Icarus 246 (2015) 310–316

Contents lists available at ScienceDirect

Icarus

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

Pluto's plasma wake oriented away from the ecliptic plane

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ARTICLE INFO

Article history:
Received 3 December 2013
Revised 11 June 2014
Accepted 16 June 2014
Available online 28 October 2014

ABSTRACT

Conditions similar to those observed in the solar wind interaction with Venus and Mars where there is a planetary atmosphere in the absence of a global intrinsic magnetic field may also be applicable to Pluto. With up to 24 μbars inferred for the Pluto atmosphere it is possible that the feeble solar photon radiation flux that reaches by its orbit, equivalent to $\sim 10^{-3}$ that at Earth, is sufficient to produce an ionization component that can be eroded by the solar wind. In view of the reduced solar wind density ($\sim 10^{-3}$ with respect to that at 1 AU) that should be available by Pluto its total kinetic energy will be significantly smaller than that at Earth. However, the parameter values that are implied for the interaction process between the solar wind and the local upper ionosphere are sufficient to produce a plasma wake that should extend downstream from Pluto. In view of its low gravity force the plasma wake should have a wider cross-section than that in the Venus and Mars plasma environment. Since Pluto rotates with the axis tilted ~30° away from the ecliptic plane the plasma wake will be influenced by a Magnus force that has a large component is the north–south solar polar direction. That force will be responsible for propelling the plasma wake with a component that can be directed away from that plane. It is estimated that transport of solar wind momentum to the upper Pluto's ionosphere implies rotation periods smaller than that of the solid body, and thus large values of the Magnus force that can increase the orientation of the plasma wake away from the ecliptic plane.

1. Introduction

Issues related to the erosion that the solar wind produces on the planetary ionospheres of un-magnetized planets have been considered in regard to an ample available amount of experimental information, Pioneer Venus Orbiter (PVO) and Venus Express (VEX) for Venus, and Mars Global Surveyor (MGS), Phobos and Mars Express (MEX) for Mars. From the results of the data analysis of those missions it has been possible to estimate the mass loss of the ionosphere for each planet (Lundin and Dubinin, 1992; Lundin et al., 2011), together with a general view of the distribution that the planetary plasma acquires as it is being driven by the solar wind. Most notable is that there is a tendency for the planetary ions located in the vicinity of the polar regions of both planets to be mostly driven downstream. At Venus this has been inferred from the interpretation of the ionospheric holes observed in the night-side hemisphere (Brace et al., 1982) in terms of plasma channels that extend downstream from the polar regions (Pérez-de-Tejada, 2004). Similar conclusions have been reached for Mars from the MEX measurements of planetary ions driven from the polar regions (Pérez-de-Tejada et al., 2009) together with the polar plasma halo reported from the X-ray emission lines detected with the reflecting grating spectrometer (RGS) of the XMM-Newton satellite (Dennerl et al., 2006).

An important difference in the manner in which the planetary ions are distributed through the wake of Venus and Mars is that near the downstream vicinity of the terminator they extend across distances that have a larger cross-section at Mars than at Venus. In fact, measurements conducted with the ASPERA-4 instrument at VEX indicate that planetary O+ ions follow trajectories that mostly maintain them in the Venus inner wake (Lundin et al., 2011), while those detected with the ASPERA-3 instrument in the MEX spacecraft are allowed to move more freely away from the Mars inner wake (Pérez-de-Tejada et al., 2009). In both cases such measurements were conducted by solar minimum conditions and thus are different from those that prevailed during the early phase of the PVO observations. Since the periapsis of the PVO trajectory occurred down to ~140 km altitude during solar maximum conditions it was possible to make frequent crossings of ionospheric holes in Venus at heights lower than the altitudes probed with the VEX and MEX spacecraft where periapsis reached ~340 km. The larger cross-section of the region where the planetary O+ fluxes are detected in the Mars wake as derived from the MEX

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http://dx.doi.org/10.1016/j.icarus.2014.06.022
0019-1035/

measurements should be related to the lower gravity force of that planet with respect to that at Venus and that leads to smaller values of the escape velocity.

Measurements have also shown a bow shock upfront from Venus and Mars and a velocity boundary layer that is adjacent to the flanks of their ionosphere. The presence of that layer supports transport of solar wind momentum to planetary ions as it was inferred for Venus from the early Mariner 5 and Venera plasma data (Bridge et al., 1967; Vaisberg and et al., 1976) and that was later examined by Pérez-de-Tejada (1986a). The outer limit of that boundary layer is a plasma transition that has been detected with instruments onboard various spacecraft that have probed the Venus plasma environment (Shefer et al., 1979; Romanov et al., 1979; Pérez-de-Tejada et al., 1995, 2011), and that is also present in the velocity profile of the O+ ion fluxes derived from the MEX observations in Mars Pérez-de-Tejada et al. (2009). The discussion presented below follows similar arguments regarding the plasma properties that are expected near Pluto and addresses issues related to the distribution of its ionospheric plasma in its wake given the direction of its axis of rotation. Arguments are presented to suggest that Pluto's plasma wake can be far wider than those at Venus and Mars, and that unlike the case at Venus where there is an ionospheric trans-terminator flow that is mostly deviated toward the dawn side of the Venus atmospheric retrograde rotation motion (Miller and Whitten, 1991; Lundin et al., 2011), the conditions at Pluto are different in view that its rotation axis is ~30° from the ecliptic plane and thus the corresponding trans-terminator flow can be oriented away from that plane.

2. Reported properties of Pluto's atmosphere/ionosphere

Despite the large distance between Pluto and the Earth it has been possible to detect the presence of an atmosphere in that body. From spectroscopic measurements first conducted in the Wise Observatory in Israel, and later using the Kuiper Airborne Observatory in occultation of stars events, there is now evidence that there is in fact an envelope of nitrogen, methane, and carbon monoxide gases originated from ices of these substances on Pluto's surface (Marsden, 1985). The surface pressure ranges from 6.5 to 24 μbar at ~40 K temperatures (Lellouch et al., 2009). Star occultation events (Sicardy and et al., 2003; Elliot et al., 2003; Pasachoff et al., 2005) have led to surface pressure values comparable to the upper limit and that could have been produced by heating Pluto's south pole which came out of its shadow after ~120 years thus producing sublimated nitrogen from the polar cap.

The photoionization of Pluto's atmosphere will be produced by the weak solar photon fluxes that reach its orbit and will extend across a large altitude range due to its low gravity force. As a result Pluto's ionosphere will have large scale heights and will reach high altitudes as it is indicated in the altitude density profile shown in Fig. 1 (Ip et al., 2000). Thus, the low plasma pressure values that can be inferred from the surface conditions will extend to high altitudes where the ionospheric plasma will be subject to weak solar wind proton fluxes. A value of the solar photon fluxes that photoionize Pluto's atmosphere can be estimated by considering that at the ~30 AU Pluto's perihelium distance the photon flux should only be ~1/1000 of that reaching the Earth. At the same time by assuming that the solar wind density decreases in a $1/r^2$ dependence it will be possible to expect values that are ~1/1000 of those present by the Earth's orbit. The dynamic pressure of the solar wind will thus be reduced by a comparable amount assuming that its speed maintains similar values (Richardson and Stone, 2009). Since the ionospheric plasma could be mostly produced by photoionization processes it may remain within a region dominated by particle collisions and be forced downwards by the solar wind dynamic pressure. In the absence of an intrinsic magnetic field at Pluto the ionospheric plasma will receive that energy input and be pressed down below an upper boundary (ionopause) as a plasma transition located downstream from a bow shock traced outside the ionosphere. The bow shock arises given the supersonic speed of the solar wind that is maintained as it reaches by Pluto and encounters its ionosphere as an obstacle. As it will be discussed below the solar wind that reaches the magnetic polar regions leads to peculiar conditions since the IMF fluxes that have draped around the ionosphere are displaced over the dayside hemisphere to enter the wake at those locations. A schematic illustration of the hair-pin geometry of the IMF lines that have draped around the dayside ionosphere and slide over a magnetic polar region is presented in Fig. 2. It is to be noted that the position of the magnetic polar regions at the terminator (between the dayside and the nightside hemispheres) varies depending on the orientation of the IMF with respect to the ecliptic plane and it is implied from the inclination of the magnetic equatorial plane.

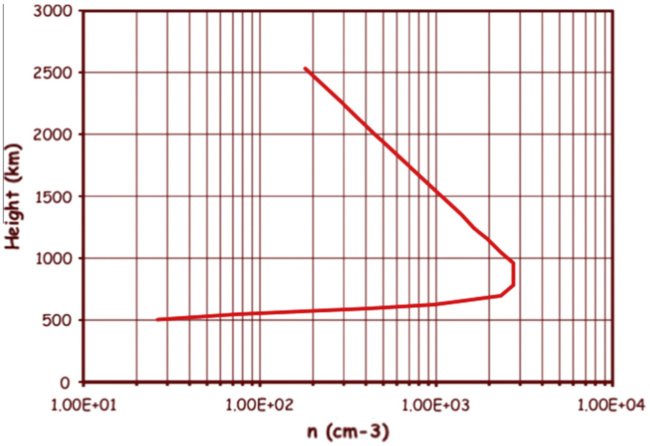

Fig. 1. Density profile of Pluto's ionosphere (extrapolated from Ip et al., 2000).

3. Solar wind erosion of the upper ionosphere

From the predicted trajectory of the "New Horizons" spacecraft that will encounter Pluto on July 14, 2015 it is expected that it will occur in the vicinity of the ecliptic plane as Pluto moves across that plane by then (its orbit around the Sun has a ~17° latitude orientation with respect to the ecliptic plane). The geometry of the encounter trajectory is illustrated in Fig. 3 to show that as the solar wind streams around Pluto's ionosphere it will produce a plasma wake that will extend radially away from the Sun and thus could be probed along the spacecraft trajectory. As it is the case at Venus the IMF will drape around Pluto's ionosphere building up a magnetic barrier above its upper boundary that will reduce the direct contact between the oncoming solar wind and the upper layers of the ionospheric plasma. Different conditions occur by the magnetic polar regions where the convected magnetic field fluxes do not pile up but stream past Pluto to enter the wake as shown in Fig. 2. From the interaction between the solar wind and the ionospheric plasma that is expected by the magnetic polar regions there should be a significant transport of solar wind momentum leading to an ionospheric trans-terminator flow similar to what has been measured in the Venus upper ionosphere (Knudsen et al., 1980). However, there is a complicating factor that will influence the direction of Pluto's plasma wake and the position of the (magnetic) polar regions. In particular, as it is the case at Uranus Pluto rotates nearly on its side with respect to the ecliptic plane (axial tilt of ~30° from that plane) and thus the pile up of the