COMPACT GALACTIC SOURCES OF COSMIC RADIATION* **

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Pulsars are considered as possible sources of high energy cosmic ray particles, in particular UHECR. We discuss physical processes in pulsar vicinity relevant to the problem of acceleration of high energy particles. Empirical information on pulsar emission is briefly reviewed. The Crab Nebula is discussed as a template for pulsar wind nebulae. The pulsar wind models are presented with particular emphasis on their acceleration capabilities. The hypothesis that a population of neutron stars with the highest magnetic fields (magnetars) in nearby galaxies are the sources of UHECR above the GZK cutoff is discussed.

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1. Introduction

Results of cosmic ray experiments strongly suggest the presence of UHECR above the GZK limit in the cosmic ray flux. There were many scenarios of the origin of such particles presented at this conference already. Most of them focused on particle physics models. However, one should not disregard astrophysical solutions as there are very many compact sources located in galaxies within 50 Mpc which could produce extremely energetic particles. Here we discuss rapidly rotating pulsars with ultra-strong magnetic field as most powerful particle accelerators which could produce the UHECR flux above the GZK cutoff.

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A lesson of the history of identifying the sources of γ-ray bursts should be kept in mind. Before discovery of the first afterglow which allowed the firm identification of the GRB source theoretical models of particle physics origin prevailed. Now GRB are thought to be associated with some supernovae and no new particle physics idea is needed to explain this phenomenon.

In the following we briefly summarize the basic astrophysical information regarding pulsars and their role as powerful cosmic ray accelerators. We will not present detailed fitting of the UHECR spectrum with this kind of model. Recently Arons [1] showed that the flux of UHECR from rapidly rotating pulsars with ultra-strong magnetic fields in Metagalaxy can nicely fit the data and we refer for details to his paper [1]. In the next section basic information on pulsar emission is given. In Sect. 3 we briefly review properties of the Crab Nebula. The pulsar wind models are presented in Sect. 4 and neutron stars with ultra-strong magnetic fields are discussed in Sect. 5. Conclusions are given in Sect. 6.

2. Pulsar emission

Pulsars are rotating magnetized neutron stars, first discovered by Bell and Hewish at radio wavelengths. Neutron stars are produced at the supernova explosion, an event that ends the evolution of massive stars. Neutron stars are born rapidly rotating with strong magnetic fields. The pulsar energy output is at the expense of kinetic energy of rotation, this implies that the rotation should be slowing down.

Standard radio-pulsars have rotation periods $P \sim 10$ ms–1 s, their spin-down rates are $\dot{P} \sim 10^{-11}$–10^{-14} s^{-1}, inferred magnetic fields are of the order of $B \sim 10^{12}$ G. The mass of the neutron star is usually not known, but in a few cases of binary systems it is measured to be about $M \sim 1.4 M_{\odot}$.

Spin-down luminosity is

$$\dot{E} \equiv \dot{E}_{\rm rot} = I\omega\dot{\omega} \sim 10^{35}\text{–}10^{39}\ \mathrm{erg\ s^{-1}}\,.$$

This is a semi-directly measured quantity, as the only non-measured model dependent quantity is the moment of inertia I. It is estimated to be $I \sim 10^{45}\,\mathrm{g\,cm^2}$ from neutron star models. This model dependence of I introduces a systematic error in the measurement of $\dot{E}$.

It is interesting to compare the energy output of pulsars $\dot{E} \sim (10^2$–$10^6)L_{\odot}$ with the luminosity of the brightest stars, which is $L \sim 10^6 L_{\odot}$. One can notice that pulsars dissipate their rotational kinetic energy at a similar rate as the brightest stars cooled by photon emission. Pulsars are thus powerful galactic emission sources, radiating at the expense of rotational energy. This energy is stored in a newborn neutron star at the supernova explosion, hence its real origin is the gravitational energy released at the collapse of the presupernova core. Total rotational energy of a young pulsar is estimated to be $E_{\rm rot} \sim 10^{51}$ erg. The time scale associated with spinning-down is $t_{\rm sp} = E_{\rm rot}/\dot{E}$. For the highest spin-down luminosities, $t_{\rm sp} \sim 10^{12}$ s $= 3000$ y, whereas it is 10^7 y for $\dot{E} = 10^2 L_\odot$.

One should also note that young neutron stars are very hot as they store also a significant amount of internal energy with which they were endowed at the collapse of the progenitor. Hence they cool by thermal neutrino and photon emission at the expense of internal energy, $E_{\rm int}$, that decreases.

Pulsars, first discovered as the radio pulsars, are now known to radiate also at other wavelengths. In fact, pulsars are detected in a broad range of electromagnetic radiation, at radio frequencies, at optical wavelengths, in X-rays and also in γ-rays. For example, Crab and Vela pulsars are detected in all four bands, whereas the Geminga pulsar is prominent in X-rays and in γ-rays. One can thus notice that a given pulsar is not always detected in all bands.

The most striking result is that the total electromagnetic emission is small compared to the pulsar's energy output measured by the spin-down luminosity: $L_{\rm em} \ll \dot{E}$. For example for the Crab pulsar X-ray and γ-ray emission is $L_{\rm X} + L_\gamma \sim 0.1\dot{E}$, and the radio emission is still smaller, $L_{\rm radio} \sim 10^{-8}\dot{E}$. We thus arrive at a somewhat surprising conclusion that the whole electromagnetic emission is in a way a by-product of pulsar's main activity that consumes most of its energy output. This main activity is production and acceleration of plasma. Electromagnetic radiation discussed above is the synchrotron radiation of charged particles produced in the pulsar's vicinity. It just reveals the existence of these particles to an outside observer.

3. Crab Nebula

It is believed that the bulk of spin-down luminosity of pulsars $\dot{E}$ is emitted as a relativistic magnetized wind. The pulsar wind becomes visible when it interacts with some external matter forming in such a case the pulsar wind nebula. Generally, pulsar wind nebulae surround very young pulsars (~ 1000 years) that are still inside their SNR. The pulsar wind is inflating a bubble immersed in the remnant's medium. The bubble is confined by the ambient pressure.

The Crab Nebula is a prototype of pulsar wind nebulae. It is a remnant of the SN 1054. The expanding bubble is observed as a radio, optical, X-ray and γ-ray nebula. The electromagnetic emission at all wavelengths is the synchrotron radiation by relativistic electrons (positrons) originating from the central pulsar. The electromagnetic emission of the nebula is supported by the pulsar's energy output which is partially converted into synchrotron radiation of the nebula. The Crab nebula synchrotron luminosity is a significant fraction of pulsar's spin-down luminosity, about $0.2\dot{E}_{\rm rot}$, exceeding twice the total electromagnetic luminosity of the Crab pulsar. The pulsar also supplies the nebula with the magnetic field which is much higher to be a frozen primordial field in the outflowing matter. This suggests that the pulsar and the nebula are strongly magnetically coupled.

Radio emission traces integrated history of the electrons as it corresponds to long electron lifetime. The radiation at short wavelengths, as X-ray emission, traces the current pulsar state corresponding to short lifetime of electrons. Since the lifetimes of X-ray emitting particles are shorter than the age of the nebula, the high energy particles must be continuously supplied by the pulsar.

The synchrotron spectrum of the Crab nebula is very nicely reproduced by the model of Kennel and Coroniti [2] in the whole range spanning 12 orders of magnitude in the photon frequencies. One can infer particle energies required to produce this spectrum to be in the range from 10 GeV to 3000 TeV.

There is some excess in high energy γ-emission from the Crab nebula above the spectrum from the Kennel and Coroniti model, which is attributed to the inverse Compton scattering of ultra-relativistic electrons on lower energy synchrotron photons (see also Ref. [3]).

From observations and the model of Kennel and Coroniti we find the following properties of the Crab Nebula:

The wind is terminated by a shock at a distance $r_s = 0.1$ pc from the central pulsar. This terminating shock is visible in X-ray images of the Crab pulsar.

The wind transports energy in the form of purely electromagnetic energy and the kinetic energy of the plasma. The wind energy can thus be decomposed into two parts

$$\dot{E} = W_{\text{Poynting}} + W_{\text{kinetic}} \,.$$

The kinetic energy is characterized by the Lorentz γ factor, and the important parameter is the ratio σ of Poynting flux to the kinetic energy of the flow. The Crab Nebula model of Kennel and Coroniti [2] provides a very good fit of the spectrum of the Crab Nebula with $\gamma_{\text{wind}} = 3 \times 10^6$ and

$$\sigma = \frac{W_{\text{Poynting}}}{W_{\text{kinetic}}} = 0.003$$

just before the shock. The wind at the terminating radius $r_s = 0.1$ pc is thus dominated by kinetic energy of plasma with $\gamma \sim 10^6$.

Also older pulsars not associated with SNR show signature of presence of the wind. Such old neutron stars move through the interstellar medium with the velocity of about ~ 500 km s^{-1}. Pulsar's wind generates a bow shock which was observed recently for a nearby neutron star Geminga which is one of the closest pulsars to Earth 500 light years away [4].

4. Pulsar wind models

The idea that pulsar winds are most natural sites of acceleration of cosmic ray particles stems from the fact that the pulsar wind is dominated by Poynting flux at the light cylinder. It is estimated that the value of the parameter σ near the light cylinder is very high, $\sigma \sim 10^4$–10^5 [5]. This is a theoretical result derived in models of pulsar magnetosphere. The basic reason is that in polar cap model only small fraction of 10^{-5} of the polar cap potential is converted into kinetic energy of produced pairs.

The wind near the light cylinder is not directly observed as there is no strong interaction of the wind with the neighbourhood. However, the theory is based on fundamental properties of electrodynamics, thus it seems credible.

We can see that the wind operates in such a way that the Poynting flux is transformed into flux of kinetic energy of particles. At the light cylinder essentially whole emitted energy is in the form of electromagnetic field, $\sigma \gg 1$, whereas at the terminating shock in Crab nebula (and in other pulsar nebulae) the kinetic energy dominates, $\sigma \leq 1$. This is exactly the same principle that governs particle accelerators in high energy labs. Hence pulsars with their winds are natural counterparts of laboratory accelerators, much more than shock waves invoked in Fermi stochastic acceleration mechanisms.

The basic idea of pulsar wind is as follows: Rotating magnetized neutron star generates electromagnetic radiation [6,7]. At the surface of the neutron star rotating with angular frequency Ω, strong electric field is induced,

$$\boldsymbol{E} = c^{-1}\boldsymbol{\Omega} \times \boldsymbol{r} \times \boldsymbol{B} \,.$$

This field injects charged particles and e^+e^- pairs, into the magnetosphere [8,9]. The electromagnetic field accelerates the plasma converting its energy into kinetic energy of the outflowing plasma. This process is sometimes referred to as the Poynting flux acceleration.

Let us start with a historically important model of Gunn and Ostriker [10], which, however, is not realistic in view of our current knowledge, but worth of studying for pedagogical purposes. One considers a magnetic dipole rotating with the frequency Ω. The dipole emits electromagnetic monochromatic spherical waves of frequency Ω. Test particles become tightly coupled to the wave by its strong magnetic field, with a coupling strength $\sim eB(mc\Omega)^{-1} > 10^8$. This strong coupling ensures that particles "ride the wave" at essentially constant phase. In this way particles are very effectively accelerated up to the energy

$$E_c = mc^2 \left[\frac{3}{\sqrt{2}}\frac{eB_0}{mc\Omega}\ln\frac{r_c}{r_0}\right]^{2/3} ,$$

where r_c is the final radius at which the acceleration stops and $r_0 = R_{\rm lc}$ is the radius of the light cylinder. For the Crab nebula the radius of the light cylinder is $r_0 = c\Omega = 1576$ km and the acceleration process ends at the cutoff radius $r_c = r_s = 0.1$ pc. For protons the final energy acquired is $E_c = 1.6\times10^{15}$ eV $\approx 1.6\times10^6 m_p c^2$. This is in a surprisingly good agreement with the result of Crab Nebula models.

The Gunn and Ostriker model is untenable because, unfortunately, pulsars do not radiate strong electromagnetic waves of rotation frequency Ω. This could occur for magnetic moment rotating in a vacuum. Magnetized neutron star, however, cannot rotate in a vacuum as strong electric field pulls the charged particles from the crust to produce extensive magnetosphere. Physics of this magnetosphere turned out to be a tough problem, not fully resolved up to now.

Let us discuss currently most promising models of pulsar winds. The above discussion provides some hints as to the properties of the model. One should seek a mechanism to effectively convert $\dot{E}_{\rm rot}$ into kinetic energy of the wind, employing magnetic field, with $\sigma \gg 1$ near the light cylinder and $\sigma \ll 1$ at a distance $r \sim 0.1$ pc.

The problem of pulsar emission, especially converting the Poynting flux into kinetic energy of the outgoing matter, turned out to be very complex and difficult [11]. However, some recent results of Contopoulos, Kazanas and Fendt [12] show an encouraging progress. These authors have found the first self-consistent solution of the axisymmetric magnetosphere of an aligned rotating magnetic dipole in MHD calculations.

The solution which is numerical displays the following interesting features: Far from the light cylinder, $r\sin\theta \gg R_{\rm lc}$, open field lines approach these of the split-monopole.

The field lines velocity

$$\boldsymbol{v}_E = c\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} = c\left(\hat{r}\frac{x^2}{1+x^2} + \hat{\phi}\frac{x}{1+x^2}\right)$$

with

$$x \equiv \frac{r\sin\theta}{R_{\rm lc}}.$$

The corresponding wind Lorentz factor reads

$$\gamma_E = \left(1 - \left(\frac{v_E}{c}\right)^2\right)^{-1/2} \to \frac{r\sin\theta}{R_{\rm lc}}\,.$$

For $r\sin\theta \gg R_{\rm lc}$ the wind Lorentz factor becomes $\gamma_{\rm wind} \to \gamma_E$. This means that the particles “surf-ride” on the electromagnetic field, with their B-parallel velocity being negligible.

The wind is a linear accelerator, with the velocity $\boldsymbol{v}_E \sim \hat{r}$ in the radial direction and with the Lorentz factor proportional to $r \sin\theta$. The most effective acceleration occurs at the equatorial plane where $\sin\theta = 1$. At large r the plasma does not cross the field lines, hence the radiation losses are negligible.

5. Neutron stars with ultra-strong magnetic fields

The maximum energy particles can acquire in the wind acceleration is [1] determined by the possible potential difference across the magnetosphere and reads

$$E_{\rm max} = 3 \times 10^{22} \frac{\mu}{10^{33}} \left(\frac{\Omega}{10^4 {\rm s}^{-1}} \right)^2 {\rm eV}\,.$$

Here μ is the neutron star magnetic moment (in cgs units). For the Crab pulsar we have the magnetic $B = 10^{12}$ G and the period $P = 0.033$ s and the maximum available energy is $E_{\rm max} = 6 \times 10^{18}$ eV.

High values of μ, $\mu_{33} \sim 1$, are obtained only for ultra-strong magnetic field $B > 10^{14}$ G. Hence the maximum energies of the order of $\sim 10^{21}$ eV corresponding to the most energetic particles observed by cosmic ray experiments, are obtained only for ultra-strong magnetic fields, $B \sim 10^{14}$ G and very fast rotation of neutron star $\Omega = 10^4$ s^{-1} which corresponds to a sub-millisecond period $P = 0.63$ ms. Neutron stars with such strong magnetic fields are referred to as magnetars. Rapid rotation with such a short period as above is still safely below the centrifugal disruption limit of a neutron star.

Let us discuss, as a final point, observations regarding the pulsars with very high magnetic fields which are thought to be the most promising sources of UHECR. At present we know a few classes of fast rotating neutron stars with ultra-strong magnetic fields

(a) Magnetars in Soft Gamma Repeaters (SGR) [13]: There are 4 sources confirmed with magnetic field $B \sim 10^{14}$ G and rotating now with periods $\sim$ 5–10 s. Extrapolating back in time we estimate that they probably were born with short periods ~ 1 ms.

(b) Anomalous X-ray Pulsars (AXP) [14]: similar magnetic fields and periods as magnetars (possibly the same class of neutron stars), do not display γ-ray bursts. There are 6 known (and some candidates).

(c) Radio pulsars with magnetar field [15]. This is very recent discovery in Parkes Pulsar Survey. There are 2 known with magnetic field $B = 10^{14}$ G and periods $P = 3$ s, 6 s.

6. Conclusions

One should conclude that the existence of slowly rotating magnetars and pulsars with ultra-strong magnetic fields suggests they were rapidly rotating in the past, possibly with submillisecond periods. In such a case they could produce particles in the 10^{21} eV range. Spectrum of such particles would not show the GZK cutoff if they are coming from galaxies within 50 Mpc. As pulsars are very common objects, the final stage of every massive star evolution, they should be seriously considered as sources of UHECR that do not suffer the GZK cutoff. Arons [1] considered a population of pulsars in nearby galaxies and concluded that magnetars are the prime astrophysical candidate for local sources of UHECR.

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