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HIGH-ENERGY PHOTONS FROM THE COMPTON-SYNCHROTRON PROCESS IN THE CRAB NEBULA*

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It is universally believed that the continuum radiation from cosmic radio sources is due to synchrotron radiation by relativistic electrons moving in magnetic fields. Sometimes these synchrotron spectra extend to the optical region and perhaps sometimes to the x-ray region. As Morrison[1] has emphasized, whenever the synchrotron process operates, there will also be the associated process of Compton scattering. An electron of energy γmc^2 moving in a magnetic field radiates characteristic synchrotron photons of energy $\epsilon_S \approx \gamma^2 \hbar \omega_L$, where ω_L is the Larmor frequency. Such a synchrotron photon can then be Compton scattered by another electron of energy $\gamma' mc^2$; this scattered photon will have a characteristic energy[2]

$$\epsilon_{CS} \approx \gamma'^2 \epsilon_S \text{ (for } \gamma' \epsilon_S < mc^2\text{)},$$
$$\epsilon_{CS} \approx \gamma' mc^2 \text{ (for } \gamma' \epsilon_S > mc^2\text{)}. \quad (1)$$

This is a result of the kinematics of the Compton scattering and depends on whether the Compton-scattered electron is relativistic in the rest frame of the electron before scattering. The spectrum from Compton scattering extends to much higher energies than the synchrotron spectrum, and since at these high energies individual photons can be counted, very low photon fluxes can be detected.

One of the most extensively studied (at all photon energies) celestial objects is the Crab Nebula, which is one of the strongest radio sources in the sky. For purposes of comparison with observations at high photon energies, I have computed the Compton-synchrotron spectrum of the Crab on the assumption that there exists therein production of a synchrotron spectrum extending from the radio to the optical to the x-ray region. The assumed synchrotron spectrum consists essentially of two branches S_1 and S_2 as seen in Fig. 1. The radio[3] (R), optical[4] (O), and x-ray[5,6] (X) observations are indicated somewhat schematically by the heavy-lined segments of this curve. While the radio and optical continua of the Crab are undoubtedly due to synchrotron radiation, it has by no means been established that the x rays are produced by this mechanism; nevertheless, it is one of the more likely explanations and

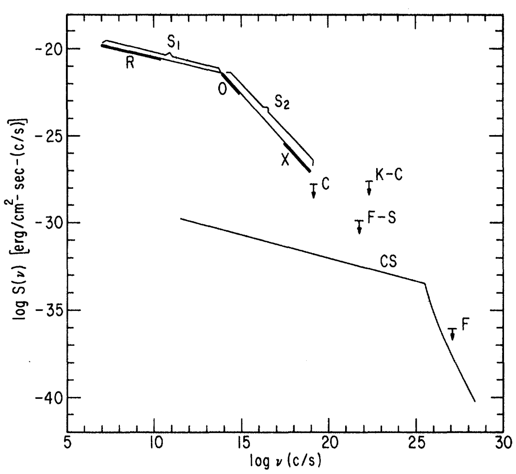

FIG. 1. Synchrotron (S_1 and S_2) and calculated Compton-synchrotron (CS) spectral energy flux from the Crab Nebula. The regions of radio (R), optical (O), and x-ray (X) observations are indicated by the heavy-lined portions of the (assumed) synchrotron spectrum. The results of several upper limit determinations of high-energy photon fluxes are indicated (see text for references). Frequencies between 10^{15} and 10^{17} cps would be unobservable in the spectra due to interstellar absorption.

is adopted here. Actually, the observable part of the spectrum S_2 would not contain frequencies between 10^{15} and 10^{17} cps which would be removed by interstellar absorption along the path between here and the Crab.

To compute the Compton-synchrotron spectrum, it is necessary to know essentially the spectral densities of synchrotron electrons and photons in the Crab, $n_e(\gamma)d\gamma$ and $n_{ph}(\nu_S)d\nu_S$. The differential Compton-synchrotron flux is then computed from

$$dJ_{CS} = (4\pi d^2)^{-1}\int dV_0 \int n_e(\gamma)d\gamma \times \int n_{ph}(\nu_S)d\nu_S c\, d\sigma_C(\gamma,\nu_S), \quad (2)$$

where d is the distance to the nebula, V_0 is its volume, c is the velocity of light, and $d\sigma_C(\gamma, \nu_S)$ is the differential cross section for the production of a Compton-scattered photon of frequency within $d\nu_C$ in the scattering of a photon of frequency ν_S by an electron of energy γmc^2. The electron and photon spectral densities can be determined from the observed synchrotron spectrum of the nebula, its distance, size, and magnetic field within. On the basis of the radio, optical, and x-ray observations, the following model for the Crab is adopted: Uniform distributions of synchrotron electrons responsible for the spectra S_1 and S_2 exist in concentric spheres of angular diameters $\theta_1 = 2R_1/d = 4'$ and $\theta_2 = 2R_2/d = 2'$, respectively. The mean times for the escape of synchrotron photons from these regions are $\tau_e \approx R_1/c$ and R_2/c, respectively, and the mean spectral photon densities in these two regions are then approximately $n_{ph}(\nu_S) \approx \tau_e dn_{ph}(\nu_S)/dt$. The photon production rates $dn_{ph}(\nu_S)/dt$ are determined directly from the observed synchrotron radiation spectrum $S(\nu)$ which is of the form $\nu^{-\alpha}$ with $\alpha_1 = 0.27$ and $\alpha_2 = 1.1$ (see Fig. 1). The dependence on the (uncertain) astronomical parameters is then simply $n_{ph} \propto \theta^{-2}$. The synchrotron electron spectrum $n_e(\gamma)$ is also determined directly from the observations, although a value for the magnetic field must be assumed. From the theory of synchrotron radiation, one finds that the electron spectrum corresponding to the above radiation spectrum $S(\nu)$ is of the form $n_e(\gamma) = K_e\gamma^{-(1+2\alpha)}$. The constant K_e may be determined from the intensity of the radiation spectrum, the distance to, size of, and magnetic field in the nebula.[7] In terms of those astronomical parameters, $K_e \propto d^2 V_0^{-1} H^{-(1+\alpha)}$.

Since we have two separate branches of both the synchrotron electron and photon spectra, there are four Compton-synchrotron spectra corresponding to scatterings of the two electron spectra by the two photon spectra. The Compton spectra can be designated by a double index referring to the electron and photon spectra involved in the scattering; thus we have the spectra $C_{e\text{-}ph} = C_{11}$, C_{12}, C_{21}, and C_{22}. In the calculation of these spectra it is necessary to employ the appropriate Compton cross section, which reduces to the Thomson cross section at low energies, while the Klein-Nishina formula must be employed at high energies. The characteristic electron and photon energies where the change-over occurs are related by [see Eq. (1)] $E_e\epsilon_{ph} \sim m^2c^4$. For the calculation of C_{11} the Thomson cross section may be applied; for C_{22} the high-energy limit of the Klein-Nishina formula may be used; for both C_{12} and C_{21} each must be used for appropriate parts of the spectrum. The spectra may then be computed readily with the help of the simplified methods outlined, for example, by Gould and Burbidge.[7] Of great importance is the dependence of the calculated Compton spectrum on the astronomical parameters

$$dJ_C \propto \theta^{-2} H^{-(1+\alpha)}. \quad (3)$$

The angular diameter θ can be determined accurately but the magnetic field is poorly known. I take a value[4] $H = 10^{-4}$ G throughout both volumes 1 and 2. It should be emphasized that the calculated Compton spectrum is independent of the assumed distance to the Crab, which is poorly known.

The results of these calculations are given in Fig. 1 where the spectral energy flux $S(\nu)$ is plotted against frequency; this is the customary way of presenting source spectra in radio astronomy. The observed assumed synchrotron spectrum is shown at the top left, and the calculated total Compton-synchrotron (CS) spectrum is given. For the low-energy portion of the CS spectrum ($\log\nu = 11.5$ to 25.5) most of the contribution is from C_{11}; from $\log\nu = 25.5$ to 26.7, C_{22} dominates, while at higher energies C_{21} is the main contributor. The dependence of the low- and high-frequency extensions of the CS spectrum on magnetic field is $(\nu_C)_{min} \propto H^{-1}$, $(\nu_C)_{max} \propto H^{-1/2}$.

Also indicated in Fig. 1 are several observational upper limits to high-energy photon fluxes: There is a balloon observation by Clark[6]

(C) for photon energies $\epsilon \geqslant 80$ keV, a balloon observation by Frye and Smith[8] (FS) for $\epsilon \geqslant 30$ MeV, satellite observations by Kraushaar and Clark[9] (KC) for $\epsilon \geqslant 100$ MeV, and a ground-based observation by Fruin et al.[10] (F) at ultrahigh energies $\epsilon \geqslant 5\times10^{12}$ eV. The observations at ultra-high energies are performed by measuring light pulses produced in the earth's atmosphere by Cherenkov radiation from high-energy particles produced in showers possibly initiated by photons. Although all of the established upper limit points lie well above the calculated spectrum for the Compton-synchrotron process, refinements of observational techniques in the near future should allow measurements of positive fluxes. In particular, balloon experiments capable of detecting photons of $\epsilon > 100$ MeV are being prepared now for the detection of fluxes as low as 10^{-6} photons/cm^2-sec; future experiments may be able to detect a flux of one-tenth this value. The corresponding expected flux from the CS process in the Crab is 1×10^{-6} photons/cm^2 sec, which should be detectable under such conditions. Further observations at ultrahigh energies are now being performed at the Smithsonian Astrophysical Observatory by G. G. Fazio; these observations are expected to be capable of detecting photons of energy greater than 5×10^{11} eV. The expected flux from the Crab above this energy is about 4×10^{-10} photons/cm^2 sec, a detectable flux. It should be emphasized that Compton photons of this energy would be produced by the optical synchrotron electrons in the Crab which have energies up to about 3×10^{12} eV. Thus, a photon flux of $\epsilon > 5\times10^{11}$ eV is expected from the Crab, independent of whether its synchrotron spectrum extends to the x-ray region.

What significant information could be gained from observation of photons from the Compton-synchrotron process? Since the physical processes are well understood and can be calculated accurately, important astronomical parameters such as the magnetic field in the Crab could be determined from the combined synchrotron and Compton-synchrotron observations. The dependence of the CS spectrum on magnetic field is as shown in Eq. (3).

The Compton-synchrotron process may produce observable high-energy photon fluxes from other astronomical objects. The quasistellar sources in particular are prime subjects for investigation. Unfortunately, little is known about the nature of these objects and their physical state (magnetic field, etc.), so that no reliable estimates can be made of their high-energy photon production rates. However, it may well be that theoretical models of these objects can be put to test by considerations of associated high-energy photon fluxes.[11]

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