PLANETARY SCIENCE

THE GEOLOGICAL HEART OF A DWARF PLANET

Located in the cold outer reaches of our solar system, Pluto was thought unlikely to be geologically active. Yet, as Veronica Bray explains, images from the New Horizons probe revealed ice-driven convection, tectonism and cryovolcanism

EXPECTATIONS were mixed as the New Horizons space probe approached Pluto back in 2015. Was Pluto geologically dead or alive? The Hubble Space Telescope had revealed clear variations in the albedo across the dwarf planet's surface, hinting at some geological activity in Pluto's past, but current geological activity wasn't really expected.

Small icy bodies located in the outer solar system are thought to have accreted less radioactive material during their formation compared to the larger rockier bodies, and so should have less residual heat. As a result, small bodies tend to lack surface expressions of any internal activity. There are exceptions to this trend, of course. For example, the inner Galilean satellites of Europa and Io are heated by tidal interactions during their orbit of Jupiter, which drives geological activity at their surfaces. However, Pluto and Charon (see glossary, p. 18) are tidally locked. →

The binary dwarf planet system of Pluto (lower right) and Charon (upper left). In this composite enhanced colour image, the relative sizes of Pluto and Charon are approximately correct, but their true separation is not to scale. The image combines blue, red and infrared images taken by New Horizon's Ralph/ Multispectral Visual Imaging Camera and highlights the compositional variations on Pluto (light yellow, nitrogen ice; dark yellow and blue, methane ice of different ages; red, tholins) *(Image credit: NASA/JHUAPL/SwRI)*

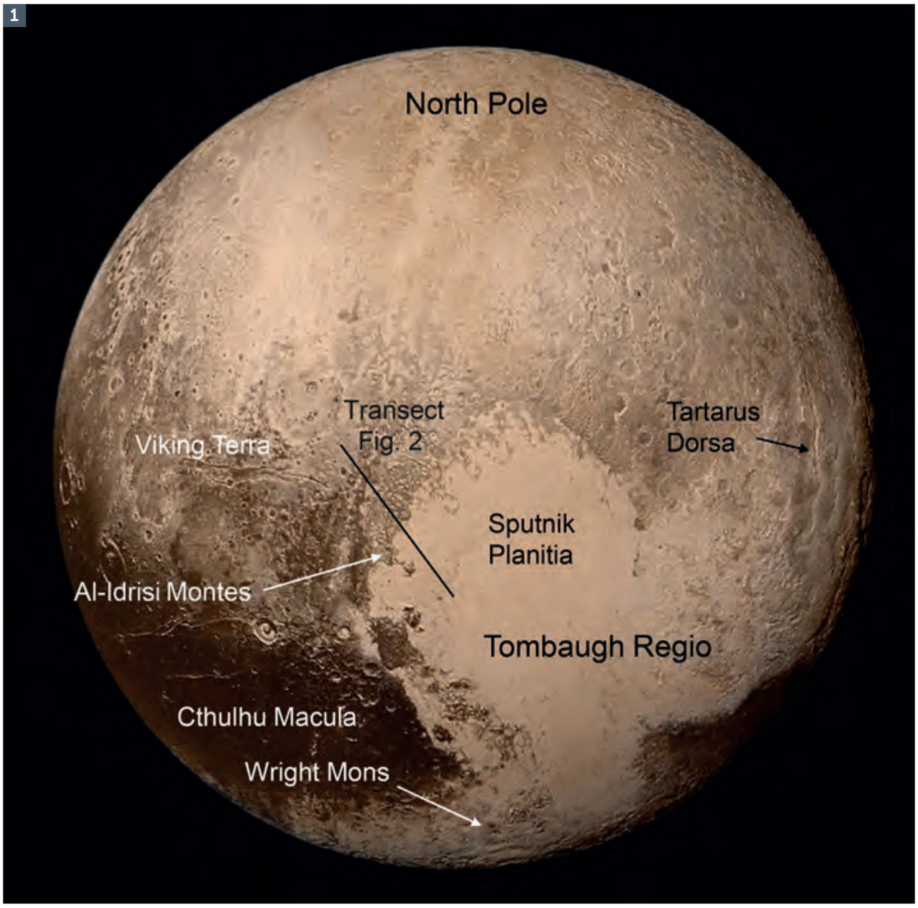

Figure 1: One hemisphere of Pluto is dominated by the Tombaugh Regio or 'Heart of Pluto'. This image is a combination of four taken from New Horizons' Long Range Reconnaissance Imager (LORRI), combined with colour data to create a global true colour view of Pluto *(Image credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute)*

They orbit each other with near-circular orbits, meaning that negligible tidal heating is currently produced in their interiors as a result of tides. With no clear source of internal heat for Pluto, there was no expectation of geological activity at its surface. Yet, a geologically dead Pluto was not what was found.

Western lobe

Images beamed back from the New Horizons probe revealed that one hemisphere of Pluto (Fig. 1) is dominated by the striking high-albedo Tombaugh Regio or 'Heart of Pluto', which is composed of two geologically distinct lobes.

The western lobe hosts a large nitrogen and carbon monoxide ice deposit that fills the Sputnik impact basin. This deep basin is thought to have provided a cold trap in which atmospheric condensation of carbon monoxide and nitrogen could readily occur, forming the wide expanse of Sputnik Planitia (Fig. 1). The concentration of mass within Sputnik Planitia then induced global tectonism, forming radial and concentric fracture systems.

Once deep enough, thermal and compositional gradients within the ice deposit prompted the initiation of convection within the nitrogen ice. Today, a pattern of troughs divides the surface of this icy plain into almost 200 oval-shaped units that mark the top of 3 to 4-km-deep convection cells (Fig. 2). Most of the cells have a pitted surface, with the pits formed by the sublimation of the surface nitrogen ice. Pit density is generally highest at the edges of the cells and more limited in the centres of the actively convecting cells.

In the southern parts and edges of Sputnik Planitia, the nitrogen ice deposit is thinner and does not convect, so the sublimation pits have had more time to develop. The pits are larger and, in some cases, have reached the base of the ice sheet, exposing a low-albedo basement. Sublimation pits are sometimes aligned, forming along flow margins, fractures, or compositional differences in the ice to create chains of pits that resemble fingerprints (Moore, J.M. et al. 2017).

From New Horizons' striking images of Sputnik Planitia came an even more striking result: no impact craters. Down to the limit of the image resolution, there was a complete lack of impact craters within Sputnik Planitia, which suggests that the surface of this feature is geologically very young – less than 10 million years old. Age estimates based on the expected rate of convective overturn and sublimation for nitrogen ice suggest a maximum age of just 180,000 (+90k/-40k) years, making Sputnik Planitia one of the youngest terrains in the solar system.

On the northern and western edges of Sputnik Planitia (Fig. 2), which comprise the rim of the ancient Sputnik impact basin, are water-ice mountains. These mountains have a veneer of methane ice and small dark particles known as tholins, which are complex organic compounds precipitated from Pluto's atmosphere after reactions between UV and cosmic radiation and atmospheric gases. Here, jumbled blocks of the ancient crater rim have collapsed downwards into the basin (Fig. 2). In the valleys between these blocks, nitrogen ice glaciers can be seen. These glaciers perhaps record a period where the level of Sputnik Planitia ice was higher, before receding.

The spectral signature of these regions suggests the ice here is predominantly methane. However, methane ice lacks the strength required to maintain topography of this magnitude. Instead, it seems that the 'bed rock' for Pluto is water ice, which is capable of supporting the large variations in topography observed across the body. Atmospheric deposition of methane and nitrogen ice then likely covered the water ice in most areas. In a few locations, such as along chasm walls and on the exposed tilted sides of ice blocks in Al-Idrisi Montes, the white of the water ice can be seen, layered with red tholins (Fig. 2).

Eastern lobe

The eastern lobe of Tombaugh Regio is an upland of sublimation-pitted methane ice. Here, eroded valleys are filled with nitrogen-ice glaciers that appear to flow into the main body of Sputnik Planitia (Howard, A.D. et al., 2017).

The eastern-most extent of Tombaugh Regio hosts the 'dragon skin' or bladed terrain of Tartarus Dorsa – an area comprised of several swells that are hundreds of metres high and separated by long narrow valleys (Fig 3). The ridges are covered by north-south trending blades of methane ice, that appear like penitentes (blade-shaped snow formations) on Earth. The consistent orientation of the blades suggests that some factor, such as solar illumination, results in the preferential deposition/removal of methane ice. The penitentes in Pluto's bladed terrain system are two orders of magnitude larger than those found on Earth – a testament to the extreme action of sublimation on this body.

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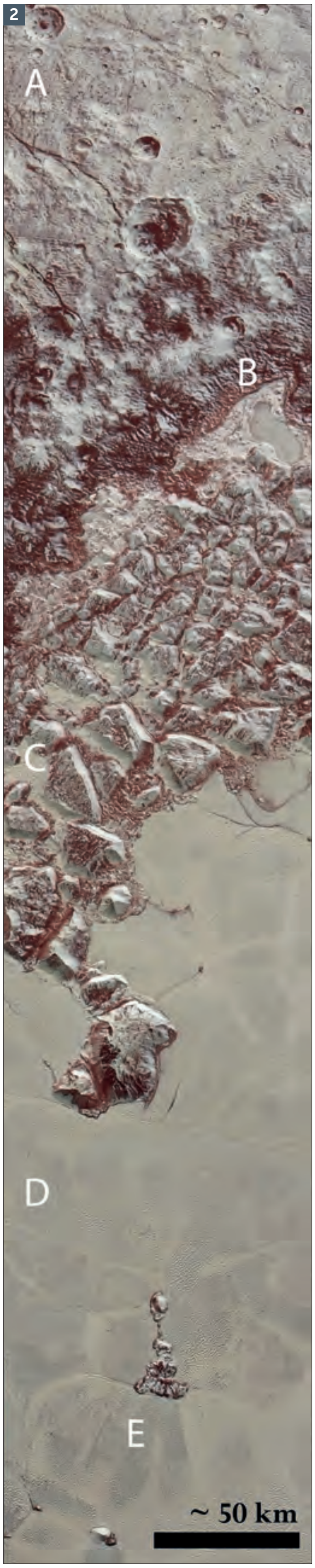

Figure 2: High-resolution swath across the rim of the Sputnik basin, from older cratered and tectonically disrupted terrain of Viking Terra at the top, to the young convecting nitrogen-ice deposit of Sputnik Planitia at the bottom. (A) Viking Terra – a bedrock of water ice, covered with methane ices and cut by craters and extensional tectonics. (B) Glacially eroded terrain with a covering of red tholins, just above a trapped glacier/frozen lake of nitrogen ice. (C) Tilted ice blocks of Al-Idrisi Montes expose water ice beneath their cover of red tholins, surrounded by pitted nitrogen ice. (D) The sublimation-pitted convecting nitrogen ice of Sputnik Planitia. (E) Light-toned dunes and dark wind streaks are observed in this part of Sputnik Planitia. They potentially formed from methane ice 'sand' blown from Viking Terra and the Al-Idrisi mountains. *(Image credit: NASA/JHUAPL/SwRI)*

Equator

Around Pluto's equator lies a band of maculae – low albedo regions where the surface is coated in a mantle of tholins (Fig. 1). Tholins are deposited globally on Pluto, but are disrupted by the continuous cycle of deposition and sublimation of the volatile methane and nitrogen ices during Pluto's extreme seasons. The relatively mild temperature changes at the equator allow tholins to deposit without disruption from volatile cycling.

Cryovolcanism

To the south of the equatorial macula, at the southern tip of Sputnik Planitia, lies the cryovolcanic field of the Wright Mons region (Fig. 4) – another startlingly young terrain based on the small number of impact craters present over its surface. Wright Mons is potentially a cryovolcanic feature, about 145 km across and rising about 4 km from base to peak, which is similar in scale to Earth's largest shield volcano, Mauna Loa. However, the similarities with terrestrial shield volcanism end there. Instead of smooth terrain, the bobbly surface texture is reminiscent of pillow basalts, but on a massive scale. Wright Mons may have a central depression, but it is much larger than that expected for collapse →

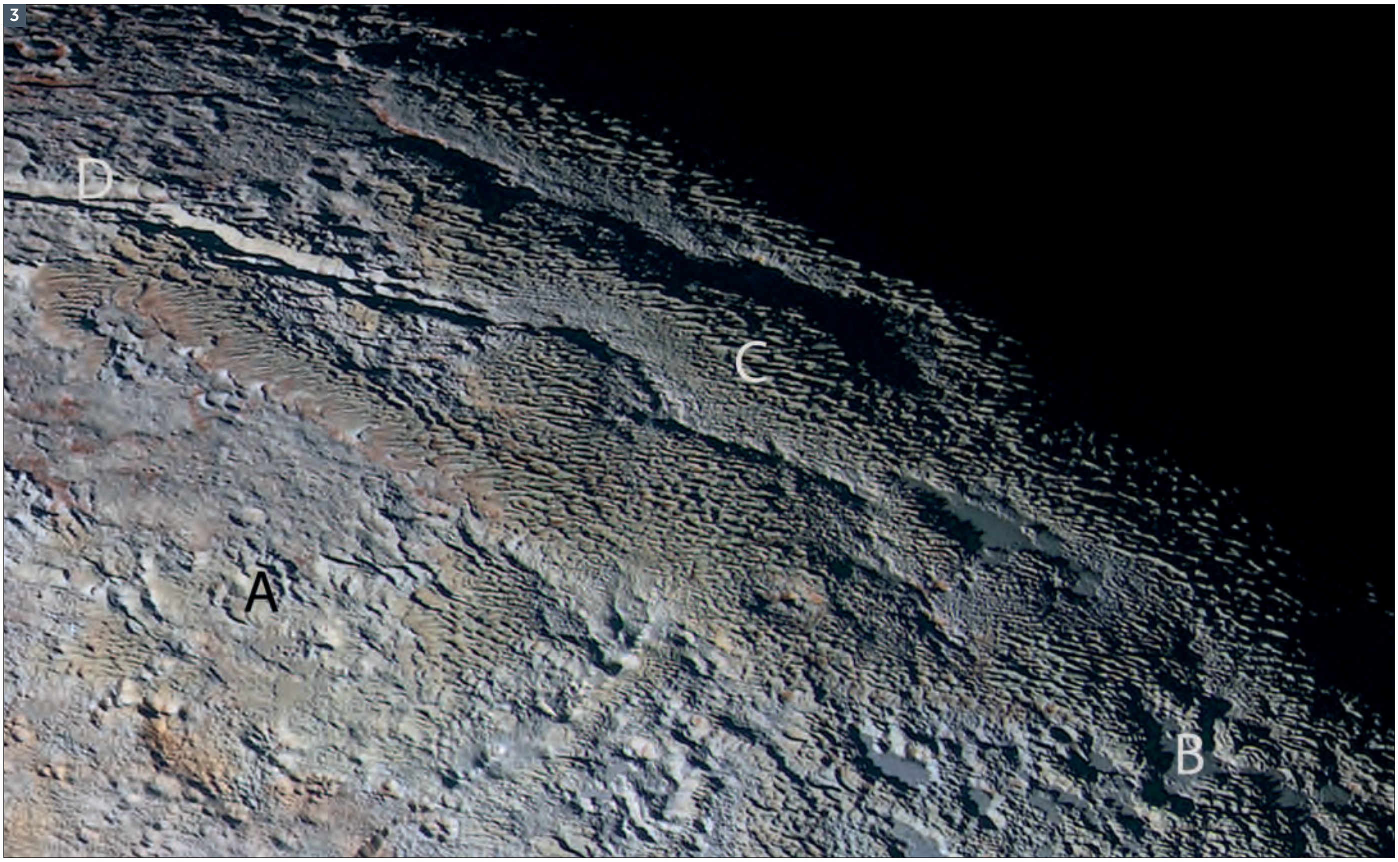

Figure 3: Eastern Tombaugh Regio. A methane-rich terrain pock-marked with sublimation pits (A), with low points filled in some places with nitrogen ice (B). Tartarus Dorsa lies to the top right of the image, at the 'terminator' where the extreme lighting angles create long shadows (e.g. B), emphasising the topography in the region. The swells of terrain with high-altitude methane-ice penitentes (C) are separated by deep tectonic valleys (D). This view is roughly 530 km across *(Image credit: NASA/JHUAPL/SWRI)*

calderas, at around 4 km deep and 56 km across. Rather than marking a central vent from which the Mons was formed, it is likely that the large central depression of Wright Mons (as well as other potentially cryovolcanic features in the region) marks an area that failed to fill with advancing viscous water/ice. Instead, this 'lava' stalled and formed an undulating cryovolcanic terrain.

The tectonic complex of Virgil Fossae, which is located in the Viking Terra region of Pluto, just west of Sputnik Planitia, also shows signs of cryovolcanism. This complex is estimated to be younger than 1 Ga. The source for this geologically recent activity is unknown, but might be due to increasing internal pressure caused by the gradual solidification of an ammonia-water sub-surface ocean or liquid chamber within the ice crust.

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North pole

Pluto's northern terrains (main feature image p. 13. and Fig. 1) are generally heavily cratered, suggesting they formed about four billion years ago. Parallel canyon systems that are now heavily eroded by glacial activity, record a period of ancient extensional tectonics, perhaps associated with the partial freezing of a sub-surface ocean, or the formation of the Sputnik impact basin.

Superposed on the ancient northern terrains are large collapse pits and ablation landforms created by sublimation. Dendritic valleys cut through the northern terrains and

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were likely formed by the deposition and transport of seasonal ices. The observations of glacial flow today (from the highlands of the eastern Tombaugh Regio, down to the Sputnik basin), suggest that many of the landforms seen in the northern terrains are due to past glacial activity. It is unknown whether this glacial action occurs annually, but it is likely; the seasons on Pluto are certainly dramatic enough to produce notable changes over the course of its 248 Earth-year orbit.

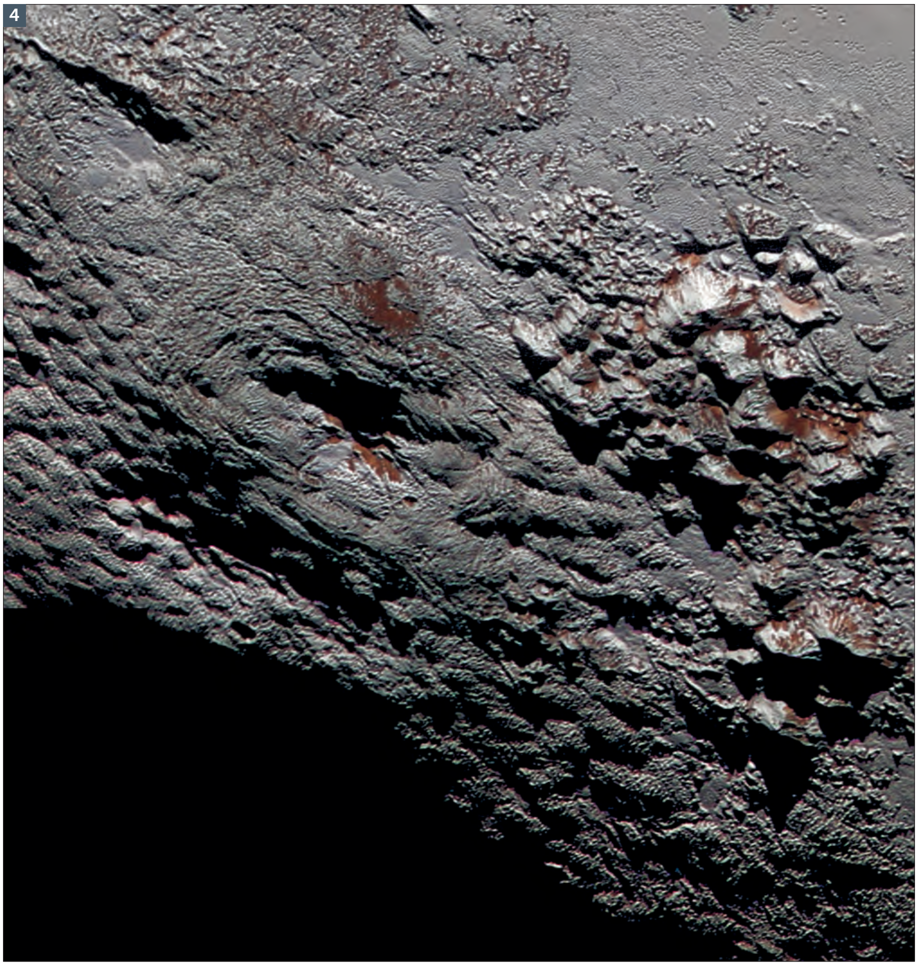

Figure 4: Wright Mons is a possible cryovolcano spotted by the New Horizons spacecraft during its fly-by of Pluto in July 2015 *(Image credit: NASA/JHUAPL/SwRI)*

Extreme seasons

The relatively mild seasonal changes on Earth are a gift of our planet’s moderate 23.5-degree axis tilt and the Moon’s stabilising influence. Pluto’s axis is tilted at 122.5 degrees (Fig. 5), which leads to much larger Arctic and Antarctic zones (those that experience ‘midnight sun’ in summer and full-day darkness in winter). This creates clear temperature zones across the dwarf planet, driving a seasonal migration of volatiles towards colder areas of the body. After the last equinox in December 1987, Pluto’s North Pole exited its 124-year-long ‘polar night’. Nitrogen ices at the North Pole began to sublimate, joining the atmosphere and condensing at the now dark south polar region.

Pluto’s orbit is also elliptical, compared to Earth’s relatively circular orbit about the Sun. The dwarf planet moves as close to the Sun as 30 Astronomical Units (AU), which is inside the orbit of Neptune, and as far away as 50 AU.

The elliptical orbit and extreme tilt mean that surface temperatures on Pluto vary between 40 to 60 K (–230 to –210 °C), which is close to the condensation point of several volatile ices (such as, 32 K for nitrogen, 45 K for methane and 52 K for carbon monoxide) and leads to significant atmosphere-surface interactions. Essentially, a portion of the atmosphere condenses out when Pluto is farther from the Sun, depositing onto the surface of Pluto as an exotic snow layer. The surface of Pluto might appear starkly different at perihelion compared to the colder, darker aphelion.

When New Horizons visited Pluto, the planet had recently been at its perihelion (September 1989), meaning that the images recorded by New Horizons were of Pluto in its warmest state. This was part of the plan: the distance between Earth and Pluto was relatively short, cutting down on travel time and fuel needs, and ensuring that the probe could visit the planet at a time when the surface wasn’t blanketed in atmosphere-derived deposits. Pluto has since continued along its elliptical orbit, →

away from the Sun. Pluto is changing, but New Horizons is long gone.

Future missions

The spectacular fly-by of New Horizons transformed our understanding of Pluto from a barely resolved dot in the sky to a surprisingly active and fascinating world. The fly-by nature of the mission meant that the close-proximity observations were largely restricted to one hemisphere, viewed over a matter of hours. Data acquisition had to be pre-planned and automated because no commands could be given to the spacecraft during its encounter (due to a signal from Earth taking 4.5 hours to travel to Pluto).

The next step is an orbiter, which will enable us to view Pluto illuminated in its entirety over an extended time period and allow for updates to the data acquisition plan in near-real time. Higher-resolution images of the far-side of Pluto will allow us to study currently unresolved geological features and thereby confirm (or not) our theories of global tectonism and temperature-related sublimation/deposition zones.

A return mission to Pluto would also likely include additional instruments to measure the gravity field, allowing us to constrain the differentiation state of Pluto's interior, including the presence (or not) of a subsurface ocean. With a return mission, we could observe how Pluto has changed since the encounter with New Horizons, potentially finding new meteor impacts, dune migration, and deposition/sublimation of seasonal ices.

Earth-based observations continue to monitor the ever-condensing atmosphere of Pluto as it races farther away from the Sun on its elliptical orbit. But without up-close imaging, we can only guess how atmospheric condensation is changing the surface of Pluto over the course of its year. Compared to the relatively warm surface imaged in July 2015, later missions may reveal a completely different face of Pluto as it hides deeper beneath its blanket of exotic snow. G

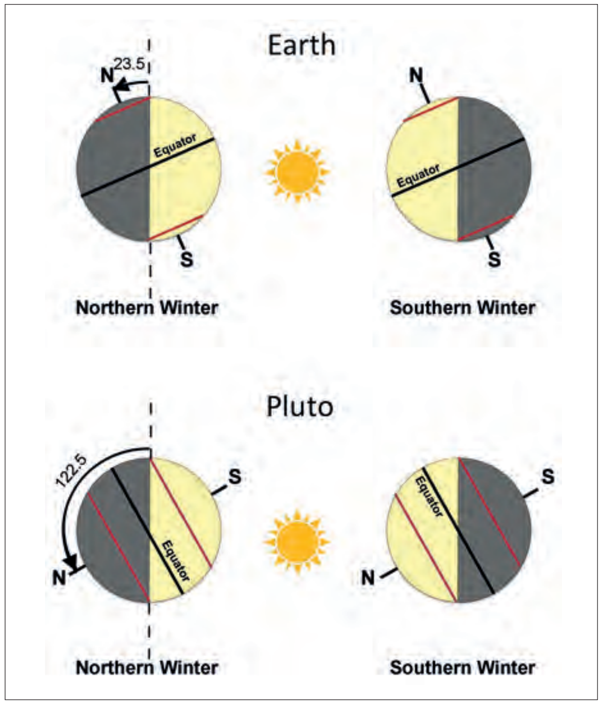

Figure 5: A simplified illustration of the larger arctic (northern) and Antarctic (southern) zones on Pluto compared to Earth, due to Pluto's larger axial tilt. The Arctic/Antarctic circles for Earth and Pluto are drawn in red. Poleward of this line is the area that experiences constant light or darkness during the summer/winter

GLOSSARY

- Al-Idrisi Montes – a mountain range in the northwest part of Tombaugh Regio
- Aphelion – the point at which a planetary body is farthest from the Sun in its orbit
- Charon – Pluto's binary partner. Together, Pluto and Charon form a binary dwarf planet system orbiting about their combined centre of mass.
- Equinox – when the centre of the Sun is directly above the equator
- Maculae – low-albedo regions with a surface mantle of tholins
- Penitentes – erosional features characterised by elongated, thin blades of ice that grade into spires
- Perihelion – the point at which a planetary body is closest to the Sun in its orbit
- Sputnik impact basin – an ancient tear-drop shaped scar created by a massive comet impact about four billion years ago
- Sputnik Planitia – a high-albedo, ice deposit, about 1,050 by 800 km in size
- Sublimation pits – depressions in the surface formed when ice is heated by sunlight and turned directly into a gas
- Tartarus Dorsa – a set of mountains in Pluto's northern hemisphere characterised by penitentes
- Tholins – particles created in and precipitated from Pluto's atmosphere by reactions between UV and cosmic radiation and atmospheric gases
- Tombaugh Regio – the 'Heart of Pluto', a high-albedo region composed of two geologically distinct lobes
- Wright Mons – a potential cryovolcano

FURTHER READING

A full list of further reading is available at geoscientist.online.

- Buie, M.W. et al. (2021) The Pluto System After New Horizons, Stern, S.A. et al. (eds). University of Arizona Press.
- Howard, A.D. et al. (2017) Icarus 287 287-300.
- Martin, C.R. & Binzel, R.P (2021) Icarus 356, 113763.
- Moore, J.M. et al. (2017) Icarus 287, 320-333.
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