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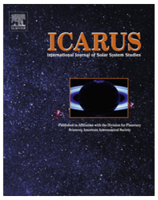

Ground-based observations of Saturn's auroral ionosphere over three days: Trends in H_3^+ temperature, density and emission with Saturn local time and planetary period oscillation

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ABSTRACT

On 19–21 April 2013, the ground-based 10-m W.M. Keck II telescope was used to simultaneously measure H_3^+ emissions from four regions of Saturn's auroral ionosphere: (1) the northern noon region of the main auroral oval; (2) the northern midnight main oval; (3) the northern polar cap and (4) the southern noon main oval. The H_3^+ emission from these regions was captured in the form of high resolution spectral images as the planet rotated. The results herein contain twenty-three H_3^+ temperatures, column densities and total emissions located in the aforementioned regions – ninety-two data points in total, spread over timescales of both hours and days. Thermospheric temperatures in the spring-time northern main oval are found to be cooler than their autumn-time southern counterparts by tens of K, consistent with the hypothesis that the total thermospheric heating rate is inversely proportional to magnetic field strength. The main oval H_3^+ density and emission is lower at northern midnight than it is at noon, in agreement with a nearby peak in the electron influx in the post-dawn sector and a minimum flux at midnight. Finally, when arranging the northern main oval H_3^+ parameters as a function of the oscillation period seen in Saturn's magnetic field – the planetary period oscillation (PPO) phase – we see a large peak in H_3^+ density and emission at ~115° northern phase, with a full-width at half-maximum (FWHM) of ~44°. This seems to indicate that the influx of electrons associated with the PPO phase at 90° is responsible at least in part for the behavior of all H_3^+ parameters. A combination of the H_3^+ production and loss timescales and the ±10° uncertainty in the location of a given PPO phase are likely, at least in part, to be responsible for the observed peaks in H_3^+ density and emission occurring at a later time than the peak precipitation expected at 90° PPO phase.

1. Introduction

1.1. Ionosphere

Saturn's ionosphere is thought to be dominated by the positive ions H^+ and H_3^+ between 900 and 3000 km altitude and by hydrocarbon ions (e.g. $C_3H_5^+$) between 500 and 900 km altitude, along with their companion electrons, which maintain the ionosphere's quasi-neutrality (Moses and Bass, 2000). Co-located with this is the thermosphere, the charge-neutral component of the upper atmosphere, which is composed chiefly of H and H_2. Charged particles in the ionosphere are continuously generated by ionizing the otherwise neutral thermosphere through two main mechanisms. The first, photo-ionization by solar extreme ultra-violet (EUV) radiation, acts across the entire sunlit portion of the planet (the dayside). The second, electron impact ionization, acts primarily in the polar regions of the planet. Both mechanisms also electronically, vibrationally and rotationally excite the atmospheric constituents, which in turn de-excite and emit photons. The emissions from these mechanisms are 'auroral' emissions and occur at multiple wavelengths including infrared (IR), visible and ultraviolet (UV). This paper focuses primarily on the infrared emissions emanating from the molecular ion H_3^+ near the poles of the planet.

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Saturn's ionosphere lies at the base of the planetary magnetosphere, a region formed by the confinement of the planetary magnetic field by the solar wind. Closed field lines extend in the equatorial region to distances ~22 R_S (R_S is Saturn's 1 bar equatorial radius, equal to 60,268 km) on the dayside (Radioti et al., 2013), while open field lines stretch into a long magnetic tail downstream from the planet on the nightside. From estimates of the open flux in the magnetotail, the boundary between open and closed field lines in the ionosphere typically lies at around planetocentric co-latitude ~15° in each hemisphere (Badman et al., 2006), the difference between the two reflecting the north–south quadrupole asymmetry of Saturn's planetary magnetic field (Burton et al., 2010). In general it is expected that field-aligned currents flow down into the ionosphere over the polar field region due to the sub-corotation of plasma on open field lines and in the outer magnetosphere (Bunce et al., 2008). The current then flows from the pole towards the equator in both hemispheres as ionospheric Pedersen currents, before returning up the field lines to the magnetosphere at lower latitudes as the flow returns to near-rigid corotation with the planet (e.g. Cowley and Bunce, 2003; Cowley et al., 2004). The main auroral oval emissions are related to the latter ring of upward current (downward electron precipitation). The auroral oval is thus expected to lie in the region just equatorward of the open-closed boundary where the plasma angular velocity rises from low values on open lines towards rigid corotation on closed lines. The main oval is in general taken to correspond to the region between co-latitudes of ~10° and ~20° in both hemispheres (see, e.g., Carbary, 2012, and references therein). Auroral emissions are also sometimes observed in the poleward region, likely associated with solar wind-magnetosphere coupling dynamics at the magnetopause boundary of the magnetosphere (e.g. Meredith et al., 2014). Here we present new observations of H_3^+ obtained with the Keck telescope in April 2013 using similar methodology to that employed by O'Donoghue et al. (2014). These observations measure the northern and southern main auroral ovals simultaneously as in the previous study, but this time they take place over three days instead of one, allowing for a wider ranging analysis of short term auroral behavior. In addition, due to the developing northern spring season at Saturn, the dataset presented here also includes and discusses simultaneous measurements of both the northern polar aurora as well as the midnight main auroral oval, owing to the viewing geometry at the time of the observations.

1.2. The H_3^+ probe at Saturn

The molecular ion H_3^+ is produced by the reaction $H_2 + H_2^+ \longrightarrow H_3^+ + H$ (Oka, 2006). The reaction time (the ion chemistry timescale) varies from 10 s at 800 km altitude to 1000 s for altitudes near 2000 km (Badman et al., 2014). The lifetime of H_3^+ is proportional to its temperature, inversely proportional to the ionospheric electron density and has been previously quoted as 500 s (Melin et al., 2011). During this lifetime, H_3^+ becomes thermally excited to a higher rotational–vibrational (ro-vibrational) state by neighboring molecules on timescales of 10^{-2} s, which is approximately the same time for the ion to relax to a lower state and emit a photon. The discrete emission line spectra of H_3^+ make it a useful probe of the conditions in Saturn's ionosphere for two reasons. The first is that H_3^+ parameters such as column-integrated temperature, density and power output (hereafter, total emission) can be derived from it (e.g. Miller et al., 2006; Melin et al., 2014). Secondly, it is considered to be in local thermodynamic equilibrium (LTE) – or at least quasi-LTE – with its surroundings (Miller et al., 1990; Moore et al., 2008), meaning that the ion temperature is equivalent to the neutral temperature.

Using the ground-based 3.8-m United Kingdom InfraRed Telescope (UKIRT), the southern auroral H_3^+ temperature was found to be 380 ± 70 K in 1999 and 420 ± 70 K in 2004 by Melin et al. (2007). Later, in 2007, the Visual and Infrared Mapping Spectrometer (VIMS) (Brown et al., 2004) on board Cassini was used to derive a southern polar auroral H_3^+ temperature of (on average) 590 ± 30 K over a period of 10 h (Stallard et al., 2012a). Measurements of the southern auroral oval at equinox in 2009, also obtained by Cassini VIMS, yielded average temperatures of ~410 K (Lamy et al., 2013). The first conjugate northern and southern main oval H_3^+ temperatures were measured at high spatial resolution in 2011 using the 10-m W.M. Keck II (hereafter, Keck) telescope by O'Donoghue et al. (2014). The 10 spectral images, when co-added, yielded an average main auroral H_3^+ temperature of 583 ± 13 K (south) and 527 ± 18 K (north) over a ~2 h period. Throughout this time interval the spectra gave temperatures that varied by tens of Kelvins; this was a similar variability to the uncertainties, so it may be considered real or due to noise. In the neutral thermosphere near the exobase (~1900 km altitude above the 1 bar surface), solar occultations were performed using the Cassini ultraviolet imaging spectrometer (UVIS) to derive temperatures (Koskinen et al., 2013), yielding temperatures of 370–540 K from low- to high(auroral)-latitudes, respectively. The inter-hemispheric temperature asymmetry measured by O'Donoghue et al. (2014) was postulated to be the result of an inversely proportional relationship between magnetic field strength and the total heating rate. Due to the lower magnetic field strength in the south, the area undergoing heating is larger in the south than in the north (see O'Donoghue et al., 2014, for a more detailed discussion). Whilst the thermospheric temperatures at high latitudes can mostly be explained via auroral region Joule heating (Cowley et al., 2004), the low-latitude high temperatures remain difficult to explain theoretically. For example, exospheric temperatures are modeled to be 143 K on the basis of solar EUV heating alone, yet observations show the exosphere to be ~400 K (at sub-auroral latitudes) (Yelle and Miller, 2004; Koskinen et al., 2013). Smith et al. (2007) and Mueller-Wodarg et al. (2012) have explored the idea that heat is meridionally transported down from the poles to the equator, but conclude that auroral heating actually provides a net cooling effect at low latitudes. This is caused by a circulation pattern in which high altitude heating (by ion drag) causes equatorward flows. The flow is balanced by the continuity equation at low altitudes in the form of poleward flows, which themselves require there be an upwelling of material from below. It is this upwelling material that expands and cools adiabatically, leading to the counter intuitive effect of low latitude cooling, despite there being a nearby heating source (Smith et al., 2007). Thus, at present, it appears some additional source of energy is required to explain equatorial temperatures. One suggestion is the breaking of gravity waves in the thermosphere, but this is modeled to account for temperature enhancements of (at most) ~10s of K (Barrow and Matcheva, 2013). A final source of note is the low-latitude precipitation along the magnetic field lines conjugate to the rings known as 'ring rain'; it is possible that this is also associated with a low-latitude current system between the rings and the planet, but as yet such currents have not been directly observed (O'Donoghue et al., 2013).

1.3. Planetary period oscillations

In 1980 both Voyager 1 and 2 spacecraft measured bursts of nonthermal radio emission which emanated from Saturn – specifically they are likely from the northern hemisphere: the period of these bursts were ~10.67 h and taken (provisionally) to be the intrinsic rotation period of the planet (Kaiser et al., 1980).