Volatile and Climate Cycles on Short and Long Timescales. . A.M. Earle[1], R.P. Binzel[1], L. A. Young[2], T. Bertrand[3], M. W. Buie[2], D. P. Cruikshank[3], K.S. Ennico[3], F.Forget[4], W. M. Grundy[5], J. M. Moore[3], C. B. Olkin[2], B. Schmitt[6], J. R. Spencer[2], J. A. Stansberry[7], S. A. Stern[2], L.M. Trafton[8], O.M. Umurhan[3,9], H. A. Weaver[10], and The New Horizons Science Teams.
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Introduction: Pluto's high obliquity (currently around 119^o) varies by 23^o over a period of less than 3 million years while Pluto's longitude of perihelion regresses 360^o over 3.7 million years [1,2]. As a result of this pair of orbital variations Pluto's sub-solar latitude at perihelion has ranged between 53^o South and 76^o North over the past 3 million years (Figure 1). Pluto has a high orbital eccentricity ($e \approx 0.25$) which causes its heliocentric distance to vary from less than 30AU out to almost 50AU, which leads to the solar constant changing by a factor ~3 over the course of its orbit [2].

Insolation intensity and distribution is dependent on instantaneous heliocentric distance and obliquity [3]. Pluto's high eccentricity coupled with its changing obliquity and sub-solar latitude at perihelion create substantial difference in insolation patterns on Pluto when averaged over different time intervals [4-6]. During Pluto's current epoch, equinox and perihelion occur relatively close together, causing both hemispheres to have fairly similar seasonal cycles. However, the phasing of Pluto's obliquity and longitude of perihelion variations create epochs of "Super Seasons" where one pole is pointed towards the Sun at perihelion, causing that hemisphere to experience a short intense summer and long period of winter darkness while the other hemisphere experiences a very short winter and much longer, but less intense summer (Figure 2)[7]. Pluto's high and varying obliquity also leads to unusual "Climate Zones" that vary over time [8]. Understanding these patterns can provide important insight in interpreting surface features revealed by New Horizons and understanding volatile transport on Pluto. Pluto's atmosphere is probably in vapor pressure equilibrium with isothermal surface ice, so the surface atmospheric pressure is controlled by the surface volatile temperature [2, 9]. Given the magnitude of Pluto's orbital variations (and consequently its insolation distribution) over millions year timescales, it could be expected that Pluto's volatile distribution, atmospheric pressure, and surface geology are impacted by these variations.

Overview: This talk will explore Pluto's insolation history and its implications for Pluto's atmospheric pressure, surface temperatures, and volatile distributions over various timescales. We will provide an overview of some of the early modeling results since the New Horizons' flyby of the Pluto system and give background and context for some of the more advanced modeling efforts currently underway. In particular we will consider how differences in insolation between the current epoch and "Super Season" epochs may impact Pluto's atmosphere and volatile distribution.

Preliminary atmospheric pressure models suggested Pluto's "Super Season" epochs may be responsible for past epochs of higher atmospheric pressure (with values exceeding 100 Pa) on Pluto that would explain some of the geomorphological features on Pluto that would be difficult to form at current atmospheric pressures [10]. More detailed atmospheric pressure modeling has since suggested pressures above 100 Pa are unlikely to occur but still supports the significance of Pluto's orbit variations as a driver of Pluto's surface evolution and volatile transport [11]. Pluto's seasonal and orbital variations likely impact Pluto's atmosphere in other ways beyond surface pressure, for example vertical structure, dynamics, and haze production [e.g. 12-14]

Pre-encounter volatile transport models [e.g. 2, 15, 16] generally focused on shorter timescales (covering just the current Pluto epoch and not including timescale long enough for Pluto's orbit variations to be considered). They also used a simple treatment of albedo and no consideration of geology (since it was not yet mapped), so their results cannot explain the stark longitudinal contrasts in composition, geology, and albedo which were revealed in detail by New Horizons [17]. The first post-encounter paper to address volatile transport adapted existing thermal models [18, 19] and compared the results to explore the significance of albedo for Pluto's volatile distribution, this work provided an early indication the Pluto's equatorial and mid-latitudes were particularly sensitive to albedo variations [7].

Since then additional time and more detailed analysis and processing of the New Horizons data has allowed for more detailed modeling of Pluto's volatile transport and atmospheric cycles. [20] has performed a more detailed study of how Pluto's surface volatiles respond to albedo differences, exploring these processes over the current epoch as well as past "Super Season" epochs. They found that Pluto's high obliquity creates unique conditions that make its equator and mid-latitudes highly sensitive to albedo feedback effects, resulting in them being able to maintain stark, longitudinal albedo and volatile abundance variations over long timescales. A global circulation model has ben developed for Pluto and used to explore N_2, CH_4, and CO cycles [21], the interactions between Pluto's atmosphere and topography [22], nitrogen cycles over astronomical timescales [11] and methane cycles over astronomical timescales [23]. Additionally, work is underway to update the model presented in [24] run over longer timescales and better account for the volatile distribution observed by New Horizons [25, 26].

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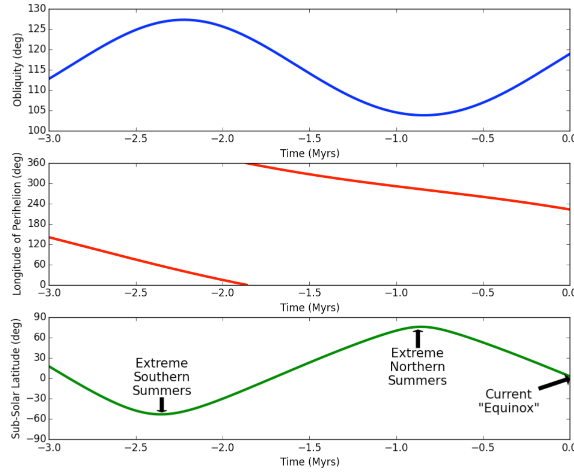

Figure 1: Top: Pluto's changing obliquity as a function of time over the past 3 million years. **Middle:** Regression of Pluto's longitude of perihelion over the same interval. **Bottom:** Pluto's resulting sub-solar latitude at perihelion as a function of time. Calculations are based on [1].

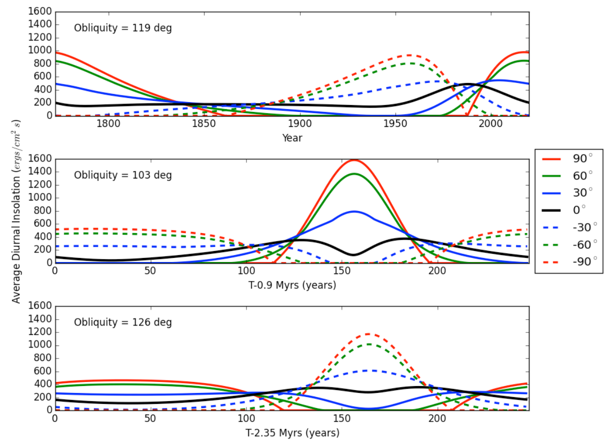

Figure 2: Diurnally averaged insolation over 1 Pluto orbit for selected latitudes. **Top:** current orbit. **Middle:** 0.9 million years ago. **Bottom:** 2.35 million years ago.