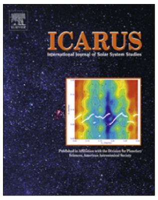
Icarus 231 (2014) 146–167

Contents lists available at ScienceDirect

Icarus

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



Neptune at summer solstice: Zonal mean temperatures from ground-based observations, 2003–2007

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ARTICLE INFO

Article history:
Received 24 September 2013
Revised 20 November 2013
Accepted 21 November 2013
Available online 10 December 2013

Keywords:
Neptune
Atmospheres, composition
Atmospheres, structure

ABSTRACT

Imaging and spectroscopy of Neptune's thermal infrared emission from Keck/LWS (2003), Gemini-N/MICHELLE (2005); VLT/VISIR (2006) and Gemini-S/TReCS (2007) is used to assess seasonal changes in Neptune's zonal mean temperatures between Voyager-2 observations (1989, heliocentric longitude $L_s = 236^\circ$) and southern summer solstice (2005, $L_s = 270^\circ$). Our aim was to analyse imaging and spectroscopy from multiple different sources using a single self-consistent radiative-transfer model to assess the magnitude of seasonal variability. Globally-averaged stratospheric temperatures measured from methane emission tend towards a quasi-isothermal structure (158–164 K) above the 0.1-mbar level, and are found to be consistent with spacecraft observations of AKARI. This remarkable consistency, despite very different observing conditions, suggests that stratospheric temporal variability, if present, is <±5 K at 1 mbar and <±3 K at 0.1 mbar during this solstice period. Conversely, ethane emission is highly variable, with abundance determinations varying by more than a factor of two (from 500 to 1200 ppb at 1 mbar). The retrieved C_2H_6 abundances are extremely sensitive to the details of the $T(p)$ derivation, although the underlying cause of the variable ethane emission remains unidentified. Stratospheric temperatures and ethane are found to be latitudinally uniform away from the south pole (assuming a latitudinally-uniform distribution of stratospheric methane), with no large seasonal hemispheric asymmetries evident at solstice. At low and mid-latitudes, comparisons of synthetic Voyager-era images with solstice-era observations suggest that tropospheric zonal temperatures are unchanged since the Voyager 2 encounter, with cool mid-latitudes and a warm equator and pole. A re-analysis of Voyager/IRIS 25–50 μm mapping of tropospheric temperatures and para-hydrogen disequilibrium (a tracer for vertical motions) suggests a symmetric meridional circulation with cold air rising at mid-latitudes (sub-equilibrium para-H_2 conditions) and warm air sinking at the equator and poles (super-equilibrium para-H_2 conditions). The most significant atmospheric changes have occurred at high southern latitudes, where zonal temperatures retrieved from 2003 images suggest a polar enhancement of 7–8 K above the tropopause, and an increase of 5–6 K throughout the 70–90°S region between 0.1 and 200 mbar. Such a large perturbation, if present in 1989, would have been detectable by Voyager/IRIS in a single scan despite its long-wavelength sensitivity, and we conclude that Neptune's south polar cyclonic vortex increased in strength significantly from Voyager to solstice.

1. Introduction

As the furthest planet from our Sun, Neptune provides an extreme test of our understanding of seasonal processes and atmospheric photochemistry. Neptune's complex meteorology is driven by a balance between its intrinsic luminosity and absorption of sunlight by methane and aerosols in the upper troposphere. Visible and near-infrared imaging of Neptune from Voyager (Smith et al., 1989; Karkoschka, 2011), the Hubble Space Telescope (Sromovsky et al., 1995, 2001; Hammel et al., 1995; Karkoschka and Tomasko, 2011), and ground-based observatories (Roddier et al., 1998; Max et al., 2003; Gibbard et al., 2002, 2003; Luszcz-Cook et al., 2010; Irwin et al., 2011), have shown the planet to be dynamically active

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http://dx.doi.org/10.1016/j.icarus.2013.11.035

despite its large distance from the Sun. Unlike Uranus, with its unusual inclination and negligible internal heat source (e.g., Pearl and Conrath, 1991), Neptune's weather layer exhibits rapidly varying cloud activity, zonal banding, dark ovals and sporadic orographic clouds. Furthermore, the extent of this meteorological activity and the planet's global visible albedo appear to vary with time (Lockwood and Jerzykiewicz, 2006; Hammel and Lockwood, 2007). In this study we attempt to connect this cloud-level activity to changes in Neptune's thermal structure and atmospheric chemistry between Voyager observations (1989) and ground-based observations close to Neptune's 2005 summer solstice.

Spectroscopy and imaging in the thermal infrared is challenging due to Neptune's cold temperatures and small angular size as viewed from Earth. Nevertheless this provides our only method of deducing the atmospheric thermal structure and composition above the cloud tops. Mid-infrared wavelengths are dominated by the collision-induced opacity of H_2 and He, along with the collection of hydrocarbons resulting from a chain of photochemical reactions initiated by UV photolysis of methane (e.g., Orton et al., 1987; Moses et al., 2005). Ethane at 12 μm was first observed by Gillett and Rieke (1977), and together with methane at 7.7 μm dominates the N-band (7–13 μm) spectrum of Neptune (Orton et al., 1992). Photometric imaging or spectroscopy is sensitive to emission from the stratosphere (0.1 mbar) down to the upper troposphere (200 mbar), and the measurement of a broad thermal-IR wavelength range allows us to disentangle the various contributions (temperatures, composition, aerosols) to the upwelling radiance. The latitudinal variability of Neptune's troposphere was first derived from Voyager/IRIS observations in 1989, showing a warm equator, cool mid-latitudes and a moderate increase in emission towards the south pole (Conrath et al., 1989, 1991; Bézard et al., 1991). This pattern of emission qualitatively supports a residual-mean circulation of upwelling and adiabatic cooling at mid-latitudes (consistent with near-IR imaging showing cloud activity concentrated at southern mid-latitudes), with subsidence at the equator and south pole (Conrath et al., 1991, 1998).

Voyager/IRIS lacked the mid-IR sensitivity to study Neptune's hydrocarbon emission, which was later used by space-based observatories to determine the disc-averaged stratospheric properties from the Infrared Space Observatory (ISO, Bézard et al., 1999; Schulz et al., 1999; Fouchet et al., 2003), Spitzer Space Telescope (Meadows et al., 2008) and ISAS/JAXA's AKARI infrared astronomy satellite (Fletcher et al., 2010). Burgdorf et al. (2003) combined Neptune's far-IR spectrum from ISO (28–145 μm) with ground-based observations between 17 and 24 μm (Orton et al., 1987, 1990) to study Neptune's disc-averaged tropospheric temperatures. Significantly larger primary mirrors are required to move beyond the disc-average to spatially-resolved imaging, such that the latitudinal and temporal variation of Neptune's tropospheric and stratospheric temperatures can be observed. In this study we attempt a synthesis of ground-based mid-IR observations from 8 to 10-m class telescopes over a five-year period surrounding Neptune's southern summer solstice (2005). This will be compared to new atmospheric models for Voyager/IRIS results in 1989 and AKARI results in 2007. The results will be used to search for spatial and temporal variations in Neptune's temperatures and composition between 1989 and 2007.

This paper is organised into three broad sections, starting with the development of self-consistent stratospheric temperature profiles and ethane abundances (both disc-integrated and latitudinally-resolved) for Keck, AKARI and Gemini observations of Neptune's 7–13 μm emission between 2003 and 2007 (Section 3). Stratospheric temperatures are then incorporated into new models for Neptune's tropospheric temperature and para-hydrogen structure from fitting Voyager/IRIS data from 1989 (Section 4), and comparing this with new ground-based observations of Neptune's 17–25 μm emission in 2003. Finally, the meridional temperature structure is used to generate synthetic images in Section 5 to compare with photometric imaging from 2003 to 2007 from Keck (de Pater et al., in preparation, 2013), Gemini-North (Hammel et al., 2007), VLT (Orton et al., 2007) and Gemini-South (Orton et al., 2012) to assess thermal variability since the Voyager encounters. A solstice-era latitudinal temperature structure will be derived from these ground-based images, and the end product will be a consistent survey of Neptunian temperatures from the time of Voyager to the epoch surrounding the summer solstice.

2. Radiative transfer modelling

A flexible radiative-transfer and retrieval algorithm is required to analyse multiple sources of thermal-IR Neptune observations using a single, consistent model. The NEMESIS software suite (Irwin et al., 2008) offers an optimal estimation retrieval architecture (Rodgers, 2000) for the inversion of remote sensing data to deduce atmospheric profiles, whilst allowing the user to pre-compute ranked tables of absorption coefficients (*k*-distributions, Lacis and Oinas, 1991) in a manner specific to individual instruments. In this study, we pre-calculate *k*-distributions for all of the infrared imaging filters used on Keck, Gemini and VLT (see Section 5), and for the spectral resolutions provided by the Voyager, Keck and Gemini spectroscopy. Despite instrumental differences, the *a priori* atmospheric state and the optimal estimation technique remain identical, allowing a robust comparison between rather different data sources. Furthermore, by using the correlated-*k* method for the calculation of spectra, NEMESIS allows rapid inversion of observations to converge on a family of atmospheric models (temperature and composition) consistent with the available data. It should be noted, however, that inversion of thermal-IR spectra remains an inherently degenerate problem (as both atmospheric temperatures and molecular abundances contribute to the emission spectrum), and these caveats will be discussed in the following sections.

The *a priori* atmospheric state provides a starting point for the retrieval process, preventing over-fitting and the occurrence of non-physical oscillations in the vertical atmospheric profiles. Here we utilise the stratospheric $T(p)$ profile from analysis of AKARI observations of Neptune (Fletcher et al., 2010) as a starting point, with tropospheric temperatures based on a combination (Moses et al., 2005) of Voyager radio science observations (Lindal, 1992) and ground-based 17–24 μm spectroscopy in the 1980s (Orton et al., 1987, 1990). Temperature and the fraction of ortho-to-para hydrogen were defined on 100 levels, equally spaced in $\log(p)$. Fletcher et al. (2010) demonstrated the extreme degeneracy between the stratospheric $T(p)$ and the assumed CH_4 mole fraction above the tropopause ($(0.9 \pm 0.3) \times 10^{-3}$ at 50 mbar, Fletcher et al., 2010), which was poorly known at the time. Subsequent analysis of Herschel sub-millimetre observations of methane rotational lines (Lellouch et al., 2010) found a best-fitting CH_4 abundance of 1.5×10^{-3}. Following Greathouse et al. (2011), we adopt the Herschel-derived CH_4 abundance for the stratosphere. The deep mole fraction was set globally to 2.2% (determined from a combination of Voyager/RSS radio occultations and ground-based measurements of the H_2 quadrupole lines, Baines and Hammel, 1994), decreasing towards the tropopause following a saturation with 100% relative humidity, and then rising above the tropopause to a stratospheric value of 1.5×10^{-3} at 40 mbar. However, note that the stratospheric spectra considered here are insensitive to the choice of tropospheric methane humidity and the deep mole fraction, which could rise to as high as 4.0% at low latitudes (equivalent to a globally-averaged value of 3.4%, Karkoschka and Tomasko, 2011). At the highest altitudes, the methane abundance decreases due to both diffusive processes and photochemical