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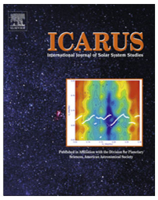

Pluto's climate modeled with new observational constraints

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ABSTRACT

Pluto has a nitrogen atmosphere in vapor pressure equilibrium with surface ice. N_2 is mobile and is transported seasonally even at Pluto's cold temperatures in the outer Solar System. A thermal model developed by Hansen and Paige in 1996 to model Pluto's climate has been re-deployed in response to new data and in anticipation of the New Horizons flyby of Pluto in 2015. A number of stellar occultations have been observed in the last 11 years as Pluto has crossed the galactic plane. New Hubble Space Telescope images show a variegated surface. These recent observations allow us to model Pluto's climate with much tighter constraints. Our findings suggest that Pluto's atmosphere will not collapse prior to the arrival of New Horizons although pressure will be dropping as N_2 condenses on the south polar cap. This finding is in contrast to the Olkin et al. (Olkin et al. [2013]. arXiv1309.0841O) prediction that permanent volatiles in the northern hemisphere maintain Pluto's atmospheric pressure throughout its orbit. The range of surface pressures predicted for 2015 for nine cases with very good matches to observables is 0.3–3.2 Pa. The best match predicts that New Horizons will detect an atmospheric pressure of 2.4 Pa.

1. Introduction

In the cold outer Solar System Pluto and Triton have nitrogen atmospheres in vapor pressure equilibrium with surface ices (*Pluto*: Stern and Trafton, 1984; Elliot et al., 1989; Hubbard et al., 1990; Owen et al., 1992, 1993; Hansen and Paige, 1996; *Triton*: Trafton, 1984; Spencer, 1990; Hansen and Paige, 1992; Spencer and Moore, 1992). Volatile nitrogen sublimates from the pole experiencing spring and condenses on the pole in autumn. This seasonal transport affects the pressure of the atmosphere, the location of polar cap boundaries (thus the albedo as seen from the Earth), and the surface temperatures. In their outer Solar System outposts, these two bodies are often compared to each other – one a Kuiper Belt Object (KBO) in an eccentric orbit in an orbital resonance with Neptune, and the other a captured KBO now in orbit around Neptune.

New Earth-based observations inform and constrain what we know about Pluto's climate and motivate updates to old climate models in anticipation of the New Horizons flyby of Pluto in 2015. One volatile transport model to which observations have been frequently compared was originally developed by Hansen and Paige for Triton (Hansen and Paige, 1992), and modified for Pluto in 1996 (Hansen and Paige, 1996, referred to hereafter as HP96). This finite-element parameterized thermal model balances and conserves energy across the body while tracking locations and quantities of N_2 sublimation and condensation in and out of the atmosphere. The model successfully predicted the increase in pressure of Pluto's atmosphere even as Pluto moved away from perihelion (Sicardy et al., 2003; Elliot et al., 2003). Note that throughout this paper the terms "frost" and "ice" are used interchangeably, and in all cases refer to condensed N_2.

Stellar occultations are key to understanding the composition and structure of Pluto's atmosphere (Elliot and Young, 1991; Sicardy et al., 2003; Young et al., 2010). At the time that HP96 was developed there was just one measurement of atmospheric pressure from a stellar occultation in 1988 (Elliot et al., 1989; Hubbard et al., 1990) to compare with model output. In the last 11 years however as Pluto has crossed the galactic plane numerous occultations have been observed.

Mutual eclipses and occultations between Pluto and Charon in the late 1980s allowed derivation of coarse albedo maps of Pluto's disk (Buie et al., 1992; Young and Binzel, 1993) – these were compared to predicted polar cap boundaries by HP96. Now disk-resolved images from Hubble Space Telescope (HST) give a more complete picture of Pluto's surface.

With over 20 years of new observations and the imminent arrival of New Horizons at Pluto (Young, 2013) it is time to take a new look at Pluto's climate.

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2. New observational data

When the HP96 model was developed Pluto observations were sparse: a single occultation in 1988, and the albedo map derived from the Pluto–Charon mutual events provided the primary constraints. In the years since the original results were published many more observations of Pluto have been acquired. Four important observational categories, described in this section, serve to constrain Pluto's surface and ice properties such that predictions can be made for the state of Pluto's climate at the time the New Horizons spacecraft passes by.

2.1. Resolved albedo maps

N_2 is a very mobile species even at Pluto's cold temperatures. It will sublimate and condense quickly as the subsolar latitude changes. From telescopes on and in orbit around the Earth volatile redistribution will manifest itself as changes in both disk-integrated brightness and resolved albedo maps. The viewing geometry from the Earth must be taken into account – when Pluto was first discovered Earth-based observers were looking at the south pole. (We follow the Pluto community and current IAU convention of defining north as the direction of the angular momentum vector of the planet.) A large polar cap (or no polar cap) would give a flat light curve and a very slow change in overall brightness as the Sun (and Earth) moved toward the equator – comparison of overall brightness accounting for the change in distance is just a 5% darkening from 1933 to 1953 (Schaefer et al., 2008), over a period of time that the subsolar latitude was fairly constant. After 1953, as the south pole rotated out of view the amplitude of the light curve over a Pluto rotation increased (e.g. Binzel and Mulholland, 1983; Marcialis, 1988), consistent with more longitudinal heterogeneity on the surface becoming visible from Earth. At the time of the mutual events ground-based observers were looking roughly at the equator and could discern a bright south pole, but results for the north polar region were mixed, with one group deriving a bright north polar region (Young and Binzel, 1993) and the other not (Buie et al., 1992).

With the resolution of the Hubble Space Telescope bright north and south poles could be discerned in 1994 (Stern et al., 1997; Buie et al., 2010b), with the north polar region larger in extent. A bright north polar region was visible in 2003, with the south pole rotated out of view as seen from the Earth (Buie et al., 2010b). As more of the north pole comes into view the light-curve amplitude is beginning to decrease again (Buie et al., 2010a).

Most importantly, HST maps show a longitudinally variegated surface (Stern et al., 1997; Buie et al., 2010b; Lellouch et al., 2011a,b). The longitudinal heterogeneity in albedo provides a strong constraint on surface properties as described in Sections 3 and 5.

2.2. Stellar occultations

A stellar occultation in 2002 broke the long hiatus after 1988. This occultation revealed that Pluto's atmospheric pressure had approximately doubled (Elliot et al., 2003; Sicardy et al., 2003; Pasachoff et al., 2005). With Pluto crossing the galactic plane, occultations in 2006, 2007, 2008, 2009, and 2010 were observed (summarized in Young, 2013). New data from occultations observed in 2011, 2012 and 2013 (Person et al., 2013; Bosh et al., 2013; Olkin et al., 2013, resp.) are now being analyzed.

Interpretation of occultation data is challenging however, due to the structure of the lowest part of the occultation light curve – it can be attributed to either a steep thermal gradient or a haze layer in the atmosphere (Elliot and Young, 1992; Eshleman, 1989; Hubbard et al., 1990; Stansberry et al., 1994; Young et al., 2008). This leads to uncertainty in Pluto's radius and the value of the atmospheric pressure at the surface. Although the pressures are routinely reported for an altitude of 1275 km, surface pressures extrapolated below that altitude can be bracketed as in Young (2013). Pressures at the reference altitude can also be compared to each other, e.g. the atmospheric pressure detected in 2006 was 1.5–3 times the pressure in 1988 (Elliot et al., 2007).

Occultation data through 2008 are clearly consistent with secularly increasing atmospheric pressure, with pressure in 2009–2010 increasing slightly or leveling off (Sicardy personal communication, 2013; Young, 2013). New results from the most recent stellar occultations in 2012 and 2013 were reported at the 2013 Pluto Science Conference ("The Pluto System on the Eve of Exploration by New Horizons: Perspectives and Predictions"). The observations show that Pluto's atmospheric pressure has increased compared to 2011 (Olkin et al., 2013; Sicardy, personal communication, 2013), or stayed constant (Person et al., this issue, 2013 – note that this group reports pressure at half light rather than 1275 km).

All simulations were passed through the same wide sieve used by Young (2013), to identify those results roughly consistent with stellar occultations in 1988 and 2006. The rationale for the sieve is expanded here, relative to Young (2013). The wide sieve used 1988 and 2006, rather than 1988 and 2002, because of the relatively large error bars on the 2002 retrieved pressures. The range of acceptable pressures for 2006 was taken to be 7–78 μbar. The lower end of the range is dictated by the fact that occultations in 2006 probed down to at least 6 μbar (Young et al., 2008). The upper end of the range is guided by Lellouch et al. (2009), who combined high-resolution IR spectra of Pluto's gaseous CH_4 with stellar occultations to derive a maximum pressure in 2008 of 24 μbar. The larger upper end of the 2006 sieve range accounts for the difference in time between 2006 and 2008, and the model dependence of the Lellouch et al. (2009) result.

Young et al. (2008) report that the pressure in 2006 at a reference radius of 1275 km from Pluto's center was a factor of 2.4 ± 0.3 times larger than in 1988. Taking into account the difficulty in relating pressure at 1275 km to Pluto's surface, spanning a gap of some 75–100 km, the sieve requires a ratio of the 2006 and 1988 surface pressures in the range of 1.5–3.1. The limits on the ratio of pressures would imply a range for 1988 of 2.2–52 μbar. However, the stellar occultation of 1988 provides an additional constraint, as it probed to 3.0 μbar. The final 1988 pressure range for the sieve is 3.0–52 μbar.

2.3. Surface properties and temperature

Thermal modeling allowed Pluto's surface (diurnal skin depth) thermal inertia to be derived from Spitzer data obtained in 2004. The derived inertia, 20–30 $J/m^2\,s^{1/2}\,K$, is lower than values expected for compact ices, possibly due to high surface porosity (Lellouch et al., 2011a). Lellouch et al. derive a temperature at the subsolar point of ~63 K in 2004 for their best-fit values for surface bond albedo and emissivity. Far infrared data acquired from the Infrared Astronomical Satellite (Sykes et al., 1987; Sykes, 1993) constrains the surface temperature to be in the range of 55–73 K in 1983.

2.4. Other ices

In addition to the very volatile N_2 ice, the ices CO, and CH_4 have also been detected spectroscopically on Pluto's surface (Cruikshank et al., 1976; Owen et al., 1993). The spectra is generally interpreted as indicating three broad terrain types (e.g., Grundy and Buie, 2001; Lellouch et al., 2011a): a large-grained terrain with dilute CO and CH_4, indicated by the N_2 feature at 2.15 μm, CO absorption,