Icarus 237 (2014) 211–238

Contents lists available at ScienceDirect

Icarus

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

Neptune's global circulation deduced from multi-wavelength observations

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ARTICLE INFO

Article history:
Received 23 October 2013
Revised 15 February 2014
Accepted 26 February 2014
Available online 13 March 2014

Keywords:
Neptune, atmosphere
Infrared observations
Radio observations

ABSTRACT

We observed Neptune between June and October 2003 at near- and mid-infrared wavelengths with the 10-m W.M. Keck II and I telescopes, respectively; and at radio wavelengths with the Very Large Array. Images were obtained at near-infrared wavelengths with NIRC2 coupled to the adaptive optics system in both broad- and narrow-band filters between 1.2 and 2.2 μm. In the mid-infrared we imaged Neptune at wavelengths between 8 and 22 μm, and obtained slit-resolved spectra at 8—13 μm and 18—22 μm. At radio wavelengths we mapped the planet in discrete filters between 0.7 and 6 cm.

We analyzed each dataset separately with a radiative-transfer program that is optimized for that particular wavelength regime. At southern midlatitudes the atmosphere appears to be cooler at mid-infrared wavelengths than anywhere else on the planet. We interpret this to be caused by adiabatic cooling due to air rising at midlatitudes at all longitudes from the upper troposphere up to $\lesssim$0.1 mbar levels. At near-infrared wavelengths we find two distinct cloud layers at these latitudes: a relatively deep layer of clouds (presumably methane) in the troposphere at pressure levels $P \sim 300$–$\gtrsim$600 mbar, which we suggest to be caused by the large-scale upwelling and its accompanying adiabatic cooling and condensation of methane; and a higher, spatially intermittent, layer of clouds in the stratosphere at 20–30 mbar. The latitudes of these high clouds encompass an anticyclonic band of zonal flow, which suggests that they may be due to strong, but localized, vertical upwellings associated with local anticyclones, rather than plumes in convective (i.e., cyclonic) storms. Clouds at northern midlatitudes are located at the highest altitudes in the atmosphere, near 10 mbar.

Neptune's south pole is considerably enhanced in brightness at both mid-infrared and radio wavelengths, i.e., from $\sim$0.1 mbar levels in the stratosphere down to tens of bars in the troposphere. We interpret this to be due to subsiding motions from the stratosphere all the way down to the deep troposphere. The enhanced brightness observed at mid-infrared wavelengths is interpreted to be due to adiabatic heating by compression in the stratosphere, and the enhanced brightness temperature at radio wavelengths reveals that the subsiding air over the pole is very dry; the relative humidity of H_2S over the pole is only 5% at altitudes above the NH_4SH cloud at $\sim$40 bar. The low humidity region extends from the south pole down to latitudes of 66°S. This is near the same latitudes as the south polar prograde jet signifying the boundary of the polar vortex. We suggest that the South Polar Features (SPFs) at latitudes of 60–70° are convective storms, produced by baroclinic instabilities expected to be produced at latitudes near the south polar prograde jet.

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http://dx.doi.org/10.1016/j.icarus.2014.02.030
0019-1035/

Taken together, our data suggest a global circulation pattern where air is rising above southern and northern midlatitudes, from the troposphere up well into the stratosphere, and subsidence of dry air over the pole and equator from the stratosphere down into the troposphere. We suggest that this pattern extends all the way from $\lesssim$0.1 mbar down to pressures of $\gtrsim$40 bar.

1. Introduction

After its discovery in 1846 by J.G. Galle, physical studies of the planet Neptune were limited due to the planet's extreme distance and thus small angular size (diameter of order 2.3″). It was evident early on from ground-based photometry and images that Neptune was an extremely dynamic planet (Hammel, 1989 and references therein). Our understanding got a tremendous boost with the Voyager flyby in 1989, when the first highly detailed images were returned to Earth (Smith et al., 1989). These images revealed a Great Dark Spot (GDS) on Neptune at a latitude of ~20°S, a smaller dark spot (DS2) at ~55°S, a bright compact feature near 42°S (Scooter), and a bright feature at ~71°S, dubbed a South Polar Feature (SPF). A bright cloud feature seen in groundbased near-infrared (NIR) data was identified as a collection of companion clouds to the GDS. With the launch of the Hubble Space Telescope (HST), scientists were able to continue observing Neptune at a relatively high angular resolution (e.g., Sromovsky et al., 1995, 2001a,b, 2003; Hammel et al., 1995; Hammel and Lockwood, 1997). A highlight of these observations was the disappearance of the GDS. With the advent of adaptive optics (AO), Neptune could be observed from the ground at NIR wavelengths at angular resolutions that rival the Hubble data (e.g., Roddier et al., 1998; Max et al., 2003; Gibbard et al., 2002, 2003; de Pater et al., 2005a; Luszcz-Cook et al., 2010; Irwin et al., 2011; Martin et al., 2012). In these images Neptune is characterized as a planet with very bright circumferential bands at both southern and northern midlatitudes, as well as occasionally an extremely bright SPF. The latitudinal bands of clouds consist of individual small elongated cloud features.

While Neptune is detected in reflected sunlight at visible and NIR wavelengths, the thermal emission from its troposphere and stratosphere can be studied in both the mid-infrared (MIR) and the radio spectrum. Voyager observations in the MIR revealed the planet's large internal heat source: Neptune emits a thermal flux about 2.6 times larger than the mean solar flux absorbed by its atmosphere (Pearl and Conrath, 1991). Such a high heat flow would naturally predict a highly dynamic atmosphere, as observed. Voyager IRIS data at 200–450 cm^{-1} (22—50 μm) and at 729 cm^{-1} (13.7 μm) further revealed latitudinal variations in brightness, with maxima near the equator and at the south pole, and a minimum at southern midlatitudes. Conrath et al. (1991) and Bézard et al. (1991) inferred from this pattern a meridional circulation of upwelling at southern midlatitudes and subsidence at low (near the equator) and high latitudes.

The first radio astronomical detection was made in 1966 by Kellermann and Pauliny-Toth (1966) at 1.9 cm; in subsequent decades the planet's disk-averaged radio spectrum at mm–cm wavelengths was measured. Even though the early observations had relatively large uncertainties, it became clear that Neptune, like Uranus, was much warmer than expected for a solar-composition atmosphere. Since the microwave absorption by ammonia gas dominates the opacity in a solar-composition atmosphere, the observations could only be explained if, somehow, the atmosphere were substantially depleted in NH_3 gas. This could be brought about if the H_2S abundance on Neptune were larger than that of NH_3, in which case the formation of NH_4SH would effectively eliminate ammonia gas from Neptune's troposphere, enabling one to probe deeper warmer layers in the planet's atmosphere (e.g., Gulkis et al., 1978; Lewis and Prinn, 1980; de Pater and Richmond, 1989). Good fits to the data are obtained if H_2S gas is enhanced by a factor of ~30–60 above the protosolar S/H abundance,[1] while NH_3 in Neptune's deep atmosphere should not exceed the solar N value (de Pater et al., 1991; deBoer and Steffes, 1996). Higher abundances of H_2S push the NH_4SH cloud deeper into the atmosphere, and increase the line-of-sight microwave opacity due to H_2S.

In order to further investigate Neptune's global circulation and potential changes therein, we observed the planet in 2003 at NIR and MIR wavelengths with the 10-m W.M. Keck telescopes in Hawaii, and at radio wavelengths with the Very Large Array (VLA) in New Mexico. Our goal was to observe the planet at high spatial resolution in all three wavelength regimes at roughly the same time to deduce Neptune's global circulation pattern from the deep troposphere upwards, well into the stratosphere. For practical reasons, the data were taken over a time period of a few months, i.e., short compared to Neptune's orbital period (164 years). Although individual cloud features observed at NIR wavelengths do change over this period, the general circulation will not.

Preliminary reports of our datasets have been presented by Martin et al. (2008); no quantitative analysis was presented, however. Some of the NIR observations were published by de Pater et al. (2005a) in a paper focused on Neptune's rings; the planet's atmosphere was not discussed at that time. In this paper we present the full data sets along with analyses; the analysis of the MIR dataset, however, was presented by Fletcher et al. (2014), and we only present a summary of their findings in this paper. In Section 2 we present all three data sets (NIR, MIR and radio). Separate analyses of each data set are presented in Sections 3–5. An overall synthesis, tying the data sets together is provided in Section 6, with a summary of our conclusions in Section 7.

2. Observations and data reduction

Over a 4-month period in 2003, from June to October, we observed Neptune at NIR, MIR and radio wavelengths. The observations are summarized in Table 1, ordered in wavelength from short to long.

2.1. Near-infrared observations

NIR observations were taken UT October 3–6, 2003 using the Near Infrared Camera 2 (NIRC2) coupled to the adaptive optics (AO) system at the W.M. Keck II telescope in Mauna Kea, Hawaii (Wizinowich et al., 2000). NIRC2 has a 1024 × 1024 Aladdin-3 InSb array detector, which we used in its high angular resolution mode, i.e., the NARROW camera at 9.94 ± 0.03 mas per pixel (de Pater et al., 2006), which corresponds to 213 km at Neptune's distance during our observations. On all 4 days, we observed Neptune in the J, H and K′ bands; on October 4, 5 and 6 we observed the planet also with several narrow-band filters, as summarized in Table 2. de Pater et al. (2005a) report a Strehl ratio SR = 0.5 at K′ band, and SR = 0.3—0.4 at H. Strehl ratios in the narrow-band

[1] We use the protosolar elemental ratios for C, N, O, and S from Asplund et al. (2009): C/H_2 = 5.90E−4; N/H_2 = 1.48E−4; O/H_2 = 1.07E−3; S/H_2 = 2.89E−5.