Modeling Relativistic Solar Particles in the Inner Solar System During an Extreme Event

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Abstract: We explore extreme conditions in the inner Solar System’s radiation environment by modeling the transport of SEPs out to the orbit of Jupiter during an extreme solar event. We use state-of-the art simulations of SEP radial transport that incorporate a radial dependence of the pitch-angle scattering mean free path based on computational results regarding solar wind turbulence. We input the SEP spectrum, injection profile, and interplanetary transport conditions as deduced for the large relativistic solar proton event of 2005 Jan 20 from an analysis of data taken by the Spaceship Earth network of polar neutron monitors. We calculate the SEP intensity profiles in interplanetary space at the orbits of Mercury, Venus, Earth, Mars, Ceres, and Jupiter. Partially supported by the Thailand Research Fund and NASA’s Living With a Star program under grant NNX08AQ18G.

Keywords:

1 Introduction

Solar energetic particles (SEPs) can damage instruments on board spacecraft and are a major hazard concern for space crew. SEP event magnitudes vary in an enormously large range, and (although not frequently) in occasions reach extreme conditions. During extreme events, SEP fluxes in space can rise to dangerous levels for extended periods of time. Computational tools that allow accurate predictions of SEP flux are thus crucial for evaluating potential effects of solar storms during space missions. State-of-the-art techniques prove successful to model SEP transport between the Sun and the Earth, but may be less accurate at longer distances. It is thus necessary to improve the computer methods for achieving similar accuracy in calculations to the orbit of Mars and beyond. In order to explore a possible “worst case scenario” it is interesting to apply such computer methods to the estimation of SEP flux during an extreme event. The extreme SEP event of 2005 January 20 had the highest levels of relativistic solar proton flux recorded in 50 years, which makes it a good candidate for a “worst case scenario” of SEP radiation in space.

In this work we revisit a common assumption employed in modeling SEP transport, namely the constancy of the pitch-angle scattering mean free path within the inner Solar System, and the effects of a departure from such assumption at different distances. Then we estimate the fluxes of relativistic solar protons associated to the 2005 January 20 event at different distances from the Sun.

2 Transport model

The evolution of SEP density along one magnetic flux tube with time is computed as the solution of a transport equation that includes all the relevant processes [1]. The transport equation is a Fokker-Planck equation for a distribution function $F$ that depends on time $t$, cosine of pitch-angle $\mu$, distance along the mean magnetic field $z$, and momentum $p$. Pitch-angle scattering is parameterized in a similar way as predicted by quasi-linear scattering theory [2] by introducing a scattering coefficient $q$ and an amplitude related to the mean free path $\lambda$. The shape of the magnetic field line is here assumed to be an Archimedean spiral [3] consistent with some value of the solar wind speed. To model SEP fluxes during 2005 January 20 we also include a compression region, associated to a previous event, which helps explain time evolution of SEP density and anisotropy measured at Earth [4].

We solve the transport equation by means of a finite difference method [1, 5]. Modeling of SEP transport in a similar way has successfully been used in the past to fit neutron monitor data during ground level enhancements [6, 7, 8, 9]. In this work we consider only radial, not transversal, transport. We assume that the magnetic flux tube of interest is well connected with the SEP acceleration site.
2.1 Effect of a radial dependence in the mean free path

A common consensus for SEP transport is that the radial mean free path for pitch-angle scattering, $\lambda_r$, is constant throughout the inner heliosphere [10]. Using a constant $\lambda_r$ as a simplifying assumption gives good results when modeling SEP transport between the Sun and the Earth. However, based on results of magnetohydrodynamical simulations of solar wind turbulence, we would expect a radial dependence of $\lambda_r$ closer to the form: $\lambda_r \propto r^{-1/2}$, where $r$ is distance to the Sun.

In order to explore the effect of either assumption, we first find numerical solutions for SEP transport after an instantaneous injection near the Sun’s surface, assuming that $\lambda_r$ is constant throughout the inner heliosphere and beyond Jupiter’s orbit. We consider radial transport along one interplanetary magnetic field line well connected with the acceleration site. We assume a standard value of the solar wind speed $v_{sw} = 400$ km/s, a value of $\lambda_r$ of 0.27 AU, and a spectral index of magnetic fluctuations $q = 1.5$.

We calculate the expected fluxes as a function of time at Earth’s orbit, the orbit of Mars (1.5 AU), and the orbit of Jupiter (5.2 AU). We then re-calculate the radial transport of SEPs from the Sun to the Earth, to the orbit of Mars, to the orbit of Jupiter, and beyond, by including a radial dependence of $\lambda_r$ of the form $\lambda_r \propto r^{-1/2}$, again taking the local value of $\lambda_r$ at Earth’s orbit to be 0.27 AU.

A comparison of SEP intensities computed in this way with those calculated assuming a constant $\lambda_r$ is shown in Figure 1. Note that the effect of a varying $\lambda_r$ is minor at Earth, as was previously expected, and also at the orbit of Mars, but becomes important at greater distances. This can be explained because, although $\lambda_r$ differs between both assumptions at smaller distances from the Sun as well, the strong effect of magnetic focusing there partially cancels the effects of scattering. At the distance of Jupiter the effect is clearly non-negligible; we find a lower and later peak flux in the profile, and slower decay. Note that at Earth or Mars we estimate that the SEP flux associated to an instantaneous injection remains relatively high for only tens of minutes, while a (relatively) high flux at Jupiter can last more than one day.

3 The 2005 January 20 event

The most extreme SEP event of the last half century was studied by combining the ground level enhancement data recorded by the SpaceShip Earth (SSE) network of polar neutron monitors. Here we summarize the main results of the modeling [4]:

We assumed a spectrum for SEP injection of the form $P^{-\gamma}$, where $P$ is the rigidity and $\gamma$ is the spectral index. The spectral index was estimated from data taken at the South Pole neutron monitor station, which had both a neutron monitor of a standard NM64 design and the Polar...
Figure 2: (a) Injection profile of solar relativistic protons in the 5%–95% range of response of polar neutron monitors (roughly, rigidities larger than 1 GV) for the 2005 January 20 event, modeled from SpaceShip Earth data. (b) Calculated flux at the orbits of Mercury, Venus, Earth, Mars, Ceres, and Jupiter predicted by the same model using solutions of the transport equation. (c) Estimated total fluence as a function of time at the orbits of Mercury, Venus, Earth, Mars, Ceres, and Jupiter (curves from top to bottom).

Bare monitor of three neutron counters with moderators but with no lead producer or polyethylene reflector [11], resulting \( \gamma = 5.0 \). The injection time profile deduced from the modeling is shown in Figure 2a. The scattering radial mean free path at Earth, obtained by the same modeling, is \( \lambda_r = 0.8 \) AU. We take the spectral index of magnetic fluctuations to be \( q = 1.0 \). The interplanetary magnetic field configuration used to model the event is an Archimedean spiral consistent with a solar wind speed \( v_{sw} = 800 \) km/s as measured during the event, and including a compression region centered at \( r = 1.6 \) AU with a reflection coefficient of 0.6–0.7, due to the passage of an ejecta from a previous event (namely 2005 January 17). The effect of the compression region seems to explain the data better, and in a more natural way, than the previously-proposed scenario of scattering conditions changing in time due to self-generated waves [12]. See [4] for details.

3.1 Flux estimations

We find numerical solutions for SEP radial transport following an injection as for the 2005 January 20 event. We consider radial transport along one interplanetary magnetic field line well connected with the acceleration site. We use the value for the scattering mean free path at Earth and the compression region deduced from the analysis of SSE data, as summarized above. We calculate the expected relativistic proton fluxes as a function of time at the orbits of Mercury (0.4 AU), Venus (0.7 AU), Earth (1.0 AU), Mars (1.5 AU), Ceres (2.8 AU), and Jupiter (5.2 AU). Results are shown if Figure 2c. As can be seen, maximum fluxes and event durations as observed from different locations span a wide range of values. The assumed dependence of \( \lambda_r \) with \( r \) at long distances predicts a specially delayed and decreased peak and slow decay. While the width at half
maximum of flux time profiles at the orbits of the inner planets, including Mars, is less than one hour, it appears to be longer than 12 h at the orbit of Jupiter.

It is also interesting to compare the estimated total fluence associated with this SEP event, shown in Figure 2b. This graph shows that, despite the maximum flux being 3 times smaller at the orbit of Mars than at Earth (for example), the total fluence is just 20% lower.

To give an idea of radiation hazard for humans in space, we may assume, as a rough minimum value, the flux of galactic cosmic ray (GCR) protons with \( P > 1 \text{ GV} \) to be about \( 1 \text{ cm}^{-2} \text{ s}^{-1} \) (during solar maximum). Then the total fluence of solar protons with \( P > 1 \text{ GV} \) at the orbit of Mars (for example) during this extreme event would correspond to about 12 days of those GCRs, though with softer spectrum.

4 Conclusions

The assumption that the radial mean free path for pitch-angle scattering, \( \lambda_r \), does not vary with distance to the Sun seems to be a reasonable approximation when performing calculations of SEP transport from the Sun to the Earth, or even to the orbit of Mars. The results out to the orbit of Jupiter, however, are very sensitive to a dependence of \( \lambda_r \) with \( r \), which needs to be modeled more accurately when solving the transport equation at such long distances. In general terms, the estimated effect of the studied dependence of \( \lambda_r \) with \( r \) at long distances consists of a delay and a decrease of the peak intensity, and also a lengthening of the decay time by (roughly) a factor of two.

Detailed calculations of SEP transport can help estimate the effects of extreme events at different distances from the Sun. Taking the 2005 Jan 20 event as an example, we estimate relativistic SEP flux and fluence in space along a well-connected interplanetary magnetic field line at different distances, and we find that harmful effects on spacecraft equipment or crew during an event like this may add up considerably to those related to GCRs at these same energies. Because of the difficulty of shielding from such energetic particles nowadays, this possible risk should be taken into account when planning space (especially manned) missions.

In this work we did not include transversal transport of SEPs in the calculations, which may be needed for the sake of accuracy when estimating flux at late times and large distances. However we can expect the effect of transversal transport to contribute to decrease or “dilute” SEP fluxes along the well-connected field line, from which we can speculate that solutions using radial transport alone are a good upper limit for flux estimations.

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