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Ionization of the venusian atmosphere from solar and galactic cosmic rays

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ABSTRACT

The atmospheres of the terrestrial planets are exposed to solar and galactic cosmic rays, the most energetic of which are capable of affecting deep atmospheric layers through extensive nuclear and electromagnetic particle cascades. In the venusian atmosphere, cosmic rays are expected to be the dominant ionization source below ~100 km altitude. While previous studies have considered the effect of cosmic ray ionization using approximate transport methods, we have for the first time performed full 3D Monte Carlo modeling of cosmic ray interaction with the venusian atmosphere, including the contribution of high-Z cosmic ray ions ($Z = 1–28$). Our predictions are similar to those of previous studies at the ionization peak near 63 km altitude, but are significantly different to these both above and below this altitude. The rate of atmospheric ionization is a fundamental atmospheric property and the results of this study have wide-reaching applications in topics including atmospheric electrical processes, cloud microphysics and atmospheric chemistry.

1. Introduction

Planetary atmospheres are exposed to a range of ionizing radiation, including: solar wind or magnetospheric particle precipitation; solar ultraviolet and X-ray photons; and cosmic ray (CR) particles. These cosmic rays are composed of fully-ionized atomic nuclei from both solar and extrasolar sources, with energies ranging from ~10^6 eV to beyond 10^{13} eV (Bazilevskaya et al., 2008). Beyond the penetration depth of solar EUV and X-ray particles, cosmic rays are typically the primary ionization source in a planetary atmosphere, as is the case in the terrestrial atmosphere below 60–70 km (Velinov et al., 2009) and in the venusian atmosphere below ~100 km (Borucki et al., 1982).

Cosmic rays are divided into two categories, galactic cosmic rays (GCR), which are believed to be produced by diffusive shock acceleration at the outer edges of expanding supernova remnants (Blandford and Eichler, 1987; Hillas, 2005) and solar energetic particles (SEP) which are produced by solar flares, coronal mass ejections and in interplanetary shocks (Reames, 1999). While the flux at the peak of the GCR spectrum (~500 MeV/nucleon) is about four orders lower in magnitude than the corresponding SEP flux, the GCR spectrum extends to extremely large energies (>10^{13} eV) at very low fluxes, and the SEP spectrum drops off very sharply beyond ~100 MeV/nucleon. Furthermore, while the GCR background is continuous and anticorrelated with the solar activity cycle due to heliospheric modulation, SEP events are sporadic in nature and positively correlated with increasing solar activity (Vainio et al., 2009). The GCR spectrum is composed of protons (~87%) and alpha particles (~12%), with a small contribution from fully ionized heavy nuclei (~1%) (Simpson, 1983). The shape and composition of the SEP spectrum varies significantly between SEP events (Reames, 1999; Schmelz et al., 2012).

While low energy CR particles lose energy to atmospheric neutrals by elastic collisions, ionization and excitation before being effectively stopped and absorbed, those primary particles with energies above ~1 GeV initiate extensive cascades of secondary particles. When such a particle undergoes an inelastic collision with an atmospheric nucleus, secondary mesons (pions and kaons), nucleons, gamma particles and nuclear fragments are created, which may in turn interact with other atmospheric nuclei, creating an atmospheric particle cascade ("air shower") as illustrated in Fig. 1. Secondary mesons decay almost instantly to produce muons, gamma particles and electrons. Therefore, a fully developed air shower is composed of a hadronic core consisting of nuclear fragments, protons and neutrons, surrounded by a spreading cone of

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muons (the “hard component”) and electrons, positrons and photons (the electromagnetic or “soft component”) (Bazilevskaya et al., 2008). The flux of secondary particles increases with depth until the Pfotzer maximum (Pfotzer, 1936), after which the average energy of the secondary particles is insufficient to produce additional particles and the flux steadily decays. The Pfotzer maximum coincides with the peak in CR ionization, and in the terrestrial atmosphere typically occurs at 16–25 km depending on location and solar activity levels (Bazilevskaya and Svirzhevskaya, 1998).

As opposed to the terrestrial case, Venus does not possess a global magnetic field capable of deflecting charged particles, and so even low energy CR primaries have unimpeded access to the atmosphere. It is also closer to the Sun, and is therefore exposed to higher particle fluxes from sporadic SEP events (e.g. flares, coronal mass ejections). Furthermore, the venusian atmosphere is significantly more dense than that of the Earth, with a total shielding depth of $\sim 10^5$ g/cm^2 compared to the terrestrial value of $\sim 10^3$ g/cm^2, and an atmospheric density at the surface over an order of magnitude greater than at terrestrial sea level. The consequence is that cosmic ray air showers develop extensively in the venusian atmosphere, whereas many secondary particles reach, and are absorbed by the terrestrial surface. As cosmic rays represent a major ionization source in planetary atmospheres, the CR ionization rates have a strong influence on fundamental atmospheric properties such as electrical conductivity, atmospheric chemistry and charging of cloud particles (Aplin, 2013). It is therefore important to quantify the effects of cosmic ray ionization, and to understand its variability over both long and short time scales (i.e. solar cycle, SEP events).

Cosmic ray ionization in the venusian atmosphere has not been extensively modeled in the past, with only three studies in the literature (Dubach et al., 1974; Borucki et al., 1982; Upadhyay and Singh, 1995; Upadhyay et al., 1994). Common to these is that they have made use of approximate transport equations to describe particle propagation within the atmosphere. Such methods employ simplifications that generally do not take into account the full range of effects from the interactions of primary and secondary air shower components with atmospheric neutrals, and are known to produce unreliable results in the lower terrestrial atmosphere (Bazilevskaya et al., 2008). This is the first study to carry out a full 3D Monte Carlo modeling of cosmic ray interactions within the venusian atmosphere, including discrete particle interactions within the extensive showers of secondary particles. Furthermore, we have implemented complete SEP and GCR primary spectra, taking into account the contribution from protons, alpha particles and heavier ions ($Z = 3$–28).

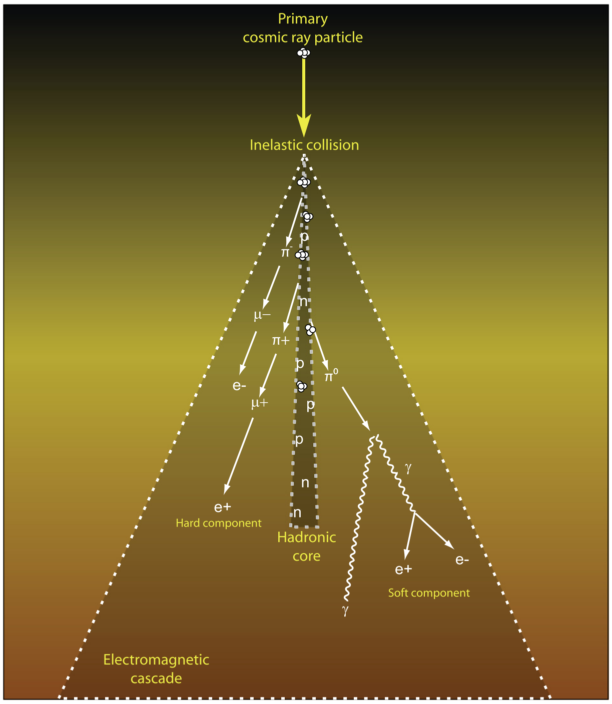

Fig. 1. Illustration of an atmospheric secondary particle (air shower) cascade initiated by a primary cosmic ray particle colliding with an atmospheric neutral. The air shower consists of a central hadronic core, surrounded by a spreading cone of muons (the “hard component”) and electrons, positrons and photons (the “soft component”).

2. Method

For this modeling study we have used the PLANETOCOSMICS (http://cosray.unibe.ch/~laurent/planetocosmics/) software application (Desorgher et al., 2005), which is based on the Geant4 Monte Carlo simulation toolkit for particle interactions with matter (Agostinelli et al., 2003) and was developed at the University of Bern for the European Space Agency. PLANETOCOSMICS simulates discrete electromagnetic and hadronic particle interactions in planetary atmospheres, including a full treatment of secondary particle cascades, and has been validated against terrestrial balloon measurements (Desorgher et al., 2005; Vainio et al., 2009). For hadronic interactions, PLANETOCOSMICS uses the Geant4 Binary Intranuclear Cascade (BIC) model at energies <10 GeV/nucleon and a Quark Gluon String Precompound (QGSP) model at higher energies.

For this modeling study, the simulation geometry was constructed as an atmospheric column 150 km high, implementing a model of representative temperature, pressure and density for the venusian atmosphere (Fig. 2). The width of the column is arbitrarily large, and was chosen such that it would be possible to track the entire atmospheric cascade without particles exiting through the sides. The atmospheric description is based on the Venus International Reference Atmosphere (Kliore et al., 1985), using the tabulated parameters of Seiff et al. (1985) for the middle and lower atmosphere (100–0 km) at low latitudes ($\varphi < 30°$) and those of Keating et al. (1985) for the daytime upper atmosphere between 100–150 km at low latitude ($\varphi = 16°$). An atmospheric composition of 96.5% CO_2 and 3.5% N_2 was used.

The irradiation geometry of an isotropic hemispherical source above the planetary atmosphere is recreated by a point source at the top of the atmosphere delivering primary cosmic ray particles according to a cosine law angular distribution.

All primary and secondary particles are tracked until they either come to rest within the atmospheric column or are absorbed by the planetary surface.

The spectrum of primary cosmic ray particles was taken from the CREME2009 (https://creme.isde.vanderbilt.edu/) model (Tylka et al., 1997), which provides fluxes of $Z = 1$–28 (protons to nickel) ions from ~ 1 MeV/nucleon up to 100 GeV/nucleon in interplanetary space at 1 AU. The GCR component of the CREME2009 model is based on the International Standard Galactic Cosmic Ray Model of the International Organization for Standardization [ISO 15390:2004(E)] (Nymmik, 2006), with additional extensions, including treatment of anomalous cosmic rays at low energies (Tylka et al., 1997). The GCR primary spectrum was extracted from CREME2009 for “solar quiet” conditions at solar maximum and minimum, which represent ambient conditions in the absence of solar energetic particle events. A power law tail was fitted to the flux spectrum for each Z species and used to extrapolate the GCR spectrum up to 1 TeV/nucleon. As the gradient of GCR flux is very low within the inner Solar System (Fujii and McDonald, 1997;