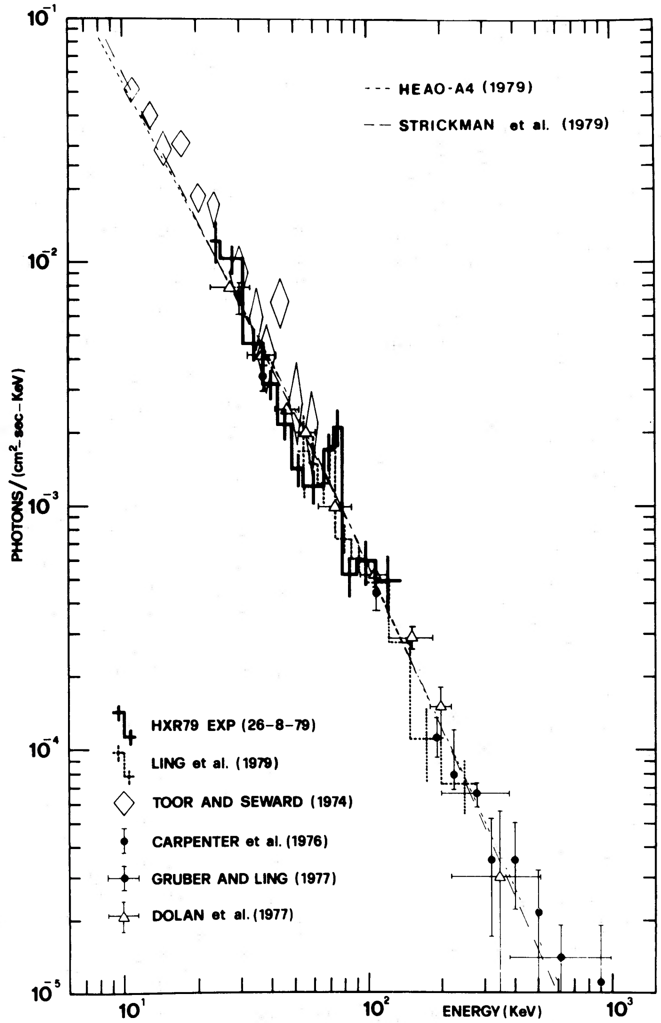

FIG. 6.—The total spectrum of the Crab Nebula is shown. The data of the other observations are shown with that obtained during the present experiment.

the X-ray energies are Am 241 (59.6 keV), Cf 251 (104 keV), and Cf 249 (180 keV). Clayton and Craddock (1965) and Jacobson (1968) computed the line intensities expected in the case of the Crab Nebula. However, no line has been predicted around 73 keV as seen by us, and the predicted intensities are short by an order of magnitude from our observation (see Apparao 1973).

Therefore, it appears that the line emission detected during the present experiment may arise from cyclotron processes in the intense magnetic field surrounding the pulsar. A cyclotron line at 58 keV, in the case of Her X-1, has been reported by Trümper *et al.* (1978). However, the nature of the two sources is quite varied. Her X-1 is known to be a binary source accreting matter from its companion star, and X-rays are generated in the hot spot at the magnetic pole. While in the case of the Crab pulsar it is the rotational energy which is manifest in various forms.

The exact physics of cyclotron emission around a neutron star is still not very clear (Basko and Sunyaev 1975; Gnedin and Sunyaev 1974; Meszaros 1978). *A priori*, it is assumed that higher electron Landau levels may be populated in the plasma which would in turn emit resonant emission at the gyrofrequency $\nu_H = eB/2\pi m_e c$. The details of radiative transfer in the accreting column and the cyclotron line formation in the case of Her X-1 has been studied by Bonazzola, Heyvaerts, and Puget (1979). However, it is shown by Daugherty and Ventura (1977) and Meszaros (1978) that the cyclotron line will have Doppler broadening because of thermal distribution of electrons.

Following the pulsar dynamics, the pulsar energy loss rate in the case of the Crab Nebula is given as:

$$dE/dt \approx I\Omega\dot{\Omega} = B^2 R^6 \Omega^4 f(R\Omega/c)/c^3 ,$$

where R is the pulsar radius, B the magnetic field, Ω the angular velocity, $\dot{\Omega}$ the spin down rate, I the moment of inertia, and $f(R\Omega/c) \sim 1$ is a dimensionless number. For the observed value of the Crab pulsar 0531+22, we get $B \sim 10^{12}$–10^{13} gauss.

Alternatively, assuming that the 73 keV line seen in the X-ray spectrum is due to resonant cyclotron emission, then at the first harmonic we have:

$$h\nu_H = 73 \text{ keV} = heB/2\pi m_e c ,$$

which gives $B \sim 6.3 \times 10^{12}$ gauss. In this case we neglected the redshift of the line by about 30% (Brecher 1977). If correct, $B \sim 10^{13}$ gauss. The two values seem to differ by about a factor of 2. Since the radiation energy at 73 keV is not negligible compared to the rest mass energy of an electron, a relativistic quantum mechanical treatment for evaluating the magnetic field will further enhance the estimate by a factor of about 2 (Brecher and Ulmar 1978). The difference by a factor of 4 between the two estimates may not be very significant in the light of many assumptions which are made in deriving the two values and many unknown parameters regarding the temperature of the electron gas and the topology of the magnetic field, etc.

The above approach has been based on the fact that the line emission is of a pulsating nature and associated with the pulsar. A straightforward test for the identification of the feature with a cyclotron process is to check the presence of the line in the pulsed spectrum. Unfortunately, it is difficult to make such a deduction from our data because of the uncertainties on timing digitization and low statistics of the pulsed flux. However, from Figure 5 we can note that the bin containing the line feature shows a pulsed fraction of about 30%, while only 15% is expected from the world data. This is a good indication, but not a definitive one, of the pulsed nature of the line feature.

If the line is a part of the nonpulsed emission, then the emission region is probably located at a certain distance from the object, where the magnetic field is far smaller than its surface value and the cyclotron scenario may be quite constrained.

If the pulsed nature of the line and its variability is ever proved, then a possible way of reconciling the cyclotron scenario with our current ideas of a *non*binary pulsar could involve the unstable confinement of the nonrelativistic, line-emitting plasma to the closed magnetosphere, while the open lines would be reserved to the ultra-relativistic carriers. This merely geometric picture would be consistent with pulsations, with the marginally higher value of B deduced from the line, and with the detection of hard X-ray bursts (27–270 keV) from the region of the Crab Nebula (Estulin 1980), but the energy supply to the trapped plasma is far from clear (M. Salvati, private communication).

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