

Did Comas Solà discover Titan's atmosphere?

Ralph D Lorenz sets the scene for the Cassini Mission with a summary of historical and current observations of Titan, 90 years after Comas Solà announced his discovery of its atmosphere.

Although Christiaan Huygens discovered Titan, and he believed that other worlds should be gifted with atmospheres, weather, and civilizations, he does not appear to consider specifically Titan's condition in these respects in his *Celestial Worlds Discover'd* (1698). A fellow Dutchman, Gerard Kuiper, is widely credited with the discovery of an atmosphere around Titan, by the spectroscopic detection of methane (Kuiper 1944).

Kuiper mentions a puzzling (to him) reference in the book by J H Jeans (1925) that "an atmosphere has been observed on Titan", and notes the difficulty in ordinary optical detection of an atmosphere on a body smaller than 1 second of arc in diameter: "In fact, such a thing would seem impossible," he states.

The earlier observation is generally attributed to the Spanish astronomer José Comas Solà. In the "discovery paper" (1908), Comas Solà reports observations of Io, Callisto and Ganymede. Following these, he writes (my translation): "Titan. On the 13th of August 1907, with a clear image and using a magnification of 750, I observed Titan with very darkened edges (somewhat similar to those one observes on the disk of Neptune), while on the central part, much brighter, one sees two round, whiter patches, which give the appearance of a blurred double star. We may suppose, reasonably, that the darkening of the edges demonstrates the existence of a strongly absorbing atmosphere around Titan."

The observation was conducted with the 38 cm Mailhat telescope, at the Fabra Observatory in Barcelona. The diffraction-limited resolution $1.22 \lambda/D$ is therefore ~ 1 microradian. Titan, at 9 AU, subtends a mere 4 microradians (1 arcsecond), the typical seeing limit for ground-based observations. Although the eye is a good "speckle" imager with a short integration time that can occasionally catch clear moments between wavefront distortions due to atmospheric turbulence, this is a remarkable observation. So much so, indeed, that it is worth calibrating the believability of the observation by Comas Solà's other work: this is, after all, the epoch in which good eyesight, guided by

wishful thinking, was able to detect the canals on Mars that elude current instrumentation.

Observations of Galilean satellites

The 1908 paper presents sketches of his observations – six of Ganymede, and one each of Titan and Callisto. The drawing of Titan has two bright patches to the north and south of the centre of the disk, with a dark border – see figure 1. The sketch of Callisto shows a dark disk, with a bright south pole. This is entirely consistent with Callisto's bright polar region. He presents sketches of Ganymede, brighter than Callisto, with a bright south pole and typically a dark circumpolar region and northern

Titan science has been dominated over the years by spectroscopy, but this article reviews recent striking images of Titan, motivated by the remarkable progress in the last five years due to the Hubble Space Telescope and ground-based adaptive optics, and the 90th anniversary of Comas Solà's observation of limb-darkening on Titan, the first hint that it might have an atmosphere.

mid-latitude band. Again this seems broadly compatible with Ganymede's appearance as revealed by Voyager (Burns and Matthews 1986): the south pole is indeed bright and the dark regions are probably Galileo Regio and Perrine Regio – see figure 2.

The observation of Io reported in the paper indicates Io as having an ellipsoidal shape. By comparison with drawn ellipses of different eccentricity, he determined the apparent flattening at 0.2, and somewhat inclined (28°) to the Jovian equatorial plane. In an earlier communication (Comas Solà 1907) he reported a provisional estimate of the flattening as 0.25 and the inclination of the long axis of about 6° . He

attributed the distorted shape to the attractive force of Jupiter. Although tidal effects give Io its singular volcanism, they do not distort the Io satellite nearly as much as Comas Solà suggested. However, Io has a rather dark surface further than about 30° from the equator, so it is likely that it would have appeared to Comas Solà as a flattened or elongate object. The difference in his flattening and inclination measurements may be due to changes in Io's surface albedo distribution due to volcanic deposits, or more likely indicates how close to the threshold of observation these measurements are.

Titan's appearance

In terms of his Titan observation, it must be remembered that Titan exhibits seasonal variations in its appearance. In 1907, the season was similar to the current southern spring. Then, as now, there should have been a significant brightness asymmetry (Sromovsky *et al.* 1981). Titan's limb darkening, and the north-south brightness contrast, are wavelength-dependent (see later, and Lorenz *et al.* 1997). The disk is virtually flat (Minnaert coefficient $k \sim 0.5$) at 350 nm but near-Lambertian ($k \sim 1$) at 600 nm. The north-south contrast increases with wavelength up to about 25% at 470 nm and then back down to zero at about 600 nm.

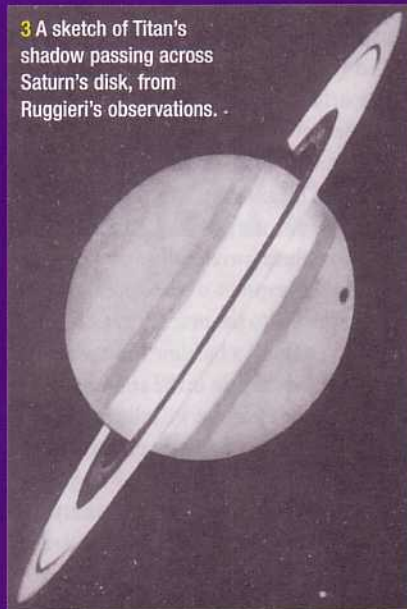
A scotopic (dark-adapted) eye is most sensitive (Ditchburn 1963) at about 500 nm (blue-green). At this wavelength, the north-south asymmetry is near its strongest and limb-darkening is fairly strong ($k \sim 0.9$). Thus Comas Solà should have seen one bright patch (in the northern, brighter hemisphere, near the sub-solar point). Since there was solar ring-plane crossing close to when he made his observation (US Naval Observatory 1907) and Titan's slightly inclined (0.33°) orbit still crossed the shadow of the rings, it is tempting to wonder whether Comas Solà saw this unique phenomenon. However, his observation was made near Eastern Elongation, at a time when Titan would have been well clear of the shadow. His report of two patches is somewhat puzzling, therefore, and again indicates that the observation was marginal.



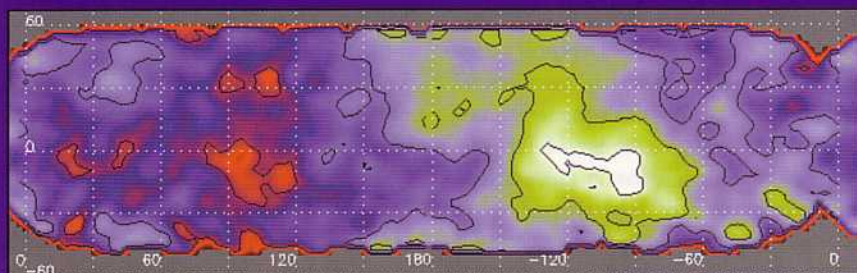
1 Comas Solà's 1907 drawing of Titan.



2 Comas Solà's 1907 drawing of Ganymede.



3 A sketch of Titan's shadow passing across Saturn's disk, from Ruggieri's observations.

4 A map of Titan's surface using HST 940 nm data, from Smith *et al.* (1996). The brightness here only gives an approximate indication of surface albedo, as it was not possible to eliminate latitudinal variations in haze opacity.

5 Titan's disk from UV to near-IR, using HST data. Wavelengths (left to right): 336 nm (UV), 439 nm, 547 nm, 588 nm, 673 nm, 889 nm (near-IR methane band). Note strong limb-darkening and smaller radius at red wavelengths, and the reversal of north-south asymmetry in the near-IR.

Lyot, at Pic-du-Midi, made a number of observations in the 1940s, and sketched markings on Titan which appeared to change with Titan's orbital position. No consistent pattern is apparent, however (Alexander 1962). Camichel and Lyot used a disk meter to determine Titan's diameter (at 9 AU) as 0.76 arcseconds; this, and Kuiper's subsequent measurement of 0.67 arcseconds at 9.43 AU put Titan's optical radius at about 3000 km.

On 6 May 1950, with a 12 cm refractor in Venezia, G Ruggieri observed a notch on Saturn's disk. As he watched, it moved towards the central meridian, becoming less elongate as it did so. This observation (figure 3) of Titan's shadow on Saturn's disk is striking in comparison with later HST results (below).

For the next 30 years, investigation of Titan was dominated by attempts to understand its atmospheric composition and structure, by photometry and spectroscopy. Imaging only returned to the fore with the 1979 encounter of the Pioneer 11 spacecraft. This small vehicle's imaging capability was modest, equipped as it was with only a spin-scan photopolarimeter. But the disk-resolved polarimetry and photometry was excellent and is used to this day.

The close (4900 km) encounter the next year with Voyager 1 was anticlimactic in that Titan turned out to be rather bland, at least in the 350–650 nm wavelength range covered by the

Voyager cameras. Apart from north-south asymmetry, a detached haze layer and a dark polar hood, Titan was a featureless disk.

Adaptive optics and HST

The fundamental problem in observing Titan is that achievable resolution is not adequate – not due to inadequate telescope apertures, but due to the problem of seeing through the turbulent atmosphere of the Earth. There are three ways around the problem of turbulence. One method is to climb above the atmosphere, to use an orbiting telescope such as the HST. Another is to take short images – speckle imaging. The integration time is short enough that the image is not blurred by shimmering. Images are then added (usually in Fourier space) to boost signal-to-noise. Finally, the most recent approach, adaptive optics, uses a deformable mirror to compensate in real time for the wavefront distortion from the atmosphere. All these methods have been applied to Titan. The first to be used was speckle imaging. Limb-darkening measurements from speckle images taken in 1980 (Nisenson *et al.* 1981) gave results comparable with the Voyager data.

The Hubble Space Telescope first observed Titan in 1990 (Caldwell *et al.* 1992) and determined that the north-south asymmetry on Titan had reversed, as predicted. Further results awaited the ability of HST to track

Solar System objects (and hence obtain exposures longer than a few seconds).

The ability of HST to observe in the near-infrared has dramatically changed our perspective on Titan. In the early 1990s a number of workers realized that Titan's haze might be relatively transparent in the near-IR. At blue wavelengths the haze is dark. At red wavelengths it is reflective, but sufficiently optically thick that few photons reach the surface. At longer wavelengths still, the haze optical depth becomes about unity. Methane in the atmosphere absorbs strongly in the near-IR, but between the absorption bands, in the methane windows at 0.94, 1.07, 1.28, 1.6 and 2 μ , light can reach the surface. In 1992 and subsequent years, a consistent lightcurve was measured for Titan at all these wavelengths, with the leading hemisphere brighter than the rest of the body.

A long-pass HST filter, the F850LP, samples the 0.94 μ window, but also includes a large amount of scattered light from the haze. Smith and co-workers in 1992 attempted to remove this contribution by subtracting an image in the 889 nm methane band. The result, hampered by uncertainties in subtraction and deconvolution, showed two bright spots in the northern hemisphere which were unlikely to be artefacts. However, without longitude or time coverage, it was not known if the bright spots were surface features or clouds.

In 1994, Smith *et al.* (1996) fared rather better. First, the HST refurbishment dramatically improved the point-spread function, such that adequate detail could be seen without deconvolution. Secondly, they were able to get observations spanning a whole Titan orbit (i.e. the full range of longitudes). With this dataset, they were able to construct maps of Titan's surface albedo at three wavelengths (see figure 4). Additionally, a snapshot of the appearance of Titan from the UV to the near-IR was obtained (figure 5) to establish a baseline from which to monitor seasonal changes in the atmosphere. A search for cloud features (Karkoschka and Lorenz 1997) was tantalizing, but inconclusive.

In 1995, the Earth's crossing of the ring plane was a great opportunity to study not only the rings, but also Saturn itself. Tomasko and Karkoschka, at the University of Arizona, timed HST observations of Saturn to catch not only Titan, but also Titan's shadow cast onto Saturn (see figure 6). Karkoschka and I, by careful measurement of the shadow's size and shape at a variety of wavelengths between the UV and near-infrared, were able to show that the northern hemisphere, just about to enter winter, has haze particles both larger and higher than those in the south. This is consistent with the northern hemisphere having the upwelling leg of a global Hadley cell during its summer, the updraught

ness in the extinction level) from a simple difference in altitude between hemispheres, or some combination of these. However, because the HST images also showed the thin shadow of Saturn's edge-on ring, this could be used as a fiducial marker to determine the centre of Titan's body, which is slightly offset from the geometric centre of the (non-circular) disk. We thus found that the raised haze layer extended northwards of 20 degrees south.

More HST imaging has been taken recently and we plan to use later this year the new STIS (Space Telescope Imaging Spectrograph) and NICMOS instruments just installed. These observations will be used as a baseline for modelling Titan's atmospheric haze structure – present models are based on disk-average albedos, which (since they are the average of a dark hemisphere and a bright one) do not necessarily describe any part of Titan's atmosphere.

Around the same time as the HST results began to come in, progress in ground-based adaptive optics (AO) allowed observations of comparable spatial resolution to be made, at 2 μ from the ground (because the coherence length scale of atmospheric turbulence becomes much shorter at shorter wavelengths, it becomes more and more difficult to compensate for atmospheric effects at much shorter than 2 μ). The initial results also suffered to an extent from “not

~70%, of the received light, so the model-dependent subtraction of haze effects may not yield the true surface reflectivity). A 2 μ AO image of Titan is compared with the HST view at 0.94 μ in figure 7. More AO results and better longitudinal coverage, with observation through variable filters, will provide useful constraints on surface composition.

Conclusions

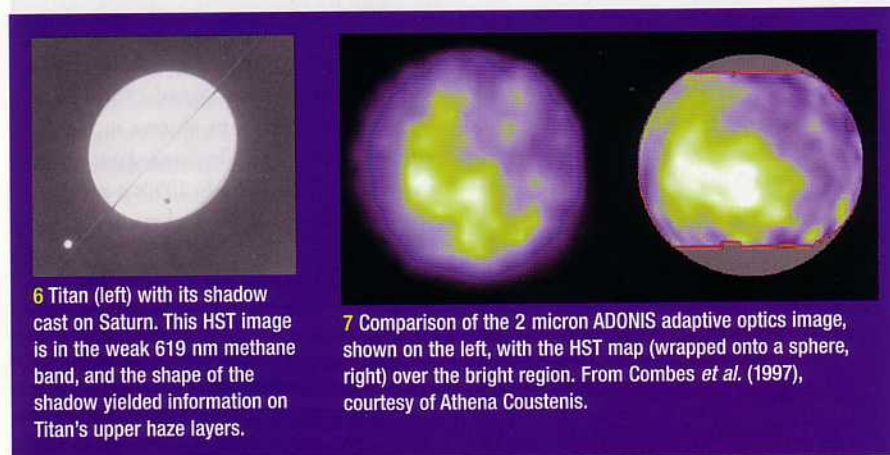
Comparison of Comas Solà's other observations with what he “should have seen”, suggests that he genuinely saw limb-darkening on Titan. Further, he correctly surmised that this was consistent with an atmosphere. By the accepted scientific standards of reproducibility, however, his observation is hampered by its difficulty. That histories generally credit Kuiper with the discovery of Titan's atmosphere is not unjust – Kuiper demonstrated its existence unequivocally and reproducibly.

Since the time when imaging led to the discovery of Titan's atmosphere, Titan has been principally an object for spectroscopists. But the technology advances of the last few years have enabled a re-emergence of imaging as a prime scientific tool for understanding Titan and observing changes in its thick atmosphere. In particular, mapping of surface features has changed our perspective on Titan, from a mere dot in the sky, to a world waiting to be explored up-close. Cassini, to be launched next October, will do just that in 2004. ●

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6 Titan (left) with its shadow cast on Saturn. This HST image is in the weak 619 nm methane band, and the shape of the shadow yielded information on Titan's upper haze layers.

7 Comparison of the 2 micron ADONIS adaptive optics image, shown on the left, with the HST map (wrapped onto a sphere, right) over the bright region. From Combes *et al.* (1997), courtesy of Athena Coustenis.

lifting a haze layer and giving particles longer to grow and coalesce. Although similar measurements can be made from direct observation of Titan's disk, these rely on (uncertain) assumptions regarding the single-scattering albedo and phase function of the haze particles.

Surprisingly, the HST measurements of Titan's shadow allow more information to be extracted than high phase angle observations by Voyager 2, half a Titan year before. In part, this is due to the wavelength coverage of HST (our observations spanned 336 nm to 953 nm, whereas the Voyager high phase angle measurements only sampled about 350 nm to 550 nm). Additionally, the Voyager data with just Titan against black space could not discriminate an equatorial “bulge” in haze altitude (an oblate-

knowing what to expect” – Titan appeared “non-circular” and had bright patches, although it was not known whether these could be clouds or surface features.

More recently, improved instrumentation has enabled mapping of similar quality and resolution (the larger ground-based aperture is compensated by the longer wavelength) to the HST results. The haze optical depth is smaller at 2 μ than at 0.94 μ , so surface contrasts are somewhat larger in the ground-based results, and show essentially the same features. Observations of the “dark side” of Titan appear to show brighter polar regions, although it is not certain whether these are real or an artefact of the image processing (AO images are deconvolved: the haze contributes a large fraction,