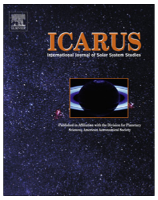
Icarus 264 (2016) 398–406

Contents lists available at ScienceDirect

Icarus

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



SPICAM observations and modeling of Mars aurorae

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ARTICLE INFO

Article history:
Received 1 April 2015
Revised 7 September 2015
Accepted 16 September 2015
Available online 26 September 2015

Keywords:
Mars, atmosphere
Aurorae
Ultraviolet observations
Terrestrial planets

ABSTRACT

Martian aurorae have been detected with the SPICAM instrument on board Mars Express both in the nadir and the limb viewing modes. In this study, we focus on three limb observations to determine both the altitudes and the intensities of the auroral emissions. The CO $(a^3\Pi–X^1\Sigma)$ Cameron bands between 190 and 270 nm, the CO $(A^1\Pi–X^1\Sigma^+)$ Fourth Positive system (CO 4P) between 135 and 170 nm, the CO_2^+ $(B^2\Sigma_u^+–X^2\Pi_g)$ doublet at 289 nm, the OI at 297.2 nm and the 130.4 nm OI triplet emissions have been identified in the spectra and in the time variations of the signals. The intensities of these auroral emissions have been quantified and the altitude of the strongest emission of the CO Cameron bands has been estimated to be 137 ± 27 km. The locations of these auroral events have also been determined and correspond to the statistical boundary of open-closed magnetic field lines, in cusp-like structures. The observed altitudes of the auroral emissions are reproduced by a Monte-Carlo model of electron transport in the Martian thermosphere for mono-energetic electrons between 40 and 200 eV.

No correlation between electron fluxes measured in the upper thermosphere and nadir auroral intensity has been found. Here, we simulate auroral emissions observed both at the limb and at the nadir using electron energy spectra simultaneously measured with the ASPERA-3/ELS instrument. The simulated altitudes are in very good agreement with the observations. We find that predicted vertically integrated intensities for the various auroral emissions are overestimated, probably as a consequence of the inclination and curvature of the magnetic field line threading the aurora. However, the relative brightness of the CO and CO_2^+ emissions is in good agreement with the observations.

1. Introduction

Even if the presence of aurorae in the Mars nightside atmosphere was expected (Fox, 1992), auroral emissions have only been detected by Bertaux et al. (2005a) with the SPICAM (Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars) UV instrument on board Mars Express, which was launched in 2003. They observed a strong emission peak lasting 7 s during orbit 716, with a spectral composition quite different from the NO nightglow emission (Bertaux et al., 2005b; Cox et al., 2008). In the auroral spectrum, the main emissions are the CO $(a^3\Pi–X^1\Sigma)$ Cameron bands between 180 and 240 nm, the CO $(A^1\Pi–X^1\Sigma^+)$ (CO 4P) Fourth Positive system between 135 and 170 nm, the CO_2^+ $(B^2\Sigma_u^+–X^2\Pi_g)$ doublet at 288.3–289.6 nm and the OI emission at 297.2 nm. They also pointed out that a close correlation between the location of this observed emission and the position of the crustal field anomalies (cusp-type regions). They deduced that the auroral emissions are caused by energetic electron fluxes moving along the crustal magnetic field lines and exciting the upper atmosphere of Mars.

Leblanc et al. (2008) further searched for auroral signatures using the limb and nadir viewing modes of the SPICAM UV instrument. They found nine additional detections on the Mars nightside: one at the limb and eight in the nadir direction. These auroral emissions were observed in six orbits spread over the database, some of them showing several events a few minutes apart. They could quantify the CO Cameron bands emission and, in some cases, the CO_2^+ doublet emission. The locations of these aurorae relative to the statistical map of open/closed magnetic field lines from the Mars Global Surveyor (MGS) measurements of Brain et al. (2007) seem to confirm that aurorae occur in the presence of cusp-like magnetic field line structures. They also compared these detections with simultaneous ASPERA-3 particle measurements and MARSIS total electron content measurements. Although dependence seems to exist between the aurorae and the

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http://dx.doi.org/10.1016/j.icarus.2015.09.023

occurrence of energetic precipitating electrons, there is a lack of correlation between the intensity of the incident electron flux and the total electron content or the auroral emission intensities.

Gérard et al. (2015) reexamined a larger SPICAM database and detected additional UV aurora during nadir observations. They confirmed that Mars aurorae are located near the open-closed magnetic field line boundary in cusp-like structures and evaluated the brightness of the CO Cameron bands and CO_2^+ emissions. They also compared the UV auroral detections with concurrent ASPERA-3 measurements and determined the characteristics of the electron energy spectra at the time of the most likely associated electron flux enhancements but did not find a clear quantitative correlation between the observed brightness and the precipitated energy flux.

In this study, we focus on limb observations, which will be presented in Section 2. While two detections during orbit 716 and one during orbit 2800 were already known (Bertaux et al., 2005a; Leblanc et al., 2008), we detected an additional auroral signature during orbit 2800. Results derived from these observations, such as the altitude of the emissions and the duration of the aurorae will be presented. The intensities of the CO Cameron bands and the CO_2^+ emissions are quantified, as well as those of the CO 4P bands and the 130.4 nm OI emissions. These observations are then compared with numerical simulations based on the model of Shematovich et al. (1994, 2008). It is an electron transport model based on a direct simulation Monte Carlo method in the Martian atmosphere that will be described in more detail in Section 3. Simulations are made for mono-energetic electrons and are compared to the auroral observations. The Monte Carlo model has also been modified so that ASPERA energetic spectra can be used as input parameters of the model. The altitudes of the aurorae are calculated as well as the intensities of the emissions forming the auroral signature.

2. Auroral detections at the limb

2.1. SPICAM observations

Auroral emissions have been detected with the SPICAM UV instrument on board the ESA Mars Express spacecraft, which is in a quasi polar orbit. The SPICAM UV spectrograph covers a 118–305 nm wavelength range. Every second, it acquires five spectra recorded in five adjacent fields of view (spatial bins), each extending along 0.32° in the sky. Two of these spatial bins (1 and 2) provide the best spectral resolution (~1.5 nm) but a lower photometric sensitivity, and two others (4 and 5) have a lower spectral resolution (~6 nm) but an 8 times higher sensitivity. The third spatial bin will not be used for quantitative study here because its sensitivity is intermediate and has not been properly calibrated (Leblanc et al., 2008). Further details about the SPICAM instrument are given by Bertaux et al. (2006) and Leblanc et al. (2006a). SPICAM UV can operate in various modes. Nadir observations of aurorae have recently been analyzed in detail by Gérard et al. (2015). They quantified the intensities of the CO Cameron bands and the CO_2^+ doublet emissions, compared auroral events to concurrent electron precipitations and confirmed that aurorae occur near open-closed field line boundaries, in the Southern hemisphere between 150° and 225° of longitude. In this observational section, only the limb viewing mode has been used, so that we can also determine at what altitude aurorae occur. The line of sight of SPICAM is perpendicular to the velocity vector at pericenter. The limb profile database was searched and the following criteria for a possible auroral detection were imposed: (i) the solar zenith angle has to be greater than 100° to ensure that the atmosphere is in darkness; (ii) the spacecraft must be less than 1000 km away from the planet, which is the altitude limit imposed by the sensitivity of the instrument to detect faint and localized emissions (Leblanc et al., 2008); (iii) observation needs to be made in the Southern hemisphere, where the magnetic field anomalies are more intense (Connerney et al., 2001). Only 30 out of 1404 limb observations acquired between 29 January 2004 and 29 March 2014 match these criteria. They have thus been individually checked and the tempo-images have been visually examined to confirm a suspected presence of an auroral emission, as shown in Fig. 1a of Bertaux et al. (2005a), by a short increase of the signal of the CO Cameron bands between the 190 and 300 nm. Finally, the spectral composition was analyzed. To do so, spectra have been summed over the elapsed time of the signal increase and compared to a pure NO nightglow spectrum and to a confirmed auroral case (orbit 716 from Bertaux et al., 2005a), which does not contain any appreciable NO airglow contribution. This methodology has been extensively described by Gérard et al. (2015) for the nadir observations. Finally, we only retain three auroral signatures. Two of them were previously identified: one during orbit 716 (Bertaux et al., 2005a) and one during orbit 2800 (Leblanc et al., 2008). The third auroral event added to this list also appears during orbit 2800, about 2 min after the first one. Hereafter, we will refer them as Detection I, Detection II and Detection III. These auroral events and the time of their detections are listed in Table 1. Fig. 1a shows the time evolution of the signal for Detection II in the five usable spatial bins. In order to extract unambiguous quantitative parameters from these

Table 1
Auroral limb detections characteristics.

Orbit	Spatial bin	Time (s)	Position A_1[a] (s)	Peak delay (s)	Duration (s)		Intensity A_0[a] (R)	Altitude (km)	
						Mean		Apparent	Corrected
716A01	1	535–540	537.2	2.2	9	9	4959	15.7	132 ± 31
	2	532–540	536.6		9		4871	15.5	
	3	532–539	536.2		9		–	15.2	
	4	532–538	535.7		9		4462	14.9	
	5	531–538	535.0		9		4043	14.7	
2800A02	1	370–395	381.6	3.2	29	29	1338	38.0	143 ± 23
	2	370–395	382.4		30		2371	47.5	
	3	372–390	382.6		27		–	54.5	
	4	373–392	382.7		29		2216	62.9	
	5	373–393	384.8		30		2396	70.1	
	1	515–550	519.5	2.5	38	37	1008	5.3	137 ± 26
	2	509–519	520.6		28		1211	14.4	
	3	515–550	521.5		36		–	22.6	
	4	515–550	521.8		40		694	30.8	
	5	515–550	522.0		42		733	39.3	

[a] Refers to the parameters of Eq. (1).