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# Climate zones on Pluto and Charon

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ABSTRACT

We give an explanatory description of the unusual “climate zones” on Pluto that arise from its high obliquity (mean 115°) and high amplitude (±12°) of obliquity oscillation over a 2.8 million year period. The zones we describe have astronomically defined boundaries and do not incorporate atmospheric circulation. For such a high mean obliquity, the lines of tropics (greatest latitudes where the Sun can be overhead) cycle closer to each pole than does each arctic circle, which in turn cycle nearly to the equator. As a consequence in an astronomical context, Pluto is more predominantly “tropical” than “arctic.” Up to 97% of Pluto’s surface area can experience overhead Sun when the obliquity cycle is at its minimum of 103°. At this same obliquity phase (most recently occurring 0.8 Myr ago), 78% of Pluto’s surface experienced prolonged intervals without sunlight or “arctic winter” (and corresponding “arctic summer”). The intersection of these climate zones implies that a very broad range of Pluto’s latitudes (spanning 13–77° in each hemisphere; 75% of the total surface area) are both tropical *and* arctic. While some possible correlations to these climate zones are suggested by comparison with published maps of Pluto and Charon yielded by the New Horizons mission, in this work we present a non-physical descriptive analysis only. For example, the planet-wide dark equatorial band presented by Stern et al. (2015; Science, 350, 292–299) corresponds to Pluto’s permanent “diurnal zone.” In this zone spanning latitudes within ±13° of the equator, day-night cycles occur each Pluto rotation (6.4 days) such that neither “arctic winter” nor “arctic summer” has been experienced in this zone for at least 20 million years. The stability of this and other climate zones may extend over several Gyr. Temperature modeling shows that the continuity of diurnal cycles in this region may be the key factor enabling a long-term stability for the high albedo contrast between Tombaugh Regio adjacent to the dark Cthulhu Regio (Earle et al. (2017) *Icarus*, special issue, submitted). (All names are informal.) Charon’s synchronous alignment with Pluto dictates that both bodies in the binary pair have the same climate zone structure, but any effects on Charon’s morphology may be limited if volatile transport there is minimal or absent. Cold-trapped methane-rich volatiles on top of its water ice surface may be responsible for forming Charon’s dark red north polar cap (Grundy et al., 2016b), and we note the most concentrated area of this feature resides almost entirely within the permanent “polar zone” (above 77° latitude) where the Sun never reaches the overhead point and arctic seasons have been most consistently experienced over at least tens of millions of years. Pluto is not alone among bodies in the Kuiper belt (and uranian satellites) in having high obliquities, overlapping tropical and arctic zones, and latitude bands that remain in a continuous diurnal cycle over long terms.

## 1. Introduction

A large value for the obliquity (defined as the angle between a planet’s spin vector and its orbit plane normal vector) of Pluto has been recognized for many decades, first deduced from long-term monitoring of its rotational lightcurve variations

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(Anderson and Fix, 1973). With the discovery of Pluto's binary companion Charon (Christy and Harringon, 1978) and the assumption that their barycentric motion defines the equatorial plane, the obliquity was deduced to be near 120°. (The current exact value is 119.6°.) Analysis of the long-term dynamics of the system by Dobrovolskis and Harris (1983) and Dobrovolskis et al. (1997) shows the obliquity to oscillate around a mean value of 115.55° with an amplitude of ±11.75° over a period of 2.76 million years. Pluto and Charon, being fully synchronously locked to one another, share the same amplitude and phase in their obliquity cycles. For simplicity of wording and labeling, henceforth we denote this obliquity oscillation as 115 ±12° (with a current value of 120°) and the period as 2.8 million years. In addition, we give reference to Charon in the text only when specifically addressing its particular characteristics.

Pluto's obliquity is extreme compared to that of Earth (23°) and Mars (25°). In addition, Pluto shows a greater maximum range (24°) of obliquity variation than does Mars (20°; Ward, 1973) although chaotic instabilities may have driven Mars' obliquity to a much greater range (Touma and Wisdom, 1993). Earth's obliquity range is only ~2°, where this variation may be stabilized by the orbital angular momentum of the Moon (Laskar et al., 1993). Obliquity variations as a factor for long-term climate cycles on Earth were proposed in the late 19th century by Croll (1886) and followed up extensively by Milanković (1920, 1938), but not generally substantiated until decades later (e.g. Hays et al., 1976). Milanković also investigated Earth's orbital eccentricity cycles and axial precession cycles; van Hemelrijck (1982, 1985) shows that for Pluto these are much smaller effects than obliquity cycles. Thus, we consider only obliquity cycles in this paper. Obliquity driven climate cycles and possible geologic consequences on Mars are described by Laskar et al. (2002) and are reviewed by Zent (2013).

In this work we describe "climate zones" on Pluto by defining and detailing which regions (latitudes) on the planet are "tropical" or "arctic" and over a broad range, both. (See Section 2.) We emphasize that our boundaries and definitions are astronomically based on sub-solar latitudes and do not include any consideration of heat transport by atmospheric circulation. Herein we use north (N) and south (S) to define the boundaries rather than Earth's labels (e.g. arctic versus antarctic). The right-hand rule of Pluto's rotation defines north. For Pluto, the arctic and tropical boundaries defined by sub-solar latitudes are not static, but oscillate during the 2.8 million year period for the 24° peak-to-peak obliquity variation cycle. Strictly speaking, we cannot be certain of these zonal limits remaining stable for time periods beyond ~20 million years due to chaotic orbital instability of Pluto (Sussman and Wisdom, 1988, 1992). However the revelation of old (several Gyr) cratered terrains at high latitudes (Stern et al., 2015; Moore et al., 2016) attest that relatively stable cyclical processes giving neither a substantial net volatile deposit nor net volatile erosion have more likely operated over much longer eras than the ~20 Myr chaotic uncertainty of Pluto's orbital longitude and heliocentric distance. (Otherwise these ancient craters would have been eroded away or completely buried.) Thus we respect the ~20 Myr limit of confident orbital computation, but propose the stability timescales for our climate zone boundaries could extend back in time by Gyr.

In this work we also consider only obliquity variation, not the 3.7 Myr regression of the longitude of perihelion of Pluto's orbit also described by Dobrovolskis and Harris (1983) and Dobrovolskis et al. (1997). When obliquity is combined with orbital variations, such that Pluto can be nearly pole-on at the time of perihelion, "super seasons" can result (Earle and Binzel, 2015; Earle et al., 2017; *Icarus* special issue, submitted). The opportunities for such extreme cases for Pluto have been previously recognized, e.g. van Hemelrijck (1985). Possible consequences of extreme seasons in terms of atmospheric pressure are discussed by Stern et al. (2017; *Icarus* special issue, submitted). Of course, the Pluto-Charon system is not unique in our solar system (and others as well) in having a high obliquity. Surface expressions in the Pluto system as revealed by New Horizons that may have a correlation to climate zones are discussed in Section 3, as well as a brief consideration of climate zone geometry being applied to other small body systems.

## 2. Climate zone definitions and boundaries

We summarize our definitions and boundaries for climate zones on Pluto and Charon in Table 1. We also illustrate the corresponding astronomically defined boundaries (including their obliquity

**Table 1**
Description of Pluto-Charon Climate Zones defined by astronomical cycles. The numbers in brackets denote the percentage of total surface area covered by the specified range.

| Climate zone | Defining characteristics | Permanent range[a] | Maximum range[b] | Epoch for maximum[c] | Current range[d] | Possible morphology signature (reference) |
|---|---|---|---|---|---|---|
| Tropics | Sun reaches overhead point during orbital year | 53N to 53S<br>[80%] | 77N to 77S<br>[97%] | −0.8 Myr | 60N to 60S<br>[87%] | Overall shows the greatest range of albedo variations. (Stern et al. 2015) |
| Arctic | Experiences periods of continuous Sun in summer, continuous dark in winter, during orbital year | 37N to 90N<br>37S to 90S<br>[40%] | 13N to 90N<br>13S to 90S<br>[78%] | −0.8 Myr | 30N to 90N<br>30S to 90S<br>[50%] | Permanent arctic latitudes may correlate to region where $N_2$ is most revealed in current maps. (Grundy et al., 2016a) |
| Tropical arctic | Experiences both overhead Sun and arctic seasons, during orbital year | 37N to 53N<br>37S to 53S<br>[20%] | 13N to 77N<br>13S to 77S<br>[75%] | −0.8 Myr | 30N to 60N<br>30S to 60S<br>[37%] | May be zone experiencing the maximum cyclical extremes; optimum for long-term seasonal layering in Al-Idrisi latitudes? (Moore et al., 2016) |
| Diurnal | Day/night cycle occurs, each and every rotation, throughout orbital year | 13N to 13S<br>[22%] | 37N to 37S<br>[60%] | +0.6 Myr | 30N to 30S<br>[50%] | Nearly uniform width dark equatorial band and region of the most sharply contrasting albedos. (Stern et al., 2015, 2017) |
| Polar | Sun never reaches the overhead point at any time during orbital year | 77N to 90N<br>77S to 90S<br>[3%] | 53N to 90N<br>53S to 90S<br>[20%] | +0.6 Myr | 60N to 90N<br>60S to 90S<br>[13%] | Charon polar cap. (Stern et al., 2015; Grundy et al., 2016b) |

[a] "Permanent" implies this latitude range always experiences the indicated characteristics throughout the entire 2.8 Myr obliquity cycle; likely a valid situation for >20 Myr and possibly Gyr.

[b] The latitude range for each zone expands and contracts as Pluto's obliquity oscillates from 103° to 127° over a complete obliquity cycle of 2.8 Myr.

[c] Epoch denoting when the maximum range was most recently (or most soon to be next) experienced. The two cases correspond to Pluto's obliquity reaching its minimum value (103°) ~0.8 Myr ago and reaching its maximum value (127°) ~0.6 Myr in the future.

[d] This latitude range corresponds to Pluto's current obliquity of 120°. Pluto's recent rate of change in its obliquity cycles has corresponded to 1° of latitude change per 50,000 years (1° per 200 Pluto orbits).

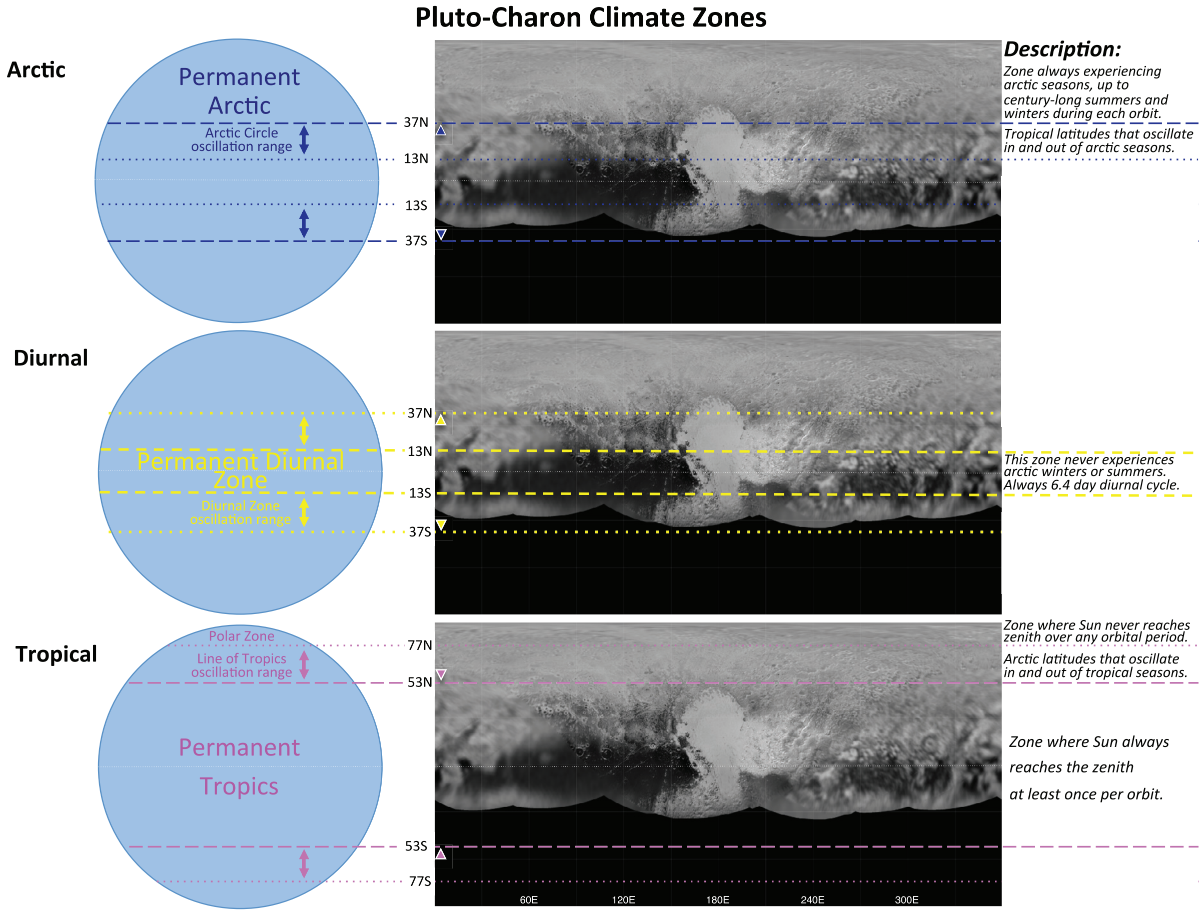

**Fig. 1.** Pluto-Charon "climate zones" as defined by astronomical cycles. For clarity these zones are depicted in three panels for each of the predominant seasonal effects. Pluto's New Horizons basemap is shown for reference (image credit: NASA/JHUAPL/SwRI). We note the synchronous coupling of the Pluto-Charon binary creates the same zones on both bodies. The vertical double arrows show the range of oscillation for each boundary created by the 2.8 Myr period of Pluto's obliquity cycle, having a mean obliquity of 115° and an amplitude of ±12°. The base of each triangle (superimposed on the maps) indicates the current location of each zone boundary, while pointing in the direction of the boundary's current migration. Explanatory labels appear at right; where written to describe northern latitudes, note that they apply identically to their southern hemisphere analogs.

oscillation ranges) in Fig. 1, where for clarity we use separate panels to diagram regions that are "tropical", "arctic", and "diurnal." The "permanent" and "current" ranges for the climate zones, as well as the instantaneous geometry for the New Horizons flyby are shown in Fig. 2.

### 2.1. Tropics

On Earth, the "tropics" have an astronomical definition as the latitude range where the Sun can reach the overhead point (zenith) on at least one date during our orbital year. The northern and southern tropical latitude limits are symmetric about the equator having values equal to the obliquity. At the exact northern and southern tropical boundaries (on Earth called the Tropic of Cancer and Tropic of Capricorn at latitudes 23N and 23S) the Sun reaches the zenith only on the date of northern and southern solstice, respectively. Otherwise throughout tropical latitudes, the Sun occupies the zenith at local noon on two dates per orbital year, exemplified by the sub-solar point crossing the equator at six month intervals (moving northward, and alternately southward) on the dates of the equinox.

We adopt the same astronomical definition for the "tropics" of Pluto, which we describe as the latitude range over which the Sun can reach the zenith during the course of one complete orbital year. For the case (such as Pluto) where the planetary obliquity is >90°, the latitude limits of the tropics correspond to the 180° complement of the obliquity. Thus for Pluto's current obliquity of 120°, the tropics extend from latitude 60N to 60S. As Pluto's obliquity value cycles down toward its minimum value of 103°, the region between the tropical latitude limits expands to the point of spanning almost the entirety of the planet from 77N to 77S latitude, consequently encompassing 97% of the planet's surface area. This is the most recent obliquity extreme that Pluto has experienced, having occurred ~0.8 Myr ago. Pluto's tropical latitude limits have since been moving back toward the equator at about 1° per 50,000 years (1° per 200 Pluto orbits) to their current location at 60N and 60S. That rate of angular change is now slowing (see Earle and Binzel, 2015; Fig. 1) as Pluto's obliquity cycles towards its maximum of 127° (will be reached in ~0.6 Myrs), thus bringing the span of the tropics to their tightest limits at 53N and at 53S latitudes (encompassing about 80% of Pluto's surface area; see Table 1). Thus, a consequence of Pluto's overall high obliquity is a seeming oxymoron: most of Pluto's surface is always "tropical." The region 53N to 53S always experiences direct overhead sunlight at some point during each and every Pluto orbit: we call this zone the "permanent tropics" of Pluto. As shown in Fig. 1, the latitudes from 53° to 77° oscillate in and out of the tropics over the 2.8 Myr obliquity cycle.

### 2.2. Arctic

On Earth, the "arctic" latitudes have an astronomical definition as being the region where the Sun may never be above the

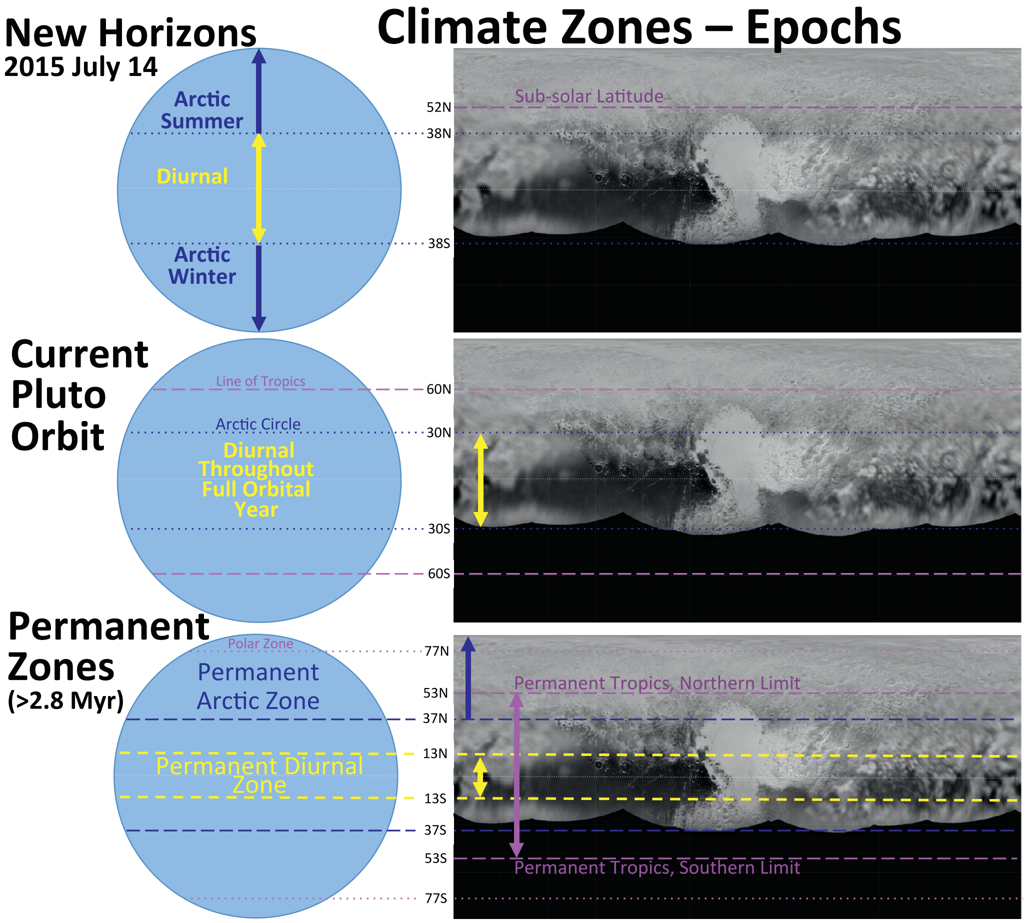

**Fig. 2.** Same as Fig. 1, illustrating Pluto-Charon climate zones at three specific epochs. (top) Insolation geometry on the date of New Horizons Pluto encounter. (middle) Climate zones defined by the current Pluto orbit and 120 degree obliquity. (bottom) Permanent zones where the indicated climate geometry recurs every orbit throughout the entire 2.8 Myr obliquity cycle, thus being the most stable climate boundaries over timescales of tens of Myr to Gyr.

horizon for one or more planetary rotations. (By complement, in this same region the Sun can also remain completely above the horizon for a full rotation i.e. "midnight Sun.") The “arctic circle” extends from each pole down to the co-latitude angle defined by the line of tropics. For Earth’s familiar tropic limits at 23N and 23S latitudes, our respective arctic regions extend from the poles to 67N and 67S latitudes.

As discussed in Section 2.1, Pluto’s latitudes that receive directly overhead sunlight at some point during every orbit constitute the “permanent tropics” extending from 53N across the equator to 53S. Thus the northern arctic region on Pluto extends from 90N to 37N (and the southern arctic from 90S to 37S) and these two ranges constitute the “permanent arctic” zones of Pluto (covering 40% of the total surface area; see Table 1). Over this latitude range, a long period of continuous arctic winter (typically lasting more than a century at the poles) occurs during every Pluto orbit for all phases of the 2.8 Myr obliquity cycle. Complementing this continually repeating arctic winter (always occurring each and every Pluto orbit over a timespan of tens of millions of years, or longer) are intervals of continuous sunlight during arctic summer, or more colloquially times of “midnight Sun.”

Pluto’s obliquity oscillation that pushes the line of tropics poleward to 77° latitude, in turn results in the arctic circle limits cycling toward the equator all the way to the co-latitude angles corresponding to 13N and 13S. The arctic zone extending to within 13° of the equator is the climate case experienced by Pluto ~0.8 Myr ago when the obliquity reached its minimum value of 103°. Since that time when 78% of Pluto’s surface was “arctic” (see Table 1), the arctic circle limits have been moving poleward at the rate of 1° per 200 Pluto orbits (see Section 2.1), currently residing at 30N and 30S. Thus for current Pluto’s northern hemisphere, the arctic circle at 30N resides closer to the equator than does the line of tropics at 60N (and identically for the southern hemisphere). As a consequence, the region imaged by New Horizons falling between 30N and 60N is currently *both* tropical and arctic. (We address these mixed climate zones in Section 2.4.)

One long-realized consequence for a high obliquity planet whose arctic circle extends down to near-equatorial latitudes is that the energy budget over a complete orbit, expressed in terms of the received solar insolation, is maximized at the poles (van Hemelrijck, 1982; Dobrovolskis and Harris, 1983). Spencer et al. (1997) as well as Binzel and Earle (2015) show this result explicitly, where a full stepwise and analytic solution for a single orbit (Hamilton, 2015a; Nadeau and McGehee, 2015) demonstrates that the total accumulated insolation received at each pole is symmetric regardless of the orbital eccentricity and whichever pole is oriented more optimally sunward at perihelion.

### 2.3. *Diurnal zone*

As described in Section 2.2, the arctic zone as defined herein is comprised by the latitude range where extended periods of arctic winter and arctic summer occur, i.e. where in the course of a daily (diurnal) rotation there are seasons when the Sun may not rise above the horizon or conversely, may not set. In this latter case, the Sun traverses 360° of azimuth around and above the horizon. On Earth this occurs seasonally within the arctic (and antarctic) circles. For all other regions on Earth, spanning between 67N and 67S, a daily cycle of sunrise and sunset occurs for each and every Earth rotation throughout our entire orbital year. We call this region continuously experiencing daily sunrise and sunset the "diurnal zone."

Pluto's high mean obliquity and oscillation cycles bring the north and south arctic circles down to 13N and 13S latitudes, thereby creating a narrow diurnal zone (symmetric about the equator; 22% of the total surface area) between these two latitudes. Only this band from 13N to 13S is in a "permanent diurnal" state continuously experiencing sunrise and sunset during each and every Pluto rotation period (6.4 days) over tens of millions of years or longer. Every latitude poleward of 13° experiences extended seasons of either constant "summer" sunlight or constant "winter" darkness owing to Pluto's obliquity oscillation periodically cycling them into the arctic zone.

Pluto's 24° (peak-to-peak) obliquity oscillation expands and contracts the diurnal zone over a 2.8 million year cycle. The diurnal zone was most recently at its most narrow range (13N to 13S) when Pluto's obliquity reached its 103° minimum ~0.8 Myr ago. As the obliquity has since increased to its current 120° value, the present day Pluto diurnal zone now spans from 30N to 30S. The maximum extent of the diurnal zone (spanning from 37N to 37S; 60% of the total surface area) will be reached in ~0.6 Myr, before once again contracting back toward its minimum range spanning just 13° above and below the equator.

### 2.4. Tropical arctic zones, oscillating tropical arctic zones, and the polar zone

For planets having moderate obliquities such as the 23° value for the Earth, the astronomically defined arctic zones and the tropical zones are fully separated in latitude by a broad range of midlatitudes (called the temperate zone) that are neither arctic nor tropical. For obliquity values greater than 45° up to 135°, a range that fully envelopes Pluto's 103–127° obliquity oscillations, the temperate zone disappears. Instead, an otherworldly type of climatic zone arises where the tropical zones and arctic zones overlap, which is unique to objects within the 45–135° obliquity range. We call this region of overlap the "tropical arctic" zone.

Thus a consequence of Pluto's high obliquity is that most of the planet is *both* tropical and arctic during the course of the 2.8 million year obliquity cycle. As discussed, Pluto's tropical Sun regions extend as far poleward as 77° latitude while the arctic circles extend as close as 13° from the equator. Thus two bands of latitude, 13N to 77N and 13S to 77S, constitute the "tropical arctic" zones of Pluto. (As this range covers 75% of the total surface area of the planet, one can describe a majority of Pluto as experiencing "tropical arctic" sunlight cycles. See Table 1.) However the latitudinal breadth of this tropical arctic zone expands and contracts over the course of Pluto's 2.8 million year obliquity oscillation. As the line of tropics oscillates between latitudes of 53–77°, these latitudes alternate from being "tropical arctic" to simply being "arctic." (This zone of oscillation is most readily illustrated in the "Tropical" panel of Fig. 1.) In an analogous way, the location of each arctic circle oscillates between latitudes 13 and 37°. Thus, this 13–37° latitude range is an additional "oscillating zone" that alternates between being "tropical arctic" to being simply "tropical" in its sunlight cycles. (This particular zone of oscillation is illustrated in the "Arctic" panel of Fig. 1.) Only the latitude range of 37N to 53N (and 37S to 53S) remains consistent as the "permanent tropical arctic" region of Pluto. For the most recent extreme epoch of minimum obliquity ~0.8 Myr ago, Pluto experienced the maximum extent of its tropical arctic region spanning the full 13–77° latitude range. Since that time, the tropical arctic zone has contracted to its current range of 60N to 30N (and 60S to 30S), where it will continue to contract to its narrowest (and permanent) range of 53–37° latitude in another ~0.6 Myr. As discussed in Section 3.1, these oscillating zones create the most significant (in terms of area) long-term cycle effects on Pluto's surface. Over the 2.8 Myr obliquity cycle, Pluto's surface area makes a complete oscillation through the range of being 75% tropical arctic (latitudes 13–77°) to being 20% (latitudes 53–37; see Table 1).

Two regions fall outside of the alternation of arctic and tropical sunlight cycles. The first is the diurnal zone (from latitude 13N to 13S) discussed in Section 2.3, a zone that is always tropical and always diurnal, and never subject to arctic seasons of continuous dark winter or constant sunlight summer. The second is the "polar zone" with a radius of 13° from each pole. The polar zone is always arctic and never tropical. The latter implies that within each polar zone (90N to 77N and 90S to 77S) the Sun never reaches the overhead point in the sky at any time during any orbital year throughout the entire 2.8 Myr obliquity cycle. Accordingly, the polar zone is the region that most consistently experiences the longest durations of arctic winter and arctic summer continuously repeating every Pluto orbit for tens of millions of years, or longer. Possible consequences are discussed in Section 3.2.

## 3. Discussion

### 3.1. Possible correlations to Pluto's surface morphology

For the purposes of discussion, we address features present within currently published New Horizons results and offer speculation as to how the astronomically defined zones we describe may play a role in the revealed morphology.

We start our discussion with regions that are narrowly constrained, most notably the latitude 13N to 13S diurnal zone that never experiences any period of continuous arctic summer or continuous arctic winter. Volatile transport models (e.g. Young, 2013) argue for the significance of these arctic seasons for driving away volatiles during continuous summer and accumulating volatiles during the long dark winter, perhaps tempered by substrate thermal inertia. As shown by New Horizons mapping results (Stern et al., 2015) and previously revealed by some of the earliest Earth-based maps of Pluto (Buie and Tholen, 1989; Young and Binzel, 1993; Buie et al., 2010), Pluto's equatorial region is predominantly a dark band with distinct boundaries coinciding closely to the 13N and 13S limits of the diurnal zone. (See Fig. 1.) Temperature modeling calculations (Earle et al., 2015, 2017) demonstrate quantitatively that the diurnal variations are effective in long-term preservation of what is "seeded" there: diurnal Sun is able to keep low albedo terrain warm enough to not become an attractive cold trap for new volatiles – and the absence of *any* interval of arctic winter darkness further limits the likelihood of cold-trapping volatiles. Analogously, a high albedo region in the diurnal zone maintains its volatiles by having the opportunity every rotation to radiate away into the night any absorbed radiation (already minimized by the high reflectivity), while over the long-term never experiencing the continuous Sun of an arctic summer. Earle et al. (2015, 2017) argue that the resulting temperature cycles near the equator are able to support the strong albedo contrast between the bright Tombaugh Regio and the adjacent dark Cthulhu Regio at longitudes 180 and 160, respectively. (All names are informal; the locations of proposed names are shown in Stern et al., 2015 and mapped in Moore et al., 2016.) Long-term accumulation of volatiles in the central basin of Tombaugh Regio, called Sputnik Planitia, is modeled by Nimmo et al. (2016). We additionally note that Pluto's dark equatorial band shows some asymmetry about the equator; the southern boundary extends to slightly greater latitudes and overall

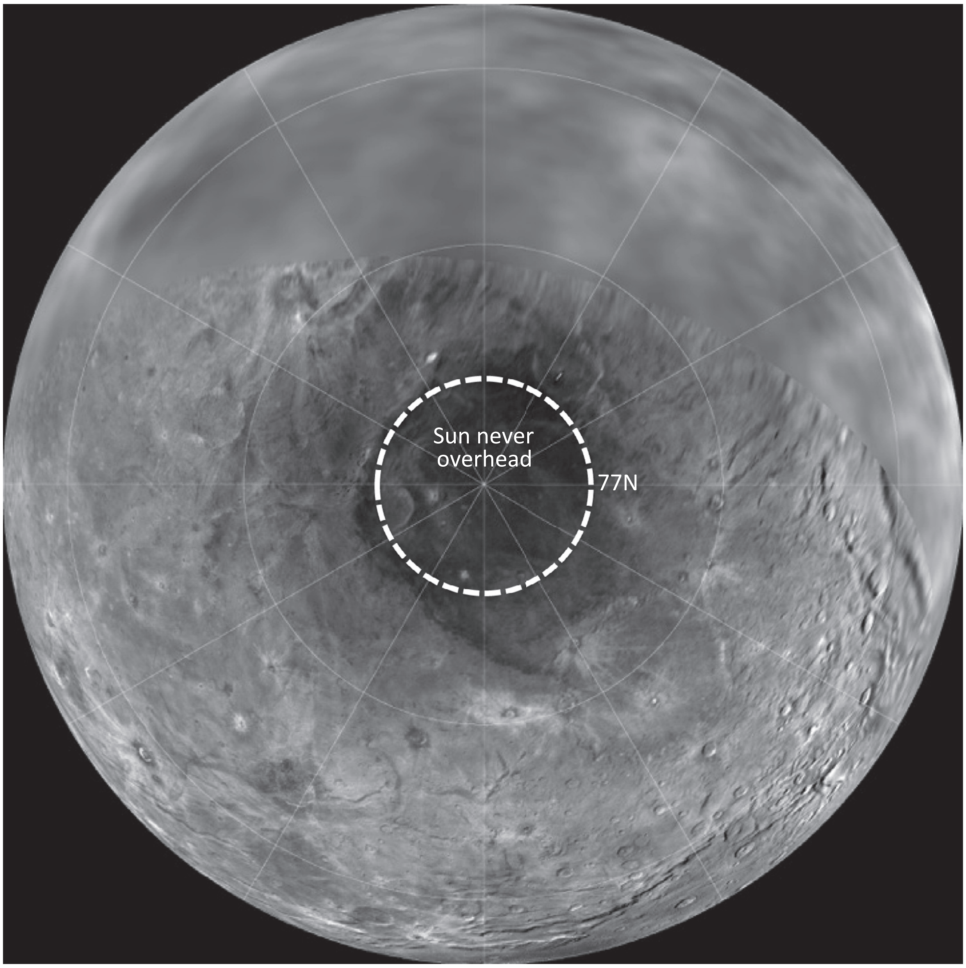

**Fig. 3.** North polar projection of Charon (Stern et al. 2015) comparing Mordor Macula to the boundary for the "Polar Zone" of Charon. This polar zone never experiences direct overhead Sun over any obliquity cycle for at least the past 20 Myr, and likely Gyr, and thus consistently may have the shallowest depth orbital (or longer term) subsurface thermal wave of any region on the satellite. Grundy et al. (2016b) model this dark polar cap to be due to trapping of escaping volatiles from Pluto.

is at lower latitudes near longitude 300E (and somewhat higher latitudes at longitude 120E). Long-term reorientation of the body axis for Pluto's maximum moment of inertia could be recognizable as a "tilt" of a previously formed symmetric dark equatorial band. Such re-orientation was proposed by Hamilton et al. (2015a, 2015b) and further discussed by Nimmo et al. (2016) and Hamilton et al. (2016).

Compositional maps for $CH_4$ and $N_2$ (e.g. Grundy et al., 2016a) can also be examined with climate zones in mind, but we consider any present interpretation to be only speculative. Outside of Tombaugh Regio and Cthulhu Regio, Grundy et al. (2016; Fig. 1) maps of $CH_4$ shows this volatile to be widely distributed with some possible suggestion of a latitudinal band at the northern boundary of Cthulhu. $N_2$ on the other hand is more distinctly present in the mapping above latitude 30N, possibly being preferentially revealed in the "permanent arctic" zone of Pluto that resides from 37N to the pole. For the epoch of New Horizons, the analogous southern hemisphere zone is not revealed.

Perhaps particularly interesting on Pluto are the zones that find themselves both tropical *and* arctic, and perhaps most especially, bands that oscillate in and out of this climate state over the 2.8 Myr obliquity oscillation period. As discussed in Section 2.4 and quantified in Table 1, a substantially large surface area of Pluto oscillates in and out of the tropical arctic climate state. As speculation we can simply note that the al-Idrisi Montes centered near 37N contain possible layering (Moore et al., 2016; Grundy et al., 2016a) due to long-term climate cycles. We find that 37N is an important boundary in climate zone oscillations involving the mix of both tropical (overhead sun) and arctic (sustained constant Sun or constant dark winter) seasons. Specifically 37N is the boundary for the zone that alternates in and out of sustained arctic seasons of sunlight and darkness over timescales of 2.8 Myr. Unfortunately, the complementary transition zone at 37S is not presently revealed.

### 3.2. Possible correlations to Charon's surface morphology

The presence of volatiles such as $N_2$, $CH_4$, and CO on Pluto having triple points within the plausible range of attainable surface (or subsurface) temperatures and pressures is likely a driving factor for the complexities of its surface morphology (Grundy et al., 2016a). Charon being predominantly $H_2O$ ice (inert at the relevant temperatures) is generally thought to be volatile free (Grundy et al., 2016b). However a distinct dark red polar cap on Charon, called Mordor Macula, discovered by New Horizons (Stern et al., 2015) requires explanation. Grundy et al. (2016b) propose that Charon's cap is the result of escaping volatiles from Pluto that become cold-trapped at Charon's pole. They further demonstrate this likelihood by models showing that Charon's poles experience the lowest temperature minima of any latitude. We note as speculation the correlation between the 77N to 90N polar zone on Charon and the extent for the darkest region of the cap (Fig. 3).

The fact that this region never receives direct overhead sunshine over >20 Myr (and ostensibly Gyr) and therefore the shallowest penetration depth of a seasonal thermal wave may contribute to it being a well-defined zone for trapping and preserving available volatiles. Grundy et al. (2016b) show evidence from New Horizons images for a similar dark cap and presumed cold-trap zone being present at Charon's south pole as well.

### *3.3. Applications to other systems*

The Pluto system is not the only high obliquity case known in our Solar System, such that unusual climate geometries (compared to Earth) can result. Uranus' obliquity of 98°, for example drives it to have polar and equinox seasons (e.g. Sromovsky et al., 2009) and imparts corresponding climate zone geometries on its satellites. More analogous to Pluto are Kuiper belt objects having satellite systems whose measurable orbit planes have revealed their high obliquities. Currently known cases tabulated by Grundy et al. (2011) include 2000 WK183, Ceto, Orcus, Salacia, 2000 OJ67, and Eris. More recently Varda also is revealed to have a high obliquity (Grundy et al., 2015). An additional case is Makemake, where the nearly edge-on orbital plane of its newly discovered satellite (Parker et al., 2016) demonstrates its high obliquity reminiscent of the Pluto-Charon binary. For now thanks to the New Horizons flyby, Pluto and Charon give us the opportunity to explore whether "tropical arctic" (or other unusual climate zones that may also experience substantial periodic oscillations) have any particular surface characteristics that may be recurrent or insightful toward understanding surface properties of outer Solar System bodies of different sizes and having a range of available volatiles near their triple points.

## 4. Conclusion

For this work we attempt no definitive conclusions other than to descriptively define climate zones that may be substantiated as being relevant to Pluto-Charon surface morphology through more detailed thermo-physical modeling exploring the long-term evolution of the system. These climate zones exist as definable boundaries simply through the geometry of Pluto's obliquity cycling, and such climate zone descriptions may analogously apply to other high obliquity planetary bodies. Many factors can arise that make any physical expression of climate zone boundaries as being indistinct. These factors may include local topography, local thermal inertia properties, and the availability of volatiles. In addition, volatile transport processes that are only weakly dependent on insolation geometries or temperature variations will not strongly express themselves along these geometric definitions.

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