# Chapter 1

# Introduction

## 1.1 Opening remarks

Titan, the largest satellite of Saturn, remains one of the most mysterious objects in our solar system. This is due to its great distance from the Earth, 8.6 astronomical units during a typical opposition, and the dense, hazy atmosphere through which the surface can only dimly be seen. The possible presence of seas of liquid hydrocarbons, and an alien meteorological cycle involving these fluids, suggests that Titan's surface may exhibit many of the morphological features due to fluid erosion which we at present associate only with the Earth. It is these intriguing similarities, on a frigid and alien world, which initially drew me to study Titan.

Discovered by Christiaan Huygens in 1655, Titan remained an unresolved point of light until the close flyby of Voyager 1 in 1980. Voyager revealed the structure of Titan's atmosphere and the complexity of its chemistry, but Titan's surface and lower atmosphere

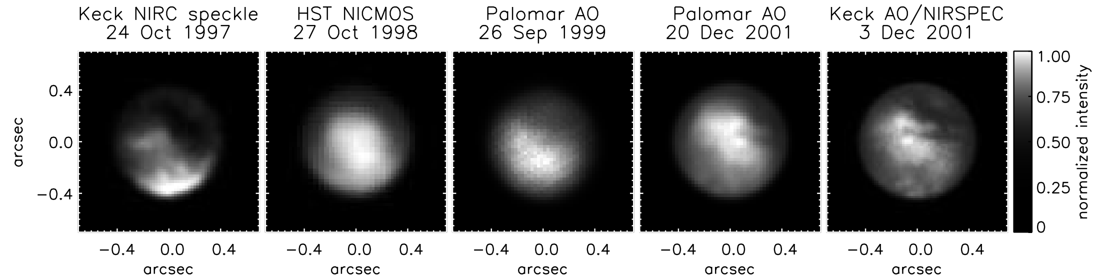
Keck NIRC speckle
24 Oct 1997
HST NICMOS
27 Oct 1998
Palomar AO
26 Sep 1999
Palomar AO
20 Dec 2001
Keck AO/NIRSPEC
3 Dec 2001

Figure 1.1: Five images of Titan's leading hemisphere, illustrating the rapidly improvements in resolution and contrast achieved in recent years. Ground-based images were taken through a K′ filter (2.0 $\mu$m) while the Hubble Space Telescope image (Meier *et al.*, 2000) was taken through filter F165M (1.6 $\mu$m).

remained hidden from its visible-wavelength cameras. It was only realized in 1991 that Titan's surface is directly observable in the near-infrared (Griffith *et al.*, 1991). This, combined with spectacular advances in the spatial resolution achievable by large telescopes, has led to a rapid evolution of our understanding of Titan's surface and troposphere over the past few years. The ever-increasing clarity with which we can view Titan's surface and troposphere is recorded in the series of papers which comprise this dissertation (Fig. 1.1). The pace of discovery is poised to intensify dramatically in July 2004, when the Cassini and Huygens spacecraft arrive at Saturn.

Though it is Titan's mysterious surface which initially motivated this work, this dissertation primarily addresses questions regarding the satellite's atmosphere. One reason is that understanding the three-dimensional distribution of absorbers and aerosols in Titan's atmosphere is a prerequisite to correctly interpreting observations of Titan's surface. The spectroscopic discovery of variable clouds in Titan's troposphere by Griffith *et al.* (1998) motivated much of the work in this dissertation. Clearly, the distribution and frequency of clouds must be understood before even such a basic property of the surface as its albedo can reliably be determined. The original intent of the observational projects described in Chapters 2, 3, and 7 was to locate these enigmatic tropospheric clouds. They were unsuccessful in this regard, but instead revealed an optically thin region of condensates near Titan's tropopause, and gradual seasonal changes in the haze structure of the stratosphere.

As the performance of adaptive optics systems steadily improved, Titan's methane clouds finally sprang into sharp focus in December 2001 (Ch. 5). Their location near Titan's south pole (currently in mid-summer) was a complete surprise and it suggests that these clouds may be analogous to summer thunderstorms on Earth, caused by the heating of moist ground by sunlight. Titan's methane storms are now routinely observed with the W. M. Keck and Palomar Hale telescopes, and more frequent observations are beginning to shed light on their lifetimes and seasonal behavior (Ch. 6). It remains to be seen how long these storms will persist, and whether similar cloud activity moves to Titan's equatorial regions as the long southern summer draws to an end in August 2009.

The observed distribution of aerosols and clouds is intimately related to the global dynamics of the Titan's atmosphere. This topic is interesting in its own right, as Titan constitutes a unique case in the solar system combining slow rotation reminiscent of Venus with substantial seasonal effects due to Titan's 26°.7 obliquity, similar to that of Earth and

Mars. Chapters 2 and 3 begin to address the general circulation of Titan's atmosphere, as it is revealed in the distribution of stratospheric haze and an unknown condensate near the tropopause at high southern latitude. Chapter 4 reports the results of an occultation of a binary star by Titan, from which wind velocities in Titan's stratosphere are directly measured.

Finally, I also present in this dissertation maps of Titan's surface albedo at both visible and near-infrared wavelengths (Ch. 2 and 6). These are the first surface maps free of artifacts induced by a zonally averaged subtraction, and reveal several surprising features of Titan's enigmatic surface.

## 1.2 Methods

### 1.2.1 Adaptive optics

Titan's hazy disk never subtends more than $0\farcs88$ as seen from the Earth. This is roughly equal to the scale of the image degradation imposed on ground-based telescopes by turbulent mixing of air of differing refractive indices in the Earth's atmosphere. Ground-based telescopes with traditional, fixed optical components can therefore resolve little or no detail on Titan.

Adaptive optics (AO) systems, whose conceptual basis was first proposed by Babcock (1953), correct the blurring induced by the Earth's atmosphere on astronomical images. The light of a guide-star, its phase aberrated due to its passage through the Earth's inhomogeneous and constantly varying atmosphere, is monitored using a wavefront sensor. Based on the wavefront measurement, a shape is applied to the surface of a deformable mirror, mechanically adjusting the length of the path which the light travels to cancel the aberrations induced by the atmosphere.

An ideal AO system would correct the light of the guide-star and of the field surrounding it to its original state, leaving the resolution of the final image limited only by the size of the telescope's primary mirror. Current AO systems, however, can provide only a partial and variable correction of the incoming light. Any object imaged with such a system exhibits a sharp, high resolution core, surrounded by a broad halo of uncorrected light. The visible effect of this blurry halo has been suppressed as much as possible in images displayed in this dissertation by a judicious choice of gray-scales, but its effect must be accounted for in the analysis of the observations.

This dissertation is based on images and spectra of Titan taken with the Advanced Electro-Optical System (AEOS), Palomar Hale, and Keck-II adaptive optics systems. The initial development and gradual improvement of these AO systems over the past five years (all achieved first light in 1998–1999) have propelled the rapid advances in our understanding of Titan's atmosphere and surface which are described herein.

### 1.2.2 Radiative transfer calculations

Titan's hazy atmosphere poses a multitude of problems to investigations of the surface and troposphere. Thought the behavior of light through an absorbing and scattering medium is well understood (see Goody and Yung, 1989) the difficulty lies in both the poorly constrained properties of Titan's atmosphere (aerosol distribution and phase function), and its physical thickness.

I have attempted in this dissertation to treat radiative transfer through Titan's atmosphere in a precise and self-consistent fashion. The vertical and latitudinal distribution of aerosols in Titan's atmosphere is determined in Ch. 3 by fitting the spectra predicted by a radiative transfer model to spatially resolved spectra of Titan recorded with the Palomar adaptive optics system over a two year period. The radiative transfer model used is that of Griffith *et al.* (1991), a plane-parallel model which assumes a simple Mie scattering phase function, with constant-sized aerosols throughout the haze layer. More details of the model are given in Section 3.4.2. Though the geometric and phase assumptions are simplifications, modeled spectra reproduce those measured to within the observational errors and constrain the thickness and vertical distribution of the haze more precisely than previous analyses of broad-band images of Titan's haze (Gibbard *et al.*, 1999; Young *et al.*, 2002). I have then used this same radiative transfer model, with the three-dimensional aerosol distribution derived from resolved spectra, to analyze broad-band images of Titan taken with the Palomar and Keck adaptive optics systems (Ch. 6).