and to clarify the nature of the absorption feature.

In parallel, the long-term evolution of the optical luminosity of the pulsar has been studied and found to be poorly constrained by the data available so far. Fitting all the available flux measurements as a function of time, we obtain a decrement of 0.008 ± 0.004 mag/yr which is consistent with the expected value of ~ 0.005 mag/yr. However, in view of the error to be attached to the data points, the result is far from conclusive and no claim for a measure of the secular decrease can be put forward at this time. New precise measurements are required to proof the presence of a secular decrease and to quantify its actual value.

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2-Micron Images of Titan by Means of Adaptive Optics

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1. Introduction

In this paper we present spatially resolved images of Titan's surface obtained in September 1994, by means of adaptive optics at the ESO 3.6-metre telescope, in narrow-band filters in the near infrared spectral range, defined in such a way that the contribution of the flux reflected by Titan's ground surface is maximised.

Spatially resolved images of Titan would provide significant clues to understand better the controversial nature of Titan's surface. Imaging Titan is a difficult task due to Titan's small angular diameter as seen from Earth (0.8 arcsec). It must be performed in the near infrared since Titan's surface cannot be observed in the visible range due to a uniform and opaque layer of aerosols in Titan's stratosphere.

During the definition phase of the Cassini-Huygens ESA-NASA mission, T. Encrenaz and M. Combes (DESPA, Paris Observatory) and, independently, M. Tomasko, P. Smith and colleagues (Univ. of Arizona) have shown that there must exist transparency windows in Titan's atmosphere where both the molecular absorption and the scattering extinction are sufficiently faint to allow to probe the Titan's surface. This has been confirmed by several authors who observed photometric or spectroscopic fluctuations of Titan's near infrared flux. The most favourable spectral range is in the near infrared around 2.0, 1.6, 1.28, 1.08 and 0.94 micron.

COME-ON+ is the first adaptive optics system devoted to astronomy. It has been developed for ESO by the Space Research Department (DESPA) of Paris Observatory with the collaboration of French companies (ONERA and LASERDOT).

2. Adaptive Optics

The aim of adaptive optics is to correct in real time the phase perturbations induced by the atmospheric turbulence on the incident wavefront reaching the telescope. These perturbations are measured by a wavefront sensor (Fig. 1) using part of the light of the observed source (if quite stellar-like and sufficiently bright) or of a close star in the isoplanetic field (~30 arcsec). Opposite phase corrections are then applied thanks to a thin deformable mirror in a pupil plan (O. Saint Pé et al., 1993, Icarus 105, 263).

The first spatially resolved image of Titan's disk was obtained, in May 1991, by DESPA (O. Saint-Pé, 1993), demonstrating the feasibility of mapping Titan's

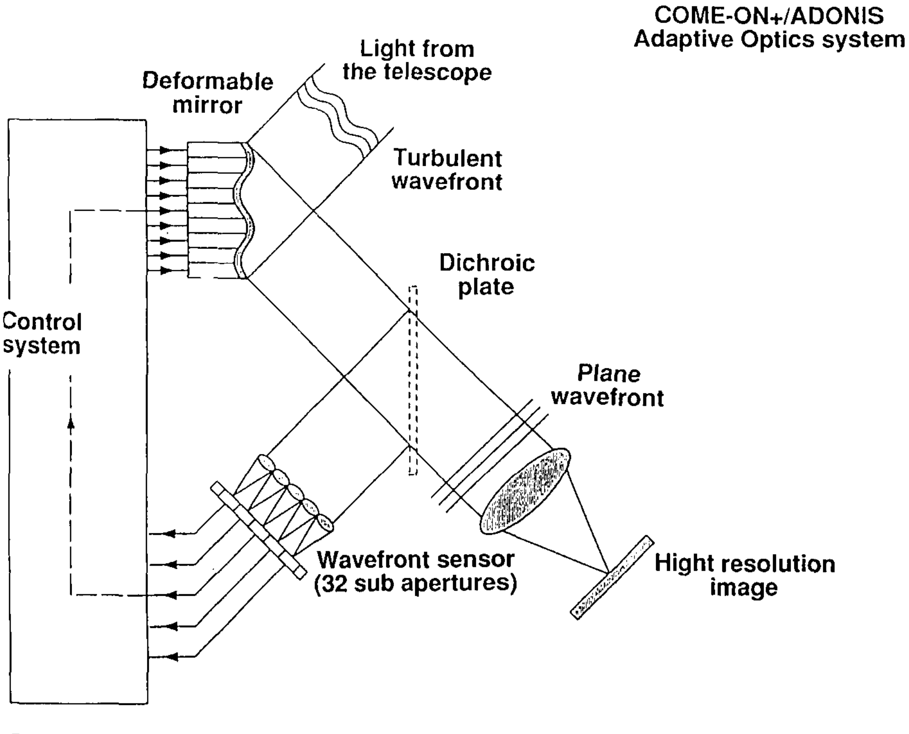

Figure 1: The COME ON+/ADONIS adaptive optics system.

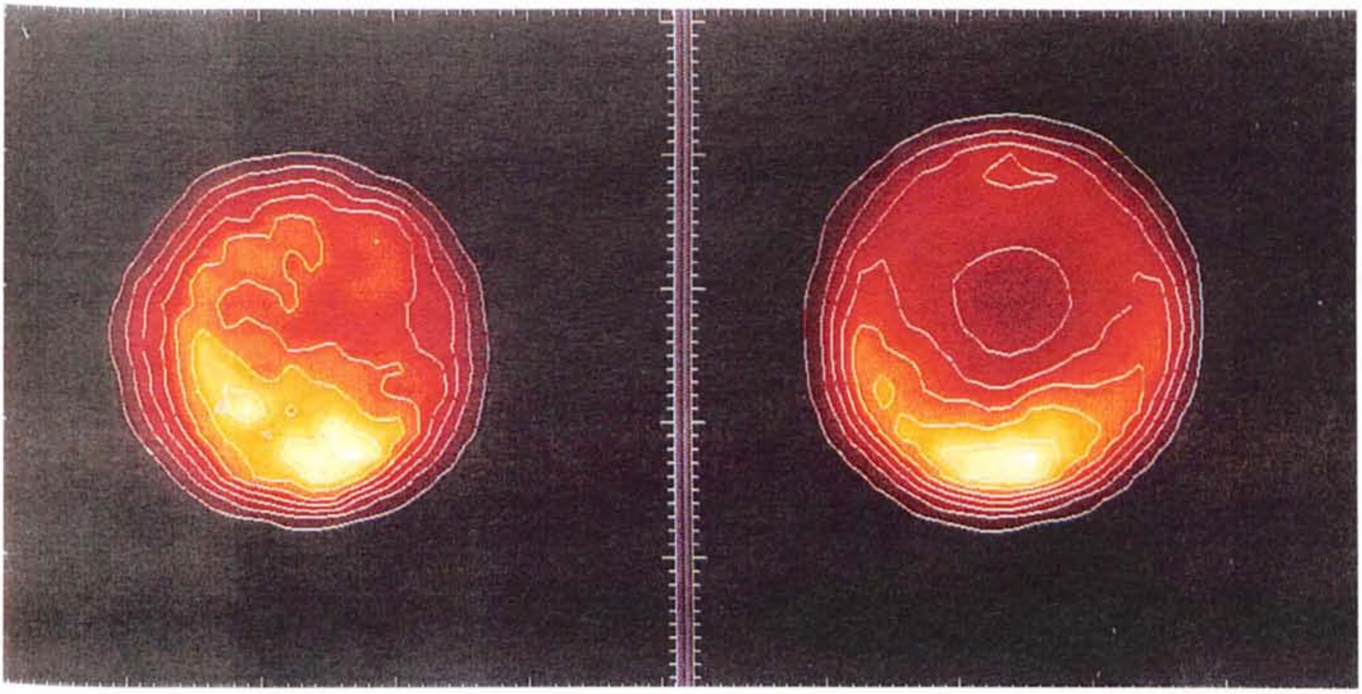

Figure 2: Titan observed in the K1 and K2 narrow-band filters, centred at 2.0 and 2.2 μm, during the night of Sept. 16, 1994. The orbital phase is about 85 degrees LCM (Greatest Eastern Elongation). The images were corrected for flat-field and centre-to-limb effects and deconvoluted by the associated PSF. The images were also oversampled by a factor 3 and then smoothed (with conservation of the recovered spatial resolution – 0.13 arcsec – and have isophot contours). Note the hemispheric asymmetry in the K2 image (more sensitive to the atmospheric contribution than K1), and in particular the bright south limb, probably due to a strong aerosol concentration in this area. The K1 image allows us to sound the deeper atmosphere and the surface. It exhibits an additional bright feature near the equator with respect to K2 images.

surface in the near infrared transparent windows of Titan's atmosphere, in spite of its small angular diameter (0.8 arcsec as seen from Earth) and of degradation effects due to the atmospheric turbulence.

3. Observations and First-Level Data Reduction

Titan was observed in the K1 and K2 narrow-band filters (2.0 and 2.2 μm) during the nights of September 14–18, 1994. The orbital phase is about 85 degrees LCM (Longitude of Central Meridian) on September 16, that is close to Greatest Eastern Elongation.

In K1, one third of the recorded flux is expected to have been reflected by Titan's surface. In K2 the recorded flux is entirely due to backscattering by the stratospheric aerosols. We have deduced the surface contribution in our K1 images by subtracting the stratospheric contribution deduced from the K2 images, according to a weighting factor estimated from the stratospheric transmission in K1 and K2, above the expected level of the aerosols responsible for this stratospheric contribution to the recorded images.

The raw images were corrected for bad pixels and correlated noise, for the sky contribution and for flat-field effects. They are diffraction-limited thanks to the efficiency of the COME-ON+ adaptive optics system. The Point Spread Function is obtained by recording a stellar

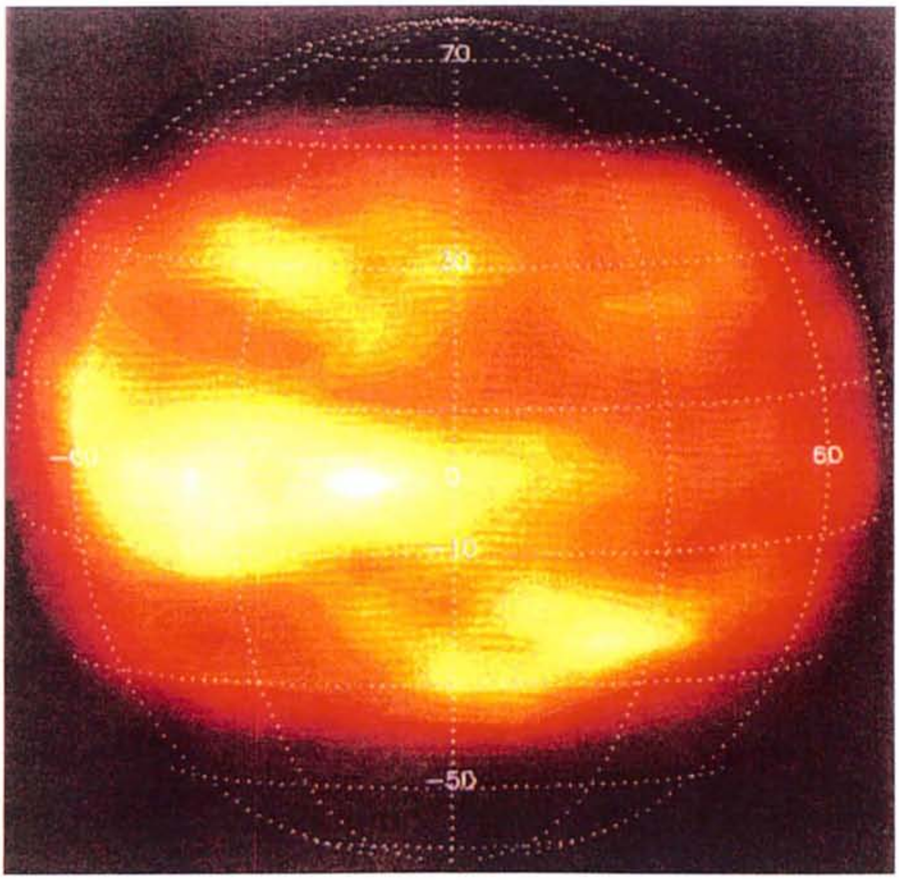

Figure 3: Titan's surface at 2 micron. This image was obtained after subtraction of two thirds of the intensity of the K2 image from the K1 image. This treatment leaves a significant bright equatorial region, centred near 114 degrees LCM and extending over 30 degrees in latitude and 60 degrees in longitude. Other bright spots are visible in the S-W region (near 25° S) and in the northern part (near 30° N).

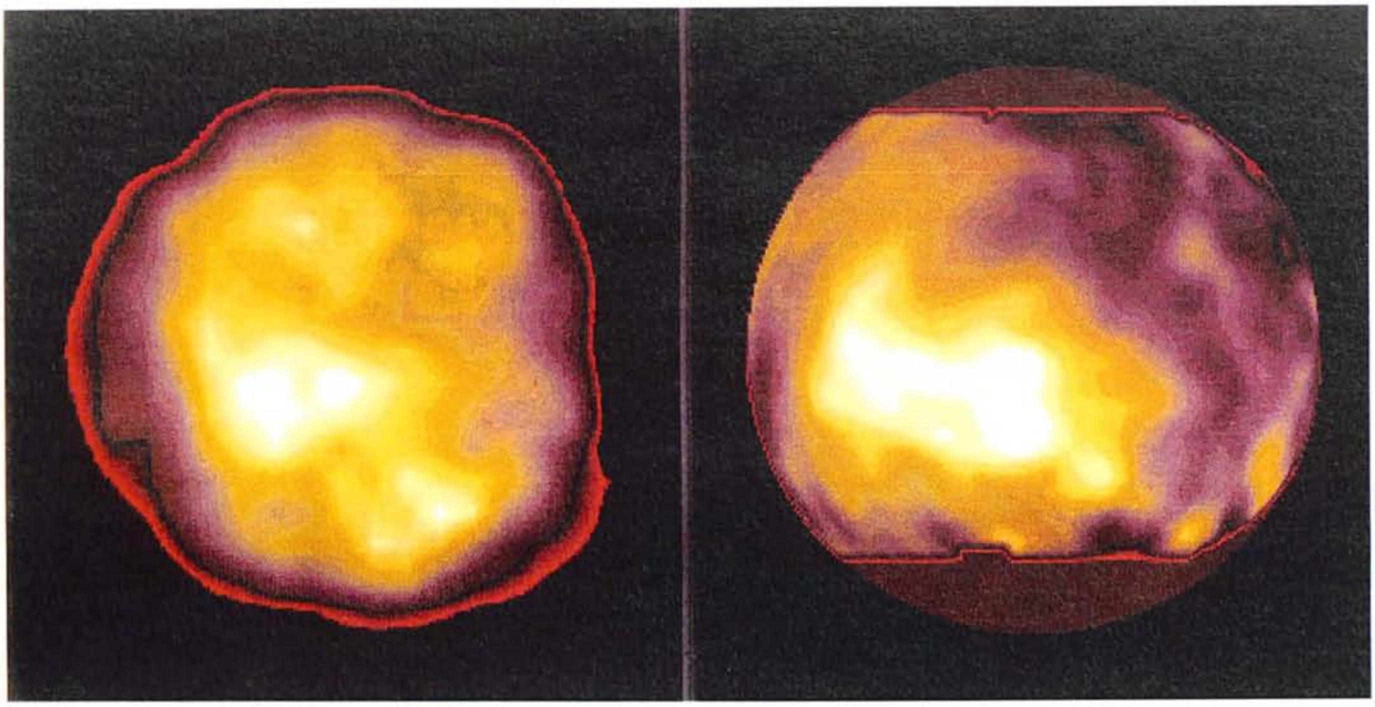

Figure 4: Titan's surface: ADONIS image at 2 micron on the left and Hubble Space Telescope image near 1 micron to the right. The central equatorial bright spot is observed on both, as well as indication of additional features near the limbs. The spatial resolution is similar, the contrast is about 3 times higher in the adaptive optics image.

source in the close vicinity of Titan, in the same filter and with similar exposure time, just after Titan's image recording. A high degree of symmetry could be noticed, showing that the fixed optical aberrations are well corrected by the adaptive optics. The very high signal-to-noise ratio in the PSF allows a very efficient *a posteriori* deconvolution process, using different methods such as Lucy-Richardson, Maximum Entropy and Maximum Likelihood. The final resolution is diffraction-limited (0.13 arcsec) with a sampling of 0.05 arcsec/pixel.

4. Preliminary Analysis and Results

The expected radiance as a function of angle from the centre of the image was modelled using results on the surface albedo and the CH4 absorption coefficients at 2.0 and 2.2 μm from Coustenis et al. (1995, *Icarus* 118, 87–104). The limb effects on each image were then corrected. There is a significant hemispheric asymmetry in the K2 images (more sensitive to the atmospheric contribution than K1), and in particular the southern hemisphere appears brighter than the northern one. After deconvolution, the K2 images show the South limb locally very bright, probably due to a strong aerosol concentration in this area. The K1 images, corresponding to the centre of the 2.0 micron atmospheric window, allow us to sound deeper in the atmosphere and down to the surface and exhibit an additional bright feature near the equator (Fig. 2).

We have deduced the surface contribution in our final images by subtracting K2 images from the K1 ones, as explained in section 3. Our images exhibit a large, well defined equatorial bright spot associated with smaller and fainter features in the southern hemisphere of Titan, all rotating over six consecutive nights at the expected rotation rate of Titan's solid body (Fig. 3).

These findings are in agreement with the Hubble Space Telescope images (Smith et al., 1995, *Icarus*, in press) both on their location and shapes (Fig. 4). As expected from the properties of scattering extinction, the contrast of the surface features is higher in our infrared images (~ 30%) than on HST red images (~ 10%). The spatial resolution (0.13 arcsec) is very similar.

The COME-ON+ Titan images, joined to HST observations, lead to the firm conclusion that the observed features are definitely due to Titan's surface structures. Titan's surface is then inhomogeneous. The model of a global ocean covering Titan must be ruled out. From comparison with 1993 images, under processing, we tentatively infer that large cloud structures are not present in the troposphere.

We have performed a preliminary analysis of 1994 CVF images near 2 micron. At 2.10 μm, in the wing of the H_2O ice band, the absorption by liquid hydrocarbons (C_2H_4, C_2H_6) is expected to be strong. However, the 2.10 μm images are quite similar to K1 images. This does not favour the presence of large (clean) hydrocarbons lakes in the "dark regions".

At 2.00 μm, at the centre of the ices absorption bands (H_20, CO_2, NH_3), a decrease in the contrast between bright and dark regions would be expected if the bright equatorial spot is related to the prominent presence of ices. The 2.00 μm images do not show such a contrast decrease. They are intermediate between K1 images and K2 stratospheric images, suggesting that the surface contribution to the flux is lower than in K1 and that the entire surface of Titan is quite dark in the ices band.

There is no evidence, at the present step of data reduction, for chemical differences between the bright features and their environment.

We have new images recorded using ADONIS in October 1995, near Titan's Western Elongation, that allow us to recover full coverage of the satellite's rotation and should provide more clues for understanding the chemical nature of the bright and dark features. The trailing hemisphere appeared completely dark in the HST images. In our data, however, with a contrast three times higher, we may hope to distinguish new features. The results should provide us with powerful tools for optimising the observing programmes of the instruments of the Cassini-Huygens ESA-NASA mission and in particular of the VIMS instrument on the orbiter and the DISR on the Huygens Probe which both will be able to clearly image Titan's surface.

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