Icarus 245 (2015) 80–86

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Ionization of the venusian atmosphere from solar and galactic cosmic rays

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ARTICLE INFO

Article history:
Received 3 July 2014
Revised 10 September 2014
Accepted 16 September 2014
Available online 23 September 2014

Keywords:
Venus
Venus, atmosphere
Ionospheres
Aeronomy

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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http://dx.doi.org/10.1016/j.icarus.2014.09.032
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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).

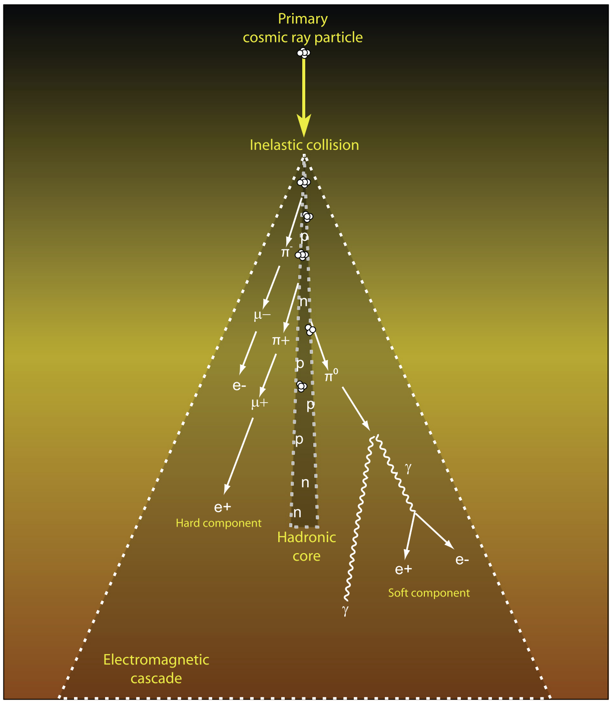

Fig. 1. Illustration of an atmospheric secondary particle (air shower) cascade initiated by a primary cosmic ray particle colliding with an atmospheric neutral. The air shower consists of a central hadronic core, surrounded by a spreading cone of muons (the “hard component”) and electrons, positrons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

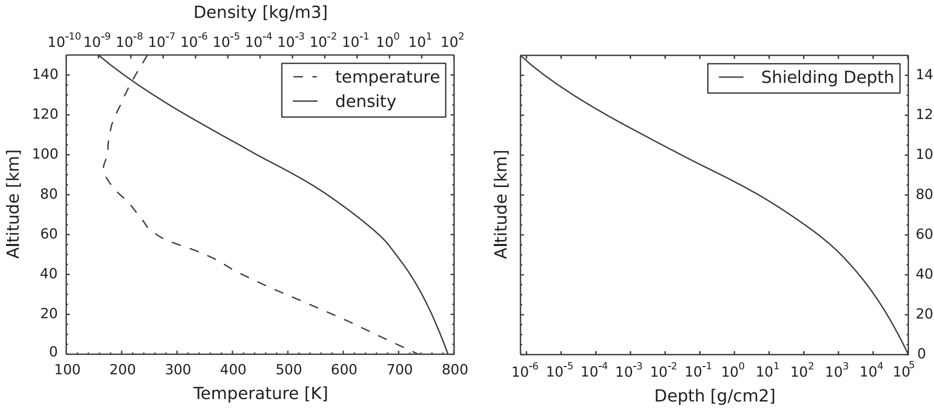

Fig. 2. Atmospheric profile used in this study, based on the VIRA model (Keating et al., 1985; Seiff et al., 1985).

Morales-Olivares and Caballero-Lopez, 2010), rescaling of the CREME2009 GCR fluxes to the orbit of Venus is not necessary. In order to illustrate the effects of a particularly strong SEP event on atmospheric ionization, the SEP primary spectrum was extracted from the CREME2009 model during “flare” conditions corresponding to a series of severe SEP events that occurred in October, 1989. Unlike GCR, the flux of SEP received from a solar event depends significantly on the orbital distance, and so the SEP fluxes were scaled to the mean orbit of Venus (0.72 AU) using a geometric ($1/R^2$) factor. The modeled GCR and SEP spectra are shown in Fig. 3, with the dominant ion species (H, He, C, O, Si and Fe) highlighted.

For both SEP and GCR, the cosmic ray spectrum was implemented by explicitly simulating He, C, O, Si and Fe primaries up to 10 GeV/nucleon – the energy limit of Geant4 light ion ($Z > 1$) physics, while primary H ions were simulated up to 1 TeV. To provide an approximation for the energy contribution of the heavier ions ($Z > 1$) above 10 GeV/nucleon, the H data was weighted

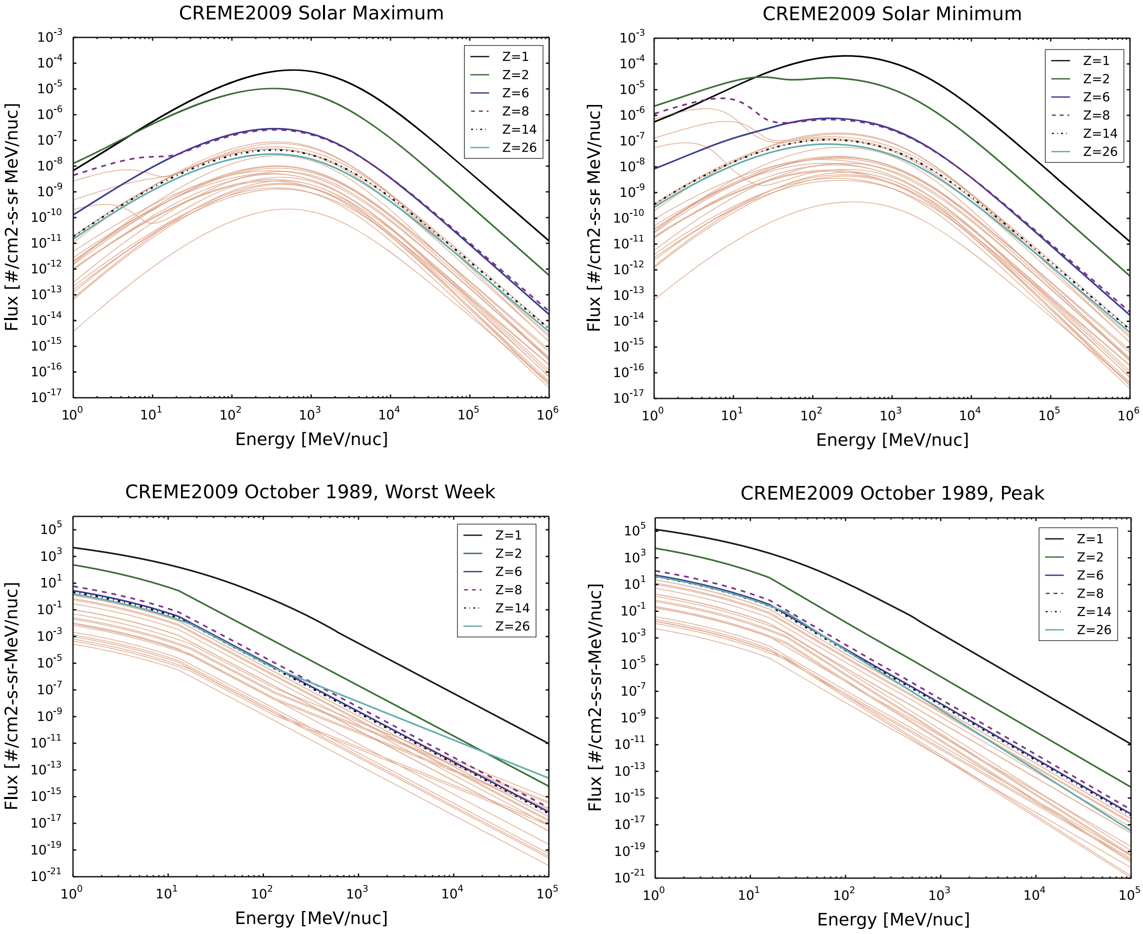

Fig. 3. Primary cosmic ray particle spectra used in this study, based on the CREME2009 model (Tylka et al., 1997). The full spectrum from $Z = 1–28$ is shown, with the dominant ion species (H, He, C, O, Si and Fe) highlighted and the remaining species shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by energy integration to account for the contribution of all species $Z = 1–28$ from 10 GeV/nucleon to 1 TeV/nucleon. Below 10 GeV/nucleon, the data from the H, He, C, O, Si and Fe primaries were weighted to account for the energy carried by all species $Z = 1–28$. In total, these six species account for ~97% of the energy in the cosmic ray spectrum, and thus we have explicitly simulated the most important components of the cosmic ray spectrum while accounting for the energy delivered by all primary ions from $Z = 1–28$ from 1 MeV/nucleon to 1 TeV/nucleon.

3. Results

Energy deposition by all primary and secondary cosmic ray particles is recorded in each geometry layer and from this, the total energy deposition versus altitude is computed. The ionization rate at a given altitude is calculated by considering the total deposited dose, the atmospheric density at this altitude and a mean ionization potential (W) for the venusian atmosphere of 33.5 eV to create one ion–electron pair in CO_2 (Borucki et al., 1982), which is consistent with theoretical (e.g. Fox et al., 2008) and experimental estimates (International Commission on Radiation Units and Measurements, 1993). Fig. 4 shows the resulting ionization rate due to GCR at solar minimum (left), compared to previous results by Dubach et al. (1974) and Borucki et al. (1982) (right), which for energies lower than 10 GeV used a primary spectrum recorded in 1963, near solar minimum (Freier and Waddington, 1965). Also shown are the results of Upadhyay and Singh (1995), for which the modeled solar conditions are not clearly stated. However, as solar minimum represents the GCR maximum, we may consider this an upper bound with which to compare their results. Our results show an ionization peak of 58 ion pairs $cm^{-3}\ s^{-1}$ at 62.5 km. The work of Borucki et al. (1982) shows an ionization peak that is ~18% greater than this study and occurs at 63–64 km. The work of Dubach et al. (1974) shows an ionization peak that is ~15% lower in magnitude than the present study, but occurring at a similar altitude of 63 km. Although a full comparison is not possible, as these studies do not have the same coverage in altitude, we observe that significantly above the ionization peak, the other two studies underestimate the ionization rates by 50% or more at 80 km. Although the analytical approximation utilized by these two studies agrees quite well with our results near the ionization peak, Borucki et al. (1982) estimates higher ionization rates in the lower atmosphere by as much as an order of magnitude at ground level. The study by Upadhyay and Singh (1995) similarly makes use of an approximate solution to treat particle propagation in the atmosphere. However, their study estimates ionization rates that are over an order of magnitude greater than the other studies at all altitudes, with an ionization peak at 64 km on the order of 10^3 - ion pairs $cm^{-3}\ s^{-1}$. Furthermore, they predict a second ionization peak near ~25 km due to the influence of muons, a feature that is not observed in the results of the other studies. Their predicted ionization rate due to cosmic rays near the venusian surface is over 5 orders of magnitude greater than what is predicted by the present study. In summary, our results are in general agreement with the previous studies of Dubach et al. (1974) and Borucki et al. (1982), but presents several important advances, particularly in the upper and lower atmosphere.

At solar maximum (Fig. 5) we observe that the ionization peak occurs at the same altitude of 62.5 km, however the ionization rate is reduced to 46 ion pairs $cm^{-3}\ s^{-1}$. Above ~80 km, the ionization rates are reduced to ~40% of the solar minimum values. These changes can be explained by the fact that the average GCR spectrum at solar maximum is significantly softer below about 10 GeV/nucleon compared to the average GCR spectrum at solar minimum. Similarly, the ionization rates below ~50 km are practically identical due to the fact that only the most energetic (> a few GeV/nucleon) component of the GCR spectrum is capable of reaching large atmospheric depths. At such high energy the GCR spectrum is not significantly modulated by solar activity.

During transient SEP events, particle fluxes at the top of the atmosphere may be many orders of magnitude above background levels during “quiet” conditions. However, the shape of the SEP spectrum is typically very steep, and thus, the enhanced particle flux occurs mainly below ~a few GeV/nucleon, with negligible fluxes beyond 100 GeV/nucleon. To investigate what effects such intense but short-lived particle enhancements may have on the venusian atmosphere, we have used measured spectra from an SEP event that occurred in October, 1989 – one of the most intense SEP events observed during the space age (Miroshnichenko et al., 2000). The “worst week” scenario corresponds to particle fluxes averaged over 180 h beginning at 1300 UTC on the 19th of October 1989, while the “peak” scenario corresponds to the peak five-minute averaged fluxes as observed by the GOES spacecraft on October 20th, 1989 (Tylka et al., 1997). Figs. 6 and 7 show the atmospheric ionization rates produced by these two scenarios. In the case of the “worst week” scenario, the ionization peak occurs at ~95 km, with ionization rates of ~7 × 10^3 ion pairs $cm^{-3}\ s^{-1}$, an enhancement of over 5 orders of magnitude compared to the average background rate due to GCR at solar minimum. However, the ionization rate due to SEP near the GCR peak is of comparable magnitude to the average GCR contribution, thus, we would expect to see an effective doubling of the ionization rate at this altitude. For the “peak”

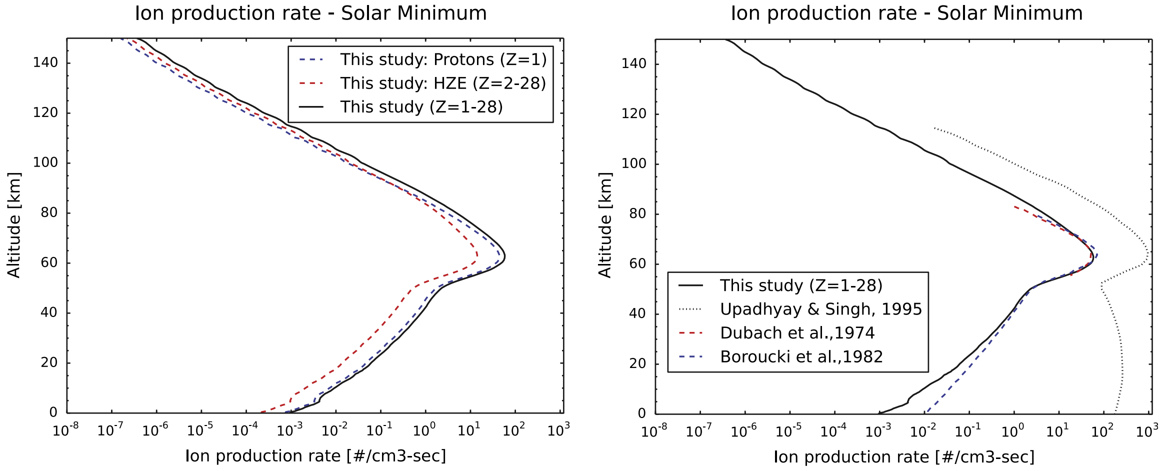

Fig. 4. Ionization rate by altitude for the solar minimum (GCR) scenario (left). Shown for comparison (right) are the predicted GCR ionization rates of previous studies (Borucki et al., 1982; Dubach et al., 1974; Upadhyay and Singh, 1995).

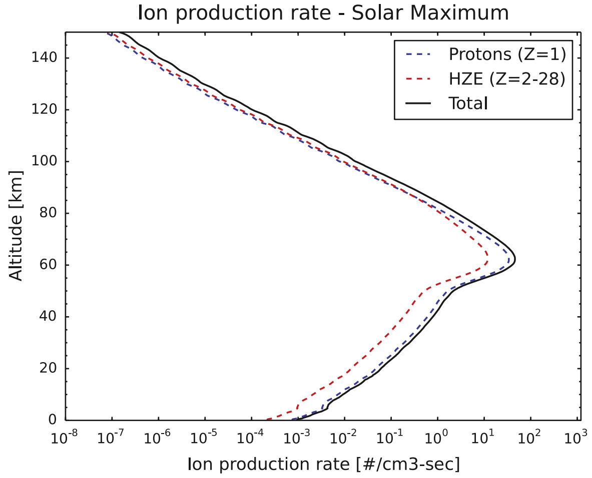

Fig. 5. Ionization rate by altitude for the solar maximum (GCR) scenario.

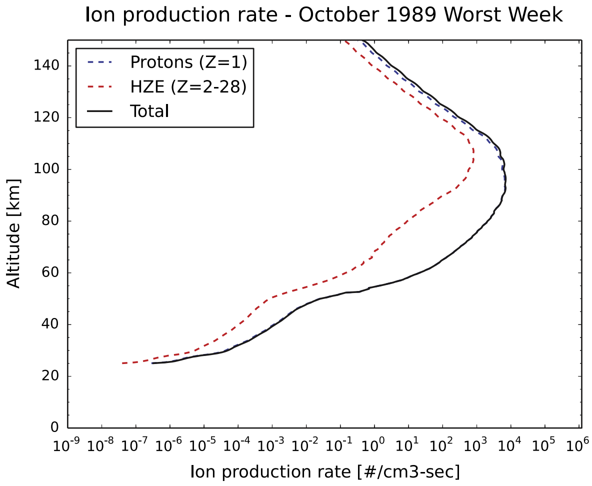

Fig. 6. Ionization rate by altitude for the “worst week” (SEP) scenario.

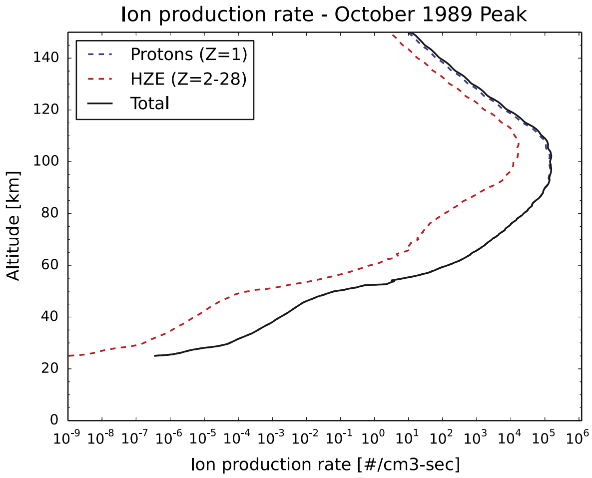

Fig. 7. Ionization rate by altitude for the “peak” (SEP) scenario.

scenario, the ionization peak also occurs at ~95 km, but ionization rates at the peak are even greater, at ~1.6×10^5 ion pairs $cm^{-3}\ s^{-1}$, over 6 orders of magnitude above GCR background levels. The ionization rate due to SEP near 63 km is over an order of magnitude greater than the contribution from the GCR peak.

While the results presented herein are computed for average conditions on the low-latitude venusian dayside, any specific atmospheric and cosmic ray conditions can be simulated by our model. This is particularly relevant for comparisons with in-situ atmospheric measurements by future missions to Venus.

4. Discussion

The interaction of SEP and GCR particles with the venusian atmosphere has been modeled for the first time using a full 3D treatment of discrete primary and secondary particle interactions. Near the ionization peak, the results for GCR conditions at solar minimum are similar to those of Dubach et al. (1974) and Borucki et al. (1982), which make use of approximate solutions to the Boltzmann transport equation (O’Brien, 1971). The reported ionization rates above the ionization peak are significantly lower than what is seen in the present study. However, these studies did not explicitly simulate primary particles of $Z > 1$, and it has been shown that the contribution from the High Z component of the GCR spectrum is significant at high altitudes on Titan and Earth (Gronoff et al., 2011; Velinov and Mateev, 2008). In addition, Borucki et al. (1982) estimates higher ionization rates in the lower atmosphere by as much as an order of magnitude at ground level. Whereas our study models the discrete interactions in the air shower, Borucki et al. (1982) makes use of an analytical approximation for the atmospheric cascade (Capone et al., 1979; O’Brien, 1971), which is known to be less reliable at large atmospheric depths, where the air shower is more fully developed and the “hard” (muon) component dominates (Bazilevskaya et al., 2008). We find that the predicted cosmic ray ionization rates of Upadhyay and Singh (1995) significantly disagree with the other studies at all altitudes.

It is worth noting that recent theoretical work by Simon Wedlund et al. (2011) suggests a new value for the ionization potential W for CO_2-dominated atmospheres that is slightly lower than the values reported by previous theoretical and experimental studies. If indeed this is confirmed by further investigations and the consensus regarding the correct value of W changes, the ionization profiles presented herein may simply be re-scaled to reflect this difference.

As illustrated in Fig. 8, cosmic rays due to SEP and GCR are the dominant source of atmospheric ionization in the middle and lower venusian atmosphere (below ~100 km). The predicted daytime EUV/X-ray ionization rates of Peter et al. (2014) for low solar zenith angles ($\chi = 23.1°$) are shown for comparison and can be seen to peak at a much higher altitude of 140 km. Based on density scaling, (Borucki et al., 1982) estimated that atmospheric ionization due to decay of radioactive minerals is confined to within ~100 m of the surface. By comparing the measured abundance of radioactive elements on the surface made by Venera 8 (Vinogradov, 1973) with that of terrestrial granites, (Aplin, 2006) estimates an atmospheric ionization rate in this near-surface layer of ~0.01 ion pairs $cm^{-3}\ s^{-1}$. While this is comparable to the atmospheric ionization rate at the surface due to cosmic rays reported by Borucki et al. (1982), we find that near the surface, the predicted ionization rates due to radioactive decay are roughly an order of magnitude greater than that due to cosmic rays.

Atmospheric ionization due to cosmic rays is a fundamental process, and the results of the present study are relevant to a wide range of interdisciplinary topics within Venus atmospheric research. In a dense planetary atmosphere, such as that of Venus, ions and electrons produced by cosmic rays will interact rapidly with atmospheric neutrals to produce secondary ions and ion clusters. The atmospheric conductivity is governed by the mobility of these long-lived secondary species, whose lifetimes are limited by their recombination rates with ions of opposite charge and by

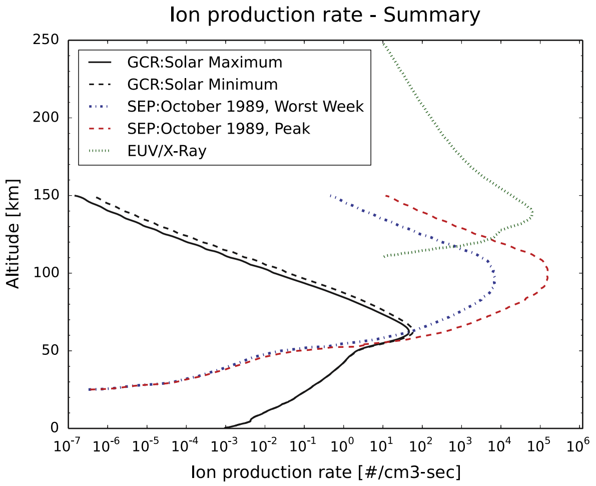

Fig. 8. Summary of ionization rates predicted by the present study for the average solar minimum and solar maximum (GCR) scenarios as well as the “worst week” and “peak” (SEP) worst case scenarios. Predicted daytime EUV/X-ray ionization rates of Peter et al. (2014) are shown for comparison.

attachment to aerosol particles (Borucki et al., 1982). While the atmospheric electron concentration (and thus the conductivity) has been measured down to ~120 km in the venusian atmosphere (Brace et al., 1997), only theoretical estimates (Borucki et al., 1982; Michael et al., 2009) based on the predicted cosmic ray ionization rates of Borucki et al. (1982) are available below this altitude. Venus possesses several global layers of clouds and haze, which consist primarily of sulfuric acid and extend from ~30–90 km, with the main cloud deck located at ~45–70 km (Mills et al., 2013). Cloud particles may become charged by electron attachment and charge transfer with positive and negative ions, thus constituting a loss mechanism for atmospheric ions and electrons. Work by Michael et al. (2009) estimates that ion loss due to the presence of cloud particles leads to a reduction in the global atmospheric conductivity of a factor of 2–6. While it is not clear if Venus has a global electric circuit, preliminary calculations seem to indicate this is plausible (Aplin, 2013). By utilizing the updated ionization profiles provided by the present study, new estimates may be made of venusian atmospheric conductivity and the possibility of a global electric circuit may be re-assessed.

The large atmospheric pressure at the surface and the high altitude of the cloud layer seems to exclude the possibility of cloud-to-ground lightning (Aplin, 2006; Gurnett et al., 2001), however, several authors have suggested that lightning discharges above, between or within clouds may occur (Borucki, 1982; Gurnett et al., 2001; Russell and Scarf, 1990). While positive detections of radio wave emissions due to venusian lightning have been reported (Ksanfomaliti et al., 1979; Russell et al., 2007; Taylor et al., 1979), radio observations by Cassini during two close flybys has not confirmed this and a lack of optical detections by Venus Express as well as ground-based observers leaves the question of venusian lightning unresolved (Yair, 2012; Yair et al., 2008). Lightning in the venusian atmosphere may be inferred by searching for Schumann resonances, Extremely Low Frequency (ELF) waves which are excited by electrical discharges within the surface-ionosphere cavity (Aplin et al., 2008; Simões et al., 2008b). The predicted signatures of such ELF waves within the venusian surface-ionosphere cavity has been studied theoretically by Simões et al. (2008a) by incorporating the conductivity profile produced by the cosmic ray modeling work of Borucki et al. (1982). While the exact mechanisms for charging within the venusian clouds is not known (Yair, 2012), it is clear that it is crucial to accurately quantify rates of cosmic ray ionization, as this is the primary ionization source at these altitudes. As such, the results of the present study serves as a fundamental input into future attempts at modeling cloud charging and lightning within the venusian atmosphere.

It has also been suggested that aerosols may form by direct condensation of gaseous sulfuric acid onto ions in the lower atmosphere within the lower cloud-forming regions at ~40 km (Aplin, 2013, 2006). Thus, it is possible that ionization by cosmic rays within the deep atmosphere may contribute to cloud formation on Venus. However, as shown in Fig. 8, there is little variability in cosmic ray ionization rates at this altitude between GCR solar minimum and maximum conditions, and the effects of SEP events at such large atmospheric depths are negligible. It therefore seems unlikely that any variability in SEP or GCR conditions will influence cloud formation rates at this altitude.

Large electron density variations induced by sporadic SEP events may also affect radio wave propagation in the venusian atmosphere. At Mars, the Mars Express Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument has experienced sporadic blackouts (Withers, 2011) and recent modeling by Norman et al. (2014) suggests that enhanced ionization due to SEP events is a plausible culprit. As we have shown that very large enhancements in the ion production rate within the atmosphere of Venus may occur during strong SEP events, this is an effect that should be considered for future missions to Venus, particularly those carrying low-frequency radar instruments.

5. Conclusion

We have provided updated cosmic ray ionization profiles for the venusian atmosphere, using for the first time a full 3D Monte Carlo modeling approach taking into account the complete GCR spectrum between 1 MeV/nucleon–1 TeV/nucleon and $Z = 1–28$. While our results are comparable to those of previous studies (Borucki et al., 1982; Dubach et al., 1974) near the ionization peak located at ~63 km, our results are significantly different above and below this altitude. We have also evaluated the influence that sporadic SEP events may have on atmospheric ionization rates, with enhancements of up to 6 orders of magnitude in the upper atmosphere and an order of magnitude near the GCR ionization peak. As GCR and SEP cosmic rays dominate ionization below ~100 km altitude in the venusian atmosphere, the rate of cosmic ray-induced ionization directly affects properties such as atmospheric electrical conductivity, cloud charging and atmospheric electrical processes, possibly including lightning. The results of the present study serves as the basis for currently ongoing investigations into venusian atmospheric conductivity and electrical phenomena.

Through the process of ion-induced nucleation of sulfuric acid onto ions, it is plausible that cosmic ray-induced ionization may influence cloud formation in the venusian atmosphere (Aplin, 2013, 2006). However, this process is predicted to operate near ~40 km, where we have shown that the variability in ionization rate due to changing SEP and GCR conditions is minimal. Thus we do not expect that different cosmic ray conditions would have a strong influence on cloud formation rates due to ion-induced nucleation. On the other hand, it’s interesting to note that the peak in GCR ionization occurs within the main cloud deck near ~60 km, and that transient SEP events may enhance ionization rates at this altitude by over an order of magnitude. It therefore seems plausible that such pronounced short-term variability may influence chemical and electrical processes that operate within this region.

Acknowledgments

We wish to thank the UCL Graduate School and Sparebank 1 SR-Bank for funding which enabled TAN to carry out this research. LRD is supported by a UK Space Agency Aurora Fellowship.

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