SH 4.3.12

Modulation effect on ACR observed at GEOTAIL satellite

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Abstract

Anomalous cosmic rays (ACRs) are thought to be accelerated at the termination shock of solar wind. So, ACR also modulated as same as galactic cosmic rays (GCRs) after acceleration. The modulation effect on cosmic rays is known to be basically described by Parker(1965)'s transport equation. We simulate the energy spectra of ACR and GCR oxygen by using of the steady state, spherically symmetric model and compare with the observation made by GEOTAIL satellite at 1AU in 1994 and 1995. In this report, it shows that this model describes the modulation effect on GCR oxygen but does not describe sufficiently the modulation effect on ACR oxygen.

1 Introduction:

The anomalous cosmic rays are thought to be originated from interstellar neutrals which are ionized by UV radiation from the sun or charge exchange between the solar wind. After ionization, they are conveyed into the outer heliosphere and accelerated at the termination shock of the solar wind (see review, e.g. Simpson, 1995). From this point of view, observed ACRs at the inner heliosphere are modulated as same as GCRs though the magnitude of solar modulation is different from that of GCRs with same energy because of the difference of charge state.

The modulation effect on cosmic rays was described first by Parker (1965) using the well-known transport equation. Recently, many studies have been reported which applied Parker's transport equation to the observation made by many spacecraft such as Voyager1,2, Pioneer10,11, Ulysses etc (e.g. McDonald, et. al.,1992, Reinecke, et al.,1993,1996, Steenberg and Moraal,1996). Observations have been made at near the Earth, in the deep-space or at high heliographic latitude. These data are useful to understand the solar modulation in the heliosphere.

In this paper, we apply the steady state, spherically symmetric model to the observation of oxygen, both of ACR and GCR, made by GEOTAIL satellite at 1AU.

2 Data and the Model:

The data to simulate the spectra were observed by MI1 and HI telescope on board GEOTAIL satellite in 1994 and 1995. We chose only the quiet time to reject the particle from the sun because that data include no information about charge state of particles. And we treat the data as a mixture of ACR and GCR components.

We use the steady state, spherically symmetric model to simulate the observed cosmic ray spectra. In this model, the cosmic ray number density $U\,(r,T)$ satisfies a Fokker-Planck equation

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 VU\right)-\frac{1}{3}\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 V\right)\right]\left[\frac{\partial}{\partial T}\left(\alpha TU\right)\right]=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial U}{\partial r}\right)$$

Here r is the radial distance from the Sun, T is the kinetic energy of particle, $\kappa(r,T)$ is the radial diffusion coefficient, V is the solar wind speed and $\alpha(T) = (T+2T_0)/(T+T_0)$ using T_0 as the rest energy of particle. We assume the uniform solar wind speed V=540 km/s for 1994 and V=430 km/s for 1995 which are determined by IMP observation. The radial density gradient is zero at the sun as the inner boundary condition. In such model, the modulation is determined by the radial diffusion coefficient which contains components of parallel ($\kappa_{//}$) and perpendicular ($\kappa_{\perp}$) to the field lines. κ is described as

$$\kappa = \kappa_{//} \cos^2 \psi + \kappa_{\perp} \sin^2 \psi$$

$$\kappa_{//} = \kappa_0 \beta \mathrm{K}_P B_e / 3B$$

$$\kappa_{\perp} = \kappa_{\perp 0} \kappa_{//}$$

Where B_e is magnetic field at the Earth, β is relative particle speed to light. Parameter ψ is spiral angle of the IMF and is given by $tan\psi=(\Omega r/V)$ using Ω as the angular speed of the sun. The magnitude of the standard Parker spiral magnetic field is given by $B = B_e/v2\ r^2\cos\psi$. κ_0 is constant which is decided as a best fit parameter. K_P is a function of particle rigidity P and its description is given by

$$\mathrm{K}_P = \begin{cases} P & (P \geq 0.4) \\ 0.4 & (P < 0.4) \end{cases}$$

On assuming these parameters, we basically follow Potgieter et al. (1992). And we set the ratio $\kappa_{\perp}/\kappa_{//}$ = 0.009.

To solving the partial differential equation, we must specify the unmodulated spectrum at the modulation boundary. We chose the modulation boundary at 100AU and assume that unmodulated spectrum of GCR oxygen is described by a power-law in total energy, $U_0=A(T+T_0)^{-2.65}$. The constant A is chosen to fit with observational data at 100GeV/n (e.g. Grunsfeld et al.1988, Simon et al.,1980, Orth et al.,1978) under assumption that cosmic rays are not modulated in this energy region and the energy spectra are stable year by year. The differential intensity corresponding to the unmodulated differential number density is $j_0=vU_0/4\pi$. The fitting result is shown in Figure 1.

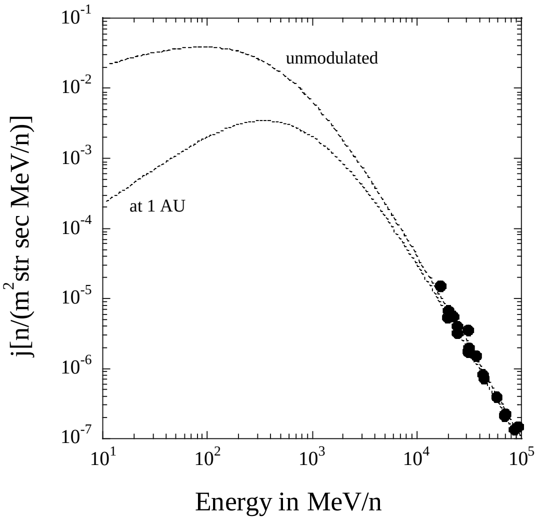

Figure 1: Energy spectra of GCR oxygen at modulation boundary and 1 AU fitted to the observed data (Grunsfeld et al.1988, Simon et al.,1980, Orth et al.,1978) described by solid circle.

We must also specify the unmodulated spectrum of ACR oxygen. ACR is thought to be accelerated at the termination shock of the solar wind. For the strong shock, it is obtained an accelerated spectrum of $j \propto p^{-2}$ with a steep roll-off at higher energy (Potgieter and Moraal,1988). We select the roll-off energy 240 MeV per charge (Jokipii, 1990) . In this report, we simulate the singly charged ACR oxygen. So, corresponding roll-off energy is 15 MeV/n.

3 Model calculation:

The results of model calculation are shown in fig.2. It seems natural to use same κ_0 for ACR and GCR. κ_0 were chosen as 1.0 x 10^{23} $cm^2s^{-1}GV^{-1}$ for 1994 and 1.2 x 10^{23} $cm^2s^{-1}GV^{-1}$ for 1995. It can be seen that sum of the ACR and GCR spectra at 1AU (notified by “s-1”, “a-1”, “g-1”, respectively) is fitted well above the energy of ~20 MeV/n. But below that energy, data keep increasing as a power-law with decreasing energy though simulated spectrum is becoming flat.

It has been reported that ACRs are multiply ionized (e.g. Mewalt et al. 1996) and that multiply charged ACRs are dominant above a energy of ~20 MeV/n (Jokipii, 1996). The sum of energy spectra is affected mainly by q=1 and q=8 spectra for anomalous oxygen. So, we should simulate with, at least, mixture of singly and fully charged anomalous oxygen. But it seems that the source spectrum of singly charged component must be steeper than that we used even if ACR is treated as a mixture of singly and multiply charged particles. Because that q>1 components are dominant in higher energy region.

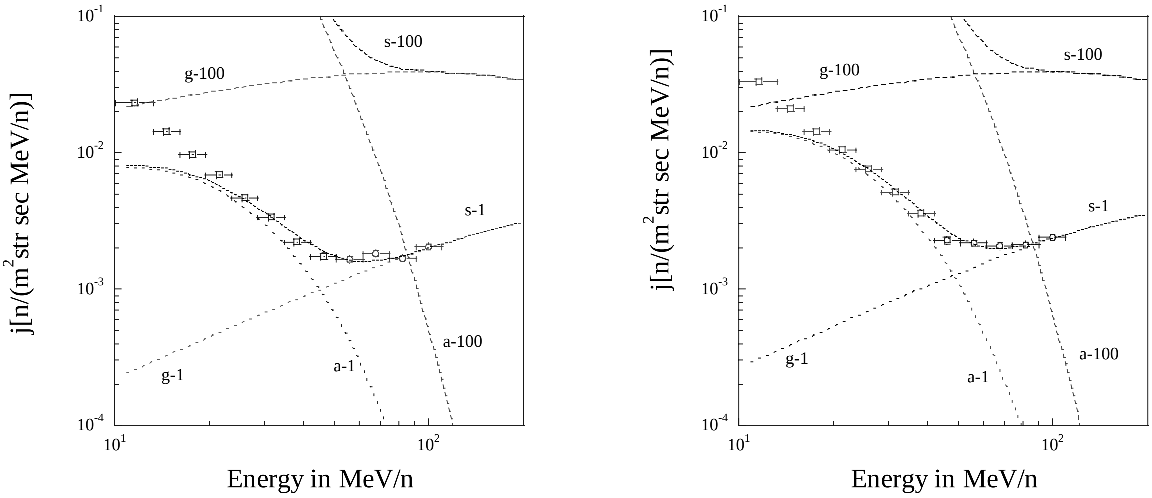

Figure 2: Results of model calculation comparing to the observation of oxygen for 1994 (left) and 1995 (right). Simulated spectra does not describe the observation in low energy region in which ACR component is dominant. “a-1”, “a-100”, ”g-1”, “g-100”, “s-1” and “s-100” notify ACR, GCR, sum at 1AU and 100AU, respectively.

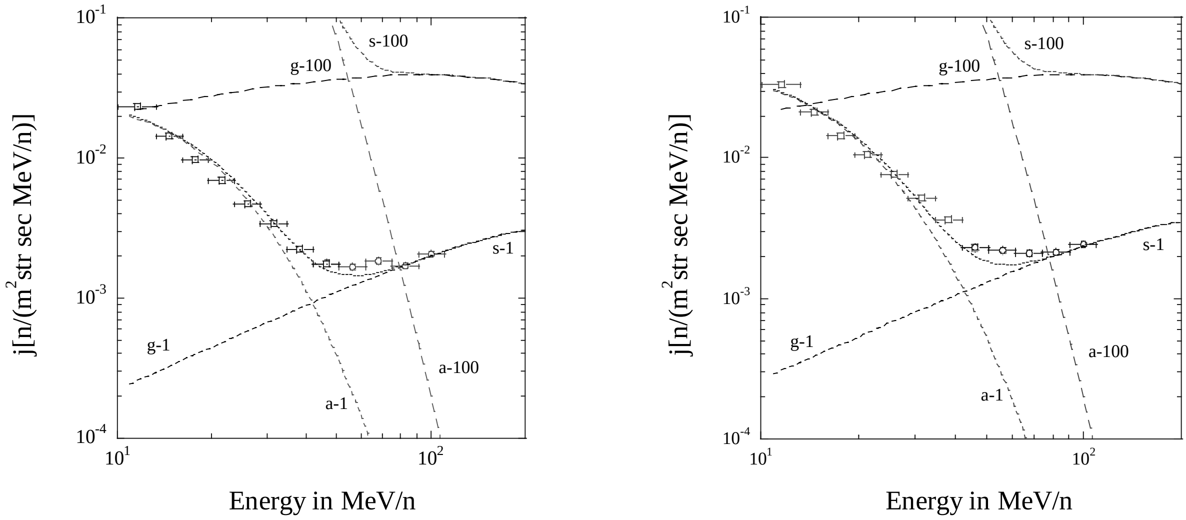

Figure 3: Same as fig.2. The model with lower roll-off energy is applied to the observation. Calculated curve seems to be fitted to the observation for both year (left : 1994, right : 1995).

Simulated spectra using the model with lower roll-off energy are shown in Figure 3. The value of roll-off energy has no meaning. This just has the same effect as using the steeper spectrum. In this figure, we can see a good agreement with observation in all energy range. Possibly, it suggest the necessity to assume the detailed source spectrum taking account of an acceleration model. For example, ACR at the termination shock has a power-law spectrum but its curvature cutoff energy is different at different latitude. In this case, it is needed to apply the two-dimensional (r,θ) model to this observation.

At the same time, it is also needed to check the possibility that observed data contains oxygen which is solar origin or which is accelerated in the inner heliospere, at the interplanetary shock, for example. The comparison with other observations and test for other component are necessary.

This result is not enough to say something sufficiently because we have compared only with the observation of oxygen. It is the next step to compare to the others using this model and also using other models.

The satellite is operated by many staffs. We thank all staffs who have operated GEOTAIL satellite.

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