Flight through Titan’s Atmosphere

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Abstract

We assembled spectral image datacubes of Titan in H-band (1.413-1.808 μm), using adaptive optics on the 10-m W.M. Keck telescope, by stepping a spectrometer slit across Titan’s disk. We constructed images of Titan at each wavelength by ‘glueing’ the spectra together, producing 1400ultra-narrowband (~0.1nm) views of the satellite. With this method one can characterise Titan’s atmosphere over the entire disk, in more specific vertical detail than possible with either narrowband imaging or slit spectroscopy at one position. Data were obtained of Titan’s leading hemisphere on UT 20 February 2001. At the shorter wavelengths we probe all the way down to the surface, revealing the familiar bright and dark terrain, while at longer wavelengths we probe various altitudes in the atmosphere. The data have been assembled into a movie, showing the surface and different haze layers while stepping up in altitude. The transitions from the surface to the tropospheric haze, and through the tropopause into the upper atmospheric haze, are clearly recognised.

1 Introduction

Titan, Saturn’s largest satellite, was discovered in 1655 by Christiaan Huygens, using a telescope that he and his brother Constantijn had just completed building. During the time of discovery Saturn’s rings were nearly edge-on, which most likely helped in the discovery since light from Saturn’s rings was greatly reduced during this period. Except for its mere existence, we did not learn much more about this satellite until about 250 years later, when Jose Comas Sola claimed to see limb darkening on Titan, and suggested that the satellite might possess an atmosphere. A clear confirmation that Titan possesses an atmosphere came in the mid-1940s, when Gerard Kuiper reported the discovery of methane absorption bands in the satellite’s spectrum. In these observations, as well as the ones we report on below (section 2), Titan is visible because sunlight is reflected back from it. At particular wavelengths, sunlight is absorbed by methane gas in Titan’s atmosphere, so that at these wavelengths the satellite looks very dark.

In the 1970s, in anticipation of the Voyager encounters in 1980 and1981, Titan was observed at wavelengths across the electromagnetic spectrum from the UV well into the radio, and at the same time models of its atmosphere were developed. The fact that only methane gas had been detected on the satellite naturally led to a class of models in which methane gas was the main constituent of the atmosphere [7,3]. Lewis [16], however, suggested that Titan's atmosphere might be rich in nitrogen due to photolysis of ammonia gas, which he expected to be present in Titan's atmosphere, in (vapour-pressure) equilibrium with ammonia-ice (pure or as a hydrate - $NH_3.H_2O$) on Titan's surface. Donald Hunten [13] developed this idea into a model atmosphere dominated by nitrogen gas. Surface pressures on the satellite in these different classes of models ranged from ~20 mbar for methane-dominated atmospheres, up to 20 bar for a Titan dominated by nitrogen gas. The first Voyager spacecraft flew by Titan in 1980, when it was springtime on the satellite's northern hemisphere. Unfortunately, the surface was not revealed because Titan is enveloped by a thick, orange-brown, smog layer, composed of condensed photochemically produced hydrocarbons. It was confirmed, though, that Titan's atmosphere is dominated by nitrogen gas, and radio occultation experiments revealed a surface pressure of 1.5 bar. Titan thus appeared to be similar to early Earth, before our planet became rich in biogenically-produced oxygen.

Images of Titan recorded by the Voyager spacecraft revealed that the northern hemisphere was covered by more stratospheric haze than the south, and the N. polar hood was a prominent feature. In the 1990s, with the launch of the Hubble Space Telescope and the development of speckle imaging and adaptive optics techniques on ground-based telescopes, spatially resolved images of Titan were obtained from the ground and Earth-orbit. These images showed the excess haze over Titan's northern hemisphere had, somehow, moved to the south when it became winter in the southern hemisphere. This apparent seasonal migration from the spring/summer pole to the winter hemisphere has now been observed at many different wavelengths during the past decade. Most interesting, however, is that this so called reversal of the North-South asymmetry clearly lagged behind at certain wavelengths compared to others. Since one is sensitive to different altitudes at different wavelengths, the collection of data could be used to derive the 3-dimensional response of Titan's atmosphere to the annual variations in insulation. The data reveal that the atmosphere responds more readily to seasonal forcing at the highest altitudes, while the seasons lag behind more significantly at lower altitudes. Rannou and collaborators [21] developed an atmospheric model that couples haze formation to atmospheric transport. The circulation in this model is dominated by a summer-to-winter-pole cell, where air flows from the summer pole to the winter pole. Haze particles are photochemically produced at high altitudes (~400-600 km), and 'blown' to the winter pole, where they accumulate to form a polar hood. Here the particles slowly sediment out, while growing in size; a return flow takes place at lower altitudes. This model can indeed explain most of the observations.

Since the surface had not been observed by Voyager, speculations about what it might look like ranged from a regular surface composed of a mixture of rock and ice, up to a body completely covered by liquid hydrocarbons. Lunine and collaborators [19] showed that methane could persist in Titan's atmosphere for only ~10^7 years, i.e., much shorter than the age of our Solar System, unless it were recycled back into the atmosphere. Since the temperature and pressure on Titan's surface are such that many hydrocarbons, including methane, would probably be present in liquid form, they suggested the satellite might contain liquid hydrocarbons, which would supply methane gas to the atmosphere, in a sense analogous to the water cycle on Earth. Soon after the Voyager encounters, it was realised that the surface could actually be probed at infrared wavelengths, since the photochemical smog on Titan, while being opaque at visible wavelengths, is transparent at longer infrared wavelengths. As long as observations were conducted away from the methane absorption bands, the surface could be seen. Over the years quite detailed surface maps of the satellite were obtained. An example of one such map is given in Figure 1.

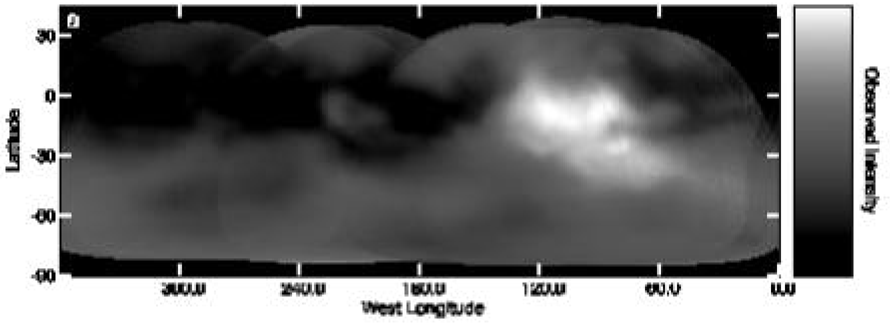

Figure 1: A surface map of Titan at 1.6 mm, constructed from Keck adaptive optics data (from: Roe et al. 2004).

On the leading hemisphere (that is, leading in Titan's orbit around Saturn) is a bright region, composed in part of exposed water-ice [6,8,12], which is suggestive of an elevated continent, perhaps washed clean of hydrocarbon residues by runoff [10,14]. The dark areas on Titan's surface maps have reflectivities close to zero, and hence may represent hydrocarbon oceans. This notion has been strengthened by recent Arecibo radar[4]observations of Titan's surface, which reveal specular reflections (a sharply-defined beam, as if incident radiation is reflected from a mirror) consistent with those expected from areas covered by liquid hydrocarbons.

Ever since the discovery of methane in Titan's atmosphere, the existence or absence of methane clouds has been debated. Some studies indicated a supersaturation of methane gas in Titan's troposphere, indicative of stagnant air without clouds [5,24], while others advocated a methane cycle analogous to Earth's hydrological cycle [26] that would form clouds. In the mid-1990s, Griffith and collaborators [10] presented the first evidence of clouds in Titan's troposphere through an analysis of disk-averaged spectra. In December 2001 we used the 10-m Keck telescope, equipped with adaptive optics, to image Titan and search for clouds at wavelengths which were sensitive only to Titan's troposphere, i.e., the lower atmosphere where clouds are expected to form. To our delight, clouds were seen, but to our surprise they were only present above Titan's south pole [2,22] (Figure 2).

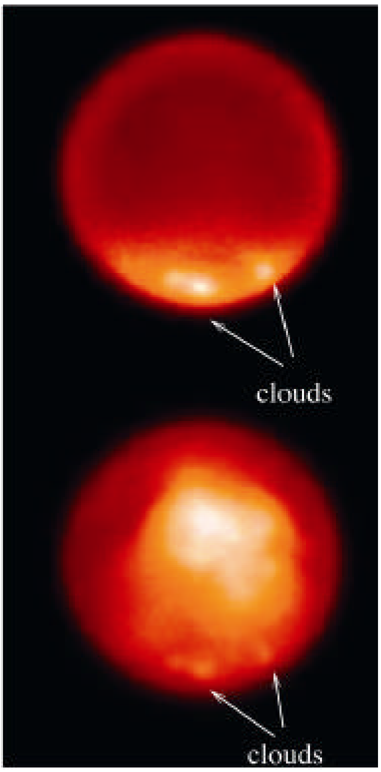

Figure 2: Clouds on Titan observed on 21 December 2001 (UT) with adaptive optics on the Keck telescope.

Top: Narrow-band filter centred at 2.108 mm, which probes just Titan's troposphere. At least 3 clouds and the tropopause haze near Titan's S. pole are visible.

Bottom: Broadband K' filter, centred near 2.2 mm, which probes both the surface and atmosphere. (Adapted from: Roe et al. 2002)

Some of us suggested that perhaps the surface temperature at the pole is high enough during the summer for convection to be triggered, and/or that fall-out of condensates from Titan's stratosphere, properly coated by ethane, provides condensation nuclei for methane clouds to form.

2 Spatially-resolved Image Datacubes

Titan's near-infrared spectrum senses?? a range of altitudes, from ~150 km down to the surface. With this in mind, we assembled spectral image datacubes of Titan in H-band (1.413-1.808 µm) using adaptive optics with spectroscopy (NIRSPAO) on the 10-m Keck telescope, by stepping the spectrometer slit across Titan's disk. (For full details on the observations, please see [1].) A nice visual explanation of this technique can be found on the VIMS (Visual and Infrared Mapping Spectrometer on the Cassini spacecraft) website:

http://vims.lpl.arizona.edu/howitworx/Howitworks.html
This link is not working!!.

The observations were carried out on the night of 20 February 2001 UT. The slit dimensions used were 3.96? x 0.076?, with a spatial resolution along the slit of about 0.05? (Titan is about 0.8? across). Simultaneously with the slit spectroscopy, images of Titan were recorded with the infrared camera (SCAMon NIRSPEC). A series of Titan images with the spectrometer slit is shown in Figure 3.

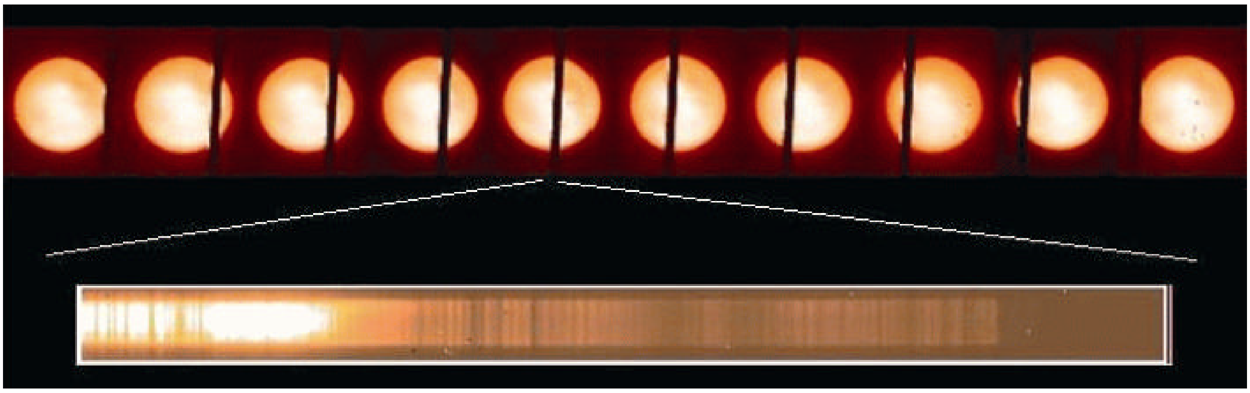

Figure 3: A series of infrared (SCAM) images of Titan taken on 20 Feb. 2001(UT) with adaptive optics on the Keck telescope, while data were obtained through the spectrometer slit (shown in each image) to construct the images shown in Figure 4 and Figure 5. One of the spectra obtained through the slit is shown as well

We then combined all spectra to construct images of Titan at each wavelength. This way we produced 1400 ultra-narrowband (~0.1 nm) views of the satellite, which were combined into a movie that can be viewed on:

http://astron.berkeley.edu/~imke/Infrared/Titan/Titanmovie.htm

Figure 4 shows the first frame of the movie on the website.

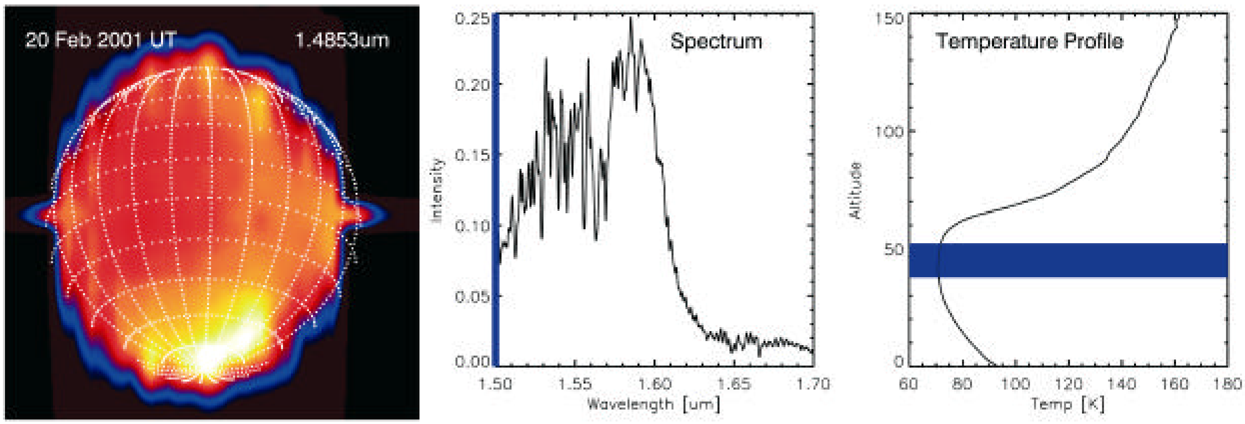

Figure 4: The first frame of the Titan movie.
The left frame shows an image of Titan's tropopause haze; the middle frame shows the spectrum (at the centre of the disk), and the right frame shows the temperature-pressure profile of Titan's atmosphere. The blue bars show, for the image on the left, at which wavelength the image was taken (centre frame; 1.42 µm) and where in the atmosphere it is probing (right frame; near tropopause).

We used a radiative transfer model to interpret Titan spectra at different positions on the disk. From these calculations we derive the altitudes in Titan's atmosphere that primarily contribute to the flux of each image. The blue bars in Figure 4 show at which wavelength (centre frame; 1.42 µm) the image on the left was taken and where in the atmosphere we probe (right frame; near tropopause). In the movie, one can see how Titan's image is changing while stepping though the spectrum/atmosphere. We note that each frame was scaled individually relative to its highest intensity, so that the large variation in intensity across the wavelength band (e.g., 0.25 → 0.01 on centre frame in Figure 4) is not noticeable in the movie.

In Figure 5 we show a subset of images from the movie.

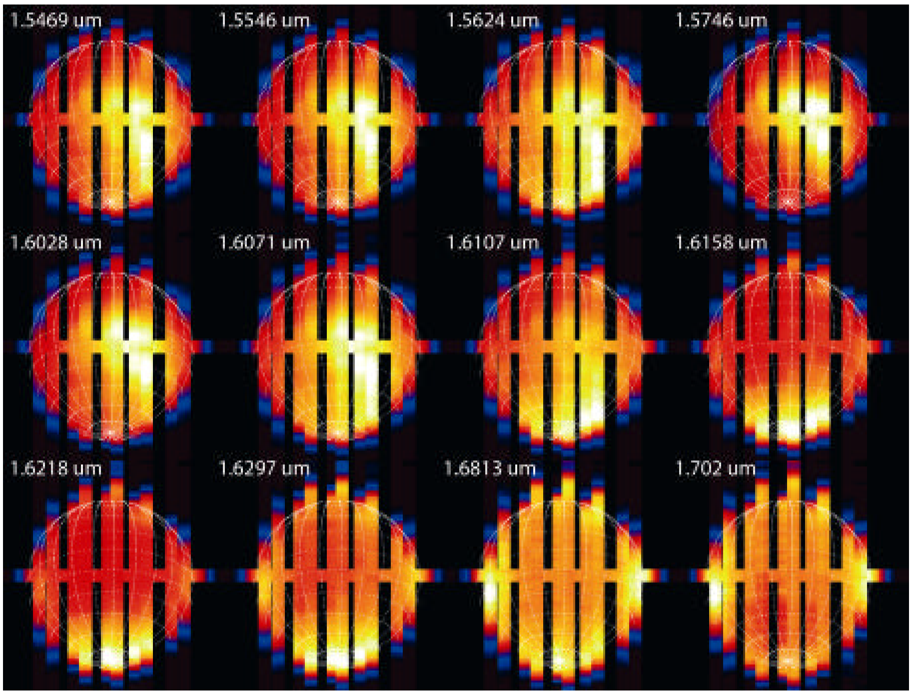

Figure 5: Spectral image maps of Titan, constructed from data obtained with adaptive optics on the Keck telescope on 20 Feb. 2001 (UT). These images were constructed from spectra through the slits indicated in Figure 3. The sub-observer point is 111° West longitude, and 23° South latitude. The wavelength is indicated in the upper left of each image.(from [1]).

The first row of images is from 1.55-1.57 µm, where methane absorption is weak, and we probe Titan's surface. However, even within this 20 nm wide window, there are wavelengths (e.g. 1.5546 and 1.5624 µm) where we see a contribution from haze particles in Titan's atmosphere near the southern pole. The dominant surface feature is the 'bright continent' located at ~100° W (see Figure 1). The middle row of images in Figure 5 show that as methane opacity increases with wavelength, flux from higher altitudes in the atmosphere is observed. At 1.6028 µm the surface dominates the signal, whereas at 1.6158 µm flux from a layer of haze near the tropopause, at altitudes between 30 and 50 km, is observed – the same haze as seen in Figure 2a. At intermediate wavelengths a combination of the surface and lower atmosphere contribute to the observed intensity. At wavelengths longer than 1.6158 µm the bright surface feature is no longer visible. Methane absorption here is strong enough to completely attenuate the light from the Sun before it reaches the surface. The observed signal is therefore from photons that are scattered from particulates in the atmosphere. At wavelengths longer than 1.6218 µm (bottom row of Figure 5), we see stratospheric haze, at altitudes between about 50 and 150 km. At these wavelengths the observed intensity is diminished, signal-to-noise decreases, and limb brightening becomes more pronounced. At the highest altitudes we see a N-S asymmetry, as discussed in the introduction, with more haze above the northern hemisphere.

3 Conclusion

With image datacubes as presented above, one can thus characterise Titan's atmosphere over the entire disk in more specific vertical detail than is possible with either narrowband imaging or slit spectroscopy at one position. At these particular wavelengths (1.4 - 1.8 μm), we probe all the way down to the surface at the short wavelengths, revealing the familiar bright and dark terrain, while at longer wavelengths we probe different atmospheric levels. At 1.62 μm we probe just the upper troposphere, while upwards of 1.64 μm we probe different levels in Titan's stratosphere. The transitions from the surface to the tropospheric haze, and through the tropopause into the upper atmospheric haze, are clearly recognised.

This work is a prelude to future observations with integral-field spectrographs, where image datacubes will be obtained directly from the telescope, so that it is no longer necessary to step a slit across the disk and painfully 'glue' the data together afterwards. These new detectors will come on-line on Keck and the VLT in 2005, which will make it possible to regularly produce image data-cubes to monitor seasonal variations in the 3-dimensional spatial distribution of hazes and clouds. Such information is necessary to test models that couple circulation and the photochemical formation of aerosols on Titan (as discussed in the introduction). Continued ground-based observation during and after the Cassini era is crucial to obtain a dynamical understanding of Titan's atmosphere, even with the detailed measurements expected from the Cassini spacecraft and Huygens probe. Since integral-field spectrographs are state-of-the-art instruments, the visual and near-infrared spectrographs on the Cassini spacecraft still consist of a slit, and hence spectral images with VIMS will be obtained by stepping their slit across Titan's disk, in the same way we constructed the Keck images shown in this paper.

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References

[1] Ádámkovics, M., I. de Pater, H. Roe, S. Gibbard, and C. Griffith, 2004. Spatially-resolved spectroscopy at 1.6μm of Titan's atmosphere and surface. Geophys. Res. Lett. **31**, L17S05, doi:10.1029/2004GL019929.

[2] Brown, M.J., A.H. Bouchez, and C.A. Griffith, 2002. Direct detection of variable tropospheric clouds near Titan's south pole. Nature **420**, 795-797.

[3] Caldwell, J., 1977. Thermal radiation from Titan's atmosphere. In Planetary Satellites. Ed. J.A. Burns (Tucson, Univ. of Arizona Press), pp. 438-450.

[4] Campbell, D.B., G.J. Black, L.M. Carter, and S. Ostro, 2003.Radar Evidence for Liquid Surfaces on Titan. Science **302**, 431-434.

[5] Courtin, R., D. Gautier, and C. McKay, 1995. Titan's thermal emission spectrum: reanalysis of the Voyager infrared measurements. Icarus **114**, 144-162.

[6] Coustenis, A., E. Lellouch,, J.P. Maillard, and C.P. McKay, 1995.Titan's surface: composition and variability from the near-infrared albedo. Icarus **118**, 87-104.

[7] Danielson, R.E., J.J. Caldwell, and D.R. Larach, 1973. An inversion in the atmosphere of Titan. Icarus **20**, 437-443.

[8] Gibbard, S.G., B. Macintosh, D. Gavel, C.E. Max, I. de Pater, A.M. Ghez, E.F. Young, and C.P. McKay, 1999, Titan: High resolution speckle images from the Keck telescope. Icarus **139**, 189-201.

[9] Gibbard, S. G., I. de Pater, B. A. Macintosh, H. G. Roe, C. E. Max,E. F. Young, and C. P. McKay, 2004, Titan's 2 micron surface albedo and haze optical depth in 1996-2004. Geophys. Res. Lett.31, L17S02, doi:10.1029/2004GL019803.

[10] Griffith, C.A., T. Owen, and R. Wagener. 1991. Titan's surface and troposphere, investigated with ground-based near-infrared observations. Icarus **93**, 362--378.

[11] Griffith, C.A., T. Owen, G.A. Miller, and T. Geballe, 1998. Transient clouds in Titan's lower atmosphere. Nature **395**, 575-578.

[12] Griffith, C. A., T. Owen, T.R. Geballe, J. Rayner, P. Rannou, 2003. Evidence for the Exposure of Water Ice on Titan's Surface. Science **300**, 628-630.

[13] Hunten, D.M., 1978. A Titan atmosphere with a surface temperature of 200K. In the Saturn System, eds. D.M. Hunten and D. Morrison (Washington, NASA Conf. publ. **2068**). pp. 127-140.

[14] Kuiper, G.P., 1944. Titan: a Satellite with an Atmosphere. Astrophys. J. **100**, 378-383.

[15] Lemmon, M.T., E. Karkoschka, and M. Tomasko. 1993. Titan's rotation: surface feature observed. Icarus **113**, 27-38.

[16] Lewis, J.S., 1971. Satellites of the outer planets: Their physical and chemical nature. Icarus **15**, 174-185.

[17] Lorenz, R.D., 1993. The life, death and afterlife of a raindrop on Titan. Planetary and Space Science **41**, 647-655

[18] Lorenz, R. D., P. H. Smith, and M. T. Lemmon (2004), Seasonal change in Titan's haze 1992-2002 from Hubble Space Telescope observations. Geophys. Res. Lett. **31**, L10702, doi:10.1029/2004GL019864.

[19] Lunine, J.I. D.J. Stevenson and Y.L. Yung. 1983 Ethane ocean on Titan. Science **222**, 1229--1230.

[20] Meier, R. B.A. Smith, T.C. Owen, and R.J. Terrile, 2000. The surface of Titan from NICMOS observations with the Hubble Space telescope. Icarus **145**, 462-473.

[21] Rannou, P., F. Hourdin, and C.P. McKay, 2002. A wind origin for Titan's haze structure. Nature **418**, 853-856.

[22] Roe, H.G., I. de Pater, B.A. Macintosh, and C.P. McKay, 2002. Titan's clouds from Gemini and Keck adaptive optics imaging. Astrophys. J. **581**, 1399-1406.

[23] Roe, H. G., I. de Pater, S. G. Gibbard, B. A. Macintosh, C. E. Max, E. F. Young, M. E. Brown, and A. H. Bouchez 2004, A new 1.6-micron map of Titan's surface, Geophys. Res. Lett. 31,L17S03, doi:10.1029/2004GL019871.

[24] Samuelson, R.E., N.R. Nath, and A. Borysow, 1997. Gaseous abundances and methane super saturation in Titan's tropopause. Planet. Space Sci. **45**, 959-980.

[25] Smith, P.H., M.T. Lemmon, R.D. Lorenz, L.A. Sormovksy, J.J. Caldwell and M.D. Allison. 1996. Titan's surface, revealed by HST imaging. Icarus **119**, 336-349.

[26] Tyler, G.L., V.R. Eshleman, J.D. Anderson, G.S Levy, G.F. Lndal, G.E. Wood, and T.A. Crofty, 1981. Radio science investigations of the Saturn system with Voyager 1: preliminary results. Science **212**, 201-206.