PARTICLE ACCELERATION AND TRANSPORT IN HELIOSPHERE

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Abstract: Gradual solar energetic particle (SEP) events is a major space hazard. In these events, energetic particles (protons and heavy ions) are accelerated at propagating CME-driven shocks, reaching energies as high as 1 GeV/nucleon. Understanding the acceleration and transport of these particles in the inner heliosphere is an active research in space physics. Observationally, a tremendous amount of data (including those of remote sensing such as X-ray, gamma-ray, white light, UV, radio observations and those of in-situ measurements such as particle composition, time intensity profiles and particle spectra) has been accumulated over the past several decades. However, modeling efforts have been lacking behind. Recently, we have developed a Particle Acceleration and Transport in Heliosphere (PATH) code, where particle acceleration at the shock and subsequent transport is followed numerically. By following single particle motion, quantities such as time intensity profiles, particle spectra, and other observables like Fe/O ratio and particle anisotropy can be obtained naturally from the model. In this work, we discuss our model and compare our model calculations with several individual events. These model calculations are very helpful in interpreting observations of particle data obtained in-situ at 1 AU.

Introduction

It is now commonly accepted that gradual Solar energetic particle (SEP) events are caused by CME-driven shocks. We believe what happens in a gradual SEP event is that hugh amount of coronal material gets ejected out (i.e. coronal mass ejection) from the Sun and propagates out at a substantial high speed $\sim 500 - 2000$ km/s. In front of the CME, a shock forms and particles are accelerated at the shock front via first order Fermi acceleration mechanism. Various in-situ observations now exist supporting the above picture. These include from earlier missions ISEE 3, GOES, IMP-8 and very recently Ulysses, WIND and ACE. With these observations, we can now collect particle data for numerous heavy ions across a broad range of energies. Information on particle time intensity profile, particle spectrum and composition are now obtained to a very good time and energy resolution for almost every single SEP event.

Besides these in-situ measurements, there are also complementary remote-sensing observations. These observations include 1) gamma ray lines and X-ray spectrum by e.g. RHESSI and Yoko, 2) radio waves by various radio observatories, and 3) white light coronograph and Ultra Violet Spectroscopy by e.g. SOHO. Studying these remote signals allow us to obtain a better understanding of the dynamical environment where the particle acceleration prcoess occurs.

For any given SEP event, these remote observations can be regarded as the initial condition of a complicate particle acceleration and transport process while the in-situ observations the result of this process at 1 AU. To link these observations, a model is needed in between. To make reasonable comparisons with observations, this model should at least have a module to follow closely the shock propagation (including track the shock parameters such as shock speed, compression ratio, etc from the Sun to 1 AU) and other modules to follow the injection, acceleration and escape of particles at the shock front as well as the subsequent transport when the energized particles escape from the shock front. Needless to say these requirements will innevitablely make a successful model very sophisticate and one can be easily bewildered by the sophistications introduced to the model through various considerations. While a sophisticate model seems innetitable to model individual SEP events, the sophistication however, come in two flavors. In the first, there is the complication from "event variability" – every CME is launched into a unique enviroment where the solar wind speed, composition, turbulence level etc differ very much from one to another.

Certainly, this "event variability" sophistication makes modeling individual event a very time-consuming practice since one need to fine-tuning the model inputs on a event by event basis. In contrast to this sophistication, the other sophistication has to do with the fact that too many physical processes are interwined in the course of particle acceleration and transport. These processes often have different time scales, for example, acceleration time scale τ_{acc}, shock propagation time scale t_{sh}, escaping time scale t_{esc} etc. During the shock propagation, these processes may take turn to become the dominate process and often the observed characteristics of an SEP event is decided by the balance of some of these processes. This sophistication is certainly different from that of the first kind. It has to do more on capturing as much as possible and as much as accurate the underlying physics and incorporate them to the model. Simply ignore or neglect some of these processes will almost surely yield an incomplete understanding of SEP events. Of course, to obtain a manageable and tractable model, certain assumptions and simplifications of these processes are necessary. These must be, however, well justified.

PATH code and a case study

We have developed a numerical model called PATH (Particle Acceleration and Transport in the Heliosphere) to study particle acceleration at a propagating CME and subsequent transport in inner heliosphere. The model consists of two major parts. The first part uses a ZEUS MHD code in simulation solar wind and a propagating CME shock. The shock is modelled as a series of shells propagating out from the Sun. At the shock front, the compression ratio and shock velocity are followed as they change with radial distance. Particle acceleration at the shock front is treated by taking the instantateous solution of the transport equation in the immediate vicinity of the shock at various time steps. By means of the shell approach, we can follow particle acceleration, diffusion and cooling in terms of shells. Particles convect with a shell and can diffuse to other shells. The solar wind suprathermal particles (or some pre-existing seed particles) are injected into the shock (the outermost shell) at a certain injection energy. The total injected particles and the injection energy are parameters which can be adjusted. Immediately upstream of a shock, enhanced levels of magnetic turbulence for the DSA mechanism are required. We suppose that for a quasi-parallel shock, this enhancement is due to steaming protons which amplify the upstream turbulence (in the form of Alfvén waves) which in turn suppresses the streaming current. A wave-particle interaction between the streaming protons and the upstream Alfvén waves yields the value of a parallel diffusion coeffient [2, 1, 6] [1]. By scattering on the MHD turbulence, suprathermal particles return to and cross the shock repeatedly, gaining energy at each cycle. The second part of the code treats energetic particle transport throughout the inner heliosphere (from 0.1 to > 1 AU) using a Monte-Calo simulation. By following single particle motion, the time intensity profiles and particle spectra are obtained. For a detailed description of the PATH model, readers are referred to [8], [6] and [4, 5]. One of the new features of the PATH model is its ability to adjust to the background solar wind parameters to model the values observed at 1AU for a particular event. This feature is achieved by setting the solar wind density, velocity, magnetic field and thermal energy at 0.1 AU through extrapolation of these values observed at 1AU.

Using PATH code, we have performed a case study for the April 21st, 2001 event and found good agreements between the modeled time intensity profiles and those from observations [3] . Here we report another case study. This is an event occurred on Spetember 29, 2001. We choose this event because it is a quasi-parallel shock at 1 AU (c.f. MIT shock database maintained by J. Kasper, the aver-

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[1] Heavy ions are treated in a way similar to the protons but are assumed to behave like test particles which means that they do not generate waves.

age angle between the shock normal and the background magnetic field is estimated as $\sim 19°$). We are particularly interested in quasi-parallel shock in this study. The shock reached 1 AU with a speed of $\sim 700 km/sec$ at 9:10 on 29 September 2001. The compression ratio was $s \sim 2.3$. Prior to the arrival of the shock, a partial halo CME with a speed of 1109 km/s was observed by SOHO/LASCO at 04:54:05 on 27 September 2001 (from the LASCO CME catalogue). From 04:32 to 04:38 on 27 September 2001, x-rays were also observed in the active region 9628, located at S20W27, by GOES.

In [7], we estimated that the shock reaches 1 AU in ~ 50 hours. Three elements are modelled. These are proton, CNO and Fe. For CNO and Fe particles, the charge to mass ratios are 14:56 and 6:16 respectively. We consider here only the event-integrated spectra of these three elements. These are plotted in figure 1, figure 2 and figure 3. The observational data are also plotted as triangles in the figures.

Note the remarkable agreements between observations and modeling results for all three species. In particular the spectral shapes for all three specifies possess a "double power- law" structure with the break in energy ordered approximately by $(Q/A)^2$, as predicted by [5] for a parallel shock. A spectrum showing broken power law may seem contradictary to the underlying diffusive shock acceleration theory as the latter predicts only strict power laws at any given time at the shock front. However, as the shock propagates out and weakens, the maximum energy accelerated at the shock decreases with time, the net result is to have an event-integrated spectrum showing a break or roll-over at high energies. That the proton, Fe, and O modelled spectra simultaneously agree so well with observations is remarkable. These suggest the shock identified in this study is very likely to be parallel throughout its propagation from the Sun to 1 AU. We note here that by comparing the modelled spectra with observations for different heavy ion species, we can examine the validity of our assumption that this event is quasi-parallel.

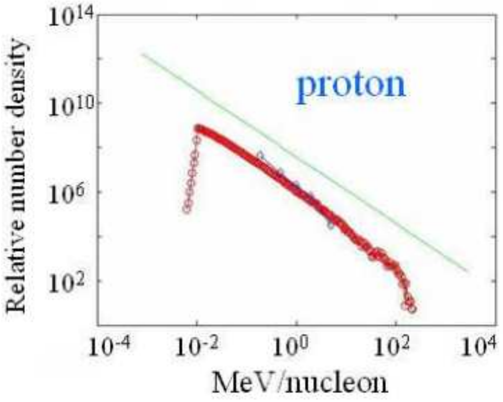

Figure 1: Spectra for proton from simulation and observation. The blue triangles represent obserations from ULEIS and SIS instrument onboard of ACE spacecraft.

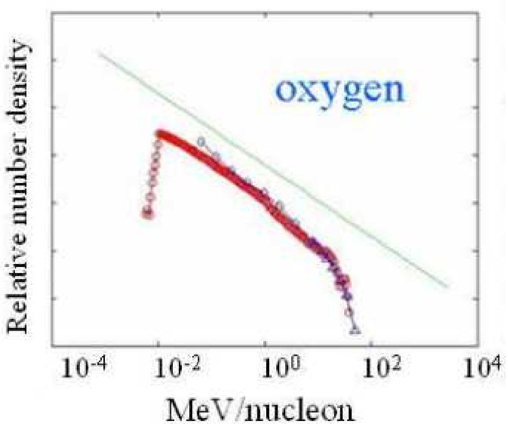

Figure 2: Same as figure 1, but for oxygen.

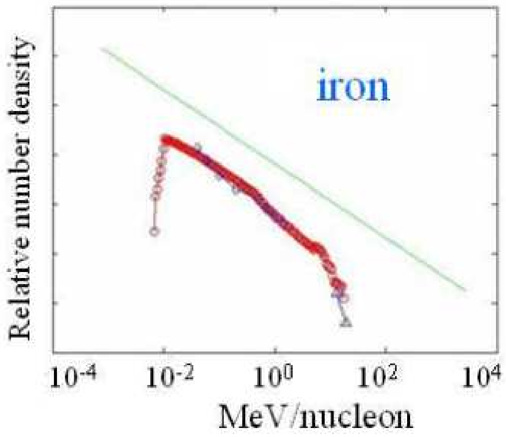

Figure 3: Same as figure 1, but for iron.

Conclusion

We have developed a model, called PATH, to investigate particle acceleration and transport in association with gradual SEP events. The model at its present form, works best for quasi-parallel shocks. The model includes local particle injection, Fermi acceleration at the shock, self-consistent excitation of the waves responsible for scattering, particle trapping and escape at the shock complex, and non-diffusive transport in the interplanetary medium, and does remarkably well in describing observed SEP events. This includes spectra, intensity profiles, and particle anisotropies. We model both proton and heavy ion acceleration and transport in gradual events, and can study simultaneously event integrated spectra for protons, Fe, and O. This allows us to understand the Fe/O ratios, for example.

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