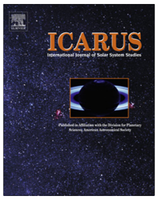
Icarus 267 (2016) 255–266

Contents lists available at ScienceDirect

Icarus

journal homepage: www.journals.elsevier.com/icarus



On the surface composition of Triton's southern latitudes

B.J. Holler [a,*,1], L.A. Young [b,1], W.M. Grundy [c,1], C.B. Olkin [b,1]

[a] Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, 1234 Innovation Dr., Boulder, CO 80303, United States
[b] Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302, United States
[c] Lowell Observatory, 1400 W. Mars Hill Rd., Flagstaff, AZ 86001, United States

ARTICLE INFO

Article history:
Received 24 August 2015
Revised 23 November 2015
Accepted 15 December 2015
Available online 28 December 2015

Keywords:
Triton
Ices, IR spectroscopy
Ices
Spectroscopy

ABSTRACT

We present the results of an investigation to determine the longitudinal (zonal) distributions and temporal evolution of ices on the surface of Triton. Between 2002 and 2014, we obtained 63 nights of near-infrared (0.67–2.55 μm) spectra using the SpeX instrument at NASA's Infrared Telescope Facility (IRTF). Triton has spectral features in this wavelength region from N_2, CO, CH_4, CO_2, and H_2O. Absorption features of ethane (C_2H_6) and ^{13}CO are coincident at 2.405 μm, a feature that we detect in our spectra. We calculated the integrated band area (or fractional band depth in the case of H_2O) in each nightly average spectrum, constructed longitudinal distributions, and quantified temporal evolution for each of the chosen absorption bands. The volatile ices (N_2, CO, CH_4) show significant variability over one Triton rotation and have well-constrained longitudes of peak absorption. The non-volatile ices (CO_2, H_2O) show poorly-constrained peak longitudes and little variability. The longitudinal distribution of the 2.405 μm band shows little variability over one Triton rotation and is $97 \pm 44°$ and $92 \pm 44°$ out of phase with the 1.58 μm and 2.35 μm CO bands, respectively. This evidence indicates that the 2.405 μm band is due to absorption from non-volatile ethane. CH_4 absorption increased over the period of the observations while absorption from all other ices showed no statistically significant change. We conclude from these results that the southern latitudes of Triton are currently dominated by non-volatile ices and as the sub-solar latitude migrates northwards, a larger quantity of volatile ice is coming into view.

1. Introduction

The images of Triton taken during the Voyager 2 flyby in August 1989 provided a tantalizing view of a diverse and dynamic surface. Two adjacent terrains on the imaged hemisphere appear drastically different in both color and texture, hinting that these two distinct surface units may have different surface ice compositions (Stone and Miner, 1989). Triton is frequently compared to Pluto, and with good reason. Triton and Pluto are comparable in size and may have come from the same initial population; it is believed that Triton is a captured Kuiper Belt Object (Agnor and Hamilton, 2006). However, Triton has a more diverse collection of surface ices, with N_2, CO, CH_4, CO_2, and H_2O ices definitively identified in ground-based spectra (Cruikshank et al., 1993, 2000). Spectral signatures, possibly due to C_2H_6 (ethane), are present as well (DeMeo et al., 2010). Two independent investigations suggest that Triton's surface temperature is about 38 K (Broadfoot et al., 1989; Tryka et al., 1993). At this temperature, the sublimation pressures of N_2 (22 μbar), CO (3 μbar), and CH_4 (0.002 μbar) are non-negligible, while the sublimation pressures of CO_2 (10^{-24} μbar), H_2O (0 μbar), and ethane (2×10^{-16} μbar) are negligible (Fray and Schmitt, 2009). Henceforth, we will refer to N_2, CO, and CH_4 as volatile ices due to their relatively higher sublimation pressures compared to the non-volatile ices: CO_2, H_2O, and ethane. CO_2 and H_2O are less mobile and presumably constitute the substrate upon which the volatile ices (N_2, CO, CH_4) deposit. The presence of volatile ices on the surface, though predicted for an object with the surface temperature and diameter of Triton (Schaller and Brown, 2007; Johnson et al., 2015), is surprising. The capture process and subsequent circularization of Triton's orbit through tidal interactions heated Triton significantly, resulting in the production of a thick atmosphere and blowoff of volatile species (McKinnon et al., 1995). Present-day surface composition is puzzling in light of the dynamical history of Triton.

The continued presence of volatile ices allows for an atmosphere around Triton. Despite its low surface temperature and high geometric albedo (0.719; Hicks and Buratti, 2004), the surface pressure on Triton was measured at 14 ± 1 μbar by Voyager 2 in

---

[*] Corresponding author.

[1] Visiting or remote observer at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement #NNX-08AE38A with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program.

http://dx.doi.org/10.1016/j.icarus.2015.12.027

1989 (Gurrola, 1995). Stellar occultations in the 1990s (through 1997) showed a surprising increase in both temperature and pressure (Elliot et al., 1998). The next occultation was observed in 2008 but the data have yet to be reduced and analyzed, so the current state of Triton's atmosphere is unknown (Sicardy et al., 2008). Triton's atmosphere is dominated by N_2 with traces of CO and CH_4 (Tyler et al., 1989; Lellouch et al., 2010). Volatile transport, driven by migration of the sub-solar point, is responsible for the observed spatial distributions and temporal evolution of surface ices on Triton (Buratti et al., 1994; Bauer et al., 2010). Previously published papers describe in more detail the significant seasonal variations on Triton due to migration of the sub-solar point (e.g., Trafton, 1984; Hansen and Paige, 1992; Moore and Spencer, 1990). Fig. 1 shows the change in the sub-solar latitude over the period 1000–3000 C.E. A subset of that figure covering 1980–2020 C.E. is presented in Fig. 2. After reaching its maximum southern extent in 2000 ($-50°$), the sub-solar point[2] has turned northward, reaching $-42°$ at the time of this writing in mid-2015. Images obtained by Voyager 2 were taken during this extended period of southern illumination. A higher albedo in the southern hemisphere led some to argue for a south polar region covered in volatile ices (e.g., Stone and Miner, 1989; Moore and Spencer, 1990). With limited spectral information in the near-infrared from Voyager 2, the composition of various regions of Triton's surface from the flyby epoch are unknown.

As measured by Voyager 2, the mixing ratio of CH_4 to N_2 in Triton's atmosphere is on the order of $\sim 10^{-4}$ (Broadfoot et al., 1989; Herbert and Sandel, 1991). The presence of CH_4, even at these levels, drives ongoing photochemistry (Lara et al., 1997; Krasnopolsky and Cruikshank, 1995). Indeed, photochemical haze was seen in Triton's atmosphere by Voyager 2 (Herbert and Sandel, 1991; Rages and Pollack, 1992). The most common photochemical products of the interaction between CH_4 and extreme-UV photons, cosmic rays, and charged particles from Neptune's magnetosphere are acetylene (C_2H_2), ethylene (C_2H_4), and ethane (Krasnopolsky and Cruikshank, 1995; Moore and Hudson, 2003). Higher order hydrocarbons may also be created in much smaller quantities. Photochemistry occurs primarily in Triton's atmosphere, as demonstrated by a calculation of the flux of Lyman-α photons reaching the surface. The optical depth for Lyman-α photons in Triton's atmosphere, τ, is the product of the UV cross-section of CH_4 at 120 nm (1.8×10^{-17} cm^2; Chen and Wu, 2004) and the column density of CH_4 (2.15×10^{18} cm^{-2}; Lellouch et al., 2010). This results in $\tau = 38.7$ and means that the flux of Lyman-α photons reaching Triton's surface is so exceedingly small as to be negligible. Photochemical reactions involving CH_4 occur exclusively in Triton's atmosphere.

Ethane, a photochemical product produced in large quantities (Krasnopolsky and Cruikshank, 1995), was cited as a possible constituent ice on Triton's surface by DeMeo et al. (2010). Theoretically, after forming in the atmosphere, non-volatile ethane would precipitate onto Triton's surface and accumulate over time. Once a 1 μm spherical grain forms, it precipitates out of the atmosphere at the Stokes' velocity (Mark Bullock, private communication):

$$v = \frac{2gR^2(\rho - \rho_{atm})}{9\mu}, \tag{1}$$

where g is the gravitational acceleration on Triton (77.9 cm s^{-2}), R is the radius of the ethane grains, ρ is the density of ethane (0.713 g cm^{-3}; Barth and Toon, 2003), ρ_{atm} is the density of the atmosphere, and μ is the dynamic viscosity of the atmosphere.

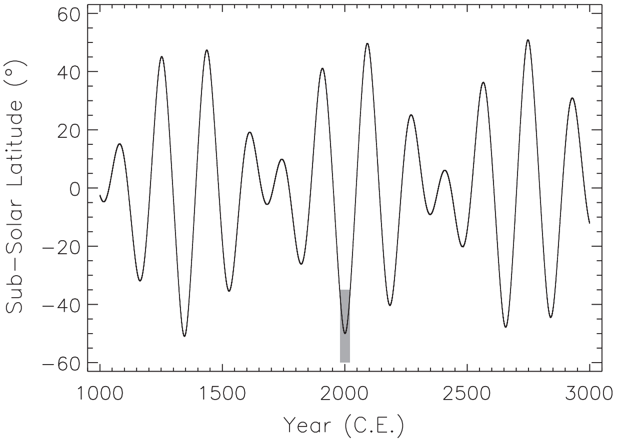


Fig. 1. Sub-solar latitude on Triton between 1000 and 3000 C.E. (data from JPL HORIZONS). The combination of Neptune's obliquity (30°), the inclination of Triton's orbit (20°), and the rapid precession of Triton's orbital node (637 ± 40 years) contribute to Triton's unique seasons (Trafton, 1984). This results in a beat pattern between the precession period and the 165-year orbit of Neptune. The shaded region covers the years 1980–2020 and is presented in more detail in Fig. 2.

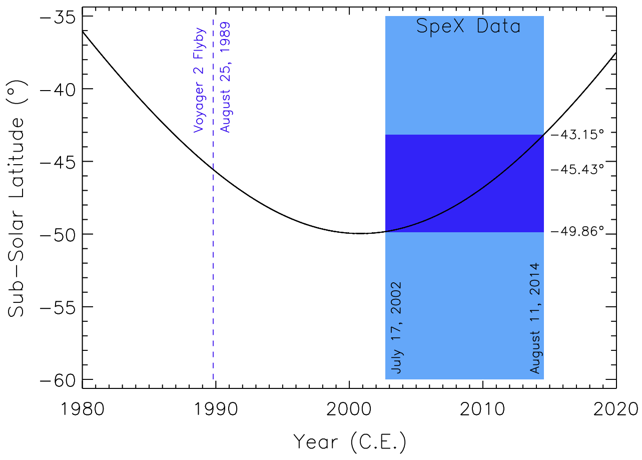


Fig. 2. Sub-solar latitude on Triton between 1980 and 2020 C.E. (data from JPL HORIZONS). The maximum southern excursion of the sub-solar latitude was approximately $-50°$ and occurred in 2000. The Voyager 2 flyby took place when the sub-solar latitude was $-45.43°$. The lighter region denotes the time baseline of the IRTF/SpeX observations analyzed in this paper. The darker region denotes the range of sub-solar latitudes observed. The sub-solar latitude has monotonically increased over the period of our observations.

The number density of the dominant component of Triton's atmosphere, N_2, is 10^{16} cm^{-3} at the surface (Herbert and Sandel, 1991), and we used this to calculate a mass density of 4.65×10^{-7} g cm^{-3}. This value is negligible compared to the density of solid ethane, so it was ignored in the calculation. We calculate the dynamic viscosity using Sutherland's formula (Eq. (2)). This gives a lower limit on the viscosity and therefore an upper limit to the Stokes' velocity since the effects of turbulence and eddies are ignored. The dynamic viscosity (μ) of an N_2 atmosphere at $T = 50$ K (temperature of Triton's troposphere; Tyler et al., 1989) is:

$$\mu = \mu_0 \frac{T_0 + C}{T + C}\left(\frac{T}{T_0}\right)^{3/2}, \tag{2}$$

where T_0 is a reference temperature (300.55 K for N_2), μ_0 is the dynamic viscosity at the reference temperature (0.0002 g cm^{-1} s^{-1} for N_2), and C is Sutherland's constant for the gas in question (111 K for N_2). We calculate $\mu = 0.00003$ g cm^{-1} s^{-1}. Combining all

---

[2] Triton is in a synchronous, retrograde orbit about Neptune. Its rotation is also retrograde with sunrise in the west. The sub-Neptune point is at 0° longitude. The south pole is the current summer pole.