Cosmic rays and gamma-rays from the pulsar in Cyg OB2

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Abstract

We argue that the gamma-ray sources observed in the direction of the Cyg OB2 association are due to a single pulsar created a few 10^4 yrs ago. The excess of cosmic rays at $\sim 10^{18}$ eV from the direction of the Cygnus region can be caused by neutrons which are produced by nuclei in collisions with the matter of the high density region of the Cyg OB2. The nuclei have been injected by the young pulsar and captured in dense core of the Cyg OB2.

1. Introduction

The Cygnus OB2 association has the mass of $\sim 3.3 \times 10^5$ $M_\odot$, and the diameter of ~ 60 pc. It contains $\sim 120 \pm 20$ O type stars [8,4], which should evolve in a few 10^6 yrs and explode as supernovae creating very fast pulsars. The EGRET telescope discovered a few sources in a field of view containing the Cyg OB2: 2EG J2033+4112, GeV J2035+4214, GRO J2034+4203, 3EG J2033+4118 (see for review [4]). Recently, the HEGRA group has reported the discovery of an unidentified, steady, and extended TeV source close to the error box of 3EG J2033+4118 [1]. The X-ray observations of Cyg OB 2 from the ROSAT and Chandra telescopes [4,9] showed that none of the several X-ray sources in the region with $\sim 11'$ diameter around the TeV source was particularly prominent [4]. However, weak diffuse X-ray emission has also been observed [4]. This is more than ten times as bright as the sum of all the point-like sources. Recent analysis of the arrival directions of cosmic rays with energies of $\sim 10^{18}$ eV by the AGASA group shows the excess of EHE particles which can be related to the Cyg OB2 association.

2. A model

We assume that a very energetic pulsar can accelerate heavy nuclei to energies equal to a significant part, χ, of the total potential drop through the pulsar polar cap region with the efficiency corresponding to the Goldreich & Julian current at the light cylinder radius [2]. The equilibrium spectra of nuclei inside the pulsar wind nebula (PWNa) at an arbitrary time are obtained by

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pp. 2365–2368 ©2003 by Universal Academy Press, Inc.

integrating their injection spectra over the activity period of the pulsar, and taking into account different processes such as: (1) inelastic collisions of nuclei with the matter (important at an early phase); (2) adiabatic energy losses of particles due to the expansion of the nebula; and (3) escape of nuclei from the nebula (see [2]). Relativistic heavy nuclei can also transfer part of their energy, ξ, to relativistic positrons in the process of resonant scattering in the region above the pulsar wind shock [7,5], accelerating them to the power law spectrum with the index ~ 2, between $m_{\rm e}c^2\gamma_{\rm Fe}$ and $\gamma_{\rm Fe}m_{\rm Fe}c^2/Z$, where $\gamma_{\rm Fe}$ is the Lorentz factor of injected nuclei, and $m_{\rm Fe}$ and $m_{\rm e}$ are masses of the iron nucleus and the positron. The equilibrium spectra of positrons inside the nebula at an arbitrary time are calculated by taking into account their radiation energy losses on bremsstrahlung, synchrotron, and inverse Compton (IC) processes, and the adiabatic losses caused by the expansion of the nebula [3]. When calculating the IC energy losses of leptons, we also consider other possible radiation fields inside the nebula like the infrared and optical radiation fields, apart from the synchrotron photons produced by these same population of leptons and the microwave background radiation (MBR). To describe self-consistently all the observed radiation processes from the direction of the Cyg OB2, we postulate that the pulsar was born with the initial period $P_0 = 2$ ms and the surface magnetic field $B = 6 \times 10^{12}$ at about $t = 2 \times 10^4$ yrs ago, within or close to the dense core of the Cyg OB2 association. If this pulsar loses energy mainly on emission of electromagnetic radiation, its present period should be ~ 210 ms. A pulsar with such parameters belongs to the group of so called Vela type pulsars.

3. High energy radiation

The GeV γ-ray emission of 3EG J2033+4118 resembles the spectra of the middle aged pulsars (the break at ~ 1 GeV and the sharp cut-off at a few tens of GeV). We suggest that this γ-ray source is caused by a yet undiscovered Vela type pulsar within the Cyg OB2 association. Fig. 1 shows the spectra of the Vela pulsar (V), after its re-normalization from the Vela distance (500 pc) to the Cyg OB2 distance (~ 1.7 kpc), and the PSR 1706-44 (P), which is at a similar distance as the Cyg OB2. The present parameters of the pulsar inside the Cyg OB2 should be ~ 210 ms, for the surface magnetic field 6×10^{12} G and initial period 2 ms. We incourage the searches of such order of periodicity in the γ-ray data of the source 3EG J2033+4118.

In terms of the hadronic-leptonic model [3], we calculate the synchrotron and the IC spectra produced by leptons, and the γ-ray spectra from decay of pions, produced in the interactions of nuclei with the matter inside the nebula. These γ-ray spectra emitted 2×10^4 yrs after supernova explosion are shown in Fig. 1. When calculating the γ-rays from leptons, we consider different possible soft photon targets inside the nebula: (1) only the MBR; (2) the MBR with

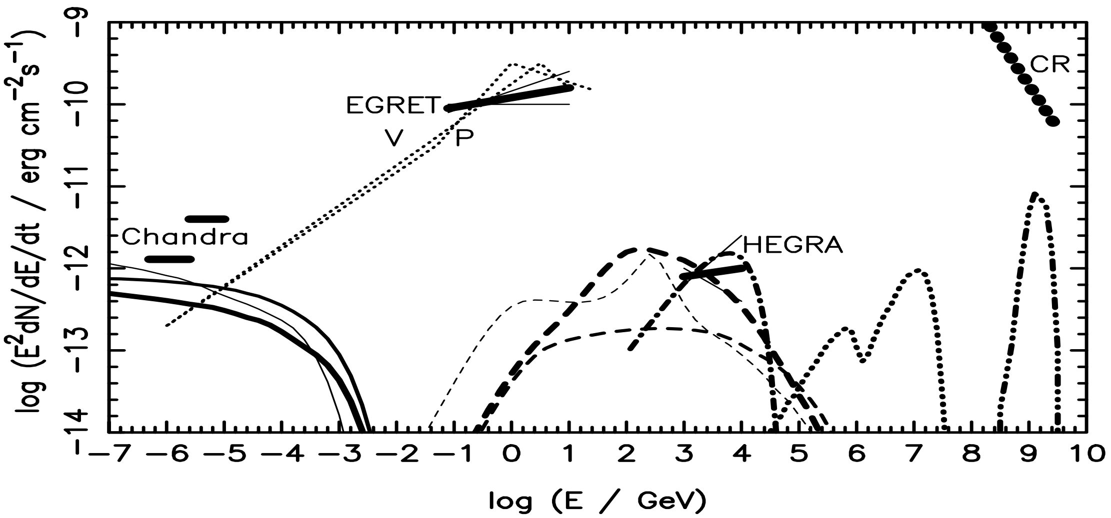

Fig. 1. The spectrum of the Cyg OB2: the diffuse X-ray emission (Chandra), the EGRET source 3EG J2033+4118, the TeV HEGRA source. The cosmic ray flux is marked by the filled circles. The spectra of the Vela pulsar (V) and PSR 1706-44 (P) (thin dotted curves). The synchrotron and IC spectrum from the nebula for different targets of soft photons inside the nebula: (1) only the MBR and synchrotron photons (middle dashed curve); (2) additional infrared photons from the nebula (thick dashed); and (3) additional optical photons from massive stars in the Cyg OB2 (thin dashed). The spectrum of γ-rays from collisions of hadrons with the matter inside the nebula is shown by the dot-dashed curve. The spectra of neutrons and γ-rays, produced in hadronic collisions of nuclei captured in the Cyg OB2, are shown by the dot-dot-dot-dashed and thick dotted curves.

additional infrared photons produced by the gas inside or around the nebula; (3) the MBR with additional optical photons from the massive stars ($\sim 10^{51}$ optical photons s^{-1} [8]). The efficiency of lepton acceleration by the nuclei has to be equal to $\xi = 0.01$, in order to be consistent with the X-ray observations. The level of expected γ-ray emission is consistent with the flux reported by the HEGRA group (Fig. 1).

The pulsar with the above initial parameters can generate electric potentials in which nuclei can be accelerated above $\sim 10^{18}$ eV per nucleon. Nuclei injected inside the nebula at the time, $t_{\rm acc}$, escape from it at the time, $t_{\rm esc}$, if their diffusion distance, $R_{\rm dif}$, in the magnetic field of the nebula is equal to the dimension of the nebula, $R_{\rm Neb}$, at the time $t_{\rm esc}$. The diffusion of nuclei through the nebula is determined by the diffusion coefficient, $D_{\rm dif} = (cR_L/3)^{1/2}$, where $R_L = E_{Fe}/eZB$ is the Larmor radius of nuclei, B is the magnetic field inside the nebula. The distance travelled by the nuclei is then obtained by integration over the time from the moment of injection up to the escape, $R_{\rm dif} = \int_{t_{\rm acc}}^{t_{\rm esc}} \sqrt{\frac{3D}{2t'}} dt'$ (see for details [2]). The condition, $R_{\rm dif} = R_{\rm Neb}$, allows us to determine the moment when nuclei with different energies and injection time escape from the nebula.

We consider the situation in which the pulsar is formed inside or close to the high density regions of the Cyg OB2. The nuclei, which escaped into the galactic medium (the magnetic field of $\sim 5 \times 10^{-6}$ G), have the Larmor radii of ~ 200 pc ($\gamma_{\rm Fe} = 10^9$), and during 2×10^4 yrs diffuse up to $R_{\rm dif}^{\rm ISM} \sim 600$ pc from the Cyg OB2. We expect that a part of these nuclei can be captured by dense regions of the Cyg OB2 for $\sim 10^4$ years. In fact, the magnetic fields in dense molecular clouds are much stronger than in the Galactic medium, and can reach the values of $\sim 10^{-4} - 10^{-3}$ G. In such magnetic fields, the Larmor radius and the diffusion distance of nuclei with the Lorentz factors $\sim 10^9$ are ~ 10 pc and ~ 140 pc during the time of 2×10^4 years. These distances are close to the radius of the central core in the Cyg OB2 estimated on $R_{\rm OB2} \sim 15$ pc (its diameter of the equal to ~ 60 pc). Since the pulsar is close to the Cyg OB2, then up to $(R_{\rm OB2}/R_{\rm dif}^{\rm ISM})^{-3} \approx 10^{-5}$ of all injected nuclei can be captured by the nearby Cyg OB2. We calculate the flux of neutrons and γ-rays produced in collisions of nuclei with the matter inside the Cyg OB2 (Fig. 1). The average density of matter in the Cyg OB2 is estimated at ~ 300 cm^{-3}, for the core radius of the Cyg OB2 equal to 15 pc and its total mass of $\sim 10^5$ M$_\odot$. Interestingly, this neutron flux is consistent with the excess of cosmic ray events at energies $\sim 10^{18}$ eV, reported from the Cygnus region by the AGASA group, equal to $\sim 8\%$ of the cosmic ray flux [6].

The muon neutrino event rate in a 1 km^2 detector during a 1 yr observation, produced by hadrons in a high density medium of the Cyg OB2, is estimated from ~ 0.14 events (direction close to the horizon) to ~ 0.05 (from the Nadir direction). The neutrino event rate produced by hadrons inside the PWNa is estimated on ~ 0.48 [2]. Since the neutrino neutrino event rate from the PWNa is below the atmospheric neutrino background, we do not predict detectable fluxes of neutrinos from the Cyg OB2.

4. References

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