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A phenomenological model of Io's UV aurora based on HST/STIS observations

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ABSTRACT

We have carried out a comprehensive analysis of a large set of spatially resolved observations of Io's OI 1304 Å, OI] 1356 Å, SI 1479 Å and SI] 1900 Å aurora taken by the Space Telescope Imaging Spectrograph (STIS) of the Hubble Space Telescope (HST) between 1997 and 2001. We find that the variability of the observed morphologies can be solely explained by the changes of the plasma and magnetic field environment of the Io torus and by the viewing perspective. The variations in brightness are strongly correlated with the periodic variations of the ambient electron density. Based on these findings we develop a phenomenological model for the spatial distribution of the oxygen and sulfur emissions in Io's vicinity. Taking into account Io's position with respect to the plasma torus, the orientation of Jupiter's magnetic field and the viewing perspective of the observation, the model calculates the auroral morphology and brightness. By fitting the model parameters to the observations we find that the model is able to reproduce the main features in all images obtained over a period of five years with one parameter set for each emission multiplet. The spatial distribution of the OI] 1356 Å, OI 1304 Å, SI 1479 Å, and SI] 1900 Å multiplets are shown to be very similar. In contrast to previous investigations, the model results reveal that the majority of the radiation from the bound atmosphere is emitted within 100 km above the surface. The equatorial aurora spots extend far into the wake region explaining observed features in the downstream region. The relative brightness of two the equatorial spots is best explained by our model if the emission on the dayside flank of Io is higher by a factor of ~1.5 with respect to the nightside flank. The measured brightness during an observation in eclipse is significantly lower than expected from the fitted model. The day–night asymmetry and the brightness decrease in eclipse support the idea of a wide collapse of Io's atmosphere in shadow. Since our phenomenological aurora model is able to reproduce the main features of the observed morphology by taking into account the variations of the magnetospheric parameters, it can be applied to predict the emission for future UV aurora observations for a given time and position of the observer.

1. Introduction

The auroral emissions emanating from Io's tenuous atmosphere have been proven to be a valuable tool for investigating both the satellite's atmosphere and the magnetospheric plasma environment. Since Io's atmosphere contains various species such as SO_2, S, O, Na, K, Cl and several compounds electron excited emissions ranging from the far ultraviolet (FUV) to near infrared wavelengths can be observed (e.g., Brown and Chaffee, 1974; Trafton, 1975; Ballester et al., 1987; Spencer et al., 2000; Lellouch et al., 1996; McGrath et al., 2000; Feaga et al., 2004). The first spatially resolved observations of the aurora were obtained by the Space Telescope Imaging Spectrograph (STIS) of the Hubble Space Telescope (HST) in 1997 (Roesler et al., 1999). The images contain among other lines the sulfur and oxygen emission multiplets at 1304 Å, 1356 Å, 1479 Å and 1900 Å. The observed emissions originate from collisional excitation of the neutral gas of Io's atmosphere by impinging magnetospheric electrons and reveal a particular pattern. Roesler et al. (1999) characterized the morphology of the imaged oxygen and sulfur aurora by distinguishing between the bright *equatorial spots*, the fainter *limb glow* and a rapidly decreasing with altitude *extended emission*.

The latitudinal location of the prominent equatorial spots and the brightness asymmetry of the limb glow are correlated with the changing magnetospheric environment (Roesler et al., 1999; Geissler et al., 2001). The varying orientation of the background

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field leads to a *rocking* of the auroral spots about the equator. The equatorial spots, the limb glow and the extended emission in the STIS aurora observations have been analyzed in-depth by Retherford et al. (2000), Retherford et al. (2003) and Wolven et al. (2001), respectively. Retherford et al. (2000) found that the rocking follows to ~80% the orientation of the jovian magnetic field at Io. Additionally, the spots appear to be shifted from the sub- and anti-jovian meridian towards the wake side by about 10–30°. By applying a plasma model to simulate the emission Saur et al. (2000) showed that the energy of the incoming electron flow is deposited preferentially on Io's flanks, which leads to the formation of the bright spots as seen by the observer. The limb glow on the hemisphere facing the plasma torus centrifugal equator is up to two times brighter than on the opposite hemisphere, which originates from the differing energy reservoirs above and below Io (Retherford et al., 2003). Besides the spots, limb glow and extended emission, a prominent wake emission has been detected in the visible (Moore et al., 2010) and UV (Retherford et al., 2000, 2007) observations. Moore et al. (2010) suggest that this wake feature is shifted to the hemisphere that faces the torus center similar to the limb glow asymmetry. The wake feature might also originate from flank emissions that extend into the downstream region as proposed by Roth et al. (2011).

Altogether, the observed morphology and brightness of the UV emissions are clearly linked to the properties of the magnetospheric environment and also reflects the local interaction of the plasma with Io's atmosphere–ionosphere. The influence of volcanic activity in generating a patchy atmosphere and its effect on the resultant UV emission pattern is unclear, although the morphology of the *visible* aurora in eclipse observations is considerably affected by local volcanic plumes (e.g., Geissler et al., 2001; Spencer et al., 2007; Roth et al., 2011). Furthermore field-aligned energetic electrons possibly contribute to the UV aurora (Michael and Bhardwaj, 2000; Oliversen et al., 2001; Dols et al., 2012). However, for a mixing ratio of O/SO_2 of ~20% the OI] 1356 Å aurora brightness can be produced entirely by collisional excitation by thermal torus electrons only (Saur et al., 2000). Analyzing the sulfur emissions at 1479 Å and 1900 Å Feaga et al. (2002) estimate that the measured SI] 1900 Å intensities are consistent with excitation of atomic sulfur by thermal electrons for a S/SO_2 ratio of ~0.1%.

Another interesting aspect is the response of the auroral emission when Io passes through Jupiter's shadow. When Io enters Jupiter's shadow, two opposing effects control the evolution of the aurora (Saur and Strobel, 2004). (1) Since the atmospheric gas partly freezes out, there is less neutral gas abundant to be excited; and (2) a decrease of atmospheric density after eclipse ingress leads to a decreasing interaction strength, whereby the deflection and cooling of the plasma flow is lower and the streamlines of the electrons are less divergent. Saur and Strobel (2004) calculated the response of Io's electrodynamic interaction and auroral radiation to a temporal change in the atmosphere. Depending on the relative contributions of volcanism versus sublimation they find three qualitatively different scenarios with two of them including a transient post-eclipse brightening. In various observations, e.g., by Clarke et al. (1994) and by Retherford (2002) the total emission intensity in eclipse was found to be lower than out of eclipse. Saur and Strobel (2004) therefore conclude that the sublimation driven part clearly dominates the direct outgassing. Time series of Io's auroral UV emissions in eclipse were obtained during the New Horizons flyby in 2007 by the on-board UV spectrograph Alice (Retherford et al., 2007). For an atmosphere with 1–3% volcanic support the measured variations were in best agreement with simulated eclipse brightness curves by Saur and Strobel (2004). Surprisingly, recent high-spectral FUV observations of Io emerging from eclipse by the HST Cosmic Origin Spectrograph did not show brightness changes related to eclipse emergence (Spencer et al., 2012).

In this paper we comprehensively analyze the full set of HST/STIS observations taken over a period of 5 years between September 1997 and December 2001 to investigate the spatial distribution and temporal variations of Io's UV aurora in more detail. We study and compare the OI 1304 Å, OI] 1356 Å, SI 1479 Å and SI] 1900 Å aurora brightness and morphology at different times and various viewing perspectives and develop a phenomenological model that describes the three-dimensional (3-d) distribution of these sulfur and oxygen emissions in the vicinity of Io.

2. HST/STIS observations

2.1. Overview

In the course of four HST campaigns STIS observed Io's UV emissions during 26 HST orbits with the 52″ × 2″ slit. Fig. 1 depicts Io's orbital location with respect to Jupiter for the 23 orbits analyzed in this paper. Three orbits are excluded, either because one of the two orbit exposures failed or because the recorded wavelengths include only emission from excited (torus) ions. During one HST orbit Io was observed in eclipse. The analyzed observations are taken in the first-order spectroscopy mode using one of the low or medium resolution gratings G140L, G140M and G230M. The 52″ × 2″ slit allows a spatial resolution of the entire disk of the satellite with a simultaneous spectral resolution determined by the dispersion of the grating. The dispersions are $\Delta\lambda = 0.584$ Å pixel^{-1} for G140L, $\Delta\lambda = 0.053$ Å pixel^{-1} for G140M and $\Delta\lambda = 0.087$ Å pixel^{-1} for G230M with bandwidths of 590 Å, 54 Å and 90 Å, respectively. The effective slit length is 25″ constrained by the FUV and NUV MAMA detectors, allowing to capture features ~20 satellite radii away in the spatial direction. Thus, on the 1024 × 1024 pixel detector several distinct images of the satellite and its environment are pictured for various spectral lines sometimes overlapping if the line dispersion is lower than the satellites' diameter. The

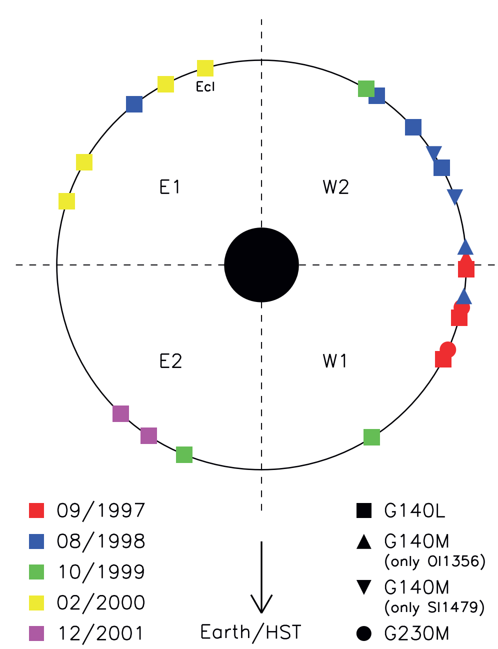

Fig. 1. Io's orbital location with respect to Jupiter for the 23 HST orbits of STIS UV observations analyzed in this work. 'Ecl' marks the eclipse observation. The orbit is subdivided in four sections: W1 and W2 (E1 and E2) are the quarters before and after western (eastern) elongation, respectively. The observation dates are color coded. The STIS observation mode (G140L/G140M/G230M) is illustrated by the shapes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)