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LOW SURFACE PRESSURE MODELS FOR TITAN'S ATMOSPHERE

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ABSTRACT

The inversion model for the atmosphere of Titan, first proposed by Danielson, Caldwell and Larach, is reviewed. The basic features of the model are: a cold surface (80 K), a warm stratosphere (160 K) and a low surface pressure (20 mbar). The model is consistent with all existing thermal infrared spectrophotometry, but it cannot preclude the existence of an opaque, cloudy, thick atmosphere. The model is strongly supported by the recent scattering analysis of Podolak and Giver, which, together with the early analysis by Trafton, excludes other gases than methane as bulk constituents. Radio wavelengths observations, including recent data from the Very Large Array, are discussed. These long wavelength observations may be the only direct means of sampling the surface environment before an entry probe or flyby. The differences between the inversion model and Hunten's model must be resolved before detailed probe design studies can be performed meaningfully.

INTRODUCTION

It has been known for more than three decades (Kuiper, 1944) that Titan is unique among the well-observed satellites in the Solar System in having a substantial atmosphere, including at least some CH_4. However, for much of the intervening time, this datum was ignored by most of the astronomical community.

In 1972, there began a revolution in our understanding of this enigmatic satallite. Trafton (1972a) reported the possible detection of H_2 on Titan and also re-evaluated the quantitative analysis of the observed CH_4 absorption at 1.1 μm, revising upward the estimate of the minimum column abundance of the Titanian atmosphere (Trafton, 1972b). Allen and Murdock (1971) had observed an anomalously high brightness temperature at 12 μm and concluded that the satellite had an atmospheric greenhouse. Morrison *et al.* (1972), influenced by their own radiometric observations at 20 μm and by the papers cited above, proposed a greenhouse model in which the opacity due to the broad, pressure-induced rotational transitions in H_2 at 17 μm and 28 μm, together with the relative transparency of H_2 in the 8-14 μm terrestrial atmospheric window, produced the observed infrared properties of Titan. Pollack (1973) presented a detailed greenhouse model, which also included the pressure-induced opacity of CH_4. He derived a surface temperature $\simeq$150 K, with a minimum surface pressure $\simeq$400 mbar and a minimum column abundance $\simeq$50 km-atm total of H_2 and CH_4.

There was an alternate interpretation of the new Titan data, however. Danielson *et al.* (1973) and Caldwell (1977) developed and refined a model atmosphere with a surface temperature $\simeq$80 K, a surface pressure $\simeq$20 mbar and a column abundance of $\simeq$2 km-atm of CH_4. This class of model, with its relatively low surface pressure, has become known as the inversion model, because it features a high altitude temperature inversion that is capable of reproducing all of the infrared observations of Titan.

There are other candidate models as well. Hunten (e.g., 1977) has been a forceful advocate for the inclusion of N_2 and has pointed out the theoretical difficulties in maintaining a substantial H_2 component on Titan against its high escape rate. Cess and Owen (1973) have included the effects of noble gases on greenhouse models.

The differences between these models must be resolved if there is to be an accurate understanding of the current state of Titan, and if its clues to the larger question of the origin and evolution of the outer Solar System are to be exploited. On a more practical level, an improved knowledge of the atmosphere is a prerequisite for many of the more useful potential spacecraft explorations of Titan.

It is the purpose of this paper to review the original inversion model, to discuss the impact of recent results on the model, and to speculate on imminent developments. In the following chapter, Hunten describes the current status of models with higher surface pressures and column densities.

THE INVERSION MODEL

The details of this model have previously been given by Danielson *et al.* (1973) and by Caldwell (1977). This section summarizes those papers.

The starting point for the model was the adoption of the smallest column abundance for the Titanian atmosphere that was consistent with observations. From the work of Trafton (1972b), that was 2 km-atm CH_4, with no other major molecular constituent. The motivation for choosing this extreme value was originally to counterbalance the then-prevailing trend among planetary scientists to favor the largest tenable column abundance. However, as will be discussed below, this choice is further justified by considerations of CH_4 vapor pressure and of the global radiation budget.

The 2 km-atm abundance was determined by Trafton from his analysis of the $3\nu_3$ band of CH_4 at 1.1 μm. Podolak and his colleagues have shown that it can be reconciled with the visible and near infrared absorption bands of CH_4 in the spectrum of Titan. This work will be summarized in the next section. However, toward shorter wavelengths, the reflectivity of Titan is not determined by CH_4 alone.

From 6000 Å down to 2600 Å, the reflectivity decreases monotonically. The shortest wavelength point, determined from broadband photometry by OAO-2 (Caldwell, 1975), corresponds to a geometric albedo of 0.033 for a radius of 2900 km. Caldwell (1974) has emphasized that such a low value is inconsistent with Rayleigh scattering even from the minimal 2 km-atm of CH_4. Models with higher abundances have greater disagreement with the observations.

The low ultraviolet albedo requires the presence of an absorbing species high in the atmosphere of Titan. The Rayleigh scattering constraint means that there can be at most a clear layer of $\approx$0.1 km-atm column abundance above the absorber if it is completely black at 2600 Å.

No molecule has been identified with the spectral characteristics necessary to reproduce the variation in reflectivity exhibited by Titan. However, laboratory simulations of Titan-like atmospheres exposed to natural energy sources such as far ultraviolet light generally produce a dark reddish-brown polymer (e.g., Khare and Sagan, 1973) that has the qualitative properties to explain the trend of Titan's ultraviolet to visual albedo curve. In this process, CH_4 is decomposed, and the fragments recombine to form the large colored particles. Such particles will henceforth be called "dust" to differentiate them from possible condensation products.

The original inversion model was based on an assumption that such a process actually occurs on Titan. Although the details on Titan are not fully understood, as will be discussed below, the short wavelength absorption is definite. It is therefore certain that a significant fraction of the non-reflected Solar radiation incident upon Titan is absorbed high in the atmosphere, and not at the surface.

An object at Titan's distance from the Sun which has a high thermal emissivity will acquire an equilibrium temperature of the order of 100 K. The actual value will depend on the object's albedo. If the object does not have a high thermal emissivity at the wavelength of peak emission ($\approx$30 μm for 100 K) the temperature will rise until the integral over all wavelengths of the emissivity multiplied by the Planck function equals the absorbed energy.

Titan's upper atmosphere has in fact reached an equilibrium temperature well above 100 K. The evidence for this is found in the middle infrared spectrophotometry of Gillett *et al.* (1973) and Gillett (1975). These data show a brightness temperature of $\approx$160 K in the ν_4 fundamental band of CH_4 at 3 μm. Since this band is very strong, it is optically thick at very high altitudes, and this brightness temperature must be very close to the actual physical temperature there.

At lower altitudes, there must be an opaque, colder level because, without an internal energy source, there is not enough incoming radiant energy to maintain the outer skin of the satellite at this elevated temperature against radiation to space. Hence, Titan has a temperature inversion, with warmer layers overlying cooler ones.

It is possible that an atmospheric greenhouse effect could maintain warmer layers below the cold, opaque level. This conjecture cannot be disproven now. The simplest model, advocated here, is that the opaque layer is in fact the physical surface.

It is postulated in the inversion model that the surface is CH_4 ice and that the atmosphere is in vapor pressure equilibrium with the surface. This fixes the surface temperature at $\approx$80 K, because this value, combined with the CH_4 saturated vapor pressure (20 mbar) gives the correct column abundance (2 km-atm). As discussed by Danielson *et al.* (1973), this temperature also leads to a reasonably accurately balanced global radiation budget for the model atmosphere and surface.

The inversion model has been successful in explaining the infrared emission of Titan. Figure 1 shows the 8–14 μm region, with the model compared to Gillett's (1975) data.

The emission peaks centered at 7.7 μm, 12.2 μm and 13.7 μm in the model are due respectively to CH_4, C_2H_6 (ethane) and C_2H_2 (acetylene). CH_3D and C_2H_4 have not been included in the model. Between the peaks, the emission is due to the (ultraviolet-absorbing) dust. This effect is more evident in the next figure. The surface in the model is too cold to influence the emission shown in Figure 1.

Figure 2 shows the computed emission out to 40 μm. The dust has been taken to have a temperature of 160 K, with an emissivity proportional to $1/\lambda$. This is a simplifying approximation, consistent with an index of refraction that is constant with wavelength.

The surface is modelled as a black body with unit emissivity at 78 K. (This value will be discussed presently.) In the model, most of the radiation at 20 μm is due to the dust; and beyond 40 μm, most is due to the surface.

The parameters of any model fitted to reflected and emitted light from a planet are sensitive to the radius. A flux is the measured datum, but the radius is required for computing the physically meaningful quantities: brightness and albedo. In refining the original inversion model, Caldwell (1977) used the occultation radius of 2906 km measured by Elliot *et al.* (1975) for the effective radiating layer and the effective reflecting layer of the atmosphere. The surface radius is unknown, but for a specific value of the surface radius, a definite surface temperature can be calculated that balances the absorbed and emitted radiation. With the vapor-pressure equilibrium envisaged in the model, this also determines the surface pressure and column abundance. Caldwell (1977) chose a baseline model with a surface radius of 2700 km, leading to a surface temperature of 78 K, surface pressure of 16 mbar and column abundance of 1.3 km-atm. The amount by which these values change as a function of surface radius is summarized in Figure 3.

In the inversion model as described above, there are no clouds of condensate particles. This is not unreasonable, even though the entire surface is postulated to be in vapor pressure equilibrium with the atmosphere, because the high altitude heating may be sufficient to cause a positive temperature lapse rate everywhere. Such an atmosphere would be extremely stable against vertical convection.

If the radiative interchange between surface and atmosphere is such that a condensation cloud forms at low altitudes, the basic features of the model would not change greatly. The situation where a major constituent of an atmosphere is condensable has been discussed by Lewis and Prinn (1973) and Hunten (1977).

Because of the postulated vapor pressure equilibrium, the atmosphere will act as an effective thermostat, to keep the surface everywhere isothermal at the temperature determined by the global average visible transmission of the atmosphere and by

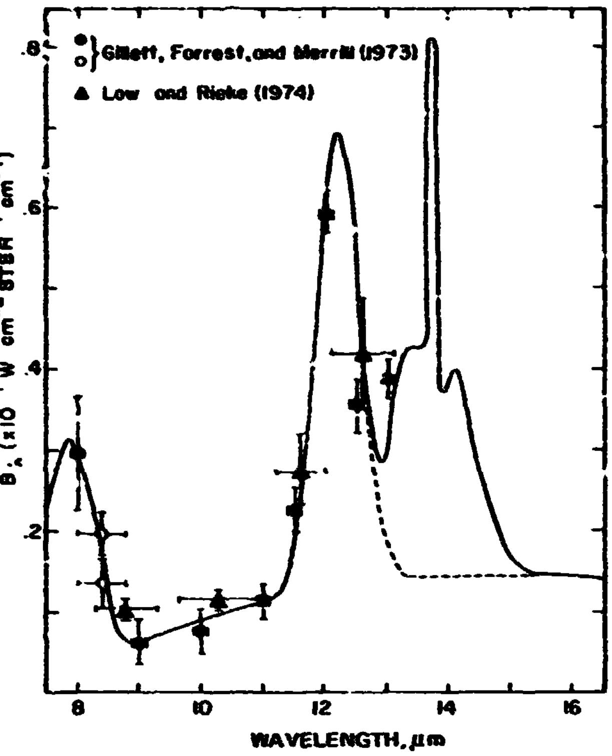

Figure 1. Details of the molecular band emission from Titan. The solid line includes emission from optically thin dust, approximate CH_4 emission and calculated emission from 0.5 cm-atm C_2H_6 and from 1.0 cm-atm C_2H_2; the broken line shows the emission with no C_2H_2. Emissions from C_2H_4 (10.5μm), CH_3D (8.7μm) and CH_3 (16.5μm) are not included in the model. The surface is not significantly bright at these wavelengths. See Gillett (1975) for further data, including additional points confirming the C_2H_2 feature. All figures in this article are reproduced from Planetary Satellites, *J. A. Burns, Editor, University of Arizona Press (1977).*

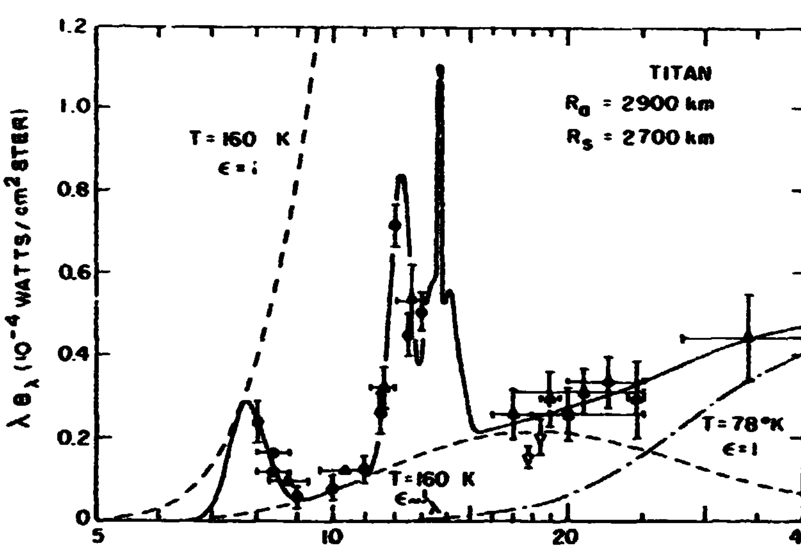

Figure 2. Comparison of the infrared photometric observations with the temperature inversion model. Axes are drawn so that the area under the curves is proportional to the energy traversing the atmospheric radius. Bandpasses for the closed circle data points are similar to the width of the circles. The solid line represents the total calculated emission from molecular bands and optically thin dust in a temperature inversion region at 160 K and a surface with unit emissivity at 78 K. The molecular abundances are 0.5 cm-atm C_2H_6 (12.2μm), and 1.0 cm-atm C_2H_2 (13.7μm). The CH_4 peak at 7.7μm is only approximate. The predicted ratio of atmospheric emission to surface emission was used to calculate the effective radius for each observational point. Closed circles are data from Gillet et al. *(1973), closed triangles are from Low and Rieke (1974), open triangles are from Knacke* et al. *(1975), and the closed square is from Morrison* et al. *(1972).*

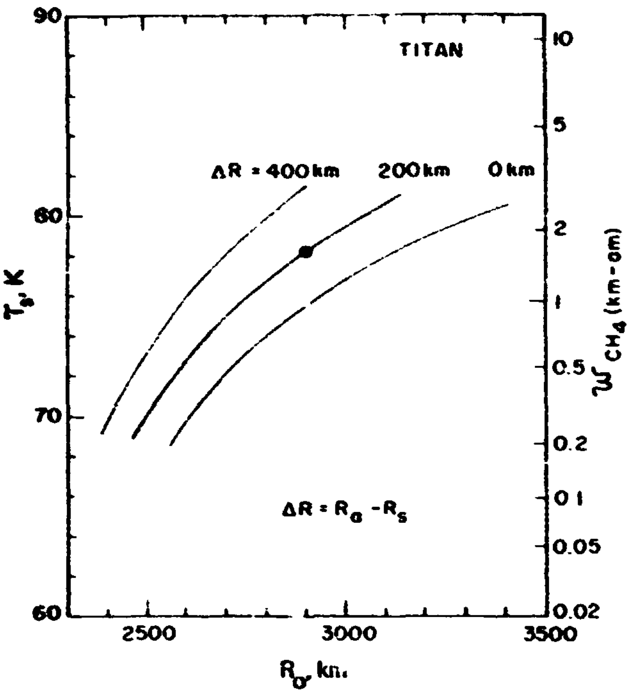

Figure 3. The energy balance of Titan. The ordinate is the surface temperature necessary in the inversion model to balance emitted and absorbed radiation from Titan, for various atmospheric and surface radii. On the right, the column abundance of CH_4 (W) corresponding to the surface temperature at the left is shown. A value of $g = 125$ cm s^{-1}, consistent with the baseline radius, was used to calculate W.

the downward infrared atmospheric emission. Any local region that found itself departing from the mean temperature in either sense would attempt to adjust its local vapor pressure by increased condensation or sublimation. Because of the sharp variation of CH_4 vapor pressure with temperature, winds would arise to restore an isobaric surface condition. The substantial latent heat of phase change of CH_4 would oppose the hypothetical temperature differential, and the local transient winds would continue until the differential disappeared.

In particular, Danielson *et al.* (1973) have shown that the atmosphere won't condense at the winter pole of Titan, because that pole never cools down. Assuming that the obliquity of Titan is the same as Saturn's, they calculated that about 5 percent of the atmosphere would condense on the winter polar during that season, without changing the surface temperature. This must be replenished by sublimation in the other hemisphere. The operative criterion in this calculation is that the surface cannot dissipate the latent heat of condensation faster than a blackbody at 80 K can radiate to space.

The assumption concerning the obliquity of Titan is not critical. For any general orientation of Titan's polar axis, precession will alter Titan's seasonal year, but most probably not enough to matter.

If the obliquity assumption is even approximately correct, then each Titan pole at its summer solstice will experience the largest diurnally-averaged solar flux of any point on the surface. Thus there are probably no absolute sinks of CH_4 on Titan. At some point during a Titan year, all locations will sublime some CH_4. However, on an annual average, the poles receive less flux than the equator, so there will be a steady, cumulative movement of CH_4 from the equator to the poles.

This situation is clearly statically unstable. Titan will respond by an equatorward flux of CH_4 glaciers to maintain its spherical shape. One effect of this motion will be to overturn the surface layer continually. Dust particles settling on the surface will not pave it over. The surface will not be hermetically sealed from the interior, and there will be fresh CH_4 exposed to the atmosphere to replenish those molecules irreversibly lost to photochemical action.

An alternate surface scenario, suggested by R. E. Danielson is that a modest greenhouse effect could raise the surface temperature to $\approx 90\,K$, the CH_4 triple point. This would permit the formation of CH_4 oceans. In this case, ocean currents, and not glaciers, would recycle the CH_4 to the equatorial zone.

RECENT DEVELOPMENTS RELATED TO THE INVERSION MODEL

1. The Hydrogen Abundance.

   Recently, Münch *et al.* (1977) observed the (3-0) S1 quadrupole line region on Titan, and found *no* evidence for absorption there. They established a 3σ upper limit corresponding to a column abundance of 1 km-atm. This result differs from Trafton's (1972a) finding of 5 km-atm. It could represent an exotic variability on Titan, but the preferred interpretation of the author is that it means there is little and possibly no H_2 there. Münch *et al.* (1977) had superior spectral resolution to Trafton (1972a), and Trafton required a sophisticated statistical analysis to extract information not evident in the raw data.

   If true, the new result of Münch *et al.* (1977) does not directly alter the inversion model. As Danielson *et al.* (1973) stated: "Although no H_2 is required, the presence of some H_2 as reported by Trafton is readily accommodated." However, the absence of H_2 will provide an obstacle to all greenhouse models which require it to provide opacity between $15\,\mu m$ and $35\,\mu m$. As will be discussed below, an atmosphere free of H_2 could have important photochemical implications. Further, it has been a continuing problem (Hunten, 1977) to understand how an appreciable steady-state concentration can accumulate on Titan because of its rapid loss to space.

2. The Methane Abundance.

Trafton (1972b) estimated the CH_4 column abundance to be 2 km-Amagat if CH_4 is the only major constituent of the atmosphere. Lesser abundances would have been allowed if there was another major gas to broaden the lines of the $3\nu_3$ band of CH_4 observed by Trafton.

Lutz *et al.* (1976) derived a CH_4 abundance of 80 m-A, thereby implying the presence of $\approx$20 km-A of some other gas, such as N_2 or Ne. Their result came from laboratory and planetary observations of the visible and near infrared overtone and combination bands of CH_4. Their two kinds of observations were scaled by a simple reflecting layer model for Titan's atmosphere.

However, Podolak and Danielson (1977) and Podolak and Giver (1978) have argued that the reflecting layer model is inadequate to represent all the CH_4 bands observed on Titan. These bands vary in intrinsic strength by several orders of magnitude. Even the strongest of them in Titan spectra have finite residual central intensity. These papers explain the central band reflectivity as being due to backscattered light from the same dust particles that cause the previously discussed ultraviolet absorption. The change in optical properties from ultraviolet to red is due to the assumed variation of the imaginary index of refraction of the dust with wavelength and also due to the modelled particle size distribution. By judiciously limiting the permitted particle sizes, Podolak and Danielson (1977) find that ultraviolet photons see the particles as large compared to wavelength, and hence experience strong forward scattering, whereas red photons see small particles and are isotropically scattered. Podolak and Danielson (1977) simultaneously explain most of the CH_4 spectral features and the continuum variation in albedo with their dust model. They require a CH_4 column abundance $\approx$1 km-atm.

Podolak and Giver (1978) have modified the model by confining the dust to the upper layers of Titan's atmosphere. This is reasonable if the dust is formed at high altitudes, grows continuously in size, and settles rapidly to the surface after reaching a critical size. This adjustment increases the observed strengths of weak bands relative to strong ones. They ultimately derive a CH_4 abundance of at least 2 km-A.

When the results of Podolak and Giver (1978) are combined with those of Trafton (1972b), the inversion model, with its column abundance of 2 km-A, is entirely consistent with the methane absorption spectrum.

3. Dust.

One of the interesting claims of Podolak and Danielson (1977) is that the continuum reflectivities of both Titan and Saturn from 2500Å to 10,000 Å can be explained by dust particles with the same optical properties for both planets. The only changes required are in the total amount of the dust and its vertical distribution. While this conclusion is not universally accepted (Scattergood and Owen, 1977; see also the discussion below), it will be stipulated for the present for the purpose of illustrating, if not proving, a point.

Although Saturn's atmosphere shows pronounced variations in color according to season, its equator is usually very dark in the ultraviolet. The standard interpretation is that this corresponds to a latitudinally restricted concentration of dust particles. However, photographs taken through a narrowband filter in the strong 8900 Å CH_4 band show the equatorial region to be relatively brighter than the rest of the planet (Owen, 1969).

Although Owen interpreted his observation as a high-altitude CH_4 condensation cloud at Saturn's equator, more recent models (e.g., Caldwell, 1977b) do not favor this interpretation. The one-way optical depth for absorption in this band is probably in the range from 1 to 3 above the cloud tops. It is more probable that Owen (1969) has actually recorded scattered light from high altitude dust particles. Unfortunately, it is not now possible to exhibit such an effect visually for Titan, because of the limits of spatial resolution. This alternate interpretation of Owen's results supports the concepts of Podolak and Danielson (1977) and of Podolak and Giver (1978).

Laboratory experiments on dust particle formation have recently been performed by Scattergood and Owen (1977). They used high energy proton bombardment of simulated planetary atmospheres to dissociate such species as H_2, N_2, CH_4, NH_3, and H_2S, and then observed the resulting particulate formation. Their work was an advance over that of Khare and Sagan (1973) because Scattergood and Owen could initiate reactions in mixtures excluding the long wavelength photon acceptors NH_3 and H_2S. Because of experimental difficulties, Khare and Sagan required these molecules to absorb light longward of 2000 Å before they could initiate any reactions. Chang (this volume) has further discussed the relevance of high energy.

Scattergood's and Owen's result indicate that particles suitably colored to reproduce observed planetary reflectivities from visual to ultraviolet wavelengths do not form unless such species as N_2, NH_3, or H_2S are present. Specifically, they claim that simple mixtures of H_2 and CH_4 do not produce particles with the required coloration.

The inversion model can readily accommodate minor amounts of most of these gases without changing the basic features of the model. However, they could not be major species, or the simultaneous satisfaction of the limits imposed by Trafton (1972b) and by Podolak and Giver (1978) would be impossible. N_2 has a high vapor pressure, and could be the remnant from primordial NH_3 previously photodissociated. H_2S also has a higher vapor pressure than NH_3, and is not excluded by any spectroscopic observations. It could conceivably have a source in the interior of Titan.

IMMINENT DEVELOPMENTS IN TITAN STUDIES

1. Ultraviolet Spectroscopy.

   On January 26, 1978, the International Ultraviolet Explorer was launched successfully. This satellite will extend the wavelength range and the resolution significantly beyond the capabilities of OAO-2 (Caldwell, 1974, 1975). The possible detection of Rayleigh scattering below 2600 Å and of spectral signatures of specific molecules could lead to model constraints too various to outline here. Titan is a high priority target for the IUE, so significant results may be expected soon.

2. Radio Wavelength Observations.

At millimeter and centimeter wavelengths, it is a fair prospect that Titan's atmosphere will be transparent. Measurements there offer the possibility of sampling the surface unambiguously and of differentiating between candidate molecules. A major problem has been that diffraction makes the detection of a relatively weak signal from Titan difficult in the presence of the very strong confusion from Saturn itself.

Existing and future radio observations are summarized in Table 1. Briggs (1974) used the NRAO interferometer at Greenbank with three baselines of 0.5, 1.9, and 2.4 km, observing at 3.7 cm for 19 hours. Scaling his result to the baseline surface radius of 2700 km (Caldwell, 1977a) gives a brightness temperature of 99 ±34K. This result supports the inversion model. The limiting factor in Briggs' work is signal to noise.

Table 1. Radio Observations of Titan

Reference	Instrument	Wavelength	T_B*	Limitations
Briggs (1974)	NRAO Interometer (Greenbank)	3.7 cm	99 ± 34	Signal to Noise, confusion with Saturn
Conklin *et al.* (1977)		3.3 mm	213 ± 38	Confusion with Saturn
Jaffe *et al.* (1978)	VLA	1.3, 2, 6 cm	90 ± 30	Signal to Noise
---	Bonn 100 m dish	1.3 cm	---	No Data Yet

* Assumed surface radius = 2700 km

Conklin *et al.* (1977) used the 36-foot millimeter dish at NRAO Tucson in the photometer mode. They made two observations three months apart. Saturn was out of the primary beam, but currently unmeasured side lobes can generate 200% systematic errors from such a close, bright object. Conklin *et al.* were careful to measure the background after Titan had moved away, but they cannot rule out temporal changes in the side lobes. The measurements were in two broad bandpasses near 3.3 mm, with the resulting brightness temperature of 213 ± 38 K for a surface radius of 2700 km.

If their measurement represents the surface temperatures, as Conklin *et al.* (1977) conclude, then the inversion model would need a major revision, along the lines suggested by Figure 20.2 of Hunten (1977), or Hunten's article in this volume.

The disagreement between the two published observations could be real because they are at different wavelengths, but the requisite atmospheric opacity to produce such numbers seems unphysical. Further observations were clearly needed. Recently, Jaffe *et al.* (1978) used the Very Large Array interferometer at Socorro, New Mexico to remeasure Titan at 1.3, 2 and 6 cm. The total observing time was 35 hours on three nights, including simultaneous observations at different wavelengths on one night. From night to night, between 4 and 8 dishes were available, with baselines up to 10 km. Ultimately, 27 dishes with baselines up to 35 km will be operable. Currently, signal to noise limits the data, but since this improves as the square of the number of working dishes, this problem will eventually diminish greatly. Confusion with Saturn is of relatively low importance. In fact, the instrument will eventually be capable of measuring the radius of the surface of Titan.

Preliminary analysis of VLA observations at 6 cm indicates a nominal brightness temperature of 90 K ± 30 K(1σ) for a surface radius of 2700 km, with an upper limit of 180 K (3σ). This is in good agreement with Briggs (1974) but disagrees with Conklin *et al.* (1977). Further analysis, to reduce the remaining uncertainty, is underway.

Finally, it is noted in Table 1 that the 100 meter dish in Bonn will also be capable of making useful measurements for Titan, but such measurements have not yet been done.

SUMMARY AND PROSPECT

Pending a clarification of the radio brightness measurements outlined immediately above, the inversion model for Titan, as proposed by Danielson *et al.* (1973) and modified by Caldwell (1977a), remains completely viable. Baseline parameters of the model are: surface temperature = 78 K; column abundance of CH_4 = 1.6 km-atm; surface pressure = 16 mbar. Engineering studies for Titan probe missions must consider these numbers.

It is probable that Titan is a highly evolved planet. It is different from the Jovian planets in that significant quantities of its atmosphere can escape over the life of the solar system. It also lacks a means of thermally recycling atmospheric dust particles to fully reduced compounds in its interior. It is reasonable to expect that the current wide range of Titan atmospheric models will soon be narrowed greatly. When this preliminary phase is complete, future studies should address the task of unravelling Titan's evolutionary history. Direct exploration by space vehicles seems to be the only means available for doing this.

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