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Runaway breakdown in the Jovian atmospheres

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[1] Using detailed Monte Carlo calculations, the properties of runaway breakdown in the atmospheres of the four gas giant planets in our solar system are investigated, and the runaway avalanche lengths and average runaway electron kinetic energies are presented as a function of atmospheric electric field strengths. The runaway breakdown threshold field for the Jovian atmospheres is found to be 10 times smaller than the conventional breakdown field when hydrometeors are present, compared to 3 times smaller for Earth's atmosphere, indicating that runaway breakdown processes may be much more efficient in the gas giants than on Earth. In the Earth's atmosphere, runaway breakdown is known to produce large bursts of x-rays and gamma-rays from thunderstorms, such as terrestrial gamma-ray flashes, and may play a role in lightning initiation. These results suggest that runaway breakdown may play an important role in thunderstorm and lightning processes on the Jovian planets as well. **Citation:** Dwyer, J. R., L. M. Coleman, R. Lopez, Z. Saleh, D. Concha, M. Brown, and H. K. Rassoul (2006), Runaway breakdown in the Jovian atmospheres, *Geophys. Res. Lett.*, *33*, L22813, doi:10.1029/2006GL027633.

1. Introduction

[2] Runaway breakdown in gaseous media occur when the magnitude of the effective drag force experienced by fast electrons is less than the electric force acting on those electrons [*Gurevich, Milikh and Roussel-Dupré*, 1992]. Such "runaway" electrons can accelerate up to nearly the speed of light and gain large amounts of energy. As the runaway electrons collide with gas atoms, they produce "knock-on" electrons that can also run away, resulting in an avalanche of relativistic electrons that increases exponentially with both time and distance. The runaway avalanche can generate large amounts of ionization plus x-rays via bremsstrahlung interactions with the gas atoms [*Gurevich and Zybin*, 2001].

[3] The x-rays generated by runaway breakdown in the Earth's atmosphere have been observed directly from thunderstorms and lightning [e.g., *Parks et al.*, 1981; *Eack et al.*, 1996; *Moore et al.*, 2001; *Dwyer et al.*, 2003, 2004, 2005] and from space in the form of terrestrial gamma-ray flashes (TGFs) [*Fishman et al.*, 1994; *Smith et al.*, 2005], indicating that runaway breakdown is a common process in our atmosphere. Indeed, runaway breakdown has been proposed as a mechanism for lightning initiation [*Gurevich et al.*, 1997, 1999; *Dwyer*, 2005], since the runaway breakdown threshold electric field, E_{th}, in air is only 284 kV/m at 1 atmosphere under standard conditions [*Dwyer*, 2003], nearly an order of magnitude below the conventional breakdown field for clear air, $E_{\mathrm{b}} \sim 3000$ kV/m [*Raether*, 1964]. Over a wide range of conditions, both E_{th} and E_{b} scale with the number density of the gas, so at thunderstorm altitudes, at 5 km above sea level, E_{th} is reduced to 150 kV/m but is still an order of magnitude below the conventional breakdown field. Furthermore, the maximum electric field observed inside thunderstorms on Earth is sometimes found to exceed the local value of E_{th} but is never near the conventional breakdown field [*MacGorman and Rust*, 1998; *Marshall et al.*, 2005]. It is possible that the presence of hydrometeors may lower the ambient field necessary to initiate conventional breakdown by creating localized enhancements in the electric field. However, even when the effects of hydrometeors are included the runaway breakdown threshold is still about a factor of 3 below the field necessary for conventional breakdown [*Solomon et al.*, 2001]. In addition, positron and x-ray/gamma-ray feedback can dramatically increase the flux of runaway electrons to the point where the electric field is rapidly discharged by the large amount of ionization generated [*Dwyer*, 2003; *Babich et al.*, 2005].

[4] While considerable amounts of theoretical and observational work has been done on runaway breakdown in the Earth's atmosphere, no observations have been attempted and little theoretical work has been done on runaway breakdown in other atmospheres such as the hydrogen/helium atmospheres of the four Jovian planets. In this paper, we present the results of detailed Monte Carlo simulations of runaway breakdown in the atmospheres of Jupiter, Saturn, Uranus and Neptune, characterizing how runaway breakdown may occur and illuminating the role it may play in electrical processes in those planet's atmospheres. This work may be relevant to understanding lightning processes that are known to occur on Jupiter and Saturn and probably Uranus and Neptune [*Desch et al.*, 2002; *Fischer et al.*, 2006]. It may also help guide future observations of Jovian gamma-ray flashes, analogous to the terrestrial gamma-ray flashes seen from the Earth.

2. Jovian Atmospheres

[5] Unlike the Earth's atmosphere, which is primarily nitrogen and oxygen, the atmospheres of the Jovian planets are primarily hydrogen and helium, with only trace amounts of other species [*Niemann et al.*, 1998]. Furthermore, the properties of runaway breakdown in the Jovian planetary atmospheres are almost completely governed by the hydrogen and helium components, so the other species, *e.g.* methane, water, etc., can be safely ignored. There is

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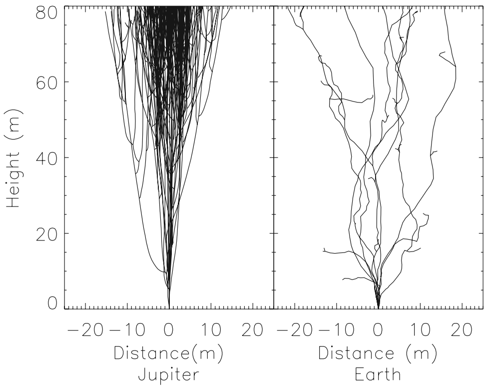

Figure 1. Results of the Monte Carlo simulation of runaway breakdown showing runaway avalanches. The trajectories are individual runaway electrons. Figure 1 (left) is for the Jovian atmospheres (13.6% helium) and Figure 1 (right) is for air, both at the same density and the same electric field E = 300 kV/m.

some uncertainty in the helium abundances in the gas giants, but the mole fraction is approximate solar (13.6% helium), with estimates ranging from 13.6% for Jupiter [*Atreya et al.*, 2003], 15% for Uranus, and 19% for Neptune [*Fegley*, 1995]. Recent estimates for Saturn's atmosphere give values in the range 10–14%, larger than earlier values that showed a marked depletion of helium [*Atreya et al.*, 2003]. In this study, we will show that the properties of the runaway breakdown are not sensitive to these differences in the helium abundances, and so results will be presented for the solar helium abundance value of 13.6%.

[6] The observations of lightning on Jupiter indicate that it is likely to occur at depths of 2–8 bar [*Borucki and Williams*, 1986; *Little et al.*, 1999] and is probably associated with water/ice clouds similar to those on Earth [*Desch et al.*, 2002]. HF radio emission, suggestive of lightning, has been observed from Saturn [*Fischer et al.*, 2006]. However, no visible lightning flashes have been observed, leading to the speculation that perhaps the discharges occur deeper in Saturn's atmosphere than in Jupiter's. Because lightning and hence runaway breakdown likely occur over a wide range of atmospheric pressures, and in order to aid in the comparison with runaway breakdown in Earth's atmosphere, we present all results for gas number densities equal to that of air at 1 atmosphere under standard conditions, i.e. $n = 2.69 \times 10^{25}$ m^{-3}. This density corresponds to a pressure of 0.48 bar in Jupiter [*Niemann et al.*, 1998; P. D. Parrish, personal communication, 2006]. No generality is lost here, since all quantities can then be calculated for other gas densities using a simple scaling law [*Lehtinen et al.*, 1999].

3. Monte Carlo Simulation

[7] The Monte Carlo simulation of runaway breakdown used in this study was developed by J. R. Dwyer at Florida Tech and is the same simulation reported on elsewhere [*Dwyer*, 2003, 2004, 2005; *Dwyer and Smith*, 2005; *Coleman and Dwyer*, 2006]. The simulation can model runaway breakdown in any gaseous medium for both spatially and time varying electric and magnetic fields. This simulation includes, in an accurate form, all the important interactions involving runaway electrons, positrons, x-rays and gamma-rays. These interactions include energy losses through ionization and atomic excitation and Møller scattering. The simulation fully models elastic scattering using a shielded-Coulomb potential and includes bremsstrahlung production of x-rays and gamma-rays and the subsequent propagation of the photons, including photoelectric absorption, Rayleigh scattering, Compton scattering and pair production. In addition, the simulation includes positron propagation and the generation of energetic seed electrons via Bhabha scattering of positrons and via Compton scattering and photoelectric absorption of energetic photons. The effects of the feedback mechanisms involving positrons and energetic photons, which are found to be important under some circumstances, are included in the simulations [*Dwyer*, 2003], but an in depth discussion of these feedback effects will be left to future work and will not be discussed here.

[8] Figure 1 shows two examples of runaway avalanches, one for the Jovian atmospheres and one for the Earth's atmosphere, both with similar conditions at the electric field strength 300 kV/m. As can be seen, the straggling of the runaway electron trajectories is much less pronounced in the Jovian atmosphere due to the smaller elastic scattering cross-sections for hydrogen and helium compared with air. The reduced elastic scattering has a large impact upon the properties of runaway breakdown as will be discussed below [also see *Lehtinen et al.*, 1999]. In addition, the avalanche multiplication of the runaway electrons is much larger for the Jovian atmospheres.

[9] Three important quantities for describing runaway breakdown are the runaway breakdown threshold electric field, E_{th}, the avalanche length, λ, and the average kinetic energy of the runaway electrons, K. E_{th} is the electric field strength above which the number of runaway electrons increases exponentially with distance. The avalanche length is the distance required for the number of runaway electrons to increase by 1e, and the average kinetic energy is calculated at the end of the avalanche region for all runaway electrons.

[10] At thunderstorm altitudes in the Earth's atmosphere, the Earth's magnetic field has a negligible effect on properties of runaway breakdown. However, at high altitudes (e.g. >30 km) the magnetic field can have a significant impact, suppressing runaway breakdown when the magnetic field and electric field are not aligned [*Lehtinen et al.*, 1999; *Babich et al.*, 2001]. Because Jupiter's magnetic field at the top of its atmosphere is about an order of magnitude larger than the Earth's field, we have investigated two cases for the Jovian atmospheres: one with and one without a magnetic field. Since most lightning on Jupiter is observed to occur between 30°–55° latitudes [*Cook et al.*, 1979; *Little et al.*, 1999] and at a depth below 2–8 bar, we will consider the typical case of 45° at an atmospheric pressure of 2 bar. Because the influence of the planetary magnetic field on the runaway breakdown decreases with increased atmospheric pressure, 2 bar should correspond to the case where the impact of the magnetic field on runaway breakdown is the largest in Jupiter's atmosphere.

[11] Avalanches were simulated at a minimum of 11 different electric field strengths, with 5 runs each, to

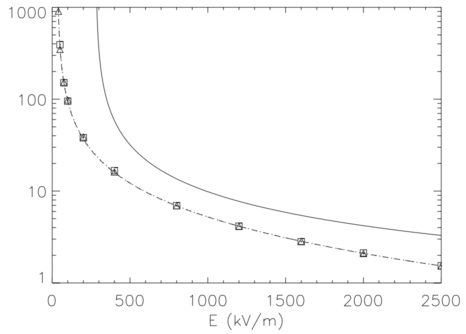

Figure 2. Monte Carlo calculations of λ for the Jovian atmospheres and for air. The data points indicate the mean value of λ as calculated by 5 runs of the Monte Carlo at each electric field magnitude. The solid curve is for air with no magnetic field. The triangles are for the Jovian atmospheres with no magnetic field and the squares are for the Jovian atmospheres with a magnetic field. The dash-dotted line is the empirical curve given by equation (1).

calculate λ and K. Each avalanche was started with 10 energetic electrons propagating at the start of the avalanche region from the same point in space with energies distributed randomly over an exponential distribution with the mean kinetic energy at 7 MeV. Each avalanche was allowed to run for a distance of approximately 6λ [see *Coleman and Dwyer*, 2006].

[12] The results of the simulations for the Jovian atmospheres are presented in Figure 2, which plots λ versus E, with and without a magnetic field. At 45° latitude, the dipole model gives that the angle between the magnetic and electric fields is 27°, and the magnetic field strength is 6.8 gauss. Because all parameters are scaled to the number density $n = 2.69 \times 10^{25}$ m^{-3} (0.48 bar), a magnetic field strength of 6.8 gauss at 2 bar ($n = 7.0 \times 10^{25}$ m^{-3}) is equivalent to a 2.6 gauss field at $n = 2.69 \times 10^{25}$ m^{-3}, just as a 680 kV/m electric field at 2 bar, for example, is equivalent to a 260 kV/m field at 0.48 bar. Also shown are the avalanche lengths for air with no magnetic field. The curve through the case without a magnetic field is an empirical fit of the formula

$$\lambda = \frac{6570}{E + 2.91 \times 10^{-4} E^2 - 32.9} [m], \qquad (1)$$

where E is the electric field strength measured in kV/m. Away from the threshold field, the curve for the magnetic field case is almost identical to that with no magnetic field.

[13] The threshold field is found to be 36.1 kV/m when no magnetic field is included, compared with 284 kV/m for air. The magnetic field increases the threshold electric field to 40.5 kV/m. Changing the amount of helium between 0–20% does not significantly impact the avalanche length or the runaway threshold. For example, $E_{\rm th}$ = 36.4 kV/m for 0% helium and $E_{\rm th}$ = 35.8 kV/m for 20% helium, both with no magnetic field.

[14] Figure 3 shows the average kinetic energy of runaway electrons in the avalanche as a function of electric field strength for both the Jovian and terrestrial atmospheres. The average is calculated for all runaway electrons reaching the end of the avalanche region with kinetic energies above the runaway kinetic energy threshold. This average would be the same as that measured by an *in situ* instrument measuring the energetic electron flux.

4. Discussion

[15] The minimum ionization energy per unit length (the effective drag force) for fast electrons in air has a value of 216 keV/m. Naively, one might expect this to give a runaway breakdown threshold electric field of 216 kV/m. However, simulations show that elastic scattering of electrons with atomic nuclei increases the threshold by 30% to 284 kV/m. For a hydrogen/helium atmosphere the minimum ionization energy per unit length is 33.5 keV/m, which is 6.4 times smaller than the value for air due to the Z dependence of the ionization rate. However, because the elastic scattering is very sensitive to changes in atomic number, scaling as $\sim Z^2$ [*Jackson*, 1975], the role of elastic scattering for the Jovian atmospheres is much reduced compared with air, bringing the runaway breakdown threshold down closer to the minimum ionization value, i.e. $E_{\rm th}$ = 36.1 kV/m, which is only 8% above 33.5 kV/m. As a result, the runaway breakdown threshold for the Jovian atmospheres is 7.9 times smaller than the threshold for air. For similar reasons, the avalanche lengths for the Jovian atmospheres are relatively short compared with air. This fact allows the runaway avalanches to grow much more rapidly in the Jovian atmospheres than would occur under similar conditions for air. As a result, runaway breakdown in the gas giants can produce larger fluxes of runaway electrons than in the Earth's atmosphere, thereby producing more ionization, for similar electric field strengths, length scales and electric potential differences.

[16] The independence of the properties of runaway breakdown on the He/H$_2$ ratio can be understood by the fact that for a given molecular number density the energy loss of a minimum-ionizing electron scales with the number of electrons per molecule in the gas. There are about 15 electrons/molecule for air, 2 electrons/molecule for H$_2$, and 2 electrons/molecule for He. Therefore, the

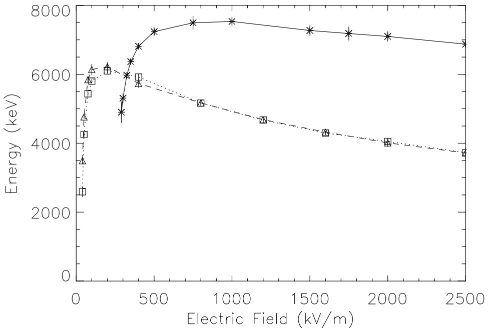

Figure 3. Average kinetic energy of runaway electrons entering a plane at a distance of 6 avalanche lengths, λ, from the start of the avalanche region. The solid curve (asterisks) is for air with no magnetic field. The dashed line (triangles) is for the Jovian atmospheres with no magnetic field and the dotted line (squares) is for the Jovian atmospheres with a magnetic field.

He/H_2 ratio should not be important, and a hydrogen-helium atmosphere has a factor of 15/2 less energy loss per unit length than air as discussed in the previous paragraph.

[17] As can be seen in Figure 2, the ambient magnetic field present in Jupiter's atmosphere does not affect the avalanche length significantly for values not too close to the thresholds. However, as presented above, the runaway threshold electric field does increase slightly, by about 12%, in the presence of the magnetic field. The Lorentz force acting on the runaway electrons moving with $v \sim c$ from the component of the magnetic field perpendicular to the electric field has a magnitude of 35 keV/m, which is comparable to force from the electric field when near threshold (and the effective drag force). At higher electric field values, the electric force completely dominates and the influence of the magnetic field is much smaller. At greater number densities, i.e. greater atmospheric pressures, the electric fields shown in Figures 2 and 3 scale up with the number density. However, the ambient magnetic field remains constant at 6.8 gauss. As a result, for parts of the thunderstorm deeper than 2 bar, the avalanche lengths and threshold fields will lie between the two cases presented here. For the other Jovian planets, the magnetic fields near the upper atmosphere are smaller than Earth's and so it should be possible to ignore the magnetic fields. This is especially true for Saturn where the lightning is also inferred to occur deep in the atmosphere at about the 10 bar level [*Desch et al.*, 2006].

[18] By several measures, runaway breakdown is more efficient in the Jovian atmospheres than in the Earth's atmosphere. As discussed above, the runaway breakdown threshold field is 7.9 times smaller than the terrestrial value. A more useful comparison is how the runaway breakdown threshold compares with the conventional breakdown field for the Jovian atmospheres. The conventional breakdown field for hydrogen, the principle component, is often reported to be about half the value for air, or 1500 kV/m [*Yair et al.*, 1995; *DeBitetto and Fisher*, 1956; *Cobine*, 1941]. However, this threshold involves the Townsend discharge mechanism in which electrons are liberated from a cathode. For the case inside a Jovian thundercloud, where the water vapor, cloud droplet, ice crystal and hydrometeor content can change dramatically, it is not at all clear what the conventional breakdown field should be. A similar problem exists for terrestrial thunderstorms [*Solomon et al.*, 2001], which has led to the current debate about the lightning initiation mechanism.

[19] Based upon estimates of the ionization rate in hydrogen compared with nitrogen, *Yair et al.* [1995] argued that the breakdown field for molecular hydrogen should be 2.3 times lower than for nitrogen. They then lowered the breakdown field by a factor of 3 to include effects from hydrometeors, concluding that the breakdown field is about 1000 kV/m at 2 bar. This corresponds to a breakdown field of 400 kV/m at $n = 2.69 \times 10^{25}$ m^{-3}, which is a factor of 10 larger than the runaway breakdown threshold field. In comparison, for Earth's atmosphere, the conventional breakdown field for clear air is about 3000 kV/m. Including hydrometeors brings the breakdown field down to roughly 1000 kV/m, which is a factor of 3 greater than the runaway breakdown threshold field.

[20] Because the avalanche lengths and threshold are so dramatically different between the Jovian and Earth's atmospheres, it is not entirely obvious how the energy spectra of the runaway electrons will differ from one atmosphere to the other. As can be seen in Figure 3, the average kinetic energy can differ by up to a factor of 2. However, the average electron energy remains in the MeV range in all cases. As a result, due to the relatively flat bremsstrahlung spectrum produced from energetic electrons, most of the x-ray energy generated by the runaway breakdown will be generated in the MeV range, i.e. as gamma-rays, in the Jovian atmospheres as it is in air.

[21] In summary, we have found that the properties of runaway breakdown in the Jovian atmospheres differ substantially from those of the Earth's atmosphere. Moreover, these properties are not sensitive to composition differences that may occur for the 4 gas giants and only change slightly when the planetary magnetic fields are included, for atmospheric depths at which lightning is likely to occur. Based upon the results presented here, it is possible that runaway breakdown is an important process for thunderstorm electrification, lightning initiation and gamma-ray flashes in the gas giants, and so further investigations are warranted. Because the physics of thunderstorm electrification, lightning initiation and gamma-ray flashes in the Earth's atmosphere are not well understood [*Rakov and Uman*, 2003], improving our understanding of planetary lightning and the role of runaway breakdown there may shed light on these processes for our planet as well.

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