Planetary science

Titan weather report

F. Michael Flasar

Cloudy but changeable. That is the outlook for Saturn's huge moon Titan, the only moon in the Solar System to have a thick atmosphere. The workings of that atmosphere are still poorly understood, but on page 575 of this issue[1], Griffith *et al.* report direct evidence of variable cloud cover.

Our attempts to learn about Titan, particularly its lower atmosphere and surface, have proceeded by fits and starts. When the Voyager 1 spacecraft approached Saturn in 1980 and made the first spatially resolved observations of Titan, its cameras showed a body shrouded in an opaque, brownish haze that blocked the view of the surface at visible wavelengths. Information about Titan's surface and lower atmosphere was limited to spectra in the middle infrared, where a window near $18.5\ \mu m$ allowed the surface temperature to be determined, and radio-occultation soundings, which yielded vertical profiles of temperature and pressure.

In the occultation experiment, radio waves emitted towards Earth by the spacecraft were refracted as they passed through Titan's atmosphere, giving rise to Doppler shifts in frequency that were used to retrieve a vertical profile of the atmospheric refractivity. For an assumed vertical profile of composition, a vertical profile of temperature and pressure on Titan could be obtained[2]. Combined with ultraviolet and infrared spectra, these radio occultation soundings showed that the mean molecular weight of Titan's atmosphere is about 28 atomic mass units and that most of it is molecular nitrogen, as on Earth. The retrieved surface pressure, $\sim$1.4 bar, is also Earth-like; but the surface temperature, 94 K, is not, because of Saturn's greater distance from the Sun[3].

Methane is also known to be an important component of Titan's atmosphere. But it should be destroyed by photolysis in less than ten million years[4,5] — and irreversibly so, because the light hydrogen atoms and molecules that are created escape. What source replenishes it? A global methane ocean was an early favourite after the Voyager encounters, and researchers imagined a 'hydrological' cycle on Titan, with clouds and precipitation not unlike Earth's, but with methane being the condensable gas.

Although the idea of a methane cycle is still reasonable, the hypothesis of a methane ocean quickly ran aground because it is inconsistent with the radio occultation results. One must either assume near saturation of methane just above the surface, implying atmospheric temperatures that decrease more rapidly with altitude than the dry adiabat (and hence are dynamically unstable) in the lowest few kilometres; or a subsaturated profile near the surface, implying fluxes of latent heat (from evaporation) into the base of the atmosphere that exceed by an order of magnitude the solar radiation absorbed at the surface[6]. Neither is physically plausible.

But a pure methane ocean is unrealistic for other reasons. Methane photolysis produces ethane, propane and acetylene in the upper atmosphere, which diffuse downward into the colder stratosphere and tropopause, where they condense and precipitate. Ethane and propane are soluble in methane, and over geological time an initially pure methane ocean would have evolved into a more complex hydrocarbon mix including dissolved molecular nitrogen[7]. The partial pressure of methane over such an ocean of liquefied natural gas would be lower than that over a pure methane ocean, and consistent with the radio occultation data.

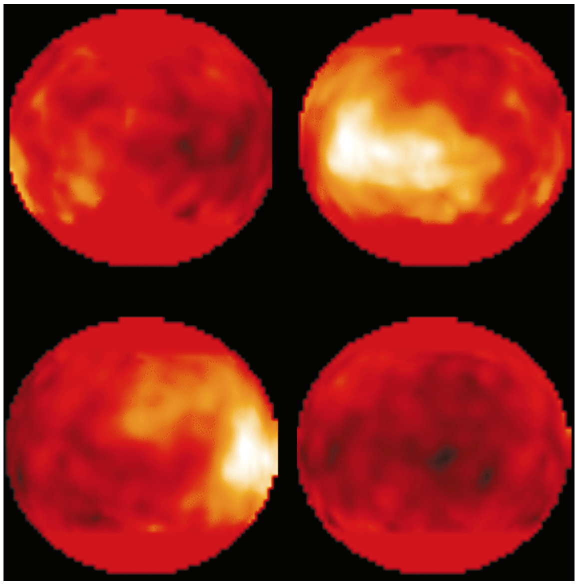
NASA/HST

Figure 1 **Four sides of Titan. These images show permanent surface structures, scuppering the idea of a global ocean of natural gas. But there is new evidence for methane clouds, perhaps part of a methane cycle similar to Earth's hydrological cycle.**

Later observations cast doubt on this idea too. Radar echoes from Titan are too strong to be explained by a smooth surface of liquefied natural gas[8]; the reflectivity is more consistent with a surface of water ice whose deep cracks duct the incident radar signal and reflect most of the energy directly back to the observer. That mechanism is thought to explain the high radar reflectivity of the surfaces of the Galilean satellites of Jupiter. Furthermore, there appear to be persistent features in the near infrared (Fig. 1), implying a solid surface[9,10]. So any global ocean seems unlikely. An ocean/landmass system similar to Earth's is also implausible, because the tidal dissipation caused by such a configuration would circularize Titan's eccentric orbit about Saturn[11]. But lakes of liquefied natural gas are still possible.

Clouds would be the other visible feature of a methane cycle, but they have been elusive. Initially, estimated absorption cross-sections of nitrogen and methane gases were too small to account for the low brightness seen by Voyager[12] at $50\ \mu m$ — the atmosphere would be too transparent. So methane clouds were suggested as an additional source of opacity. Analogies with terrestrial meteorology suggested that moist convection and cumulus clouds might be important in Titan's lower atmosphere.

But improved calculations gave gaseous opacities of nitrogen and methane that were higher than originally thought — high enough to explain the observed far-infrared spectra if the methane is somehow supersaturated[13,14] in the lower atmosphere, with a relative humidity of about 200%. This decidedly non-terrestrial situation could be accounted for by the lack of nucleation sites. On Earth, condensation nuclei abound, ranging from soluble salts from the oceans to airborne dust particles, whereas on Titan the inventory of available nuclei is probably much more limited, consisting perhaps of stratospheric aerosols making up the visible haze. Whether cumulus activity would occur in such an atmosphere is questionable. So direct evidence for clouds and their type is needed.

All of which brings us to the new work. On two nights in 1995, Griffith *et al.*[1] saw that Titan's disk was brighter than on previous occasions when the same central meridian faced Earth. The authors can explain this brightening as being due to a thick cloud at an altitude of roughly 15 km covering about 9% of Titan's disk. In later observations, in 1997, they saw no such brightening. This is the first direct indication of cloud activity on Titan. But the temporal resolution thus far is not very high, so one hopes for a systematic programme with more frequent observations to confirm and better characterize the phenomenon.

The Cassini mission, a joint NASA/ESA effort, may fit the bill. Launched in the autumn of 1997, the Cassini spacecraft will arrive at Saturn in the summer of 2004. In the following November, the Huygens probe it carries will descend into Titan's atmosphere, armed with a camera to search for clouds as well as with a battery of instruments designed to measure temperatures, pressures, winds, gas composition (including methane), condensates and the properties of the surface.

For four years the spacecraft itself will orbit Saturn, making 40 or more close passes of Titan and employing instruments capable of observing from ultraviolet to radio wavelengths, including an onboard radar system that uses the high-gain antenna normally used for telecommunication and radio-occultation soundings. Data from the orbiter and the probe should clarify many issues about Titan, and will no doubt raise other perplexing questions. But the four-year life of the Cassini nominal mission is short compared with Titan's year (29.5 Earth years) and several natural atmospheric timescales, so long-term coverage by ground-based and Earth-orbiting telescopes will still be important. ☐

F. Michael Flasar is in the Laboratory for Extraterrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA.
e-mail: mike@leprss.gsfc.nasa.gov

1. Griffith, C. A., Owen, T., Miller, G. A. & Geballe, T. *Nature* **395,** 575–578 (1998).
2. Lindal, G. F. *et al. Icarus* **53,** 348–363 (1983).
3. Hunten, D. M. *et al.* in *Saturn* (eds Gehrels, T. & Matthews, M. S.) 671–759 (Univ. Arizona Press, 1984).
4. Hunten, D. M. *J. Atmos. Sci.* **30,** 726–732 (1973).
5. Strobel, D. F. *Planet. Space Sci.* **30,** 839–848 (1982).
6. Flasar, F. M. *Science* **221,** 55–57 (1983).
7. Lunine, J. I., Stevenson, D. J. & Yung, Y. L. *Science* **222,** 1229–1230 (1983).
8. Muhleman, D. O., Grossman, A. W., Butler, B. J. & Slade, M. A. *Science* **248,** 975–980 (1990).
9. Lemmon, M. T., Karkoschka, E. & Tomasko, M. *Icarus* **103,** 329–332 (1993).
10. Smith, P. H. *et al. Icarus* **119,** 336–349 (1996).
11. Sagan, C. & Dermott, S. F. *Nature* **300,** 731–733 (1982).
12. Samuelson, R. E., Hanel, R. A., Kunde, V. G. & Maguire, W. C. *Nature* **292,** 688–693 (1981).
13. Courtin, R., Gautier, D. & McKay, C. P. *Icarus* **114,** 114–162 (1995).
14. Samuelson, R. E., Nath, N. R. & Borysow, A. *Planet. Space Sci.* **45,** 959–980 (1997).

Molecular endocrinology

Two orphans find a home

Didier Picard

The superfamily of ligand-regulated transcription factors has grown to the point where the founding members — the steroid and thyroid hormone receptors — have become respected elders. To qualify for membership in this family, all that a protein needs is some homology to the DNA-binding or ligand-binding domains (or both) of a seasoned member. Being a transcription factor or, at least, being able to bind canonical DNA sequence elements is a plus, but being a receptor for a known ligand is not a requirement. As a result, most members are considered 'orphan' nuclear receptors, waiting to be adopted by a ligand[1]. Finding parents, assuming there are any at all, has been tedious and rarely successful. But, on page 612 of this issue, Forman and colleagues[2] report such a success story with several unexpected twists.

When the constitutively active receptor (CAR) was cloned by Moore and colleagues (a sub-set of the collaborating authors here), this orphan nuclear receptor was presumably given that name because of its constitutive transcriptional activity[3]. What incredible foresight in choosing this acronym — Forman *et al.*[2] now show that CAR is a constitutive androstane receptor (Fig. 1). Not only is it the receptor for two steroids, the androstane metabolites androstenol and androstanol, but, surprisingly, these steroids switch the activity of CAR *off.* Although ligand-deactivated repressors (such as the *lac* repressor) are known in prokaryotes, it is unusual to see this effect on a ligand-repressed transcription factor such as CAR. One example is the thyroid hormone receptor, which can be regulated similarly, but only on a rather unusual DNA response element[4]. It will be interesting to see how CAR's next of kin, the human orphan receptor MB67 (ref. 3; now called hCAR-α to distinguish it from the mouse CAR-β discussed here), responds to androstane metabolites.

Does CAR-β bind directly to androstenol and androstanol? Because radiolabelled ligands are often not available for ligand-binding assays, preliminary evidence is usually obtained indirectly. This is the case here. Transcriptionally active nuclear receptors associate with transcriptional co-activators, and Forman *et al.* found that, as expected, *in vitro* translated CAR-β associates with the steroid-receptor co-activator-1 (SRC-1). Androstenol induces the dissociation of CAR-β and SRC-1. This, and the fact that activity of CAR-β is also repressed when assayed in yeast, suggests that androstenol and androstanol may not have to be further metabolized. But from the point of view of a receptor purist, this has yet to be shown with purified components. For example, perhaps these compounds are metabolized to the active form, even in yeast. Or maybe they signal through another component, present in both yeast and *in vitro* translation extracts. Moreover, CAR-β has a dimerization partner, the retinoid-X receptor (RXR). So, does CAR-β form the ligand-binding pocket by itself, or only in conjunction with RXR? RXR has been caught in very intimate liaisons, with the ecdysone receptor, for example, where both subunits are required to bind the ligand[5].

Should the CAR-β ligands be thought of as inverse agonists or as antagonists? This is not just semantics, because antagonists act against agonists, whereas inverse agonists simply have the opposite effect to an agonist. We cannot exclude the hypothesis of an endogenous ligand, although it would have to be present in mammalian cells, yeast and the *in vitro* system. Moreover, there does seem to be a precedent in the nuclear-receptor family. LXR-α is a nuclear receptor for oxysterols[6] that can be constitutively active, presumably owing to endogenous ligands. It can be inhibited by geranylgeraniol (but,

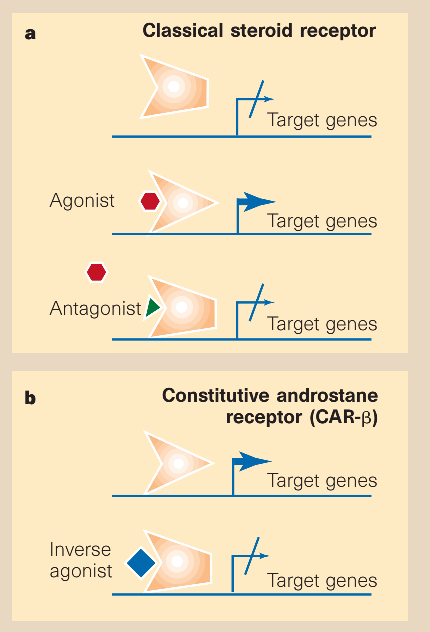

Figure 1 **Alternative pathways for signalling through intracellular receptors.** a, **Classical steroid receptor. The receptor cannot activate transcription unless it is activated by binding of an agonist. Antagonists can block this interaction and prevent transcription.** b, **The constitutive androstane receptor (CAR-β), described by Forman *et al.*[2]. The receptor is constitutively active, but binding of the androstane metabolites androstenol or androstanol turns the receptor off. (Note that sources for agonists, antagonists and inverse agonists can be autocrine or paracrine as well as endocrine.)**