Reports of Enlarged Session of the
Seminar of I. Vekua Institute
of Applied Mathematics
Volume 29, 2015

ON THE NOVEL MECHANISM OF ACCELERATION OF COSMIC PARTICLES

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Abstract. A novel model of particle acceleration in the rotating magnetospheres of active galactic nuclei (AGN) and pulsars is constructed. The particle energies may be boosted up to enormous energies in a several step mechanism. In the first stage, the Langmuir waves are centrifugally excited and amplified by means of a parametric process that efficiently pumps rotational energy to excite electrostatic fields. By considering the pulsars it is shown that the Langmuir waves very soon Landau damp on the relativistic electrons already present in a magnetosphere. It has been found that the process is so efficient that no energy losses might affect the mechanism of particle acceleration. Applying typical parameters for young pulsars we have shown that by means of this process the electrons might achieve energies of the order of 10^{18} eV. The situation in AGN magnetospheres is slightly different. In the second stage, the process of "Langmuir collapse" develops, creating appropriate conditions for transferring electric energy to boost up already high proton energies to much higher values. As in the previous case, one can show that various energy losses are relatively weak, and do not impose any significant constraints on maximum achievable proton energies of the order of 10^{21} eV.

Keywords and phrases: Particle acceleration, cosmic rays, High energy astrophysics.

AMS subject classification: 85A30, 76Y05.

Introduction. It is observationally evident that energies of cosmic rays (CR) range from several GeV, to thousands of EeV, therefore the major question concerns the origin of such enormous energies. Generally speaking it is strongly believed that Gamma ray bursts (GRB), AGN and pulsars might be responsible for high and ultra-high energy (UHE) CRs. In this context one of the puzzling and enigmatic problems, is a concrete mechanism that provides efficient acceleration. In the last century Fermi has proposed a mechanism (Fermi acceleration) [1], that in most of the astrophysical scenarios works very well. Although, acceleration of leptons might encounter serious problems concerning pre-acceleration [2-3] and in certain cases it is necessary to find alternative ways of acceleration.

It is worth noting that AGN and pulsars have rapidly rotating magnetospheres that potentially might significantly influence dynamics of charged particles. For typical AGN with mass $M_8 \equiv M/(10^8 M_\odot)$ ($M_\odot \approx 2\times 10^{33} g$ is the solar mass) the equipartition magnetic field is of the order of

$$B \approx \sqrt{\frac{2L}{r^2 c}} \approx 27.5 \times \left(\frac{L}{10^{42} erg/s}\right)^{1/2} \times \frac{R_{lc}}{r} G, \tag{1}$$

where L is the bolometric luminosity of AGN, $R_{lc} = c/\Omega$ is the light cylinder radius, r is the distance from the black hole and we have taken into account that the angular velocity of rotation of the AGN magnetosphere is given by

$$\Omega \approx \frac{ac^3}{GM} \approx 10^{-3}\frac{a}{M_8} rad/s^2. \tag{2}$$

Generally speaking, magnetic field is thought to be huge if its energy density exceeds that of plasmas

$$\frac{B^2}{8\pi} > n\epsilon. \tag{3}$$

where n is the particle number density and ϵ is energy of a single particle. From the above expression it is clear that in AGN magnetospheres corotation of particles takes place up to $\epsilon \approx 700$GeV.

Similarly, by taking into account the magnetic field of pulsars close to the light cylinder area

$$B \approx 3.2 \times 10^6 \times \left(\frac{P}{1s}\right)^{1/2} \times \left(\frac{\dot{P}}{10^{-15}ss^{-1}}\right)^{1/2} G, \tag{4}$$

and the Goldreich-Julian number density of electrons, $n_{GJ} = B/Pce$, where P is the pulsar period, c is the speed of light and e is the electron's charge, one can straightforwardly show that condition of corotation (see Eq. (3)) is satisfied for a broad range of energies.

Direct centrifugal acceleration. We see that corotation is maintained up to the light cylinder surface in the magnetospheres of AGN and pulsars. Therefore, it is interesting to estimate efficiency of a centrifugal mechanism developed in [4]. In particular, in [2] and [5] we have studied efficiency of centrifugal acceleration in the magnetospheres of AGN and pulsars respectively. Dynamics has been studied for electrons "sliding" along corotating straight magnetic field lines inclined with respect to the rotation axis. It has been shown that the Lorentz factors behave as to be

$$\gamma = \frac{\gamma_0}{1 - \frac{r^2}{R_{lc}^2}}, \tag{5}$$

where γ_0 is the initial Lorentz factor of the electron. It is clear from the above equation that on the light cylinder it behaves asymptotically, indicating the existence of certain limiting factors. In general one can show that acceleration lasts until the particle encounters a soft photon, limiting the maximum attainable energy (Inverse Compton (IC) mechanism) [2]

$$\gamma_{IC} \approx \left(\frac{6\pi m_e c^4}{\sigma_T L\Omega}\right)^2, \tag{6}$$

where $m_e \approx 9,1 \times 10^{-27}$g is electron's mass, L is the bolometric luminosity of a source and $\sigma_T \approx 6.65 \times 10^{-25}$cm^{-2} is the Thomson cross-section. Another mechanism that potentially might limit the maximum energies of electrons is the so called Breakdown of the bead on the wire (BBW) approximation, leading to the following upper limit [2]

$$\gamma_{BBW} \approx \frac{1}{c}\left(\frac{e^2 L}{2m_e}\right)^{1/3}. \tag{7}$$

It is clear that the real maximum attainable Lorentz factor should satisfy the condition $\gamma = min\{\gamma_{IC}, \gamma_{BBW}\}$, which For AGN leads to the maximum energy of the order of 20TeV [2] and in case of Crab-like pulsars the value is even less 1TeV [5].

As we see direct centrifugal acceleration has limits and cannot explain ultra-high energies of cosmic rays.

Acceleration via damping of centrifugally excited Langmuir waves. In this section we consider a slightly moderate mechanism of acceleration. In particular, in [6,7] we have shown that rotation energy might be very efficiently pumped into that of Langmuir waves. On the next stage, under certain conditions, energy of electrostatic modes might be converted into energy of plasma particles.

In this approach magnetospheric plasmas are considered to be composed of two species: relatively low energy particles and high energy particles. The process is governed by the system of equations: Euler equation, continuity equation and Poisson equation, which after Fourier transforming in time lead to the "dispersion relation" of the centrifugally excited electrostatic modes [8]

$$\omega^2 - \omega_1^2 - \omega_2^2 J_0^2(b) = \omega_2^2 \sum_{\mu} J_{\mu}^2(b) \frac{\omega^2}{(\omega - \mu\Omega)^2}, \tag{8}$$

where $\omega_{1,2} \equiv \sqrt{4\eta\pi e^2 n_{1,2}/m_{1,2}\gamma_{1,2}^3}$ are the relativistic plasma frequencies, $\gamma_{1,2}$ are the Lorentz factors, $m_{1,2}$ - masses for the corresponding components respectively, $b = 2ck \sin\phi$, ϕ is half of the phase difference between different species, $J_{\mu}(x)$ is the Bessel function of the first kind and $\eta = 1$ for electron-proton plasmas and $\eta = 2$ for electron-positron plasmas. The growth rate of the instability is given by

$$\Gamma = \frac{\sqrt{3}}{2} \left(\frac{\omega_1 {\omega_2}^2}{2}\right)^{\frac{1}{3}} J_{\mu_{res}}(b)^{\frac{2}{3}}, \tag{9}$$

where $\mu_{res} \equiv \omega_1/\Omega$. For typical values of magnetospheric parameters of AGN: $\gamma_1 \sim 10^6$, $\gamma_2 \sim 10^3$ one can straightforwardly show that $1/\Gamma$ is less than the kinematic timescale, $2\pi/\Omega$. The similar situation is found in the case of pulsars, indicating that the energy pumping from rotation into Langmuir waves is extremely efficient.

For these waves to effectively transfer their energy to particles, the waves phase velocity must be close to the speed of light. Further, in the vicinity of υ_{ph}, there should be more particles a little slower than the wave than particles which are a little faster . For the given problem it is always possible to situate υ_{ph} in the desired part of the primary beam spectrum. Since the distribution function decreases with the Lorentz factor, the number of electrons with $\upsilon_b < \upsilon_{ph}$ exceeds that of the electrons with $\upsilon_b > \upsilon_{ph}$, where υ_b denotes the electron speed. Thus the optimum conditions for effective Landau damping will pertain.

It has been shown that the total energy gained by the beam electrons in magnetospheres of pulsars is given by [9]

$$\epsilon \approx \frac{n_1 F \delta r}{n_{GJ}}, \tag{10}$$

where $\delta r \sim c/\Gamma$, $F \approx 2m_e c\Omega\xi(r)^{-3}$, $\xi(r) = (1 - \Omega^2 r^2/c^2)^{1/2}$. It has been shown that the Crab-like pulsars might provide with energies of the order 400TeV, whereas in the magnetospheres of newly born millisecond pulsars electrons might be accelerated up to 10^{18}eV.

Since the AGN magnetospheres are predominantly composed of protons and electrons, it has been found that the efficient Langmuir collapse develops after centrifugally inducing electrostatic waves. This process leads to even higher accumulation of energy, finally transformed to energy of protons via the Landau damping. The corresponding expression of proton energy is given by

$$\epsilon_p\,(eV) \approx 2 \times 10^{20} \times \left(\frac{10^2}{\gamma_2}\right)^5 \times M_8^{-5/2} \times L_{43}^{5/2}, \tag{11}$$

where $L_{43} \equiv L/10^{43}$erg/s is the dimensioneless luminosity of AGN. As it is clear the present mechanism can explain energies of cosmic rays. Therefore, it would be interesting to further develop our model to apply for neutrino astrophysics.

Acknowledgment. The research was partially supported by the Shota Rustaveli National Science Foundation grant (N31/49).

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Received 22.05.2015; revised 12.11.2015; accepted 18.12.2015.

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