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Simulations of Polar-Region Atmospheric Ionization Induced by Large Solar Storm on 20 January 2005

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Ionizing radiation in the Earth's troposphere is mainly due to Galactic cosmic rays, high-energy particles from outside the Solar System. Typical solar energetic particles do not have enough energy to penetrate to aircraft or cloud altitudes. However, occasionally solar storms can produce relativistic ions with such enormous intensity that their ionization effect in the Earth's lower atmosphere is significant. One of the largest solar storms ever observed occurred on 20 January 2005, which resulted in very large increases in the count rates of ground-based particle detectors, especially near the polar regions. We use data recorded by two neutron monitor stations located near the magnetic south pole (McMurdo) and north pole (Inuvik) to reconstruct particle energy spectra at the top of the atmosphere for each location as a function of time. We create realistic atmospheric models from measured meteorological data and use them along with the reconstructed particle flux to perform Monte Carlo simulations of particle-air interactions. We calculate atmospheric ionization at different altitudes and times during the 2005 solar storm for each location. The real-time ionization profiles obtained will be useful for studying aircrew health effects, correlations with cloud formation, and climate change.

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1. Introduction

There is a variety of "space weather" effects on human activity due to high speed solar wind streams and solar storms, including those associated with solar energetic particles (SEPs). While humans at Earth are relatively well protected by Earth's magnetic field and atmosphere, there are occasional solar storms that produce SEPs of sufficient energy and intensity to shower in the atmosphere and significantly enhance the flux of ionizing radiation above the background level due to Galactic cosmic rays (GCRs), which have a harder spectrum. Higher in the atmosphere, the less energetic SEPs have a relatively stronger contribution to the ionizing radiation. Even at ground level, neutron monitors (NMs), as the ground-based detectors that are most sensitive to relatively low-energy cosmic rays (CRs), can sometimes detect SEPs. Such events are known as ground level enhancements (GLEs).

Potential space weather hazards for air travelers and aircraft electronics are closely related to atmospheric ionization, as both are due to ionizing radiation from atmospheric showers. Atmospheric ionization can be measured (e.g., [1]), providing a reality check on calculations. Furthermore, atmospheric ionization is important to the formation and development of condensation nuclei for clouds, and a purported link between CRs and clouds [2, 3] that could imply a substantial effect of solar activity on Earth's surface temperature [4], though this conclusion remains controversial [5, 6, 7]. Thus the present study aims to estimate the distribution of atmospheric ionization expected from a large GLE.

The giant GLE of 20 January 2005 was the strongest event in the past 59 years, and relativistic solar particle fluxes were well measured by polar NMs, including the *Spaceship Earth* network [8]. The CR flux as measured by the high-altitude South Pole NM increased by 5500%. Fortunately such high increases occurred only at or near Antarctica, with no commercial air travel; this event highlights the potential effects on polar air flights if such increases occur over the North polar region in the future. With such a large increase in particle fluxes, this event provides a good example case for estimating atmospheric ionization [9]. Here we make direct use of accurate measurements by NMs at different locations, combined with detailed Monte Carlo simulations based on the estimated atmospheric structure at those locations and times, to estimate atmospheric ionization due to relativistic solar particles as a function of altitude and time.

2. Methods

2.1 Neutron Monitor Data

When CRs strike the upper atmosphere, showers of secondary particles, including neutrons, are produced and can be detected by NMs on the ground. An important advantage of NMs is a high detection rate, allowing precise measurement of secondary neutron count variation. We can use the NM count rate data to obtain information about the CR spectrum at the top of the atmosphere as a function of time. This is discussed in detail in section 2.2.

For a given location on Earth, only CRs above a certain rigidity (momentum per charge) can penetrate the Earth's magnetic field to interact with the atmosphere. This cutoff rigidity varies from $\sim$0.1 GV near the geomagnetic poles to $\sim$17 GV near the geomagnetic equator. Therefore, NM stations at different locations are sensitive to different rigidity ranges of the CR spectrum. SEPs, mostly relativistic protons and He, can have rigidity up to ∼10 GV and may arrive on Earth mostly near the polar regions, resulting in increases of NM count rates above the background GCR count rates. On 20 January 2005 starting from 6:50 UT, a major GLE was observed near the polar regions. Satellite instruments also clearly registered this event in enormous increases of particle fluxes and significant changes of spectral parameters. Percent increases of selected polar-region NM count rates of this GLE are shown in Figure 1.

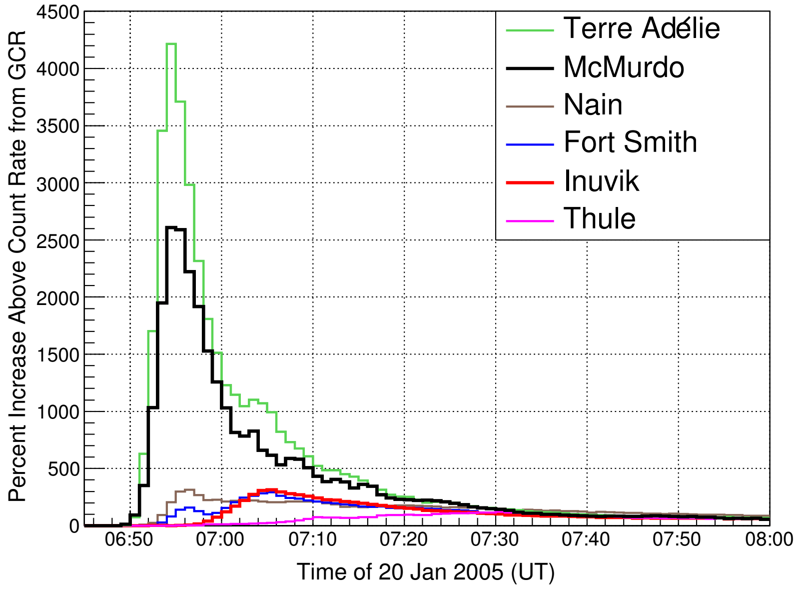

Figure 1: One-minute averaged percent increases of count rates (above the background rate produced by GCRs) from six polar-region NM stations due to the large solar storm on 20 January 2005 [8]. McMurdo and Inuvik data are emphasized in this work.

This GLE had a significant anisotropy of particle fluxes arriving near the South and North poles. To study atmospheric ionization in those regions, we use NM count rate data from McMurdo (77.86 °S, in Antarctica) and Inuvik stations (68.36 °N, in Canada) to calculate the CR spectra at the top of the atmosphere. An important motivation to study the location at Inuvik station is the dense air traffic in that region, for relevance to health effects on airline passengers.

2.2 Estimations of GCR and SEP Spectra

We use the parameterization of local GCR proton and He spectra from [10], taking into account the solar modulation effect by putting in the force field potential $\phi = 1188$ MV [11]. Other types of particles are neglected. Solar modulation can affect GCRs up to ∼30 GV and is known to follow a cycle of ∼11–12 years. For the time scale of a few hours in this study, GCR spectra are assumed to be constant in time and isotropic.

The SEP spectra of this GLE are more complicated to model. Different measurements do not completely agree (see, e.g., [8] and [12]). Nevertheless, it is generally accepted that the SEP spectra are well approximated by a steep power law with the spectral index of ∼5. In order to extract the SEP spectra from NM count rates, we exploit results from latitude survey analysis

[13], which was performed by carrying NMs on a ship across many geographical locations with different geomagnetic cutoff rigidity between October 2004 and April 2005. Using the average solar modulation potential during this period ($\phi = 636.3$ MV[1]) along with the local GCR model by [10], we obtain the NM yield function, which can then be used to approximate the SEP spectra above McMurdo and Inuvik NM stations from the measured percent increases of NM count rates under these assumptions:

- Only two species of particles, proton and He, are considered.
- The time-dependent proton and He energy spectra are described by a power law in rigidity with a constant spectral index of 5 (from [8]) and a sharp low-energy cutoff T_c:

$$\frac{dN}{dT}(t) = I_0(t)\left(\frac{R_0}{R(T)}\right)^5 \exp\left(\frac{1}{T_c(t)-T}\right) \quad \text{for } T > T_c(t), \tag{2.1}$$

  where T is kinetic energy per nucleon, R is rigidity, and t is time.

- The low-energy cutoff of the spectra $T_c(t)$ decreases with time, depending on the arrival of particles with different velocities traversing the distance of 1.1 AU following an Archimedean spiral along the mean interplanetary magnetic field. Particles with $T > 1$ GeV/nuc start to arrive at 6:50 UT. (See top left plot of Figure 4 in [8].)
- The normalization I_0 for He is assumed to be 5% of that for protons [12].
- The NM yield for primary CR He is a factor of 3.67 of that for primary CR protons at the same rigidity. This value is obtained from our own Monte Carlo simulations.
- The yield functions for the ship-borne NM in the latitude survey [13] are the same as those at McMurdo and Inuvik, which is reasonable given that they use the same type of NM.

We use 100 MV [13] as the apparent geomagnetic rigidity cutoff at both McMurdo and Inuvik. This value does not significantly affect the result because low-energy particles rarely penetrate the atmosphere to altitudes of interest (below 20 km).

2.3 Monte Carlo Simulations of Atmospheric Ionization

Realistic models of Earth's atmosphere for McMurdo and Inuvik are created with meteorological data from the Global Data Assimilation System[2] (GDAS) below ~25 km altitude, and from NRLMSISE [16] above that. The GDAS database provides average atmospheric properties (e.g., humidity, density, pressure, temperature) from actual measurements between 6:00–12:00 UT, while the NRLMSISE model is averaged monthly. Our atmospheric models are composed of 0.25-km thick layers from the altitude of each NM up to ~70 km.

We use the FLUKA package [14, 15] to perform the simulations of atmospheric ionization. GCR and SEP particles with energy spectra described in section 2.2 are simulated to interact with the modeled atmosphere, assuming that particle spatial distributions are isotropic above relatively

[1] http://cosmicrays.oulu.fi/phi/Phi_mon.txt

[2] https://www.ready.noaa.gov/gdas1.php

small locations near the McMurdo and Inuvik NM stations. In one-minute time steps from 6:50–8:00 UT, the energy deposited in each atmospheric layer is recorded and converted into an ionization rate using the average ionization potential of air of 35 eV [9].

3. Results

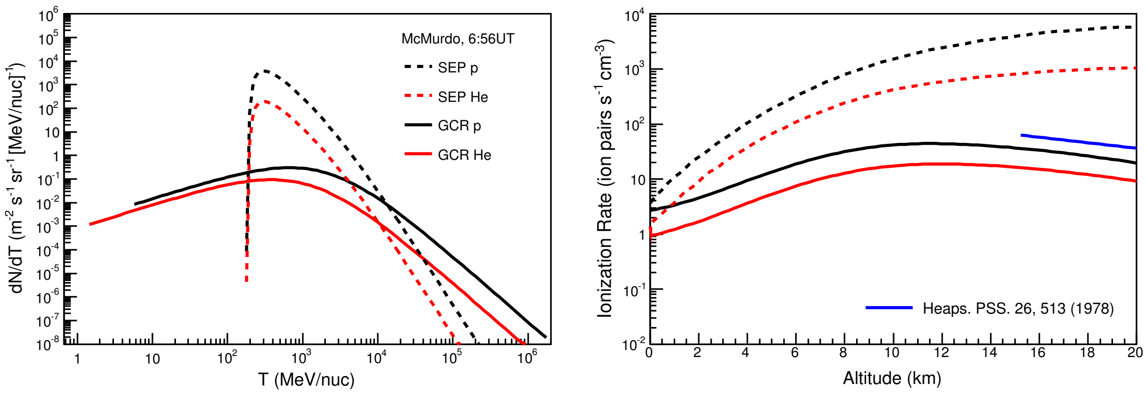

Figure 2: Modeled CR spectra (left) used as inputs to simulate the atmospheric ionization production rate (right) above McMurdo NM monitor station at the peak time of this GLE (6:56 UT, see thick black line in Figure 1). Here the black, red, dashed, and solid lines are associated with protons, He, SEP, and GCR, respectively. The parameterization of measured ionization production rate due to GCR at maximum solar modulation by [17] is shown in blue for comparison.

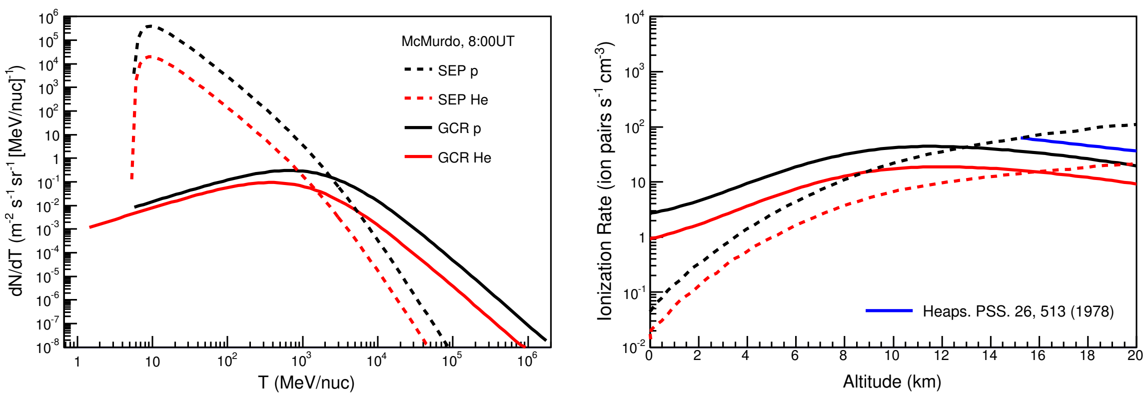

Figure 3: Same as Figure 2 during the decay of the GLE (8:00 UT).

Figures 2–5 show our calculated SEP and GCR spectral models in the left panels. The peaks of NM count rates differ in time between McMurdo (6:56 UT) and Inuvik (7:06 UT). Near the peak time of the GLE, our estimated SEP fluxes become comparable to those of GCRs near 10 GV with many orders of magnitude higher abundance of particles at lower rigidity, similar to Figure 7 in [12]. Note that only an order-of-magnitude comparison may be made because of the strong anisotropy of this GLE and hence the strong location dependence of particle fluxes.

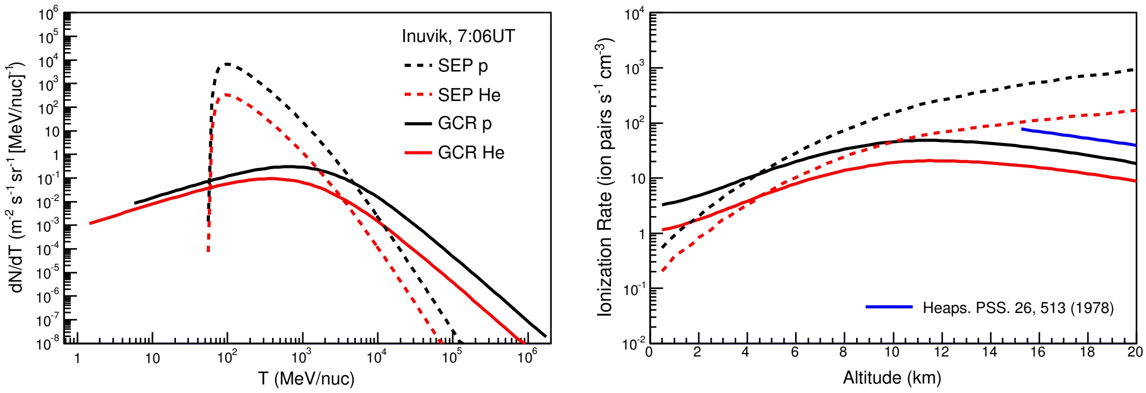

Figure 4: Same as Figure 2 for Inuvik NM station at the peak time of the GLE (7:06 UT, see thick red line in Figure 1).

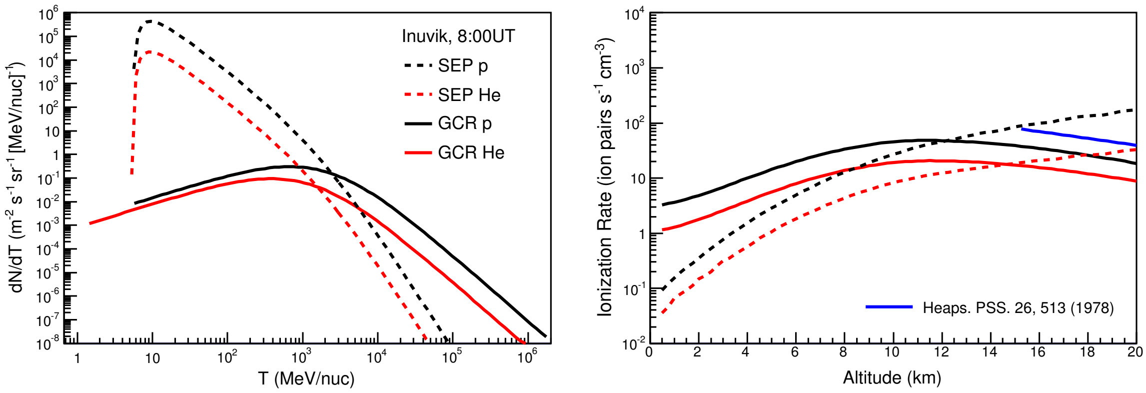

Figure 5: Same as Figure 4 during the decay of the GLE (8:00 UT).

Simulation results of atmospheric ionization production rates as a function of altitude are shown in the right panels of Figures 2–5. First we note the ionization rates at 10 km, a typical altitude for passenger aircrafts. Near the peak time of the GLE, the total ionization rate at 10 km above McMurdo increases by ∼2 orders of magnitude over the ionization rate from GCR alone. For Inuvik, simulations suggest an order-of-magnitude increase at 10 km altitude. At sea level, the ionization rate at McMurdo due to SEPs is somewhat higher than the background rate due to GCRs, so the total ionization is more than doubled during the GLE. At Inuvik, the rate due to SEPs is about an order of magnitude smaller than that due to GCRs.

During the decay of this GLE, at 8:00 UT, the SEP-induced ionization rates at ∼10 km are only ∼50% of the GCR-induced rates and become negligible at sea level for both locations. However, at higher altitude (above ∼15 km), the SEP-induced rates remain many times greater than the GCR-induced rates. This is because a large number of low-energy particles, which tend to ionize air at higher altitude, arrive during the decay of the GLE. Our simulations suggest that CRs with energy below 400 MeV contribute less than 5% to the total atmospheric ionization below 18 km at all times during this GLE for both locations.

Parameterized models of GCR-induced ion-pair production rates from balloon measurements [17] are shown in the right panels of Figures 2–5. The parameters used are for magnetic latitudes of McMurdo and Inuvik at solar maximum. Our simulation results for GCR-induced ionization rates are ∼30% lower than this parameterization, but the profile shapes are very consistent. The difference in normalization may be explained by the substantial reduction of GCR flux during this GLE (see, e.g., Figure 6A in [1]). Our simulated ion-pair production rates are consistent with previous studies (see, e.g., Figure 2 in [1] and [9]).

Acknowledgments

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