THE TIME DELAY OF EXTRAGALACTIC COSMIC RAYS IN THE GALACTIC MAGNETIC FIELD

A. A. Elyiv, B. I. Hnatyk

Astronomical Observatory of the Taras Shevchenko
Kyiv National University, Kyiv, Ukraine
e-mail: elyiv@observ.univ.kiev.ua

ABSTRACT. We investigate the propagation of extragalactic cosmic rays (ECRs) in the regular component of the Galactic magnetic field. Especially we numerically calculate the expected time delay of ECRs due to curvature of trajectories. The maps of time delay depending on energy and arrival directions of ECRs have been constructed. We show that regular component of Galactic magnetic field increases the time delay up to 700 kyr for low-energy part ($E \geq 3 \times 10^{17} \, eV$) of ECRs. This value is noticeably larger than the expected time delay in a random (turbulent) component of the Galactic magnetic field. Both regular and turbulent components of Galactic magnetic field do not modify considerably ECR flux and spectrum at energy $E \geq 10^{18} \, eV$.

Keywords: cosmic rays: general – Galaxy: magnetic fields.

1. Introduction

Transition from Galactic to extragalactic component in total flux of cosmic rays is still a point at issue (Berezinskii et al., 1990; Berezinskii et al., 2004). As it is argued in (Berezinskii et al., 2004) extragalactic cosmic rays (ECRs) are expected to dominate in the total flux of cosmic rays at energy $E \geq 1 \times 10^{18} \, eV$ and are comprised predominantly of protons. Galactic and extragalactic magnetic fields affect the trajectories and propagation time of ECRs and can considerably change the total flux and spectrum of ECRs (Sigl et al., 2004; Parizot, 2004). For example, it is expected that the random extragalactic magnetic field and both regular and random components of Galactic magnetic field considerably increase the time-in-flight of low energy part of ECRs outside and inside Galaxy - up to the energy loss time scale, which can result in suppressing of ECR flux (low-cut filter (Parizot, 2004)). In our work we analyse the influence of the Galactic magnetic field on the time delay of ECRs. For symmetric and asymmetric models of regular component of the Galactic magnetic field (Han&Qiao, 1994; Sofue&Fujimoto, 1983; Tinyakov&Tkachev, 2002) we numerically calculate the maps of time delay

depending on energy and arrival directions of ECRs. We estimate also the time delay created by random (turbulent) component of the Galactic magnetic field and show that both regular and turbulent components of the Galactic magnetic field do not modify considerably ECR flux and spectrum at energy $E \geq 10^{18} \, eV$.

2. The Galactic magnetic field model

Galactic magnetic field consists of a regular and a random (turbulent) components. Both components have similar amplitudes ($B_{reg} \approx 3 \times 10^{-6} \, G$ and $B_{tur} \approx 5 \times 10^{-6} \, G$ for regular and random component respectively), but different scales. Basic scale of turbulent magnetic field is of order of $l_c \sim 100 \, pc$. For regular magnetic field we use model proposed in (Tinyakov&Tkachev, 2002), in which regular component traces the spiral structure, reversing (bisymmetric model) or not (axisymmetric model) field direction between spiral arms. Radial and transverse (toroidal) field components are $B_r = B(r,\theta)\sin(p)$ and $B_\theta = B(r,\theta)\cos(p)$, respectively, where $p = -8°$ is the pitch angle of the local magnetic field,

$$B(r,\theta) = B(r) \times \cos(\theta - \beta \times \ln((r/R) + \phi)),$$

$\beta = 1/\tan(p)$, $\phi = \beta\ln(1 + d/R) - \pi/2$, $B(r) = B_0 R/(r\cos(\phi))$, $R = 8.5 \, kpc$ is the distance from the Galactic center to the Sun, $B_0 = 1.4 \, \mu G$ is the strength of magnetic field near the Sun, $d = -0.5 \, kpc$ is the distance from the Sun to the position of the first field reversal (in direction to the Galactic center).

Following (Tinyakov&Tkachev, 2002) we consider bisymmetric model with halo (magnetic field extends up to $R_{max} = 20 \, kpc$ from Galactic center) with two possibilities for halo field: symmetric model with parallel fields above and below the disk

$$B_{sym}(r,\theta,z) = B(r,\theta) \times \exp\left(-\frac{|z|}{h}\right),$$

and asymmetric one with anti-parallel fields: $B_{asym}(r,\theta,z) = sign(z) \times B_{sym}(r,\theta,z)$, where $h = 1.5 \, kpc$ is the height scale of the disk.
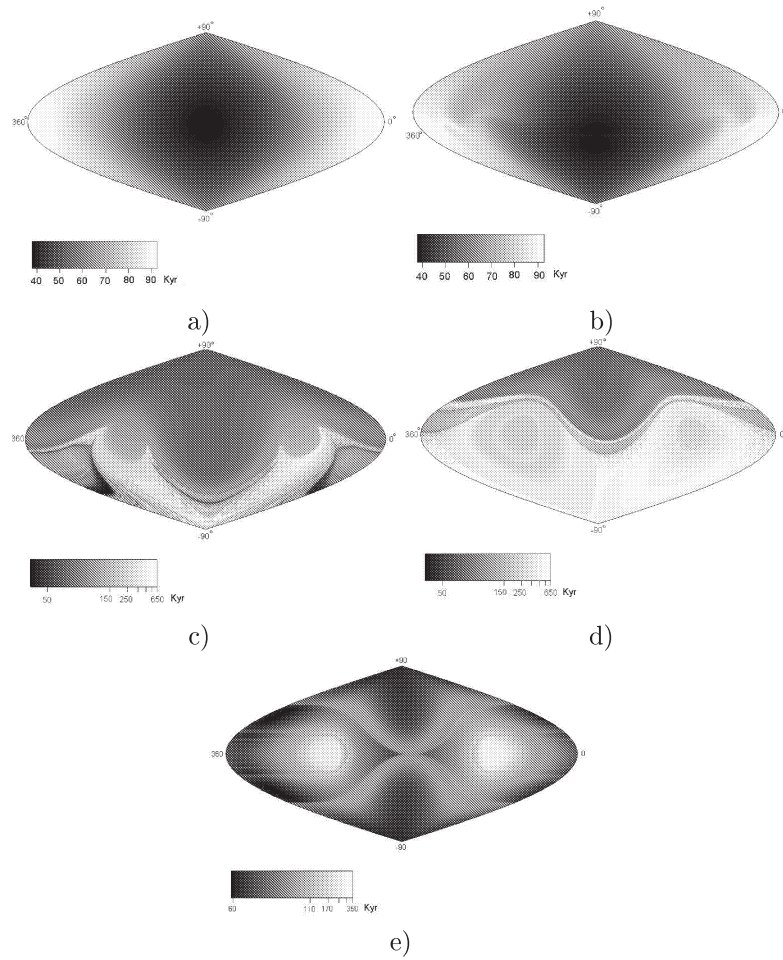
Figure 1: The propagation time maps for cosmic rays with energy $10^{20}\,eV$ (a), $10^{19}\,eV$ (b), $10^{18}\,eV$ (c), $3 \times 10^{17}\,eV$ (d) in the symmetric magnetic field and with energy $3 \times 10^{17}\,eV$ in the asymmetric magnetic field (e).

3. The maps of the propagation time

We assume that extragalactic cosmic rays are protons (Berezinskii et al., 1990; Berezinskii et al., 2004). If we eject from Earth an antiproton (a particle with the proton mass but with opposite to proton electric charge) in arrival direction of proton from ECR flux, antiproton will restore the original proton trajectory.

Therefore, we eject antiprotons with certain energy in the all possible directions from the Earth, and calculate trajectories and the propagation time of antiprotons from Earth to the edge of the Galactic magnetic field (and vice versa for cosmic ray protons).

In Fig.1(a) we show the propagation time for protons with energy $E = 10^{20}\, eV$. As the distance from Earth to the Galactic center is 8.5 kpc, the propagation time changes in the range from 37 to 93 kyr. Due to the fact that at such a high energy protons move practically rectilinearly, the time delay (as a difference between propagation time for proton and photon for given direction) in this case is practically absent.

With decreasing of energy of ECRs the propagation time increases (Fig.1(b-e)) and reaches a saturation for 10^{17}eV - 10^{18}eV at a maximum value of order of 650 kyr, i.e., the maximum value of time delay is $T_{max} \sim 600\, kyr$. The main reason for the limited value of time delay is the regular character of the Galactic magnetic field considered.

4. Turbulent component of the magnetic field

Larmor radius $r_L = E/eB_{tur}$ of ECR proton with energy $E \geq 3 \times 10^{17}\, eV$ in magnetic field $B_{tur} = 5 \times 10^{-6}\, G$ is considerably larger than basic scale of turbulent magnetic field $l_c = 100\, pc$. Therefore, penetrating in the turbulent Galactic magnetic field ECRs move initially quasi-rectilinearly with the random small-angle scattering, resulting in the r.m.s. deflection angle θ over a distance r (Sigl et al., 2004)

$$\theta \sim 40°(\frac{E}{10^{18}\, eV})^{-1}(\frac{r}{1\, kpc})^{1/2}$$

and the time delay

$$\tau \sim 0.38(\frac{E}{10^{18}\, eV})^{-2}(\frac{r}{1\, kpc})^2\, kyr$$

For all directions out of Galactic plane ECRs with $E \geq 10^{18}\, eV$ can penetrate Galactic disk and reach Earth in ballistic regime without considerable flux suppression. The transition to diffusive regime takes place at distances where $\theta \sim \pi$ or $r_{dif} \geq 2\, kpc$ at energy $E \geq 3 \times 10^{17}\, eV$. Since $r_{dif} \geq h$, diffusive regime does not affect considerably the time delay of ECRs.

To summarise, both regular and turbulent components of the Galactic magnetic field do not modify considerably ECR flux and spectrum at energy $E \geq 10^{18}\, eV$.

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