THE ELECTROMAGNETIC SPECTRUM OF THE CRAB NEBULA

KRISHNA M. V. APPARAO*†
*Smithsonian Astrophysical Observatory and Harvard College Observatory,
Cambridge, Mass., U.S.A.*

The electromagnetic spectrum of the Crab Nebula has been determined experimentally in the radio, optical, and X-ray regions [1], in which it follows a power law of the type $S(\nu)=A\nu^{-\alpha}$, where $S(\nu)$ is the power (in watts/m^2 sec Hz), A and α are constants, and ν is the frequency in Hz. Recent measurements [2–5], however, show a deviation from a power law in the microwave region (see Figure 1). In this paper, we investigate the origin of this deviation and calculate the γ-ray spectrum due to this increase in the microwave photons via the Compton scattering from high-energy electrons.

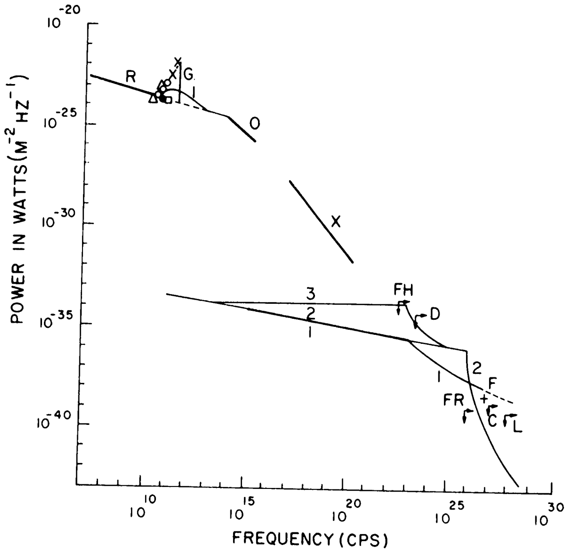

Fig. 1. The electromagnetic spectrum of the Crab Nebula. The thick lines R, O, and X are the observed radio, optical, and X-ray spectra. The symbols around 10^{10} Hz indicate the observations of authors given in references [2–7]. The points with double arrows are upper limits and are integral values as given by Fazio *et al.* [10], Delvaille *et al.* [11], Fazio *et al.* [12], Chudakov *et al.* [13], Long *et al.* [14], and Fegan *et al.* [15]. The various curves are explained in the text. Curve 3 is the present calculation.

The radio spectrum between the frequencies 2×10^7 and 2×10^{10} Hz follows a power law of the form $\nu^{-\alpha}$, with $\alpha=0.28\pm0.05$. Between the frequencies 3×10^{10} and

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3×10^{11}, the new observations indicate $\alpha \simeq -2$. (This change in the exponent is being disputed by Hobbs *et al.* [6] and Oliver *et al.* [7].) In the near-infrared and optical regions ($\nu > 10^{14}$ Hz), $\alpha \sim 0.8$. In the X-ray region, $\alpha \simeq 1$.

The difference in the exponent α between the radio spectrum and the optical spectrum is usually understood in terms of a model where there is continuous injection of electrons and where the electrons lose their energy predominantly by synchrotron radiation. Shklovsky [1] suggests that the change in slope at $\nu \sim 3 \times 10^{10}$ Hz could be due to injection of energetic electrons at the time of the explosion of the supernova; again due to synchrotron radiation, the electrons bunch together at a certain energy. It turns out that this hypothesis does not explain the increase of microwave radiation.

Let us consider the solution of the kinetic equation [8] for the differential energy spectrum of electrons $N(E, t)$, with a burst-injection spectrum at the time of the explosion of the form $KE^{-\gamma}$ (K and γ are constants) and a continuous injection of the term $qE^{-\gamma_1}$ (q and γ_1 are constants). With only the synchrotron radiation as the main energy-loss process, the solution is

$$\begin{aligned} N(E, t) = {} & KE^{-\gamma}(1 - \beta tE)^{\gamma - 2} \\ & + [qE^{-(\gamma_1 + 1)}/\beta(\gamma_1 - 1)]\,[1 - (1 - \beta tE)^{\gamma_1 - 1}]. \end{aligned} \tag{1}$$

Here t is the age of the nebula, and β is a function of the magnetic field H and is given by the equation for synchrotron loss, $(\mathrm{d}E/\mathrm{d}t) = -\beta E^2$. Equation (1) leads to the asymptotic forms

$$N(E, t) = \begin{cases} KE^{-\gamma} + qtE^{-\gamma_1} & \text{for} \quad E \ll 1/\beta t \\ \dfrac{qE^{-(\gamma_1 + 1)}}{\beta(\gamma_1 - 1)} & \text{for} \quad E \gg 1/\beta t. \end{cases} \tag{2}$$

Comparing the asymptotic forms of the synchrotron spectra obtained from Equation (2) with the observed optical and radio spectra and using $H = 3 \times 10^{-4}$ gauss, we obtain K, q, γ, and γ_1. Using these, the actual electron spectrum, we derive $N(E, T)$, where T is the present age of the Crab Nebula. The synchrotron spectrum from this $N(E, T)$ is obtained between 10^{10} Hz and 10^{14} Hz (plotted as curve 1 in Figure 1). We see that such a burst injection is not sufficient to account for the observations. Beckman *et al.* [5] suggest that excess radiation in the microwave region may be due to a cool gas. We fit a Planck spectrum to the observations with the maximum at 1.2 mm (the observation with the highest frequency in the microwave region); the curve is shown as G in Figure 1.

We have calculated the γ-radiation due to the Compton-synchroton process by using the model given by Gould [9] and bearing in mind that the excess microwave photons are not of synchrotron origin. The γ-ray spectrum is plotted as curve 3 in Figure 1, along with the predictions from the calculation of Gould (curve 1) and that by Apparao (curve 2), who calculated the γ-radiation resulting from the Compton scattering of universal microwave photons from the electrons in the Crab Nebula. Selected observations of γ-radiation are also shown in Figure 1; these are the best upper limits. At energies $E_\gamma \geqslant 100$ MeV, the flux predicted is 2×10^{-5} photons/cm^2

sec, while the observed limit of Fazio *et al.* [10] is 3.5×10^{-5} photons/cm^2 sec. At energies $E_\gamma \geqslant 1$ GeV, the flux predicted is in 7×10^{-6} photons/cm^2 sec, which is to be compared with the limit 1.2×10^{-5} photons/cm^2 sec given by Delvaille *et al.* [11].

We conclude that the deviation from a power law of the spectrum of the Crab Nebula in the microwave region cannot be accounted for by the synchrotron process under the usual models. It could be of a thermal origin. If the excess of the microwave photons is due to a thermal gas, an upper limit to the temperature of ~5K is obtained by comparing the experimental upper limits of γ-radiation and the predicted fluxes. Further observations of the microwave spectrum and the γ-ray spectrum in the 100- to 1000-MeV region will throw light on this question.

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