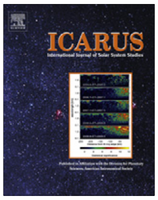
Icarus 221 (2012) 525–543

Contents lists available at SciVerse ScienceDirect

Icarus

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



Small-scale variability in Saturn's lower ionosphere

Katia I. Matcheva [a,*], Daniel J. Barrow [a,b]

[a] Department of Physics, University of Florida, Gainesville, FL 32611-8440, United States
[b] Buchholz High School, Gainesville, FL 32606, United States

ARTICLE INFO

Article history:
Received 16 March 2012
Revised 16 July 2012
Accepted 16 August 2012
Available online 1 September 2012

Keywords:
Atmospheres, Composition
Atmospheres, Dynamics
Ionospheres
Saturn, Atmosphere

ABSTRACT

We perform and present a wavelet analysis on all 31 Cassini electron density profiles published to date (Nagy, A.F. et al. [2006]. J. Geophys. Res. 111 (A6), CiteID A06310; Kliore, A.J. et al. [2009]. J. Geophys. Res. 114 (A4), CiteID A04315). We detect several discrete scales of variability present in the observations. Small-scale variability ($S < 700$ km) is observed in almost all data sets at different latitudes, both at dawn and dusk conditions. The most typical scale of variability is 300 km with scales between 200 km and 450 km being commonly present in the vast majority of the profiles. A low latitude dawn/dusk asymmetry is noted in the prevalent scales with the spectrum peaking sharply at the 300 km scale at dusk conditions and being broader at dawn conditions. Compared to dawn conditions the dusk ionosphere also shows more significant variability at the 100 km scale. The 300 km vertical scale is also present in the few available profiles from the northern hemisphere. Early observations from 2005 show a dominant scale at 350 km whereas later in 2007–2008 the spectrum shifts to the shorter scales with the most prominent scale being 300 km. The performed wavelet analysis and the obtained results are independent of assumptions about the nature of the layers and do not require a definition for a "background" electron density profile.

In the second part of the paper we present a gravity wave propagation/dissipation model for Saturn's upper atmosphere and compare the wave properties to the characteristics of the observed electron density variability at different scales. The general features observed in the data are consistent with gravity waves being present in the lower ionosphere and causing layering of the ions and the electrons. The wave-driving mechanism provides a simultaneous explanation for several of the properties of the observed variability: (i) lack of variability in the electron density above the predicted region of wave dissipation; (ii) in most cases the peak amplitude of variability occurs within the altitude range for dissipation of gravity waves or below; (iii) shorter scales have smaller amplitudes than the longer scales; (iv) shorter scales are present at lower altitudes whereas longer scales persist to higher altitudes; and (v) several layers often form a system of equally spaced maxima and minima that can be traced over a large altitude range.

1. Introduction

Our current knowledge of the structure of the ionosphere of Saturn is based mostly on spacecraft radio occultations (Pioneer 10 and 11, Voyager 1 and 2, and Cassini) and observations of the auroral emission in the UV and the near IR. In addition, the detection and monitoring of the Saturn Electrostatic Discharges (SEDs) by the Voyager Planetary Radio Astronomy (PRA) experiment and by the Cassini Radio and Plasma Wave Science (RPWS) experiment carry information about the maximum electron density and its evolution with time (Warwick et al., 1981, 1982; Fischer et al., 2006, 2011). The thermal structure of the atmosphere at ionospheric heights is constrained by stellar and solar occultations performed by the Voyager UVS and the Cassini UVIS teams (Festou and Atreya, 1982; Smith et al., 1983; Nagy et al., 2009). The observations reveal an ionosphere with complex vertical structure which strongly varies with time and latitude (Nagy et al., 2006; Kliore et al., 2009).

Previous theoretical models of Saturn's ionosphere have focused on its overall structure (the maximum of the electron density and total electron content of the ionosphere) and its latitudinal and time dependence in an attempt to capture the main physics and chemical processes that control the ionosphere (Moore et al., 2010). Difficulties arise from the unconstrained abundance of vibrationally excited H_2 molecules and the unknown amount of water influx from Saturn's rings, both of which are bound to have a strong impact on the ionospheric chemistry. Both quantities have been previously used as free parameters to reduce the lifetime of H^+ ions and to decrease the predicted values for the maximum of the electron density in order to fit the observations (McElroy,

---

[*] Corresponding author. Address: Department of Physics, University of Florida, P.O. Box 118440, Gainesville, FL 32611-8440, United States.

E-mail addresses: katia@phys.ufl.edu (K.I. Matcheva), barrowdj@gm.sbac.edu (D.J. Barrow).

0019-1035/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2012.08.022

1973; Connerney and Waite, 1984; Majeed and McConneell, 1991, 1996; Moses and Bass, 2000; Moore et al., 2004). Furthermore, very little is known about the dynamics of Saturn's ionosphere since the available observations contain no direct information about the wind system at these altitudes. Doppler shifts in the H_3^+ thermal emission lines can be used for measuring strong winds in Saturn's auroral region. In contrast to Jupiter, though, where thermospheric temperatures are in excess of 900 K, Saturn's H_3^+ mid-to-low latitude emission has been difficult to detect even with the Cassini instruments (Melin et al., 2011).

The Cassini Radio observations, resulting in 31 published electron density profiles to date, provide us with the most detailed picture so far of the structure of Saturn's ionosphere. The observations have been made during the first phase of the Cassini mission from 2005 to 2008, corresponding to southern hemisphere summer and early fall. The following features have been previously pointed out in the literature: (1) The maximum electron density as well as the total electron content (TEC) increase with latitude with a maximum in the polar regions (Moore et al., 2010). (2) At low latitudes the dawn electron density peak is smaller and occurs at higher altitudes (referred to as dawn/dusk asymmetry) (Nagy et al., 2006; Kliore et al., 2009). (3) A complex system of sharp layers of enhanced electron density is observed in the lower ionosphere at most latitudes. (4) Some profiles exhibit large vertical regions of near depletion of electrons (referred to as bite-outs).

In this paper we investigate the small-scale vertical layering present in a significant fraction of the 31 Cassini electron density profiles of Saturn published in the literature to date. Multiple layers in the electron density are observed in virtually all Cassini profiles as well as in the Voyager and Pioneer profiles although some of them do not extend to very low altitudes. The layers are seen in dusk and dawn conditions at low, mid and high latitudes. The number of identifiable layers, the magnitude of the electron density peaks, the vertical scale (thickness) of the layers, and the spacing between the individual peaks vary. In this paper we present a statistical analysis for the scale and the magnitude of the vertical variations present in the individual Cassini electron density profiles. The large number of observations allow us to study the spectrum of the vertical variability at different latitudes and to even compare dawn and dusk conditions.

It is well known that the terrestrial night-time ionosphere often displays similar systems of narrow layers of electrons which are usually attributed to atmospheric waves or plasma instabilities (Kelley, 1989). Similar layers have also been observed in the Galileo J0-ingress electron density profile of Jupiter which samples the ionosphere at dusk conditions (Hinson et al., 1997). This system of layers has been successfully modeled as a signature of an atmospheric gravity wave propagating in Jupiter's thermosphere (Matcheva et al., 2001; Barrow and Matcheva, 2011). The corresponding dawn electron density profile of Jupiter however showed very different ionospheric structure with no well pronounced small-scale layers.

In the second part of this paper we model the propagation of atmospheric gravity waves in Saturn's thermospheric/ionospheric region and compare the predicted properties of the waves to the spectral characteristics of the observed variability in the electron density.

2. Vertical variability in the electron density

The first step in our analysis is to study the variability in the data with minimum theoretical assumptions about the nature of the fluctuations and/or the state of the ionosphere. We perform a wavelet analysis on all 31 electron density profiles published to date by the Cassini Radio Science Team to identify the prevalent scales of variability in the vertical electron density distribution. A brief mathematical introduction to the theory and application of the wavelet analysis can be found in Torrence and Compo (1998) along with a downloadable software for public use. For the purpose of our study we use the continuous wavelet transform together with the Morlet wavelet basis as it provides us with optimal scale discrimination and vertical resolution. For a discrete series of measurements, x_n, $(n = 0 \cdots N-1)$, with equal spacing δt (in our case the sampling is done in space rather than in time) the functional form of the Morlet wavelet is

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2}, \tag{1}$$

where $\eta = \frac{n\delta t}{S}$ is a dimensionless "time" parameter, ω_0 is the dimensionless frequency, and S is a scale of variability (analogous to the wavelength in a Fourier transform). The Morlet function is essentially a cosine function multiplied with a Gaussian. The frequency ω_0 reflects the number of oscillations within the Gaussian envelope. In this study we use $\omega_0 = 6$ which assures that the wavelet function has enough vanishing moments and can resolve high frequency signals.

The wavelet coefficients $W_n(S)$ for a given scale s and position n are then calculated using the continuous wavelet transform

$$W_n(S) = \sum_{n'=0}^{N-1} x_{n'} \psi_0^* \left[\frac{(n'-n)\delta t}{S}\right], \tag{2}$$

where $(^*)$ indicates a complex conjugate. Similar to the Fourier coefficients the square of the wavelet coefficients presents the energy within a given scale of variability. In many cases the wavelet analysis is a preferred tool for data analysis as it also shows how the magnitude of these variations changes within the length of the data set. In our analysis the calculated wavelet coefficients (2) are normalized so that the square of the wavelet coefficient is equal to the square of the amplitude of the observed variation rather than the power of the present scales.

The results from the wavelet analysis for selected latitudes are shown in Figs. 1–4. The results for the remaining 27 cases are shown in the Appendix in Figs. A.1–A.27. Fig. 1 shows the analysis of a high latitude observation (72°S at dusk), Fig. 2 presents a mid latitude case (28°S at dusk), Figs. 3 and 4 correspond to low latitude conditions at dusk (3°S) and dawn (9°S), respectively. The choice of latitudes is to illustrate the fact that layering in the ionosphere of Saturn is present at all latitudes at diverse local conditions and time of the day.

Each of the figures has three panels showing the local electron density profile (left panel), a color map of the variations $Re(W_n(S))$ present in the data at different scales as a function of altitude (central panel), and a color map of the amplitude of the variations $|W_n(S)|$ at different scales as it changes with height (right panel). The variations N_e' are normalized to the peak electron density, $N_{e,max}$, and the result $\frac{N_e'}{N_{e,max}}$ is presented in percentage. By definition the variation cannot exceed 50%. The contours are drawn at 5% intervals. A vertical slice through the amplitude color map shows how the amplitude at a given scale S changes with height. A horizontal cut through the map at a given altitude produces the spectrum of the scales present at this height. Similar to the Fourier analysis the wavelet analysis suffers from edge effects. The effect is scale dependent and results in distortion of the power at the edge of the map at a distance one scale length away from the edge.

To answer the question, how significant are the scales identified in Figs. 1–3, we present the wavelet analysis of S56 exit occultation together with a contour of the 5% significance level as defined by Torrence and Compo (1998) (Fig. 5). The calculation is based on the variance in the observed electron density profile and assumes a white power-spectrum for the noise. The 5% significance Level is equivalent to the 95% confidence level tested against a white noise background. One can see that the 5% significance level in