Aurora in Martian Mini Magnetospheres

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Auroral processes are active at Mars, which lacks a global dynamo field. Observations of relatively faint UV emission in crustal magnetic fields demonstrate that upper atmospheric species are excited in cusp regions, presumably by incident particles directed along cusp flux tubes. Measurement of particles and fields above the crustal fields, including counterstreaming energized ion and electron populations, suggest that electrons are accelerated downward into the atmosphere, at least partly by a quasi-static field-aligned potential. A variety of additional mechanisms may be contributing to aurora, including day-night transport of ionospheric particles, waves and reconnection, and particle acceleration in the magnetotail current sheet. Future observations and modeling should help to distinguish between the different mechanisms, constrain the variation in auroral acceleration and brightness at different wavelengths, correlate auroral activity with external conditions, and determine the importance of auroral processes for upper atmospheric electrodynamics and atmospheric escape.

1. INTRODUCTION

Mars is one of the earliest solar system bodies to have been visited by spacecraft, and one of the most frequently visited. So it may seem surprising that aurora were not discovered there until the twenty-first century, after the discovery of aurora on seven (Jupiter, Saturn, Uranus, Neptune, Io, Europa, and Ganymede) other solar system bodies, including three smaller than Mars and with more tenuous atmospheres [*Mauk and Bagenal*, this volume].

Aurora at Mars was not reported until 2005 for two reasons. First, no spacecraft successfully visited Mars with the right combination of instrumentation and observing plan to detect faint, small-scale, UV emission until Mars Express (MEX) arrived in late 2003. The early Mariner spacecraft, 6 and 7 (flybys) and 9 (orbiter), carried UV spectrometers with the appropriate wavelength range and spectral resolution, but did not prioritize nightside observations. Subsequent orbiting spacecraft, such as Viking 1 and 2, Phobos 2, Mars Global Surveyor (MGS), and Mars Odyssey lacked any UV instruments at all. Only MGS passed sufficiently close to Mars to easily detect the particle and field signatures of auroral acceleration, and these were not recognized until after the first report of UV auroral emission [*Bertaux et al.*, 2005].

Second, until the late 1990s, there was little reason to suspect that auroral processes were active at Mars. The magnetic field observations made by early spacecraft to visit Mars suggested that it was a Venus-like unmagnetized planet with a magnetosphere induced via interaction between the flowing solar wind and the conducting planetary ionosphere [*Luhmann et al.*, 1992]. Though there had been reports [*Fox and Stewart*, 1991] of UV auroral-like emission at Venus, which lacks a planetary magnetic field, most studies assume that aurora result from the acceleration of charged particles

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along *planetary* magnetic field lines into an atmosphere. Thus, while planetward acceleration of electrons into the Martian atmosphere was considered as a process for forming a thin nightside ionosphere [*Haider et al.*, 1992; *Fox et al.*, 1993], Mars was believed to lack the planetary magnetic field to focus precipitating particles. Hence, there was little reason to search for faint Martian aurora using in situ spacecraft or terrestrial telescopes.

Magnetic field measurements from MGS confirmed in 1997 that Mars lacked a significant global magnetic field and also revealed the presence of localized regions of intense crustal magnetization [*Acuña et al.*, 1998]. Likely to have been created in the presence of an ancient global dynamo, crustal fields are strongest and most concentrated beneath the oldest portions of the Martian crust. Closed loops of crustal magnetic field extend well above the main peak of the Martian ionosphere (near 120 km) and the Martian exobase region near 200 km [*Mitchell et al.*, 2001]. Though nonglobal, the discovery of crustal fields revealed the possibility that aurora could occur at Mars.

Given the historical and scientific context outlined above, we review studies of Martian aurora that have progressed over the last 6–7 years. In sharp contrast to terrestrial aurora, it is currently possible to become familiar with most or all of the relevant literature on Martian aurora rather quickly. Here we describe the observations of auroral emission and particle acceleration at Mars (section 2), the mechanisms that may explain the observations (section 3), and the consequences that these observations have for ongoing and future investigation of the Martian upper atmosphere, plasma environment, and climate (section 4).

2. OBSERVATIONS

2.1. UV Emission

The first observation of aurora at Mars was fortuitous. In August 2004, the Spectroscopy for the Investigation of Characteristics of the Atmosphere of Mars (SPICAM) UV spectrometer on MEX conducted limb scans of the nightside upper atmosphere in a successful effort to detect nightglow [*Bertaux*, 2005]. During one of the scans (Figure 1a), a large but spatially confined increase in UV brightness was recorded in all five groups of pixels read from the instrument during the observation [*Bertaux et al.*, 2005]. Further analysis showed that the emission came along a line of sight that passed through a region of nearly vertical crustal magnetic field, analogous to the terrestrial polar cusps. The duration of the increase in brightness was used to infer the width of the emitting region (~30 km), and the time offset between the brightness increase in the five groups of pixels was used to infer the distance between the spacecraft and the emitting region (~450 km). The distance corresponded to the location of vertical crustal magnetic field at an altitude of ~130 km, near the typical altitude of the main ionospheric peak.

The average SPICAM spectrum recorded shortly before and after the unusual observation was subtracted from the observation to obtain a spectrum of the emission coming

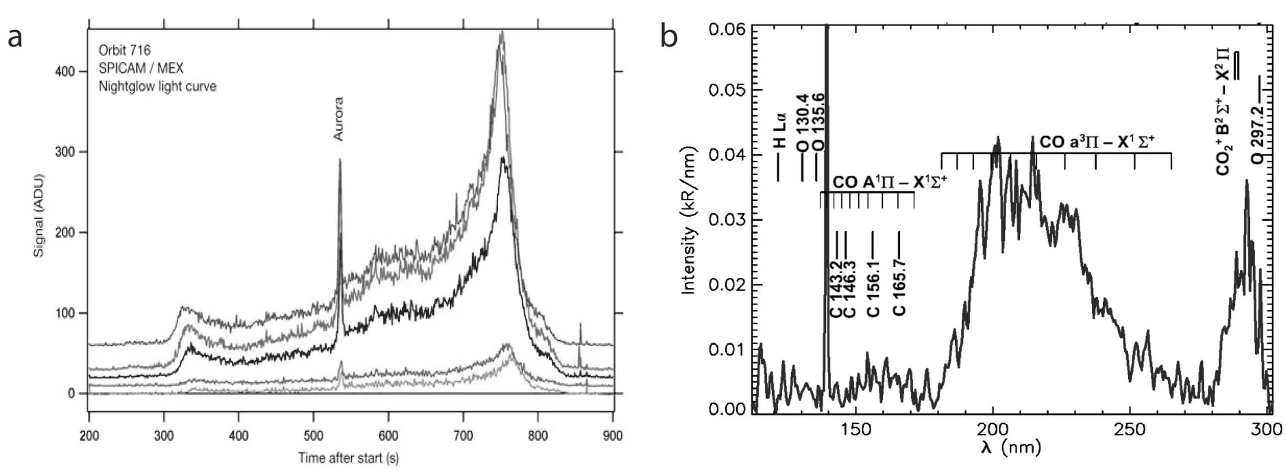

Figure 1. (a) SPICAM count rate in each of five spatial pixels as a function of time for Mars Express (MEX) on 11 August 2004. From *Bertaux et al.* [2005]. Reprinted by permission from Macmillan Publishers Ltd: *Nature*, copyright 2005. The observation took place on the nightside, and brightness increased as MEX progressed toward the dayside. A spike in brightness associated with auroral emission is identified ~525 s after the start of the observation. (b) The spectrum of the aurora is obtained by subtracting average spectral information from the measurements immediately before and after the brightness spike [from *Leblanc et al.*, 2006].

from the cusp [*Bertaux et al.*, 2005; *Leblanc et al.*, 2006]. Emission was identified from species common in the Martian upper atmosphere (Figure 1b). The CO Cameron Bands ($a^3\Pi - X^1\Sigma^+$; 180–240 nm) were brightest, at ~2 kR, and CO_2^+ doublet emission ($\tilde{B}^2\Sigma_u^+ - \tilde{X}^2\Pi_g$; 289 nm) was also clearly identified with brightness ~200 R. A marginal detection of emission from atomic oxygen (^1S–^3P; 297.2 nm) with brightness ~90 R was also reported. From this observation, it was inferred that Martian upper atmospheric species emitted in a narrow crustal field cusp region after excitation by a flux of incident particles. Mars, for the first time, was known to have aurora.

The discovery of aurora prompted MEX and the SPICAM team to conduct a nightside observing campaign dedicated to identifying auroral emission. Nine additional auroral events from six orbits have been reported, and all occurred near the strong crustal magnetic fields in the southern hemisphere of Mars [*Leblanc et al.*, 2008]. Correlation of the emission regions with maps of the average Martian magnetic field topology produced in the work of *Brain et al.* [2007] showed that aurora occur near the boundary between open and closed magnetic field lines, similar to terrestrial aurora. All but one of the events was recorded using a nadir viewing geometry. All events were substantially fainter in the Cameron bands (~105–825 R) than the first event, although the first event was recorded when SPICAM was limb pointing, which may have allowed for a longer path length through the emission. Emission by CO_2^+ at 289 nm was detected for all but one event (10–160 R), and emission from atomic oxygen at 297.2 nm was not reported. It was not possible to obtain a reliable estimate of how often auroral emission can be detected due to the varying orbit geometry of MEX; though 66 orbits were examined (most or all near crustal fields), more than half had very unfavorable SPICAM viewing geometry.

2.2. Particles and Fields

Reports of auroral emission prompted examination of in situ particle and field measurements for evidence of auroral plasma processes near the Martian crustal fields. MGS carried both a vector magnetometer and an electrostatic analyzer designed to measure suprathermal electrons and from 1999 through 2006 was in a nearly circular orbit at ~400 km altitude with fixed local time near 02:00 local time on the nightside. Examination of these observations revealed hundreds of events in which an energized electron population (peak energy: ~200 eV to 4 keV) was evident, analogous to energized electrons measured in terrestrial auroral regions [*Brain et al.*, 2006]. One such event near a strong crustal field region is shown in Figure 2. An energized electron population is evident in regions where the horizontal components of magnetic field are small compared to the vertical component (i.e., in a cusp region). The electron pitch angle distributions reveal one-sided loss cones in these regions (with fewer electrons moving upward from below the spacecraft), indicative of an open magnetic field topology. The energized electrons are observed to be near regions with two-sided loss cones, indicative of a closed field topology. Nearby perturbations in one of the horizontal magnetic field components are consistent with vertical (field-aligned) currents with current density (~1 μA m^{-2}) comparable to terrestrial field-aligned currents. Overall, the event reveals an auroral-like energized incident electron population in a crustal field cusp region, near a field-aligned current region and the boundary between open and closed fields. It is possible that such a population could impact the atmosphere, causing UV emission in cusps.

Hundreds of "auroral" events have been identified in MGS observations, with ~13,000 individual auroral-like energized electron energy spectra. Given the repeatable orbit of MGS during the period in which these events were recorded, the energized electron distributions could be correlated with geographic location and external conditions without orbital bias. Energized electron distributions are measured predominantly in the southern hemisphere of Mars, near strong and moderate crustal magnetic fields (Figure 3). Both their existence in observations and their characteristics are observed to vary with location, Martian season, solar wind pressure, and the clock angle of the upstream interplanetary magnetic field [*Brain et al.*, 2006]. Further, the most energetic events are more likely to be observed during periods of disturbed solar wind conditions (typically the result of a passing coronal mass ejection).

Caution must be taken when interpreting the particle and field results described above. First, not all of the "auroral events" are similar. For example, *Halekas et al.* [2008] noted that each of the MGS events could be classified as one of three types: localized events predominantly near strong crustal fields (similar to Figure 2 above), extended (longer duration) events located mostly near moderate or weaker crustal fields, and current sheet events where energized electrons were identified in current sheets on the Martian nightside. The typical properties of the electron distributions and local magnetic topology differ for each of the three types of events, suggesting the possibility that the physical mechanisms responsible for the observations differ as well. Next, it is not certain that all of the MGS observations result in the deposition of energized electrons into the Martian upper atmosphere. Since the magnetic field below the spacecraft should increase when it is above crustal fields, it is likely that some (or even most) of the incident flux is adiabatically reflected before it can reach the collisional atmosphere. Finally, though the number of "auroral events" in each location

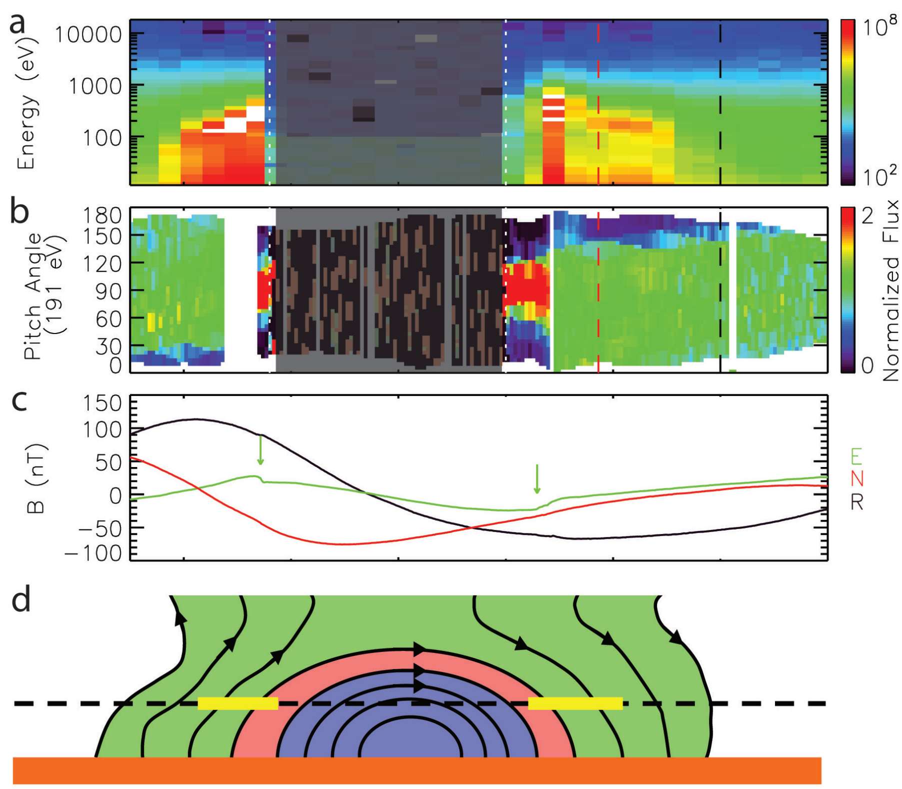

Figure 2. Auroral electron event observed over 6.5 min at 400 km altitude near strong crustal fields by *Brain et al.* [2006]. (a) Electron energy flux versus time. (b) The 191 eV electron pitch angle distribution versus time (with each distribution normalized separately). (c) Radial (black), eastward (green), and northward (red) vector magnetic field components. (d) A cartoon of the spacecraft trajectory through open and closed magnetic field lines, highlighting where auroral-like electron distributions are observed.

varies with external conditions, it is not clear whether changes in external conditions prevent energized electron distributions from forming, or simply move flux tubes containing energized electrons to locations outside of the 02:00 local time orbit of MGS.

While MGS measured suprathermal electrons and magnetic field from a circular orbit, MEX measures suprathermal electrons and ions from an elliptical orbit. Using the Analyzer of Space Plasma and Energetic Atoms (ASPERA-3) ion mass analyzer and electrostatic analyzer, *Lundin et al.* [2006b, 2006a] have identified a number of "inverted-V" events near local midnight. The events are characterized by downward traveling electrons and upward traveling planetary ions, each with a peak in the energy distribution ranging from tens to hundreds of eV for electrons and hundreds to few keV for ions (Figure 4a). The events occur when the spacecraft is above moderate or strong crustal fields, though it can be difficult to unambiguously associate the events with specific crustal field cusps due to the usually higher altitude of the spacecraft (up to ~8000 km) compared to MGS. Events are clustered near midnight, with a preference for the "premidnight" sector.

Since the ASPERA measurements are made at a variety of altitudes, it is also possible to explore the altitude variation in peak energy of the accelerated particle distributions. Within individual events, the energy of the electron beams takes up an increasingly larger fraction of the total (ion + electron) beam energy as altitude decreases [*Lundin et al.*, 2006a]. The same is true generally, as shown in Figure 4b. The ion beam energy relative to the total beam energy increases with altitude, consistent with a region extending up to ~2000 km altitudes that accelerates ions upward and electrons downward. One mechanism that could achieve this is a quasi-static field-aligned potential, as has been proposed for terrestrial aurora.

Further, ASPERA measures ion mass in addition to ion energy. Therefore, the observations reveal additional clues about the possible particle acceleration mechanisms. Analysis

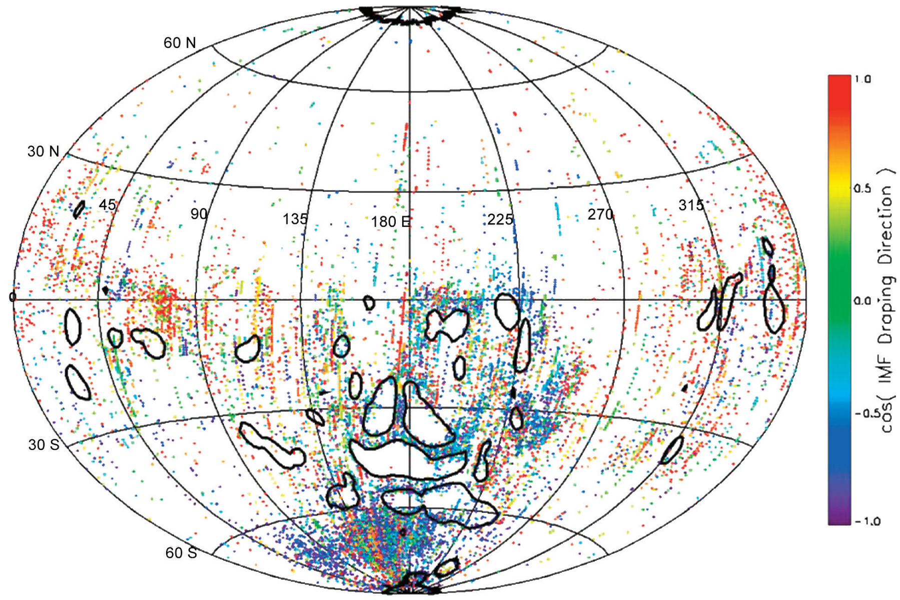

Figure 3. Geographic locations of ~13,000 peaked electron distributions recorded by Mars Global Surveyor from 400 km altitude at 02:00 local time. The location of each distribution is colored according to the cosine of a proxy for the clock angle of the upstream interplanetary magnetic field (essentially the orientation of the external magnetic field). Locations of crustal field regions that are typically closed to the solar wind at 400 km are outlined in black.

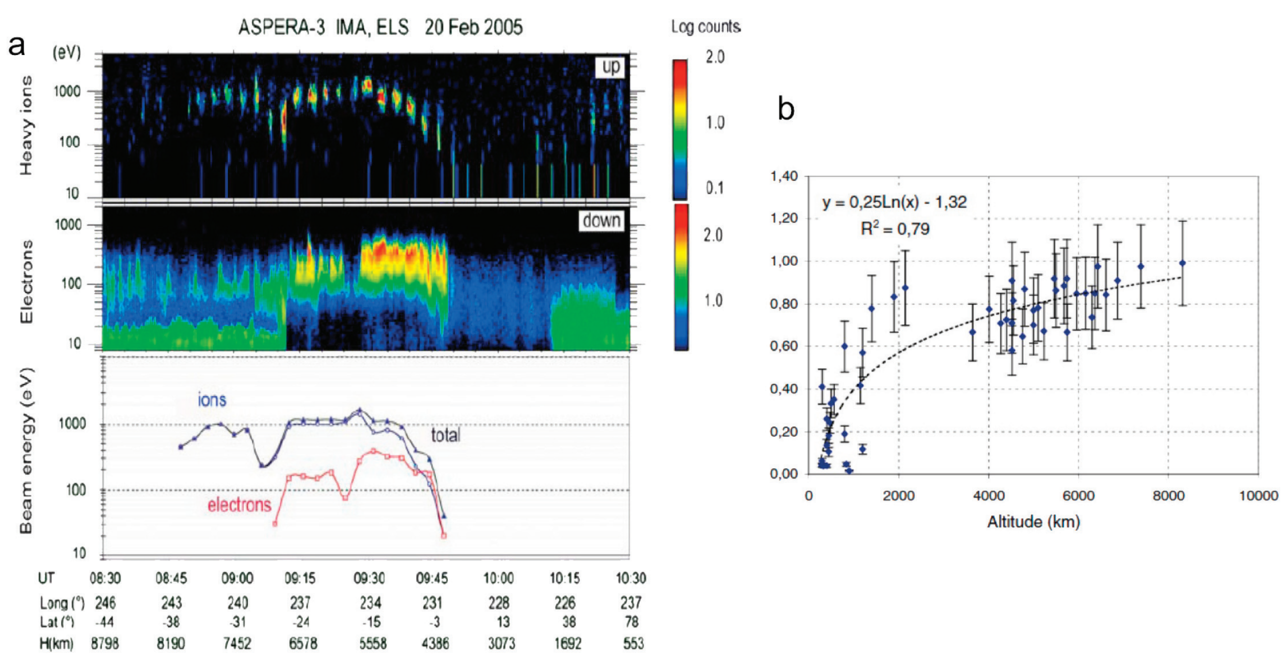

Figure 4. Inverted-V particle events observed by MEX ASPERA. (a) Time series observations of planetary (top) heavy ions and (middle) electrons, along with the (bottom) peak energy of the particle beams. (b) Fraction of the total beam energy (ion + electron) taken up by ions. From *Lundin et al.* [2006a].

of the ion beams for some ASPERA events shows that lower-mass species (e.g., O^+) have lower energy than high-mass species (e.g., CO_2^+) [*Lundin et al.*, 2006a]. If the ions were all accelerated from the same initial energy, then the observations imply that a mass-dependent acceleration mechanism must operate on these flux tubes; that is, a field-aligned electrostatic potential is not capable of completely explaining the observations.

One main challenge in observational studies of Martian auroral processes is demonstrating that the three different classes of observations (UV emission, MGS electrons and magnetic field, MEX ions and electrons) are related. Fortunately, MEX carries both SPICAM and ASPERA. It has been possible to correlate the UV emission with the particle measurements in a few instances [*Leblanc et al.*, 2008]. During some auroral emission events, ASPERA measured narrow electron beams at a time when SPICAM was nadir oriented, observing enhanced UV emission coming from a magnetic cusp region directly below the spacecraft. Further, the Mars Advanced Radar for Subsurface and Ionosphere Sounding instrument on MEX simultaneously recorded an enhancement in the total electron content of the upper atmosphere below the spacecraft. Accurate correlations between in situ particle and UV measurements are complicated by curvature of magnetic field lines below the spacecraft. Regardless, these observations lend credence to the idea that accelerated downgoing electrons measured at spacecraft altitude encounter the atmosphere and lead to both enhanced ionization and emission.

3. MECHANISMS

Auroral emission occurs at Mars in crustal magnetic field cusp regions, as do auroral-like particle acceleration processes. The emission and particle acceleration signatures are related. But the observations, so far, suggest that Martian aurora is relatively weak (faint emission, small acceleration) by terrestrial standards. So how do the mechanisms responsible for aurora in the small-scale crustal fields compare to mechanisms discussed for terrestrial and other planetary aurora? The cartoon in Figure 5 provides an overview of the various mechanisms that are discussed at present for Mars.

The observed brightness ratio between different auroral emission lines can yield insight into the energy of the particle population responsible for the emission. Analysis of the ratio of CO Cameron band emission to CO_2^+ doublet emission for the auroral emission reported by *Bertaux et al.* [2005] suggested a relatively low-energy (tens of eV) incident electron population excited the upper atmosphere [*Leblanc et al.*, 2006]. It was noted that dayside ionospheric photoelectrons have nearly the correct energy distribution to explain the emission and that the auroral emission could be airglow due to photoelectrons transported from day to night (Figure 5a). Events observed subsequently have a variety of brightness ratios, which are inversely correlated with the peak energy of the electron beam observed above the atmosphere [*Leblanc et al.*, 2008]. Peak energies range from 40 to 350 eV for events where emission and electron beams are observed simultaneously, suggesting that at least some of the events

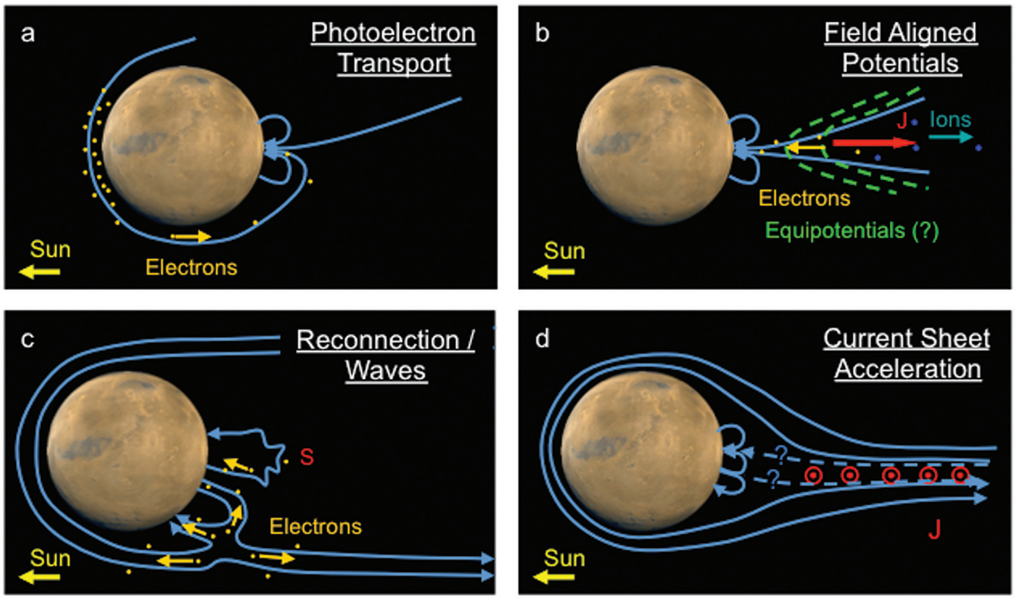

Figure 5. Possible mechanisms for Martian aurora.

cannot be explained by photoelectron transport. Further, *Liemohn et al.* [2007] mapped the magnetic field topology for the *Bertaux et al.* [2005] event using a global plasma model and found that the modeled magnetic field lines connected to the emission site do not cross the Martian terminator. Instead, auroral particles for this event should come from the Martian tail or nightside magnetosheath. Still, low-energy electrons appear to be responsible for a subset of the observations, and transport of electrons from day to night should occur [*Haider et al.*, 2002; *Liemohn et al.*, 2007; *Uluşen and Linscott*, 2008].

Many of the observations presented in section 2 are consistent with the existence of quasi-static field-aligned potentials above cusp regions on the Martian nightside (Figure 5b), analogous to terrestrial auroral particle acceleration [*Marklund*, 2009]. Peaked "inverted-V" particle energy distributions are reminiscent of charged particles observed in field-aligned current regions at Earth [*Brain et al.*, 2006; *Lundin et al.*, 2006b]. Counterstreaming ions and electrons suggest that the acceleration region has been sampled at Mars and extends upward to ~2000 km altitudes or higher [*Lundin et al.*, 2006a], but the typical lower boundary of this region has not been determined. Furthermore, magnetic field perturbations observed near cusp boundaries are consistent with the presence of field-aligned currents above crustal fields [*Brain et al.*, 2006].

Despite the similarities between the Martian and terrestrial measurements, there are still a number of open questions about the ability of this picture to explain any or all of the observations. For example, how and where do the field-aligned currents close? Are auroral acceleration regions long-lived, or do they constantly form and dissipate? Martian crustal field strengths in the ionosphere are weaker than the Earth's magnetic field, with the consequence that the Pedersen conductivity is much higher [*Dubinin et al.*, 2008]. This work concludes that a region of strong parallel electric field is required to sustain field-aligned potential drops above the ionosphere. Alternatively, magnetic field stresses at high altitudes may be periodically dissipated through connection with the conducting ionosphere. Auroral particle signatures have been observed repeatedly in the same locations on several repeating MEX orbits, over periods of weeks, implying that the mechanism is likely to be stable [*Dubinin et al.*, 2009].

Field-aligned potentials are only one possible mechanism for accelerating particles (Figure 5c). For example, based on the mass dependence of the planetary ion energy in inverted-V structures, *Lundin et al.* [2006a] proposed that waves may play a significant role in accelerating ions. Angular ion distributions in the acceleration region reveal evidence for heating or acceleration transverse to the magnetic field [*Dubinin et al.*, 2009]. Magnetic reconnection is also known to occur on the nightside of Mars [*Eastwood et al.*, 2008]. Reconnection has been at least indirectly demonstrated to occur in crustal field cusp regions as well [*Brain*, 2006]. Reconnection near crustal fields is a leading candidate mechanism for the creation of electron conic pitch angle distributions observed on the Martian nightside [*Uluşen et al.*, 2011] and should provide a source of energy for electrons passing near the reconnection diffusion region. The extent to which plasma waves and reconnection contribute to particle acceleration and aurora at Mars is not well determined at present, however.

A final intriguing mechanism is illustrated in Figure 5d. Acceleration of electrons in current sheets on the Martian nightside may result in their propagation into the nightside atmosphere. Many of the most energetic peaked electron distributions recorded by MGS occur in current sheets [*Halekas et al.*, 2008], and current sheets are often observed at low altitudes on the nightside [*Halekas et al.*, 2006]. It is not certain whether the observed current sheets are the main magnetotail current sheet induced at Mars or whether they are independently associated with crustal fields. Their observed geographic distribution is not strongly correlated with crustal field location, suggesting the main magnetotail current sheet extends to very low altitudes on the nightside. However, it is not clear whether or how the observed current sheets provide access for accelerated electrons to the nightside upper atmosphere.

All of the four mechanisms illustrated in Figure 5 may occur at Mars and likely contribute to the observations of auroral processes. Continued analysis and future observations should help to reveal which acceleration mechanisms dominate, how they operate, and where the accelerated particles originate.

4. CONSEQUENCES AND FRONTIERS

4.1. Consequences

Three main types of observation related to Martian aurora have been reported to date, and each suggests further consequences of auroral processes.

Reports of UV auroral emission in cusps naturally lead to questions of whether visible aurora may occur at Mars (Figure 6a), as they do at Earth. Early estimates are divided on this point. Certainly, there are species in the Martian upper atmosphere that emit at visible wavelengths. The question is whether the relevant transitions are sufficiently excited to create visible emission that is bright enough for spacecraft instruments to distinguish. Based on the energy flux of inverted-V electron distributions and an assumption of an

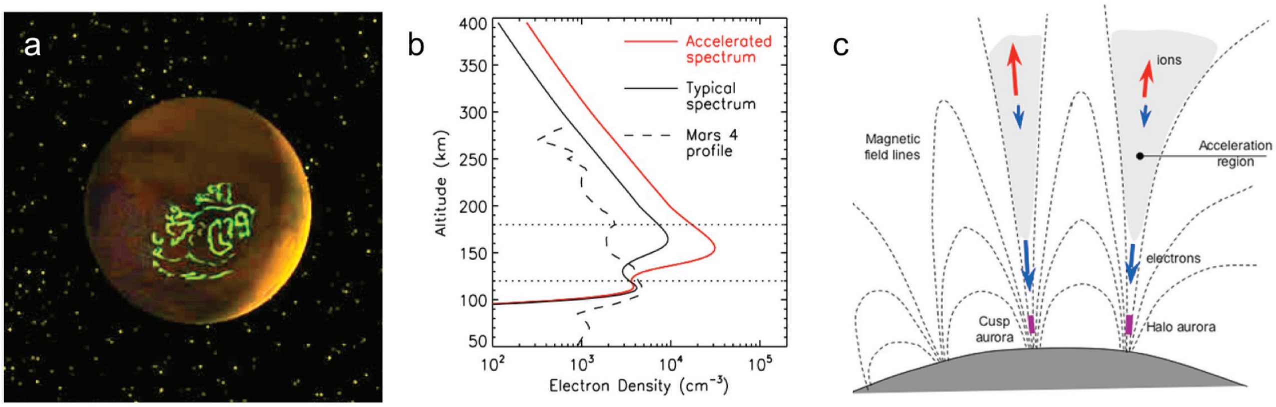

Figure 6. Consequences of Martian aurora. (a) Visible aurora might be visible at midlatitudes (image courtesy M. Holmstrom/European Space Agency). (b) Localized "patchy" ionospheres exist in cusps [*Fillingim et al.*, 2007]. (c) Atmospheric ions escape along auroral flux tubes [*Lundin et al.*, 2006b].

earthlike upper atmospheric composition, *Lundin et al.* [2006b] estimated that the oxygen green line at 557.7 nm should produce as much as 2–80 kR of emission, easily observable by instruments or even the naked eye. This estimate assumes that there are inverted-V events at Mars that are more energetic than those that have been observed so far. A more cautious estimate (still assuming a terrestrial atmospheric composition) of ~220 R is obtained by using the observed 557.7 nm/297.2 nm emission ratio at Earth [*Slanger et al.*, 2006] and applying it to the brightest UV observation at Mars. Finally, models of the brightest (and first reported) emission event assuming a Martian upper atmospheric composition yield a green line brightness of only 30 R [*Bertaux et al.*, 2005]. This issue is most likely to be resolved by direct observation of cusp regions, either from cameras on the surface or from orbiting spacecraft.

Measurements of downward traveling electrons suggest that they influence the upper atmosphere in localized regions on the nightside (Figure 6b). Auroral emission is only one consequence of this interaction between incident plasma and atmospheric species. Another consequence is enhanced ionization in cusp regions, as both modeled [*Fillingim et al.*, 2007] and measured [*Safaeinili et al.*, 2007; *Leblanc et al.*, 2008]. The localized "patchy" ionosphere may have densities >10% of the subsolar ionospheric density. Further, their presence will create gradients in ionospheric density that leads to significant horizontal plasma transport and electric fields [*Fillingim et al.*, 2007]. This transport, in turn, should lead to Joule heating of the upper atmosphere as charged particles attempt to flow in the neutral background.

Measurements of upward traveling ions in crustal field cusps suggest that auroral flux tubes may lead to enhanced escape rates from the Martian ionosphere (Figure 6c). Atmospheric escape is a major topic in studies of Martian climate evolution [*Jakosky and Phillips*, 2001]. Present estimates of the "auroral contribution'" to ion escape vary. A back of the envelope calculation based on terrestrial analogy yields an upper bound to the O^+ escape rate on auroral flux tubes of $\sim 5 \times 10^{25}\ s^{-1}$ [*Ergun et al.*, 2006]. However, an estimate based on ASPERA observations of energized electron and ion distributions leads to an upper bound escape rate 2 orders of magnitude lower, at $\sim 5 \times 10^{23}\ s^{-1}$ [*Dubinin et al.*, 2009]. Auroral flux tubes in the present epoch occupy a small fraction of the upper atmosphere. Auroral ion escape rates are likely to have been larger long ago, when Mars had a global dynamo magnetic field and shortly afterward when crustal fields may have occupied a larger fraction of the Martian crust.

4.2. Frontiers

There are several frontiers for auroral research at Mars in the coming years. Chief among these is continued analysis of the existing observations of UV emission, accelerated ions and electrons, and magnetic field. MEX continues to make measurements from Mars orbit and is likely to contribute new information about auroral variability under different external conditions. Perhaps most exciting among the potential new observations is a determination of the influence of solar activity on auroral brightness.

There is also a need for improved modeling of auroral processes at Mars. At present, global plasma models lack either the spatial resolution or the necessary physical assumptions to adequately simulate auroral acceleration processes. Localized electron transport models have been developed and applied to open crustal field flux tubes [*Seth et al.*, 2002; *Liemohn et al.*, 2006; *Lillis et al.*, 2009], but currently lack a complete picture of the physics operating on those flux tubes (e.g., ion motion and waves). Models of auroral emission are reasonably sophisticated, however, and should be applied more vigorously to the existing measurements to provide constraints on how often visible aurora are measurable at Mars or whether aurora might be observed on the dayside of the planet.

One future set of measurements has the potential to better constrain auroral mechanisms and brightness. The MAVEN spacecraft mission, scheduled to arrive in the fall of 2014, will carry a full complement of particle and field instruments to measure in situ accelerated ion and electron populations, magnetic fields, and the background upper atmosphere. It will also carry a UV spectrometer capable of measuring aurora with greater sensitivity and spectral resolution than SPICAM. Combined with MAVEN measurements of the Sun and solar wind, the mission has the potential to distinguish between the various auroral mechanisms described in section 3.

In summary, given the presence of crustal "mini magnetospheres" near Mars, it is not surprising that auroral processes appear to be active there. The aurora is faint and the particle acceleration is relatively weak compared to typical terrestrial aurora. But this does not mean that Martian aurora should be dismissed as a curiosity. On the contrary, the study of auroral processes in an "end-member" situation such as Mars provides has the potential to better constrain our understanding of the limits of auroral processes everywhere.

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