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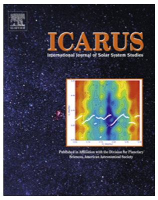

Gas transfer in the Pluto–Charon system: A Charon atmosphere

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ABSTRACT

Recent hybrid fluid/molecular kinetic models demonstrated that Pluto's upper atmosphere is warmer and more extended than previously thought (Erwin, J.T., Tucker, O.J., Johnson, R.E. [2013]. Icarus 226, 375–384; Tucker, O.J., Erwin, J.T., Deighan, J.I., Volkov, A.N., Johnson, R.E. [2012]. Icarus 217, 408–415). Here we examine the effect of Charon on the molecular escape rate from Pluto's extended atmosphere, simulate the spatial distribution of N_2 in this binary system, and describe the resulting accumulation of N_2 on Charon. These Monte Carlo simulations are carried out for approximate solar medium conditions at ~33 AU. Including Charon's gravity and orbital motion, the atmosphere on the Pluto's Charon-facing hemisphere is more strongly bound to the system and is more extended than the atmosphere on Pluto's anti-Charon hemisphere. Accounting for Charon's gravity the net escape from the system is reduced by ~5%. Most of the loss is direct from Pluto's exobase region with ~1–2% due to scattering by Charon. About ~0.2% of the flux from Pluto's exobase impinges on Charon: $\sim 5.7 \times 10^{25}$ N_2/s at nominal solar medium conditions. This is a source of condensed N_2 for Charon's night side and forms a tenuous atmosphere. For the approximate range of surface temperatures, the residence time of N_2 on the surface can range from a fraction of a second to 10s of years with the near surface line of sight column densities varying from $\sim 3 \times 10^{18}$ N_2/m^2 up to $>6 \times 10^{19}$ N_2/m^2. Such an atmosphere could be detectable during the solar occultation that will occur during the New Horizon encounter providing a measure of the transfer of gas between bodies in this binary system.

1. Introduction

The transfer of gas between objects in a binary system is a ubiquitous problem in astronomy. Since Pluto and Charon form a dwarf-planet binary to be visited by the New Horizons (NH) spacecraft in 2015, new data on gas transfer in such a system will soon be available and can be used to test simulations of gas transfer in binary systems. Therefore, in anticipation of the NH encounter we calculate the effect of Charon on the escape of atmosphere from Pluto, the resulting distribution of gas in the binary system, the concomitant transfer of gas from Pluto to Charon and the likelihood that Charon might acquire a detectable tenuous atmosphere. These calculations are carried out ignoring the effect of the other much smaller satellites.

Charon is approximately half the size of Pluto and the bulk densities inferred from occultation observations of Pluto (2.03 g/cc) and Charon (1.62 g/cc) suggest they have somewhat different ice to rock fractions (Elliot et al., 2007; Gulbis et al., 2006). Spectroscopic observations indicate Pluto's surface is covered by N_2 ice containing CH_4 and smaller amounts of CO (Owen et al., 1993). By contrast, Charon lost its primordial component of the highly volatile species so that its surface is predominantly covered with water ice (Grundy et al., 2002; Cook et al., 2007; Schaller and Brown, 2008). Comet impacts have been suggested to contribute volatiles (Stern et al., in press) and, as at Enceladus, cryovolcanism could in principal release trapped volatiles (Cook et al., 2007). Here we focus on the transfer of N_2 from Pluto's atmosphere. If this is the primary source of volatiles to Charon's surface, its detection during the solar occultation (Fig. 1) could also provide a constraint on simulations of Pluto's N_2 escape rate and on the exchange of volatiles in a binary system. Therefore, we simulate the effect of Charon on Pluto's extended atmosphere, and the subsequent atmospheric mass transfer between the two bodies.

As is the case for many binary systems (e.g., Thomas, 1977), there is an exchange of material between Pluto and Charon. When it was assumed that Pluto's atmosphere was predominantly CH_4, it was estimated that the extension of Pluto's bound and escaping gas

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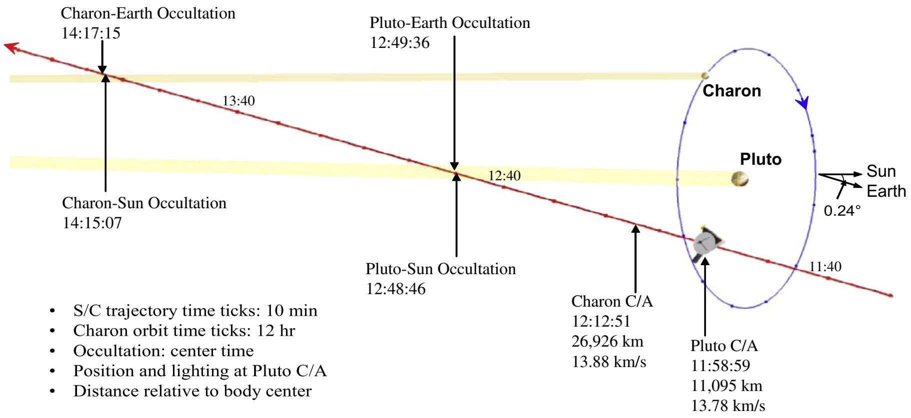

Fig. 1. Encounter geometry: occultation of the Sun will allow line of site absorption features to be detected at both Pluto and Charon (e.g., Guo and Farquhar, 2009).

had a density $\sim 10^9 < n < 10^{10}$ m^{-3} in the vicinity of Charon, but its weak gravity could not sustain a detectable CH_4 atmosphere (Stern, 1992; Whipple et al., 1989). Nitrogen is now known to be the dominant escaping volatile as described in a number of papers (e.g., Hunten and Watson, 1982; McNutt, 1989; Krasnopolsky, 1999; Strobel, 2008). Recently we showed those models of the upper atmospheric structure and escape were incorrect and that the radial position of Pluto's exobase is much larger than typically predicted (Tucker et al., 2012; Erwin et al., 2013; Zhu et al., 2014). Since the atmosphere is more extended and a heavier species, N_2, is the dominant gas, we re-examine the transfer and retention of atmosphere from Pluto to Charon when the Pluto system is near the NH encounter distance, ~33 AU. Using a simpler model to calculate the average effect of Charon on Pluto's escape rate at approximate solar minimum conditions, Tucker et al. (2012) showed the transfer rate was non-negligible. Here we use the results of our more recent simulations of Pluto's upper atmosphere (Erwin et al., 2013) to examine the effect of Charon on escape of nitrogen from Pluto and its redistribution in a system rotating about the Pluto/Charon center of mass. In re-examining this process we show that at the NH encounter Charon might have a detectable gravitationally bound component of N_2 gas over certain regions of its surface and will accumulate a significant layer of condensed N_2 over the cold regions. In addition, the ambient nitrogen in this binary system will be detectable as pick-up ions and, possibly, in radiolytically produced compounds on Charon's surface.

Table 1
System properties.[a]

Orbit (years)	248	
Perihelion (AU)	29.66	
Encounter (AU)	~33	
Separation: R_{pc} (R_p)	17.0	
Roche Lobe (R_{pc})	0.69	
Rotational period (s)	5.5×10^5	
	Pluto	Charon
R (km)	1150	606
M (10^{22} kg)	1.3	0.15
v_{orb} (m/s)	~23	~200
R_{COM} (R_p)	1.76	15.24

[a] Orbital properties used: R (radii), M (masses), v_{orb} (orbital speeds), R_{COM} (distance from center of mass), R_{pc} = distance from Pluto to Charon, R_p = Pluto radius (estimates vary, ~1150 to ~1190 km, but results here are insensitive to the size of this uncertainty).

Table 2
Atmosphere at Pluto's exobase.[a]

	Solar minimum	Solar medium	Solar maximum
R_x (R_p)	5.30	6.84	9.8
T_x (K)	87	79	66
λ_x	5.7	4.8	4.5
n_x (m^{-3})	7×10^{11}	5×10^{11}	3×10^{11}
φ_{exo} (s^{-1})	2.3×10^{28}	2.5×10^{28}	3.0×10^{28}
φ_{es} (s^{-1})	1.17×10^{27}	2.54×10^{27}	2.0×10^{28}
$\varphi_{es}/\varphi_{\rm Jeans}$	2.0	2.3	~3

[a] R_x, T_x, n_x and λ_x are the exobase radius, temperature, number density and Jeans parameter; φ_{exo} is the flow rate across the exobase, φ_{es} is the unperturbed escape rate and $\varphi_{\rm Jeans}$ is the Jeans rate: from Erwin et al. (2013) using nominal solar conditions for ~33 AU.

2. Model description

Transfer of gas between astrophysical binary objects (e.g., Layton et al., 1998; Stevens, 1988) is often described by transonic flow. The gas from the more extended atmosphere is described as being transferred into the Roche Lobe or past the L1 point beyond which the gravitational effect of the other object dominates. In the system considered here the Roche Lobe occurs at ~0.69 times the distance between Pluto and Charon, but a fluid description is not applicable because of the low gas density (Tucker et al., 2012). For example, for a plutonian exosphere density of $\sim 10^{12}$ m^{-3} assuming a hard sphere collision cross section of $\sim 10^{-19}$ m^2 the mean free path for a collision is approximately $\sim 6R_p$, using a Pluto radius of $R_p = 1150$ km. Therefore, we use a 3D ballistic transport Monte Carlo model to simulate the nearly collisionless, time dependent interaction of Pluto's extended upper atmosphere with Charon. In Table 1 we give properties of the system and in Table 2 we summarize the results from our earlier simulations of Pluto's atmosphere for a variety of solar conditions where it is seen that the exobase radii are a significant fraction of the Roche Lobe distance. For instance, Pluto's exobase is seen to be less than $2R_p$ from Charon's Roche Lobe for approximate solar maximum conditions, and the gas densities about Charon are similar to Pluto's exobase densities. However, in this paper we focus on results for approximate solar medium conditions that are closer to the conditions expected at the NH encounter.

The evolution of the gas escaping from Pluto is simulated using a set of modeling particles each of which represent $<10^{28}$ N_2 molecules. The trajectories of Pluto, Charon and the molecules are tracked in an inertial frame where the x and y axes are chosen to be in the Pluto–Charon orbital plane and the origin is chosen to be at the center of mass between Pluto and Charon as indicated in Table 1. Looking at the system from the Earth, both bodies orbit the center of mass counter-clockwise as indicated in Fig. 1. It is assumed for simplicity that the Sun is in the z direction

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