Icarus 307 (2018) 17–24

Contents lists available at ScienceDirect

Icarus

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

An upper limit on Pluto's ionosphere from radio occultation measurements with New Horizons

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ARTICLE INFO

Article history:
Received 11 August 2017
Revised 5 December 2017
Accepted 7 February 2018
Available online 7 February 2018

Keywords:
Pluto
Ionospheres
Occultations
Radio observations

ABSTRACT

On 14 July 2015 New Horizons performed a radio occultation (RO) that sounded Pluto's neutral atmosphere and ionosphere. The solar zenith angle was 90.2° (sunset) at entry and 89.8° (sunrise) at exit. We examined the data for evidence of an ionosphere, using the same method of analysis as in a previous investigation of the neutral atmosphere (Hinson et al., 2017). No ionosphere was detected. The measurements are more accurate at occultation exit, where the 1-sigma sensitivity in integrated electron content (IEC) is 2.3×10^{11} cm^{-2}. The corresponding upper bound on the peak electron density at the terminator is about 1000 cm^{-3}. We constructed a model for the ionosphere and used it to guide the analysis and interpretation of the RO data. Owing to the large abundance of CH_4 at ionospheric heights, the dominant ions are molecular and the electron densities are relatively small. The model predicts a peak IEC of 1.8×10^{11} cm^{-2} for an occultation at the terminator, slightly smaller than the threshold of detection by New Horizons.

1. Introduction

New Horizons sped past Pluto in July 2015 (Stern et al., 2015). Its reconnaissance of the Pluto System included radio occultation (RO) measurements at both Pluto and Charon (Tyler et al., 2008; Young et al., 2008). These observations were implemented in an uplink configuration, using signals transmitted by four antennas of the NASA Deep Space Network and received by the spacecraft (Hinson et al., 2017). The flight component of the radio science instrument consists of two radio receivers, which are used routinely for communication and navigation (Fountain et al., 2008). Each receiver also contains a specialized signal processor — known as REX — designed specifically to support the radio occultations and other scientific observations (Tyler et al., 2008).

The Pluto radio occultation addressed two objectives of the New Horizons Mission (Young et al., 2008). The primary objective was to determine the atmospheric pressure at the surface and the temperature structure of the lower atmosphere. Gladstone et al. (2016) reported the initial results, which were later refined and extended by Hinson et al. (2017) in a more thorough analysis of the full data set. The REX observation yielded a mean surface pressure of 11.5 ± 0.7 microbar at a radius of 1189.9 ± 0.2 km and the first atmospheric temperature profiles that extend all the way to the surface. The measured air temperature adjacent to the surface was 38.9 ± 2.1 K at occultation entry and 51.6 ± 3.8 K at occultation exit.

The subject of this paper is the secondary objective of the Pluto occultation, to characterize the ionosphere. We apply the method of analysis developed in the previous investigation of the neutral

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https://doi.org/10.1016/j.icarus.2018.02.011
0019-1035/

atmosphere (Hinson et al., 2017), and we show that the sensitivity of the measurements is consistent with expectations (Tyler et al., 2008). Although Pluto's ionosphere eluded detection by REX, we have derived a tight upper limit that serves as a constraint for modeling the chemistry of the ionosphere.

As part of this investigation we also constructed a simple model for Pluto's ionosphere, which plays an important role in the interpretation of the RO data. The model has been updated in response to discoveries by New Horizons about the temperature structure and composition of the neutral atmosphere, most importantly by Alice, the ultraviolet imaging spectrograph (Kammer et al., 2017; Young et al., 2018). This greatly reduces some of the uncertainties inherent to previous models.

New Horizons has explored Pluto's plasma environment through observations by the Solar Wind Around Pluto (SWAP) instrument and the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) instrument (Bagenal et al., 2016). In particular, SWAP has revealed the presence of plutogenic heavy ions, probably CH_4^+, and has characterized their distribution around Pluto and their interaction with the solar wind (McComas et al., 2016). Comparatively little is known about the tenuous ionosphere that lies at the base of this interaction region. As reported here, our search for Pluto's ionosphere in the REX measurements was unsuccessful. In the only other relevant observation, Alice detected faint emission in the N^+ multiplet at 108.5 nm (Steffl et al., 2016), which arises primarily from dissociative photoionization of molecular nitrogen by solar EUV and X-ray photons. However, this detection of ion production in Pluto's upper atmosphere is not diagnostic of the ambient ion density.

The paper is organized as follows. Section 2 introduces the ionospheric model and applies it to Pluto. Section 3 describes the implementation of the radio occultation. Section 4 discusses the basic steps of data reduction and derives an upper limit on Pluto's ionosphere. Section 5 compares the results with previous measurements of Triton's ionosphere and briefly summarizes our findings.

2. A post-New Horizons model for the ionosphere of Pluto

Pluto's ionosphere has been modeled previously (Summers et al., 1997; Krasnopolsky and Cruikshank, 1999; Ip et al., 2000), but prior to New Horizons there was considerable uncertainty about its fundamental properties, such as the peak electron density, the altitude of the peak, and the identity of the most abundant ion. With the reconnaissance of the Pluto System by New Horizons, significant improvements to the ionospheric models are now possible, owing to dramatic advances in our understanding of the structure and composition of the neutral atmosphere (Gladstone et al., 2016; Cheng et al., 2017; Forget et al., 2017; Hinson et al., 2017; Kammer et al., 2017; Young et al., 2018).

2.1. Formulation of the model

We constructed a new but simple model for the ionosphere with two unique features. It incorporates New Horizons measurements of the neutral atmosphere, and it accounts for the variations of ionospheric structure with both radius r and solar zenith angle χ. Because the RO measurements are sensitive only to free electrons and not to the far more massive ions, the primary goal is to characterize the spatial distribution of ionospheric electrons.

We adopted the "nominal" solution for the overall structure of Pluto's neutral atmosphere derived by Young et al. (2018), which combines the REX pressure and temperature profiles at altitudes below about 100 km (Hinson et al., 2017) with Alice solar occultation measurements of neutral number density and composition at higher altitudes (Young et al., 2018). Key characteristics of the model include an isothermal upper atmosphere with a temperature of 68 K, a CH_4 mixing ratio at the surface of 0.3%, and an eddy diffusion coefficient of $1000\,\mathrm{cm}^2\ \mathrm{s}^{-1}$. The CH_4 mixing ratio at ionospheric heights is about 5% (Young et al., 2018), similar to its value on Titan (Cui et al., 2012) but much larger than on Triton (Strobel and Summers, 1995).

To compute the primary production rate of ions, by ionization of N_2 and CH_4, we adopted the TIMED SEE SSI solar EUV data (http://lasp.colorado.edu/lisird/data/timed_see_ssi_l3/) for the date of the flyby, 14 July 2015. Ionization cross sections for N_2 and CH_4 were obtained from standard sources (e.g., http://satellite.mpic.de/spectral_atlas/cross_sections/, http://home.strw.leidenuniv.nl/~ewine/photo/data/photo_data/all_cross_sections/) with assumed ionization potentials of 15.58 and 12.61 eV, respectively. For simplicity we assumed that the total absorption cross sections are equal to the ionization cross sections.

Absorption of high-energy solar photons leads to ejection of very energetic photoelectrons, which produce additional ionization through collisions with neutral molecules. In modeling this process, we used calculations by Simon Wedlund et al. (2011) of the yield W of electron-ion pairs as a function of the photoelectron energy. They considered a variety of atmospheric gases, including N_2 and CH_4, and validated the approach with laboratory data.

The ionization rates of N_2 and CH_4 are given by

$$q_1(r,\chi) = n_1(r)\sum_j \sigma_{1j} f_j \left(1 + W_{1j}(E_j)\right) \times \exp\left[-\sigma_{1j}\int n_1\,ds - \sigma_{2j}\int n_2\,ds\right], \tag{1}$$

and

$$q_2(r,\chi) = n_2(r)\sum_j \sigma_{2j} f_j \left(1 + W_{2j}(E_j)\right) \times \exp\left[-\sigma_{1j}\int n_1\,ds - \sigma_{2j}\int n_2\,ds\right]. \tag{2}$$

The subscripts $i = 1$ and 2 denote N_2 and CH_4, respectively; n_i is neutral number density, which depends only on radius r; f_j is the solar flux at wavelength interval j; σ_{ij} is the cross section; and W_{ij} is expressed as a dimensionless yield of electron-ion pairs as a function of the photoelectron energy E_j. Each integral is along the line of sight from the Sun to the location of interest at radius r and solar zenith angle χ. From calculations by Simon Wedlund et al. (2011), we can approximate the W functions by

$$W_{1j} = \frac{(1240/\lambda_j) - 15.58}{86\left[\frac{20}{(1240/\lambda_j)-15.58}\right]^{2.5} + 34.3}, \tag{3}$$

and

$$W_{2j} = \frac{(1240/\lambda_j) - 12.61}{86\left[\frac{20}{(1240/\lambda_j)-12.61}\right]^{2.5} + 34.3}, \tag{4}$$

where λ_j is the wavelength in nanometers. Units are eV for $1240/\lambda_j$ and all other numbers.

A substantial portion of the negative charge in Titan's lower ionosphere is carried by negative ions rather than electrons (Coates et al., 2007; Shebanits et al., 2013). With its similar N_2-CH_4 chemistry, the same may be true for Pluto. However, no data are currently available concerning negative ions at Pluto, and consideration of this complex aspect of ion chemistry is beyond the scope of our model. We assume that only free electrons carry negative charge.

Summers et al. (1997) previously examined the effect of atmospheric composition on Pluto's ionosphere. In models with a