An Understanding of the Non-thermal Radiation from the Crab Nebula

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Abstract

The Crab nebula is the most extensively studied supernova remnant, which is powered by its pulsar. The remnant radation is non-thermal in nature measured over 20 decades in energy from radio to high- energy gamma rays. The propagation of electrons in the remnant has been studied in detail and the elecrons in the present epoch could explain the observed radiation over the entire energ domain. It is found that there are two kinds of accelerated spectrum that are required and we discuss some the conseqences.

1. Introduction

Crab is a supernova remnant powered by a pulsar at its center. The steady emission from the nebula is non-thermal in nature and is measured over 20 decades in frequency from about 10^7 to 10^{27} Hz. The spectrum over the first 5 decades is a simple power law with a spectral index, -0.27 ± 0.04 [1]. The spectrum steepens continuously beyond 10^{14} Hz up to about 10^{23} Hz and the spectral shape repeats itself above this freqency. The energy spectrum of electrons, which radiates below 10^{14} Hz, has a power law index $\beta = -1.54$. It is clear from the observation that the electron spectrum beyond this energy continues to steepen. The radiation above 10^{23} Hz is due to inverse-Compton scattering of the black body and synchrotron photons by the same electrons. Knowing the physical processes leading to the non-thermal emission, the spectral shape of electrons giving rise to the observed radiation can be determined [2]. An attempt is made here to examine how the electron spectrum evolved to the present shape and the kinds of accelerated spectrum is required to achieve this.

Propagation of Electrons

When N(E,t) is the number of electrons per GeV in the SN and P(E,t) is the rate of electrons per GeV injected into the nebula at time t, the spectral evolution which includes all energy loss processes can be described by the propagation equation,

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$$\frac{\partial N(E,t)}{\partial t} = \frac{\partial}{\partial E}\left\{N(E,t)\frac{dE}{dt}\right\} - \int_0^1 \left[N(E,t) + N(\frac{E}{1-v},t)\right]\,\psi_{rad}(v)\,dv + P(E,t) \quad (1)$$

where, the first term on the RHS is the energy loss term and the integral term is for the Bremsstrahlung process. In this investigation, synchrotron, inverse Compton and adiabatic processes were used at all energies, and ionization loss in an ionized medium was considered at low energies.

The energy loss term are not properly considered in the past studies. This term is $\frac{\partial}{\partial E}\left\{N(E,t)\frac{dE}{dt}\right\} = N(E)\frac{\partial}{\partial E}\left[\frac{dE}{dt}\right] + \left(\frac{dE}{dt}\right)\frac{\partial}{\partial E}\left[N(E)\right]$. If the spectrum can be represented by a power law over a small energy region at E, then for synchrotron radiation, which is the dominant energy loss in the nebula during evolution, the above expression becomes $\frac{\partial}{\partial E}\left\{N(E,t)\frac{dE}{dt}\right\} = 3.753\times10^{-6}N(E)\,(2.0+\beta)\,\langle B_\perp\rangle^2\,E$ particles/GeV/s. Here, the magnetic field is in Gauss and E in GeV. It can be noticed that when $\beta > -2.0$, the energy loss does not deplete the specrum because more electrons from higher energies come into the energy bin than those leave to lower energies. In the case of Crab, it becomes obvious that there should be a high energy cut-off in the acceleated spectrum in order that the spectrum steepens continuously due to propagation.

2. Evolution of Crab Nebula

It is generally believed that Crab nebula is powered by the pulsar at the center and its evolution has been studied in detail by many authors e.g[3]. These calculations carefully deal with the dynamic evolution of the supernova (SN)remnant under different models, and include the role of shocks in the distribution of relativistic particles. In principle, one needs to solve simultaneously these dynamical equations along with equation (1) which is very difficult. However, what one requires for the evolution of elecrons is the the mean magnetic field, the radius and velocity of the expanding SN with time. These are not available explicitly from such treatments. Therefore, for simplicity, we assume the SN expansion to be determined by the initial explosion in a uniform ISM. For the Crab nebula, it is sufficient to consider Phase I and II, characterized by the free expansion and adiabatic phases.

The initial explosive energy was taken to be $E_0 = 10^{50}$ ergs, an ejected mass of $M_0 = 2M_\odot$ expanding in a medium of $n_H = 3\,atom/cm^3$ with the normal ISM composition. It is usually assumed that in Phase I, the expansion velocity is constant untill the swept-up mass $M \geq M_0$. The fact that the total kinetic energy in the expanding envelope is equal to E_0, one can obtain the radius and velocity of expansion as a function of time by solving simultaneously the equations $dR(t) = v(t)\,dt \quad (2a), \quad dM(t) = 1.526\times10^{-56}\,n_H\,R^2(t)\,dR(t) \quad (2b) \quad and \quad dv(t) =$

$1.0 \times 10^9\, E_0^{0.5}[M_0 + M(t)]^{1.5}\, dM(t)$ (2c). Here, velocity is expressed in cm/s, radius in cm, mass in $M_\odot$ and E_0 in 10^{51} ergs.

In the case of Phase II, R(t) and v(t) are given by the relations, $R(t) = 9.65 \times 10^{14}\,(E_0/n_H)^{0.2}\, t^{0.4}$ (3a) *and* $v(t) = 0.4\, R(t)/t$ (3b). The pulsar luminosity at time t is $L(t) = L(0)/(1 + t/\tau)^{\alpha}$, where L(0) is the initial luminosity, the characteristic breaking time $\tau \approx 300$ yr and $\alpha = 2.3$, which is related to the breaking torque. If one assumes that the ratio of the magnetic luminosity to electron luminosity $L_m/L_e = k$, the evolution of the magnetic field can be obtained from the relation, $dB^2(t)/dt = 6\,[k\, L(t)/(k+1)]/R^3(t) - B^2(t)\,[v(t)/R(t)]$ (4).

3. Synchrotron and Inverse Compton Spectra from the Crab

In order to solve Eqn.1 as a function of time, one also requires two types of injection spectra for Es. The first one is consistent with the radio spectral index and the second one is steeper. Both are given below; the first one was obtained by equating the total energy with L$e(t)$.

$$P_1(E,t) = A\left[\frac{L(t)}{(1+k)}\right](2.0+\beta)\left[E_{c1}\,\frac{L(t)}{L(0)}\right]^{-(2+\beta_1)} E^{-\beta} exp\left[-E\,\frac{L(0)}{E_{c1}\,L(t)}\right] \quad (5)$$

$$P_2(E,t) = A\left[\frac{L(t)}{(1+k)}\right]\left[1.0 - \frac{L(t)}{L(0)}\right](E_L + E)^{-\beta_2}\, exp(-E/E_{c2}) \quad (6)$$

Here, A $= 6.242 \times 10^6\, particles/GeV/s$, L$(t)$ is in 10^{40} ergs/s and E in GeV. The evolution of Es was obtained by solving Eqn.1 with the help of equations 2 to 6. The inverse Compton loss with the synchrotron photons was included, which covers both Thompson and Klein-Nishina regimes [4]. This contributes much larger than that with black body (BB) photons, especially in the early stages. Using the spectrum of Es and mean magnetic field, the synchrotron spectrum in the remnant was calculated for the present epoch from $10^7 to 10^{24}$ Hz. The calculated spectrum is shown in Fig.1 by the solid curve S along with the measurements (from the compilation [4,5]). One can see a good fit to the data upto a few times 10^{22} Hz. The evolved electron spectra are shown in Fig.2; the 1st component by the dashed Curve A, the 2nd component by the dash-dotted curve B and the total spectrum by the solid curve C. The first component steepens sharply beyond a few hundred GeV and the second component beyond 10^4 GeV.

The inverse Compton spectra resulting from the interaction of the same Es are shown in Fig.1, with BB photons (dotted curve Cb) and synchrotron photons (dashed curve Cs). They were evaluated using cross-sections, which cover both the Thompson and Klein-Nishina regimes [6]. The shape of the dotted curve is similar to the synchrotron spectrum as the BB photons have a peak in its spectrum. Compton spectrum from the synchrotron photons dominates at all energies upto a few times 10^{27} Hz. The total spectrum is shown by the solid curve T and one can see a very good fit to the entire data over 20 decades of energy.

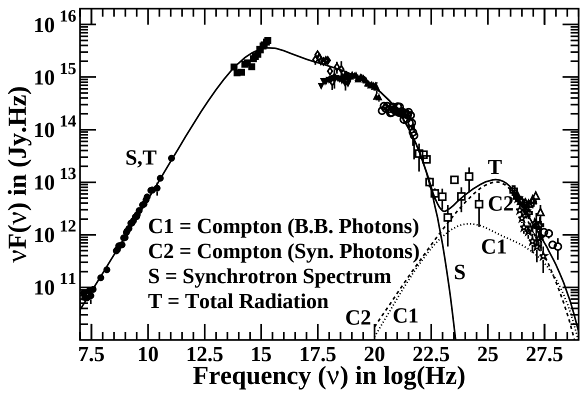

Fig. 1. The calculated radiation is compared with the observation.

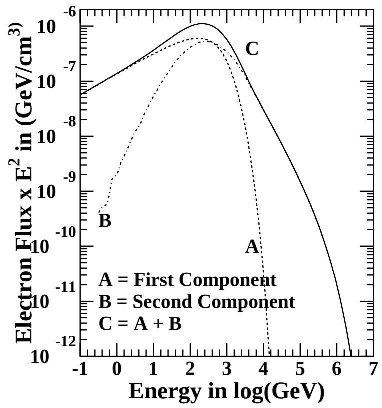

Fig. 2. Electron spectra from different components.

4. Discussion

We have used 1.1×10^{39} ergs as as the initial pulsar lumnsity and the ratio of magnetic to particle energies is 10. The evolved Es spectrum at the present epoch in Fig.2 shows that the spectrum steepens only beyond 100 GeV. This can be compared to the requirement that the injection spectrum of primary shoul have a specral index of about -1.54 upto 5 GeV, which steepens by about one power beyond this energy [4,7]. This can be achieved by incorporating proper variation of the relative contributions of the components with time from the present epoch till the nebula becomes part of the ISM. However, it is very important to find a mechanism by which both these components are dominated by negative electrons.

5. References

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