The Tenuous Atmospheres of Pluto and Triton Explored by CRIRES on the VLT

Emmanuel Lellouch[1]
Catherine de Bergh[1]
Bruno Sicardy[1]
Hans-Ulrich Käufl[2]
Alain Smette[2]

[1] LESIA-Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot, France
[2] ESO

The dwarf planet Pluto and Neptune's largest satellite, Triton, are two small icy bodies surrounded by tenuous and poorly known atmospheres. The high spectral resolution and high sensitivity of CRIRES on the VLT have permitted a major step forward in the study of these atmospheres, and especially of their composition. Absorptions due to methane and carbon monoxide in these atmospheres have been detected at 1.66 and 2.35 μm, providing an insight into the way in which these atmospheres are maintained, the surface–atmosphere interactions, their seasonal evolution and thermal balance.

Pluto and Triton: Frigid twins in the outer Solar System

Pluto and Triton are twins in the outer Solar System. Once the ninth planet and now classified as a dwarf planet, Pluto is a prominent member of the Kuiper Belt, the population of small primitive bodies orbiting the Sun beyond Neptune (e.g., Barucci et al., 2010). Its heliocentric orbit, fairly typical for a body in 3:2 resonance with Neptune, is elliptical (perihelion at 29.5 Astronomical Units [AU] and aphelion at 49.0 AU) and inclined (by 17° to the ecliptic plane). Pluto's axis of rotation is inclined by 120° to its orbital plane. Since its discovery in 1930, Pluto has covered only one third of its 248-year orbit and its most recent closest approach to the Sun occurred in 1989. With a diameter of about 2340 kilometres, Pluto is, along with Eris, one of the two largest members of the trans-Neptunian population.

At a mean distance of 30 AU from the Sun, Triton is the largest satellite of Neptune, with a diameter of 2707 kilometres. Its orbit around the planet — retrograde and out of Neptune's equatorial plane — indicates that it is most likely a Kuiper Belt object that has been captured by Neptune. Triton's orbit and obliquity are such that at some time during the 165-year-long Neptune year, each of Triton's poles points almost directly toward the Sun — the obliquity of the current orbit is 50°, resulting in large seasonal effects in the insolation.

Beyond their similar sizes and dynamical kinship, Pluto and Triton have similar, albeit not identical, compositions. Earth-based near-infrared (NIR) observations indicate that both are covered by ices dominated by nitrogen, plus some methane and carbon monoxide. Ethane ice has also been detected on Pluto, while carbon dioxide and water ice are present on Triton. Detailed studies of ice band positions indicate that most of the ices are "diluted" by N_2 ice, i.e. are mixed with it in small proportions at the molecular level. The *Voyager 2* encounter with Triton in 1989 unveiled a frigid (38 K) but remarkably active world, with high surface diversity (see Figure 1). Until the *New Horizons* spacecraft gets to Pluto — the encounter is scheduled for July 2015 — and reveals how similar Pluto's appearance is to Triton's, Pluto will remain a crudely resolved 0.1-arcsecond dot. Yet even at the modest resolution of the Hubble Space Telescope (HST; see Figure 2), Pluto exhibits large brightness contrasts, up to 6:1 in reflectance. The brightest areas are attributed to N_2 ice, while dark regions are thought to result from the irradiation of methane ice-rich areas, giving birth to tholins (heteropolymer molecules formed by UV radiation). The large surface variegation of Pluto is also responsible for a large heterogeneity in the surface temperature, varying from about 40 K in the bright areas to 60 K in the darkest regions.

Tenuous and poorly understood atmospheres

Pluto and Triton both have tenuous atmospheres formed by the sublimation of the more volatile surface ices, whose composition, to first order, must reflect that of the surface and the relative volatility of the various ices. In spite of their large distance from the Sun, these atmospheres are strongly driven by solar heat. Given the large inclination of the rotation axes (and in Pluto's case the orbital eccentricity) they must also vary with time. Pluto's atmosphere is expected to completely collapse at aphelion — around 2113.

Triton's atmosphere was discovered by *Voyager 2*. Its main component, N_2, was detected in the ultraviolet, with a ground pressure of 14 μbar, and gaseous CH_4 could also be observed. On Pluto, N_2 must also be the major gas, but cannot be observed from Earth, and only a low signal-to-noise (S/N) detection of

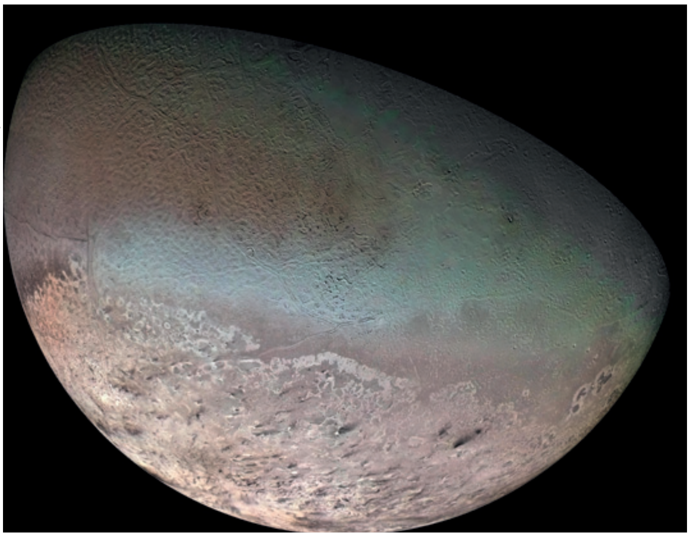

Courtesy NASA/JPL-Caltech

Figure 1. Image of Triton's South Polar cap, seen by *Voyager 2* in 1989.

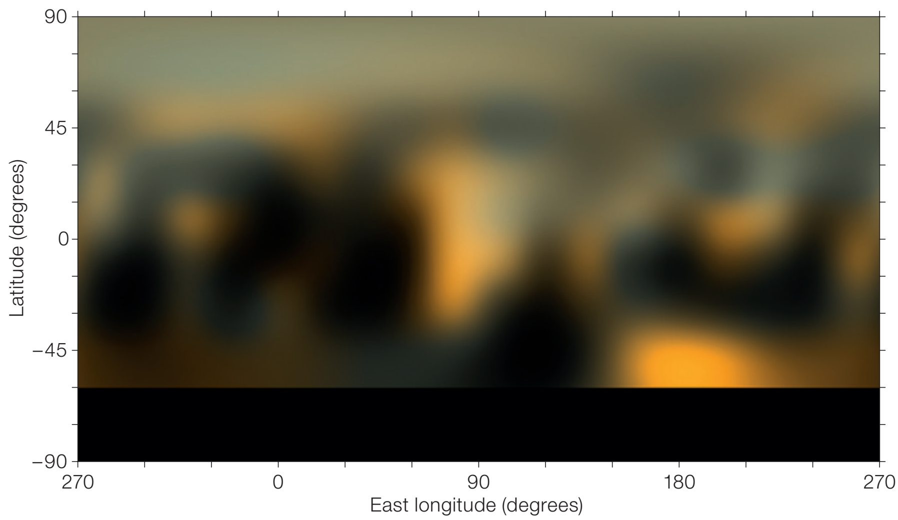


Figure 2. A map of Pluto from HST observations (from Buie et al., 2010). The brightest region near 180° longitude is suspected to be CO ice-rich.

atmospheric methane was achieved, using observations from the NASA Infrared Telescope at 1.67 μm (Young et al., 1997). Pluto's atmosphere, on the other hand, has been much more studied from stellar occultations. Although these observations cannot identify a particular species and are also unable to probe the atmosphere down to the surface itself, occultations are an extremely powerful way of revealing the atmosphere's thermal structure. Pluto's upper atmosphere appears to be "warm" ~ 100 K, as opposed to ~ 60 K for Triton at the same pressure level), a likely effect of heating by methane (similar to ozone heating in the Earth's stratosphere). In contrast, Pluto's lower atmosphere and the way the upper atmosphere connects to the 40–60 K surface are poorly understood. Remarkably, repeated occultations showed that Pluto's atmosphere has expanded, roughly doubling in surface pressure, from 1988 to 2002, even though Pluto has started to recede from the Sun. Similarly, Triton's surface pressure has been shown to increase through the 1990s.

Despite these remarkable findings, the composition of the atmospheres of Triton and Pluto, and how they may change with time, remain very poorly characterised. Atmospheric methane was not reobserved and the search for additional compounds failed. In the last three years, however, CRIRES observations at the VLT have brought about very significant progress.

CRIRES spectra of the atmospheres of Pluto and Triton

The unprecedented combination of sensitivity and spectral resolution in the NIR offered by CRIRES makes it a very powerful instrument to study tenuous and distant atmospheres. During a first service run in August 2008, we obtained a high S/N detection of the $2\nu_3$ band of methane at 1.67 μm in Pluto's spectrum. As Pluto's atmospheric pressure is typically only ~ 15 μbar, lines are purely Doppler-broadened and the highest spectral resolution is desirable. We used a slit of 0.4 arcseconds, combined with the adaptive optics module MACAO, obtaining an effective spectral resolution of ~ 60 000. This high resolution was also instrumental in separating the methane lines of Pluto from their telluric counterparts, so that methane lines from Pluto, interlinked within the Q-branch of the $2\nu_3$ band of telluric methane (see Figure 3), could be observed. The quality of the spectrum (17 individual lines, including high-*J* lines) made it possible to separate abundance and temperature effects in Pluto's spectrum (Lellouch et al., 2009). Pluto's mean methane temperature is 90 K, which implies that Pluto cannot have a deep and cold troposphere as had been proposed (otherwise the bulk of the methane would be at ~ 40 K). By linking this to a re-analysis of occultation measurements, new constraints on the structure of Pluto's lower atmosphere and surface pressure could also be derived, indicating that Pluto's

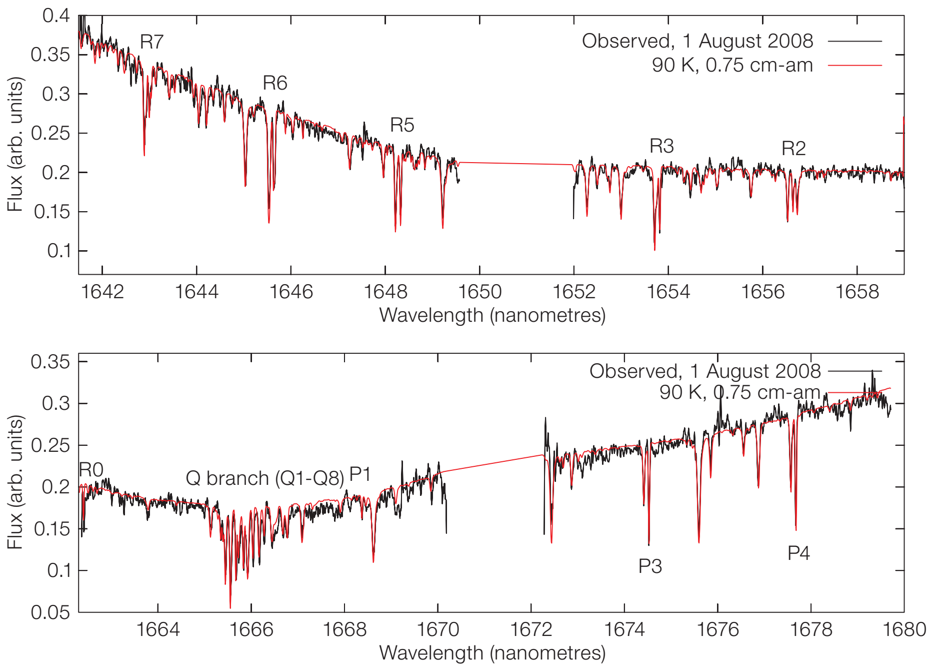


Figure 3. The spectrum of Pluto's atmosphere showing the fit to the $2\nu_3$ band of methane, observed by CRIRES (from Lellouch et al., 2009).

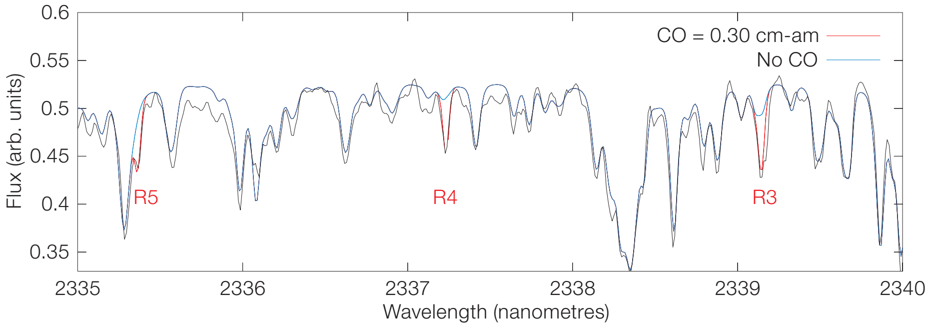


Figure 4. A section of Triton's spectrum in the 2.35 μm range, as seen by CRIRES, showing the detection of CO in Triton's atmosphere (from Lellouch et al., 2010).

current pressure is between 6.5 and 24 μbar (i.e. 40 000–150 000 less than on Earth), and that the CH_4 atmospheric abundance (CH_4/N_2 mixing ratio) is 0.5 %.

Encouraged by the instrument's capabilities, we decided to conduct a search for atmospheric CO on Triton and Pluto. The best spectral region to look for CO is the 2.35 μm (2–0) band. In July 2009, after four hours of integration with CRIRES under excellent sky conditions, we detected a strong signal of this molecule in Triton's atmosphere (shown in Figure 4), indicating a CO/N_2 abundance of about 6×10^{-4} (Lellouch et al., 2010). As a bonus, the spectrum, which has a S/N of ~ 80, showed many lines from the $\nu_3 + \nu_4$ band of gaseous methane. This was the first time that methane had been observed at Triton since Voyager, and the data showed that the column density of methane had increased by a factor of about four since 1989. This is in line with the occultation results, and certainly results from a seasonal effect, with increased insolation on Triton's ice-covered Southern polar cap.

Obtaining a spectrum of similar quality for Pluto is very challenging, as Pluto is not only somewhat smaller than Triton, but very dark in *K*-band (geometric albedo ~ 0.2 *vs*. 0.6 for Triton, due to strong methane ice absorption; see, for example, Figure 3 in Barucci et al., 2010). This warranted another dedicated run in July 2010, during part of which we experimented with the fast ("windowed") readout mode of CRIRES. In this mode, only detectors 2 and 3 of CRIRES are read and windowed, resulting in a noticeable gain in sensitivity for faint targets. Overall, after 7 hours 20 minutes on source, we obtained a spectrum with a S/N of 15–20. This spectrum clearly showed the spectral signatures of methane, and hints for CO at the position of nine lines. When these lines are co-added, evidence for CO is obtained at 6σ confidence (Lellouch et al., 2011), providing a likely detection — but not as obvious as on Triton. For completeness, let us add that the detection of CO in Pluto's atmosphere has been claimed independently by Greaves et al. (2011) from James Clerk Maxwell Telescope observations, but their results are hard to understand and inconsistent with the CRIRES ones.

Surface–atmosphere interactions

Our results on the abundances of CO and CH_4 in Pluto and Triton's atmospheres are summarised in Table 1, assuming current total pressures of 15 and 40 μbar, respectively. They are compared to the abundances of these species measured in the surface. Note that the amounts of atmospheric CH_4 and CO correspond to a few tens of nanobars only at 60–90 K. With hindsight, it is fascinating to think that CRIRES is able to measure these quantities on 0.1-arcsecond-sized objects 4.5 billion kilometres away!

Pluto's atmosphere is thus much (~ 20 times) richer in CH_4 than Triton's — this explains the warmer stratosphere on Pluto; in contrast the two atmospheres have similar CO abundances. The same is true for the surface abundances, and the striking result in Table 1 is that within the measurement uncertainties (which are about 20–40 % for CH_4, but as much as a factor 2–3 for CO, due to the difficulty of determining abundances from unresolved, saturated lines) for both species, the atmospheric and surface abundances are the same.

This result looks remarkably simple, yet was not anticipated at all. Since for the most part ices on the surface of Pluto and Triton are dissolved in N_2 to form a solid solution, one would expect from simple thermodynamics (Raoult's law) that their atmospheric mixing ratio would be equal to the ratio of their vapour pressures to that of N_2, multiplied by their ice phase abundance. Because CO and especially CH_4 are less volatile than N_2, this would lead to atmospheric abundances much lower than observed (by a factor of about seven for CO and over three orders of magnitude for CH_4). Therefore, surface–atmosphere interactions or exchanges must proceed in a different way. Essentially there are two means to explain the enhanced atmospheric CH_4 and CO abundances.

The first explanation is that the enhanced atmospheric abundances result from the sublimation of pure patches of CH_4 and CO ices. This is probably what occurs for CH_4, whose much lower volatility compared to N_2 is expected to lead, over the course of seasonal sublimation–condensation cycles, to geographically segregated (warmer than the N_2 ice) CH_4 ice patches. Evidence for pure methane ice, co-existing with diluted methane, is in fact present in the surface spectra of Pluto (Douté et al., 1999). On Triton the case for pure methane is not as clear, but the longitudinal distribution of methane ice is known to be different from that of N_2. This suggests that, in a similar way to Pluto, a region, or regions, of enhanced CH_4 possibly controls the CH_4 atmospheric abundance. Calculations indicate that pure or enhanced CH_4 patches covering typically a percent of

	Pluto		Triton	
	Atmosphere	Surface	Atmosphere	Surface
CH_4/N_2	5×10^{-3}	4×10^{-3} (a)	2.4×10^{-4}	5×10^{-4}
CO/N_2	5×10^{-4}	1×10^{-4}	6×10^{-4}	1×10^{-3}

(a) Pure methane is also present

Table 1. Comparison of surface and atmospheric molecular abundances on Pluto and Triton.

the surface are sufficient to maintain the high methane abundance in both objects.

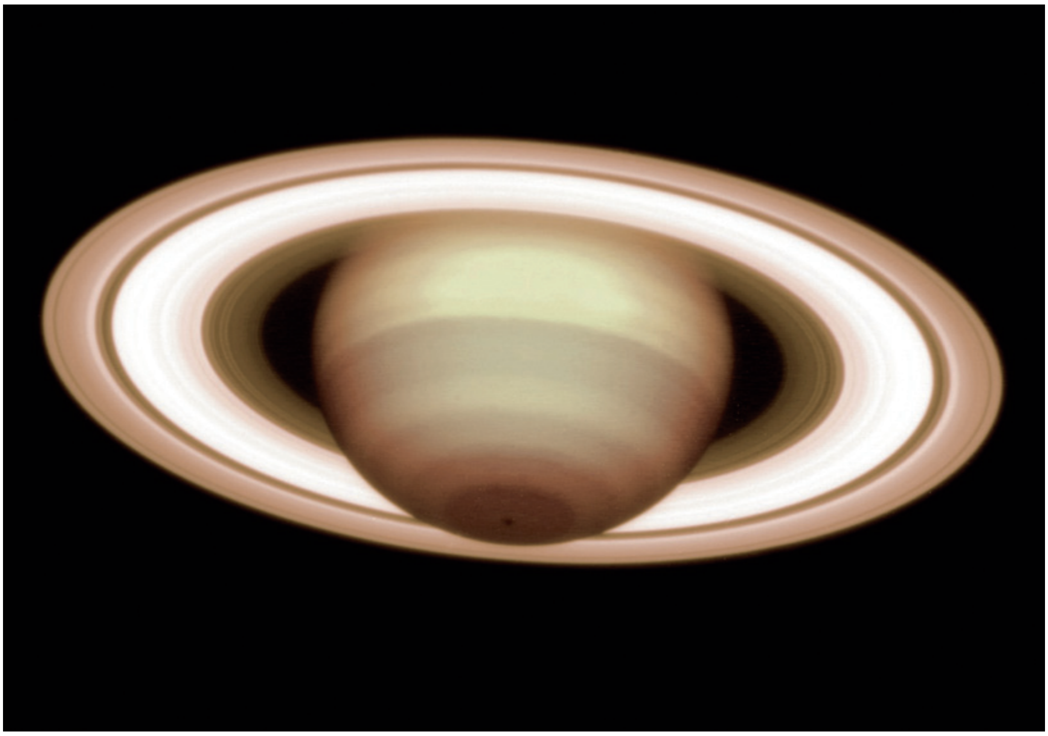
This "pure ice" scenario is probably not valid for CO, which is thermodynamically not expected to segregate from N_2 and can stay mixed with it in all proportions, and an alternative situation is likely to occur. For this second explanation, it is thought that seasonal cycles form a very thin (a few molecules) surface upper layer enriched in CO (Trafton et al., 1998) that inhibits the sublimation of the underlying main ice layer. Exchanges between this thin layer (termed "detailed balancing layer") and the atmosphere lead to an atmospheric composition reflecting that of the volatile reservoir, as observed. Yet a mystery remains, as it seems that at least one very bright area on Pluto's surface (Buie et al., 2010; and Figure 2) is associated with a CO ice-rich region. It is hoped that data from *New Horizons* in 2015 will provide more information on this bright spot and its possible connection with CO's atmospheric abundance.

Validating these scenarios will require additional observations. Direct spatial resolution on the discs of Pluto and Triton is not possible, yet repeated observations, taking advantage of their rotation, would allow one to search for possible longitudinal variability of the CH_4 and CO atmospheric content. A correlation with the appearance of the surface features and the longitudinal distribution of ices would strongly advocate for the "pure ice" scenario. Monitoring the evolution of the minor compounds in the atmosphere over the upcoming years will also further reveal the nature of atmosphere–surface interactions. In the future, spatially-resolved observations with an instrument such as SIMPLE on the ELT (Origlia & Oliva, 2009; Origlia et al., 2010) will permit direct imaging, constraining, for example, the latitudinal distribution of these atmospheres.

Studying Pluto and Triton's atmospheres is not only interesting in itself, but it opens a window on this class of tenuous atmospheres dominated by sublimation equilibrium (of which Io is another example). Other ice-covered trans-Neptunian objects, especially the largest of them (Quaoar, Eris, Makemake), may have retained their volatiles over the age of the Solar System (Schaller & Brown, 2007) and be able to develop atmospheres near perihelion. While such atmospheres have not yet been detected, searches are underway, especially from stellar occultations. Should they be discovered, spectroscopy with the Extremely Large Telescope (ELT) could play a pivotal role in characterising them.

References

Barucci, M. A. et al. 2010, The Messenger, 141, 15
Buie, M. W. et al. 2010, AJ, 139, 1128
Douté, S. et al. 1999, Icarus, 142, 421
Greaves, J. S., Helling, C. & Friberg, P. 2011, MNRAS, 414, L36
Lellouch, E. et al. 2009, A & A, 495, L17. See also ESO PR-0809.
Lellouch, E. et al. 2010, A & A, 512, L8. See also ESO PR-1015.
Lellouch, E. et al. 2011, A & A, 511, L4
Origlia, L. & Oliva, E. 2009, Earth, Moon & Planets, 105, 123
Origlia, L., Oliva, E. & Maiolino, R. 2010, The Messenger, 140, 38
Schaller, E. L. & Brown, M. E. 2007, ApJ, 659, L61
Trafton, L. M., Matson, D.L. & Stansberry, J. A. 1998. In *Solar System Ices*, Kluwer Academic Publishers, 773
Young, L. et al. 1997, Icarus, 153, 148



The giant planet Saturn, as observed with the VLT NACO adaptive optics instrument on 8 December 2001 when the planet was at a distance of 1209 million kilometres. The image is a composite of exposures in the near-infrared *H*- and *K*-bands and displays well the intricate, banded structure of the planetary atmosphere and the details of the ring system. The dark spot close to the south pole is approximately 300 km across and is a polar vortex. More details can be found in Release eso0204.