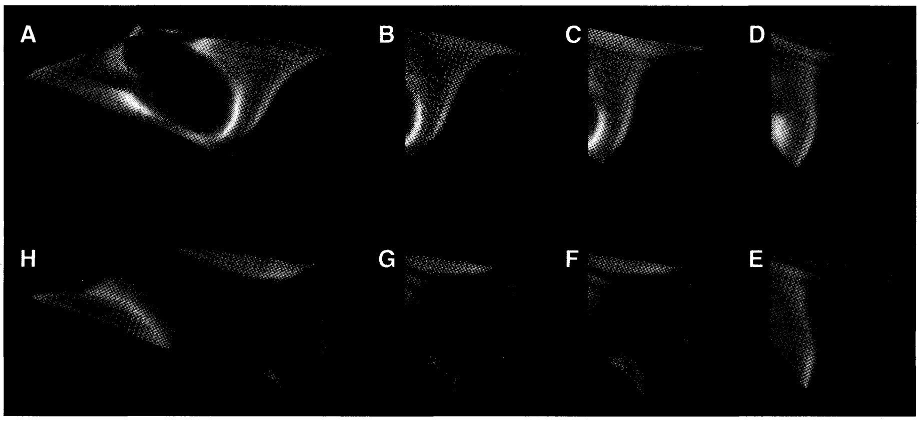

Perspective view of simulated magnetization waves after a transverse field stimulation. The dimensions of the rectangular platelet are: 0.5 μm × 0.25 μm × 5 nm. The right-hand upper corner in each image is seen to beat as a function of time. In this representation, the platelet surface deformation is proportional to the out-of-plane magnetization component, a representation similar to that of fig. 4 in (*3*). Colors monitor the magnitude of the in-plane component along the short side of the platelet. Time between frames: 12.5 ps.

combined with advanced photoemission electron microscopy (*8*), may soon provide images with an estimated spatial resolution of a few nanometers and a time resolution conditioned by the synchrotron source itself. Last, Acremann *et al.* demonstrate dynamical excitations that reverse their amplitude upon reflection along boundaries, contrary to ordinary waves. Such a seemingly non-wave-like behavior has also been observed in time-resolved numerical simulations (*7*) (see the second figure). Clearly, this calls for further understanding.

As now well demonstrated, magnets can respond extremely fast. They can also be made small. But space and time responses are interdependent, potentially giving rise to finite amplitude magnetization waves (nonlinear spin waves). Thus, the use of patterned elements in magnetic memories or the extension of digital recording into the picosecond time domain both lead to the need for focused studies of magnetization dynamics where, both in the space and time domains, neither the magnetization nor the applied field should be viewed as uniform.

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PERSPECTIVES: PLANETARY SCIENCE

The Weather on Titan

Ralph D. Lorenz

Climate is what you expect, weather is what you get, goes the old definition. We know precious little about either on Saturn's giant moon Titan, the only planetary satellite with a significant atmosphere and the only body in the solar system other than Earth that has a thick atmosphere dominated by molecular nitrogen. Titan's 1.5-bar atmosphere looked bland and nearly featureless to Voyager 1's cameras in 1980. But as Griffith *et al.* (*1*) report on page 509 of this issue, these first impressions were deceiving: Titan's atmosphere seems to have had a turbulent history and may today have a vigorous methane-based meteorology.

For a long time, the big question about Titan's atmosphere was how could it be so thick, given that Titan's same-sized jovian cousins Ganymede and Callisto have none. The conditions for acquiring and retaining a thick nitrogen atmosphere are now readily understood (*2*). The low temperature of the protosaturnian nebula allowed Titan to acquire the moderately volatile compounds methane and ammonia (later converted to nitrogen) in addition to water. The higher temperatures of the jovian moons, which were closer to the sun, prevented them from acquiring such an atmosphere. Recent millimeter-wave measurements of the nitrogen isotopic ratio (*3*, *4*) in Titan's atmosphere suggest that Titan's atmosphere was once some 30 times thicker than it is now. How can Titan's atmosphere be so much thinner now than in the past? One hypothesis is that the sun had an extended phase of high mass loss, with enhanced solar winds (*5*) that eroded the upper atmosphere and thus preferentially the lighter nitrogen isotope. If true, this would have profound implications for solar evolution and the climates of the early solar system.

Strangely, the same isotopic fractionation has not occurred with carbon isotopes in methane, which makes up 2 to 8% of Titan's atmosphere. Like the atmospheres of the terrestrial planets, the methane cannot have been exposed to the same loss process; in other words, it must have appeared later (*4*). This is consistent with the hypothesis that the methane was initially trapped in ice as a clathrate hydrate (*6*) and was only released 500 million years after the end of accretion.

Methane is an ephemeral molecule in Titan's atmosphere: The entire methane content of the atmosphere would be destroyed in only 10^7 years or so by the action of solar ultraviolet light. This process is irreversible, because the hydrogen thus liberated escapes to space and the photolysis products including ethane and a host of other organic compounds, 20 of which have already been detected, drizzle down to the surface. For the methane we see today not to be a bizarre fluke, it must be continuously resupplied from a surface reservoir or by cryovolcanism (that is, volcanism where the molten "rock" is just water ice). Even if the methane is resupplied by continuous or episodic cryovolcanism, rather than a large surface reservoir, it would form at least some lakes and seas because the volcanism rate would be unlikely to exactly match the photolysis rate through time. A surface reservoir—lakes and seas of ethane and methane, both liquids at Titan's surface temperature of 94 K—need not be the single global ocean that post-Voyager models assumed (*7*). Much of the reservoir may exist in the near subsurface, although there is evidence from analysis of recent adaptive-optics images from the Keck Telescope (*8*) that dark regions on the surface are literally pitch black—consistent with pools of hydrocarbons hundreds of kilometers across.

A large surface reservoir of hydrocarbons would also dissolve substantial amounts of nitrogen, and like the martian atmosphere, the Titan atmosphere may be controlled by thermodynamic equilibrium with a surface

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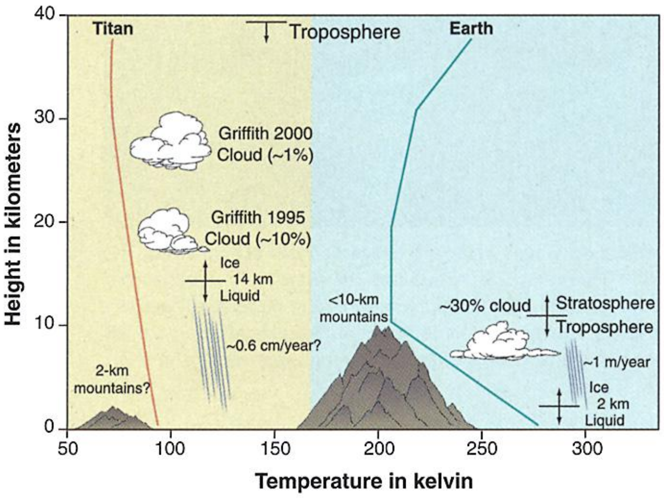
volatile reservoir. The presence of the condensible greenhouse gases nitrogen and methane opens up the possibility of strong positive climate feedbacks, like the runaway greenhouse that forever estranged Venus from its cooler twin, Earth. Models of Titan's greenhouse effect suggest that if Titan has a large surface volatile reservoir, it may be on the brink of a runaway (*9*) to a state about 30 K warmer, and many bars thicker, than at present.

It now appears that Titan's atmosphere is dynamic not only on time scales of eons but also on time scales of minutes and hours. No clouds were initially seen in Voyager images of Titan, although some workers later claimed to find hints of discrete cloud features (*10*). Similarly, no obvious clouds were seen in Hubble Space Telescope (HST) images of Titan that probed down to the surface (*11*, *12*), but but more detailed analyses (*13*, *14*) have reported features strongly suggestive of clouds. Also, using ground-based spectroscopy, Griffith *et al.* (*15*) detected a cloud (more likely a strom) covering 10% of Titan's disk and determined its altitude. Now (*1*), they report variations in cloud cover of less than 1%, which change on time scales of hours.

Voyager measurements indicate that Titan's upper troposphere may be supersaturated with methane, which makes it hard for clouds to persist: Any cloud particle at these altitudes would quickly grow into a raindrop or hailstone. In Titan's thick atmosphere and moonlike gravity, methane raindrops could be over 9 mm wide (*16*)—rather larger than terrestrial raindrops—yet would fall at a languid 1.6 m/s, not unlike snowflakes on Earth [a picture already embraced in science fiction (*17*)]. The near-surface atmosphere near the equator has a methane humidity of only 25 to 60%, and the sluggish drops would evaporate before reaching the ground. In a sufficiently heavy rain shower, however, a saturated rain shaft would develop, where the first drops evaporate but allow their successors to reach the ground. Whether they reach the ground or not, the descent time scale of hours is consistent with the observed duration of "cloud" events. Furthermore, elevated terrain would be washed by heavier rainfall (*16*) than the surrounding lowlands. This is a leading explanation for the Australia-sized bright feature seen in HST (*11*, *12*) and ground-based imaging (*8*): The thermodynamics of methane and nitrogen (which acts as an antifreeze in methane) are such (*18*) that this bright feature is unlikely to be caused by methane frost.



Altitude/temperature profiles of Titan and Earth. Because of Titan's low gravity, its atmosphere is vertically extended compared with that of Earth. The inferred altitudes of clouds detected recently on Titan (*1*) are above the altitude at which average conditions cross the expected freezing point of methane/nitrogen. The clouds are therefore likely to consist of ice crystals, although rain may fall below. Titan's jovian cousins have topography of little more than 2 km; Titanian mountains are expected to be similar and thus rarely if ever poke through the clouds.

On average, weather on Titan is gentle. Not only is there less sunlight to drive weather, but on cold Titan the harsh laws of thermodynamics insist that sunlight is converted less efficiently into motion than on Earth. Convective motions on Earth dissipate roughly 100 W m^{-2} (around 30% of the absorbed sunlight). Expressed in terms of the latent heat of water, this flux corresponds to an upper limit of 1.2 m of rain for Earth (within a factor of two of the observed amount). In contrast, on Titan, convection amounts to 0.05 W m^{-2} [about 10% of the absorbed light, weakened both by Titan's distance from the sun and the thick haze (*19*)], and the calculation yields a mere 0.6 cm of rain in every Earth year.

However, consideration of hydrologically active planets such as Earth warns us to be wary of average conditions. The southwestern U.S. desert around Tucson typically receives a mere 30 cm of rain in 1 year (less than the global average), yet the geomorphology of the area is dominated by erosion by water, partly because the rain falls in sudden, powerful downpours. Titan may be similar—rain cannot be frequent, as otherwise the supersaturation hinted at by Voyager could not be sustained, but it may be spectacular. The sheer amount of methane in the dense Titan troposphere implies that a single event could dump a meter of rainfall. Thus, most rivers on Titan may run dry, but river valleys may nevertheless be abundant and deep.

All this suggests that the Cassini spacecraft, which will fly by Jupiter at the end of this year and will arrive at Saturn in 2004 for a 4-year tour making about 40 flybys of Titan, will have plenty to see. Although Titan's clouds may be frustrating to geologists hoping to see the surface in the near infrared with Cassini's imager and mapping spectrometer, meteorologists will be able to watch weather, mapping the methane distribution and tracking the development of weather systems. Happily, Cassini is formidably instrumented and also carries a synthetic aperture radar mapper that will penetrate clouds to map the rivers and shorelines. It may reveal a landscape bizzare in its chemistry but perhaps strangely familiar in appearance. Titan is a strange little world that may have much to teach us about weather. Christiaan Huygens, the discoverer of Titan after whom Cassini's European-built atmosphere probe is named, would have been pleased. Three hundred years ago, he wrote (*20*) "But since 'tis certain that the Earth and Jupiter have their Water and Clouds, there is no reason why the other Planets should be without them. I can't say they are exactly of the same nature with our Water; but that they should be liquid their use requires, as their beauty does that they be clear. For this Water of ours, in Jupiter or Saturn, would be frozen up instantly by reason of the vast distance of the sun. Every Planet therefore must have its waters of such a temper, as to be proportion'd to its heat: Jupiter's and Saturn's must be of such a nature as not to be liable to Frost..."

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