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Saturn's northern auroras as observed using the Hubble Space Telescope

J.D. Nichols[a,*], S.V. Badman[b], E.J. Bunce[a], J.T. Clarke[c], S.W.H. Cowley[a], G.J. Hunt[a], G. Provan[a]

[a] Department of Physics and Astronomy, University of Leicester, Leicester, UK
[b] Department of Physics, Lancaster University, Lancaster, UK
[c] Center for Space Physics, Boston University, Boston, MA 02215, USA

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ABSTRACT

We discuss the features of Saturn's northern FUV auroras as observed during a program of Hubble Space Telescope observations which executed over 2011–2013 and culminated, along with Cassini observations, in a comprehensive multi-spectral observing campaign. Our 2011–2013 observations of the northern aurora are also compared with those from our 2007–2008 observation of the southern aurora. We show that the variety of morphologies of the northern auroras is broadly consistent with the southern, and determine the statistical equatorward and poleward boundary locations. We find that our boundaries are overall consistent with previous observations, although a modest poleward displacement of the poleward boundaries is due to the increased prevalence of poleward auroral patches in the noon and afternoon sectors during this program, likely due to the solar wind interaction. We also show that the northern auroral oval oscillates with the northern planetary period oscillation (PPO) phase in an elongated ellipse with semi-major axis $\sim$1.6° oriented along the post-dawn/post-dusk direction. We further show that the northern auroras exhibit dawn-side brightenings at zero northern magnetic PPO phase, although there is mixed evidence of auroral emissions fixed in the rotating frame of the northern PPO current system, such that overall the dependence of the auroras on northern magnetic phase is somewhat weak.

1. Introduction

Saturn's southern ultraviolet (UV) auroras have been observed extensively over the past decade using high-sensitivity instruments onboard the Hubble Space Telescope (HST) such as the Space Telescope Imaging Spectrograph (STIS) and the Advanced Camera for Surveys (ACS) (e.g. Gérard et al., 2004; Grodent et al., 2005; Clarke et al., 2009). The southern auroral emission consists of a $\sim$2° wide 'oval' of radius $\sim$10–20° co-latitude (Badman et al., 2006; Clarke et al., 2009; Carbary, 2012). The oval is generally brighter on the dawn side, and patches of emission are observed to slide along the oval at $\sim$20–70% of corotation (Grodent et al., 2005; Meredith et al., 2013; Lamy et al., 2013). Transient, bright features are occasionally observed both poleward and equatorward of the oval (Gérard et al., 2004, 2005; Meredith et al., 2013; Radioti et al., 2013; Meredith et al., 2014), and separate emission has been observed $\sim$3° equatorward of the main oval on the nightside (Grodent et al., 2010). This collection of features is thought to be the manifestation of a number of different magnetospheric phenomena, such as sub-rotation of magnetospheric plasma, plasma injections and day- and night-side reconnection. The morphology of the auroras has also been observed to change dramatically following the arrival of an interplanetary shock, with bright aurora expanding significantly toward the pole on the dawn side (Crary et al., 2005; Clarke et al., 2005, 2009), a form associated with the compression-induced collapse of the tail (Cowley et al., 2005; Nichols et al., 2014). The quiet time oval also exhibits an oscillation of amplitude $\sim$1° along the prenoon–premidnight meridian with a period consistent with that of the Saturn Kilometric Radiation (SKR) (Nichols et al., 2008, 2010b), a phenomenon that has been shown to be associated with planetary-period oscillations (PPOs) in the magnetic field (Provan et al., 2009), the high latitude plasmapause-like boundary (Gurnett et al., 2011) and the location of the field-aligned currents as measured in situ by Cassini (Bunce et al., 2014). The brightness of the oval is also modulated at the PPO period, with the brighter dawn-side auroras pulsing in phase with the SKR, whilst the less intense dusk-side auroras oscillate in anti-phase, implicating a weak rotational modulation of the auroral field-aligned currents with a strong superposed dawnside strobe-like enhancement (Nichols et al., 2010a). Such behaviour was later confirmed using magnetic field and radio observations (Andrews et al., 2011; Lamy, 2011).

* Corresponding author.
E-mail address: jdn4@le.ac.uk (J.D. Nichols).

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However, prior to the program of observations discussed in this paper, HST had only previously been able to view the planet's northern auroras from extremely oblique viewing angles due to the planet's seasons (Nichols et al., 2009), such that the above results relate to southern hemisphere data obtained during southern summer, and comparable images of the northern auroras had not been yet obtained. Using the equinoctial images Nichols et al. (2009) were, however, able to show that Saturn's northern and southern auroras often simultaneously differ significantly in size, intensity and morphology. For example, the northern oval was observed to be typically $\sim$1.5° smaller than the southern, ascribed to the stronger internal magnetic field in the north (e.g. Dougherty et al., 2005), and individual blobs of emission do not always have a conjugate counterpart. The latter phenomenon was shown by Meredith et al. (2013) to be consistent with even modes of ULF field line resonances producing hemispherically anti-symmetric field-aligned currents, leading to auroral emission in one hemisphere with no conjugate counterpart. Meredith et al. (2014) went on to examine the HST images of Saturn's northern auroras obtained in 2011 and 2012 as part of the program discussed in this paper, with reference to prevailing upstream conditions in the interplanetary medium as observed by Cassini. They found that the patches and arcs observed just poleward of the main oval near noon are present during intervals of northward IMF, thus favouring low-latitude dayside reconnection. None of these patches were observed when the IMF was southward, although a very high latitude form observed during such an interval was associated with lobe reconnection on open field lines, as discussed previously by Bunce et al. (2005) and Gérard et al. (2005). Recently, auroral storms observed in 2013 during the HST program discussed in this paper were discussed by Nichols et al. (2014), who reported bursts of emission moving quickly toward the morningside on the poleward edge of the expanded auroras. These bursts, somewhat reminiscent of terrestrial poleward boundary intensifications and coincident with a $\sim$1° poleward motion of the poleward boundary, were associated with the ongoing rapid closure of lobe flux in the tail. A later, more evolved, storm form, i.e. a region of bright, poleward-expanded emission, was shown by those authors to map to the trailing region of an energetic neutral atom enhancement observed by the magnetospheric imaging instrument (MIMI) onboard Cassini. This emission was thus associated with the upward field-aligned continuity current flowing into the trailing region of the eastward-directed partial ring current imaged by MIMI.

The planet's northern auroras have also been observed using the Ultraviolet Imaging Spectrograph (UVIS) and the Visual and Infrared Mapping Spectrometer (VIMS) instruments onboard the Cassini orbiter, results from which have revealed a brightening associated with plasma energisation in the nightside sector (Mitchell et al., 2009), and small-scale features such as the Enceladus footprint (Pryor et al., 2011), auroral spots near the main oval (Grodent et al., 2011), bifurcations in the auroral oval in the noon to dusk sector (Radioti et al., 2011) possibly associated with dayside reconnection, features associated with injections (Radioti et al., 2013), and tail dipolarisations (Jackman et al., 2013). A number of similar structures have been observed in the infrared (IR) (Badman et al., 2012a). However, the 'pseudo-images' obtained using UVIS are obtained by slewing the instrument's slit over the auroral region, a process which results in the last pixel being obtained tens of minutes after the first, such that caution must be exercised when comparing the results with the exposures obtained by HST. Thus, while individual aspects of the northern auroras as observed during the present HST program and by UVIS have been previously presented, an overview of the statistics and morphology of Saturn's northern auroras as observed using FUV imaging with HST remains to be presented. We discuss the recent 3-year program of HST/ACS observations of Saturn's northern auroras, which executed over 2011–2013 and culminated in the 2013 multi-wavelength program which is the subject of the present issue. Specifically, we discuss the morphologies observed, the overall statistics of the auroral location and modulation of the emission with PPO phase.

2. HST images

Over 2011–2013, a total of 570 images of Saturn's northern UV auroras were obtained near opposition using the Solar Blind Channel (SBC) of the ACS from sub-Earth latitudes increasing from $\sim$8.5° in 2011 to $\sim$18.6° in 2013. The observing intervals were 1–9 April 2011, 28 March–6 April 2012, and 5 April–22 May 2013, and the program comprised 5 orbits in 2011, 10 in 2012, and 15 in 2013, with nineteen individual exposures obtained during each orbit. The reduction of such ACS/SBC images of Saturn's auroras has been extensively discussed previously (see e.g. Clarke et al., 2009; Nichols et al., 2009), such that here we simply note that in each orbit nineteen 100s exposures were obtained using the ACS/SBC detector, which is a 1024×1024 Multi-Anode Microchannel Array with a field of view of 35×31 arcsec^2. Images were mostly obtained using the F115LP and F125LP longpass filters, which have cut-off wavelengths of 115 and 125 nm respectively, such that the latter admits H_2 Lyman and Werner bands, while the former also includes H Lyman-α emission. Exposures have been co-added in groups of 5 (F125LP), 5 (F115LP), 4 (F115LP), and 5 (F125LP) in each orbit in order to increase the signal-to-noise at the cost of $\sim$5° blurring at the central meridian longitude (CML) for corotating features. A few exposures each year were obtained using the F145LP and F165LP filters, which block the auroral emissions and are thus used for background subtraction as discussed by the above-cited works. The units were converted from counts to kR (where 1 kR represents a source flux of 10^9 ph cm^{-2} s^{-1} radiating into 4π steradians) of H_2 emission using the conversion factors 1 kR $= 2.05 \times 10^{-3}$ and 1.20×10^{-3} counts s^{-1} for the F115LP and F125LP filters, respectively (Gustin et al., 2012), and the images were projected onto a planetocentric latitude–longitude grid assuming an emission altitude of 1100 km above the 1 bar reference spheroid, in conformity with the observed peak in the emission (Gérard et al., 2009).

3. Analysis

3.1. Morphology

We first discuss the variety of auroral morphologies observed in the north over this program. All the images obtained in the program are available in movies (files sat11.mov, sat12.mov and sat13.mov for images obtained in 2011, 2012, and 2013, respectively) in the Supplementary Material (SM), which show both the unprojected and projected views of the images. Representative images from each year are displayed in Figs. 1 (2011, 2012) and 2 (2013), which show Lambert Equal Area Azimuthal projections of the images as viewed from above the north pole, with the central meridian longitude (CML) oriented toward the bottom. Note that, as discussed above, a number of features of the 2011 and 2012 images have been discussed by Meredith et al. (2014), and we initially briefly review these images here. Although, particularly for 2011, the sub-Earth latitude permitted only a view of the dayside auroras, it is first apparent that the northern auroras exhibit a variety of morphologies, similar to those in the south. Hence, the quiet-time oval associated with interplanetary rarefaction regions is evident in all years, e.g. in Figs. 1a, e and i, and 2c, brighter in the dawn than in the dusk, and in some cases the