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Simultaneous multi-scale and multi-instrument observations of Saturn's aurorae during the 2013 observing campaign

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ABSTRACT

On 21 April 2013, during a co-ordinated Saturn auroral observing campaign, the northern and southern poles of the planet were observed from the Earth using the NASA Infrared Telescope Facility (IRTF), Keck, and Hubble Space Telescope (HST) simultaneously with the Cassini infrared, visible, and ultraviolet remote sensing instruments. We present simultaneous multi-scale and multi-wavelength analysis of the morphology of auroral emissions at Saturn. The visible main auroral emission vary between ~2 and 10 kR on timescales of minutes and across spatial scales of down to ~14 km on the planet. The H_2 Far Ultraviolet (FUV) brightness varies by a factor of ~10, from ~4–40 kR, over timescales of 1 min and spatial scales of 720 km. H_3^+ infrared emissions vary less than the H_2 emissions, from ~5–10 μW m^{-2} sr^{-1}, over similar spatial scales (~300 km) and timescales of a few seconds to a few hours. The fine-scale temporal and spatial features seen in the main oval show that complex structures are present even during quiet solar wind conditions. Diffuse ultraviolet emissions southward of the southern midnight main oval that are not seen in the infrared, implying a steep temperature gradient of ~50 K over 2–4° latitude equatorward of the main oval. Dynamics on scales of ~100 km at the poles are revealed by lower spatial resolution observations, the morphologies of which are partly consistent with overlapping local-time fixed and co-rotating current systems. We also present the first direct comparison of simultaneous infrared, visible, and ultraviolet auroral emissions at Saturn. Finally, the main auroral emissions are found to be approximately co-located in the midnight sector, forming an arc with a width of ~0.5–1°, at 72–74° southern latitude, moving slightly equatorward with increasing local-time.

1. Introduction

The upper atmosphere of Saturn is mostly composed of neutral atomic and molecular hydrogen. Co-located with this is the ionised part of the upper atmosphere, the ionosphere, is dominated by H^+ (protons) and H_3^+. When energetic electrons enter the upper atmosphere of a giant planet, by way of precipitation delivered along the magnetic field lines, they can either excite or ionise the constituents therein. Badman et al. (2014) reviews the auroral process in detail.

Auroral emissions at ultraviolet and visible wavelengths are a direct result of the interaction between the atmosphere and precipitating electrons. Secondary electrons resulting from this interaction excite the molecular hydrogen which produce photons in the 70–180 nm range and visible H_2 transitions from 'higher' to 'lower' Rydberg states (Shemansky and Ajello, 1983). At lower

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altitudes some of this emission, mainly below 135 nm, is attenuated by the hydrocarbon layer situated at or above the aurora. The amount of H_2 absorption by these hydrocarbons, measured by the colour ratio CR = I(155–162 nm)/I(123–130 nm), where I is the brightness in a certain spectral range, is correlated to the penetration depth via atmospheric modelling, and hence the primary energy, of the precipitating electrons. When no absorption is observed, the CR of the emergent emission is 1.1 (Gustin et al., 2013, and references therein). H Lyman-α is produced by de-excitation from the $n = 2$ to the fundamental $n = 1$ electronic level of H atoms, whilst the visible Balmer series is due to the de-excitation from $n > 2$ to the $n = 2$ level of H (Aguilar et al., 2008).

When molecular hydrogen is ionised, it is rapidly converted to H_3^+ by the exothermic reaction

$$H_2^+ + H_2 \longrightarrow H_3^+ + H, \tag{1}$$

where the energy required to produce H_2^+ is delivered either via energetic particles or solar extreme ultraviolet (EUV) photons. The intensity of the infrared H_3^+ emission is both an exponential function of ionospheric temperature (Neale et al., 1996; Miller et al., 2013) and a linear function of the ionisation rate of H_2. The emission rate of a particular H_3^+ emission line is given by

$$I = N \frac{K^i}{Q(T)} \exp\left(-\frac{hc\omega_u^i}{kT}\right), \tag{2}$$

where N is the number of H_3^+ ions that are emitting thermal emission at temperature T, k is Boltzmann's constant, ω_u^i is the wavenumber of the upper energy level of the transition i, $Q(T)$ is the temperature dependent partition function given by Miller et al. (2013), h is Planck's constant, c is the speed of light, and K^i is a composite constant determined by the properties of the transition i we are considering. For more information see e.g. McCall (2001).

The analysis of auroral emissions in each wavelength band tells us about different aspects of the precipitation process and how this injection of energy affects the makeup of the upper atmosphere. The auroral morphology tells us where in the magnetosphere the precipitation originates from, and via analysis of infrared and ultraviolet spectra one can monitor physical parameters like ion density, thermospheric temperature, precipitation flux, and precipitation energy of the auroral primaries.

The time between electron impact and emission in the UV and in the visible of H and H_2 is very short, about 10^{-2} s (Menager et al., 2010; Badman et al., 2014), giving an instantaneous view of the precipitation process. In contrast, H_3^+ radiates thermally and can have lifetimes of around 500 s (Melin et al., 2011a), producing a temporally averaged view of the auroral radiation during the lifetime of the ion. Therefore, both the integration times of the instrumentation and the chemical lifetimes of the species concerned become important factors when comparing simultaneous infrared and ultraviolet/visible auroral emissions.

For example, Melin et al. (2011a) analysed simultaneous infrared and ultraviolet observations of Saturn's southern aurora at a high spatial resolution and noted that, outside of the main oval emission, the intensity of H_3^+ did not necessarily map well to that of either H or H_2, with a diffuse equatorward oval being most prominent in H Lyman-α. These differences are likely attributable to both the fact that the intensity of emission of the H_3^+ ion is strongly dependent on temperature, and that it has a lifetime of about 500 s. In contrast, multispectral analysis of Lamy et al. (2013) observed a one-to-one correspondence between the emission seen in the infrared and ultraviolet.

One of the most intriguing features of the Saturn system is the presence of rotating phenomena near the planetary rotation period, but with two separate periods that slowly evolve with time, one associated with the northern hemisphere and the other with the southern (Galopeau and Lecacheux, 2000; Espinosa and Dougherty, 2000; Gurnett et al., 2009; Provan et al., 2009, 2014; Andrews et al., 2010; Southwood and Cowley, 2014). The signatures of these periodic phenomena, known as the planetary period oscillations (PPO), are present in many observations, e.g. Saturn kilometric radiation (SKR, Gurnett et al., 2009; Lamy et al., 2011), the infrared H_3^+ aurora (Badman et al., 2012b; Lamy et al., 2013; O'Donoghue et al., 2016), the ultraviolet H_2 aurora (Lamy et al., 2009; Nichols et al., 2010a; Lamy et al., 2013; Bunce et al., 2014), the magnetospheric energetic electrons (Carbary et al., 2009), and the magnetopsheric magnetic field (Southwood and Kivelson, 2007; Provan et al., 2009; Andrews et al., 2012). Badman et al. (2012b) observed the intensity of the auroral H_3^+ emission in each hemisphere to be dependent on both local-time and the appropriate PPO phase. This is consistent with the superposition of two current systems, one fixed in the Sun–Saturn frame, the other rotating at the PPO period. The ultimate origin of the rotating current systems has been proposed to be driven by either the magnetosphere (Goldreich and Farmer, 2007) or the atmosphere (Smith, 2006; Jia et al., 2012; Southwood and Cowley, 2014). In the latter case, it remains an open question as to what mechanism could provide the required relatively stable and sustained atmospheric vortices (Smith, 2014).

The main auroral oval of Saturn maps near to the boundary between open and closed field-lines (Cowley et al., 2004; Bunce et al., 2008; Carbary et al., 2008; Belenkaya et al., 2011). On or close to this oval there are a number of specific features that are attributed to separate processes. These include dawn brightened signatures of Dungey cycle plasma convection (Cowley et al., 2005), interactions between Saturn's magnetosphere and the solar wind at the magnetopause (Gérard et al., 2005; Radioti et al., 2011; Badman et al., 2013; Meredith et al., 2014), and signatures of injections from the hot plasma populations in the night-side magnetosphere (Mitchell et al., 2009b; Grodent et al., 2010; Lamy et al., 2013).

Saturn's ultraviolet emissions were first discovered by a rocket-borne spectrograph in 1975 (Weiser et al., 1977), whereas H_3^+ was first detected by Geballe et al. (1993) using the United Kingdom Infrared Telescope (UKIRT). It was not until the arrival of the Cassini spacecraft that visible auroral emissions were discovered (Kurth et al., 2009). The infrared, visible, and ultraviolet auroral emissions have been used in multiple studies as a diagnostic for the ionosphere–magnetosphere–thermosphere interaction but also as an in-situ diagnostic of the physical conditions in the thermosphere. See Bhardwaj and Gladstone (2000), Kurth et al. (2009), and Badman et al. (2014) for excellent overviews.

Lamy et al. (2013) analysed a set of radio, infrared, ultraviolet, and energetic neutral atom (ENA) Cassini observations over the duration of a full Saturn rotation. This set of observations coincided with an injection event in the magnetotail, producing dawn intensifications of the auroral oval seen in both the infrared and ultraviolet remote sensing data. They also noted features in the auroral emissions compatible with two superimposed current systems, one fixed in local-time and one rotating at the PPO phase, as outlined above.

Most remote sensing studies of Saturn's aurora have used observations from a single vantage point, obtained from either the surface of the Earth, low altitude Earth orbit, or from the Cassini spacecraft in orbit at Saturn. By definition, such observations cannot get a complete view of the northern and southern auroral ovals, since at least one portion of the system is hidden from view. Ground-based observations are limited by always observing the sunlit hemisphere, such that the effects of solar-related emissions cannot easily be disentangled from those created by auroral processes. A study of Cassini-UVIS, FUSE (Far Ultraviolet