Titan’s inventory of organic surface materials

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[1] Cassini RADAR observations now permit an initial assessment of the inventory of two classes, presumed to be organic, of Titan surface materials: polar lake liquids and equatorial dune sands. Several hundred lakes or seas have been observed, of which dozens are each estimated to contain more hydrocarbon liquid than the entire known oil and gas reserves on Earth. Dark dunes cover some 20% of Titan’s surface, and comprise a volume of material several hundred times larger than Earth’s coal reserves. Overall, however, the identified surface inventories (>3 x 10^3 km^3 of liquid, and >2 x 10^5 km^3 of dune sands) are small compared with estimated photochemical production on Titan over the age of the solar system. The sand volume is too large to be accounted for simply by erosion in observed river channels or ejecta from observed impact craters. The lakes are adequate in extent to buffer atmospheric methane against photolysis in the short term, but do not contain enough methane to sustain the atmosphere over geologic time. Unless frequent resupply from the interior buffers this greenhouse gas at exactly the right rate, dramatic climate change on Titan is likely in its past, present and future. Citation: Lorenz, R. D., et al. (2008), Titan’s inventory of organic surface materials, Geophys. Res. Lett., 35, L02206, doi:10.1029/2007GL032118.

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2. Lakes

[6] Although a surface reservoir of hydrocarbon liquids was long expected on Titan, convincing evidence for such liquids was not found until radar imaging covered high latitude areas [Stofan et al., 2007]. Above 55°N, radar observations have now (through T30 – May 2007) covered 55.4% of the terrain: of this, some 10% (∼400,000 km², or 0.5% of Titan’s surface) is identified as covered by lakes or seas; see Figure 1. A variety of lake morphologies imply diverse formation mechanisms that may include terrain flooding and karst dissolution (K. L. Mitchell et al., Titan’s north polar lake district: Insights from the Cassini Titan RADAR mapper, manuscript in preparation, 2007). Features range in size from a few kilometers (the smallest recognizable in our best data of ∼300 m/pixel) to several hundred km. The combination of low radar reflectivity and
high microwave emissivity plus the feature morphology and association with channels together point to present-day liquid.

[7] To determine the lake depth we use terrestrial analogs as a guide. A brief survey of terrestrial lakes (see Figure 2) indicates that a convenient and reasonably effective estimate is that a lake has an aspect ratio of 1/1000 (i.e. the average depth \( d = 0.0010 \times \) area, where the lake area is \( X^2 \), or equivalently its depth in meters equals the size in kilometers.) A least-squares linear fit to the world’s 20 largest lakes yields \( d = 0.0015 \times + 66 \). In practice, the diverse lake formation settings - from deep rift, fault or glacial lakes to shallow playas - lead to variations of an order of magnitude about these values. A survey (A. G. Hayes et al., Titan’s lake distribution and classification from the Cassini RADAR, manuscript in preparation, 2007; see also Figure 1) of the Titan lakes indicates a median area of \( 100 \text{km}^2 \), and thus a depth of \( \sim 10 \) m and a volume of \( 1 \text{km}^3 \). However, a ‘similar-shape’ model like this will find the liquid volume dominated by the largest lake - so far the largest lake or sea imaged is a \( 400 \times 200 \) km (80,000 km\(^2\)) section of what is presumably a rather larger (as yet unnamed) feature at \( 70^\circ \text{N}, 315^\circ \text{W} \), which would correspondingly be \( \sim 300 \) m deep, or have a total volume of some \( \sim 25,000 \) km\(^3\), even without allowing for unobserved areas of this feature (which near-infrared imaging shows to be part of a large, irregular optically-dark feature with an area of some 340,000 km\(^2\) [Turtle et al., 2007]).

[s] Another metric is the height of nearby topography. Terrestrial examples suggest that average lake depth is often a factor of 10 less than the height of the highest nearby terrain, although again there are extremes (e.g., Lake Baikal, Earth’s deepest lake at 1600 m, has mountains of \( \sim 3400 \) m nearby, whereas the Great Salt Lake has a depth of only a few m but has nearby km-high mountains - i.e. the depth/terrain ratio can vary from about 2 to several hundred.) Altimetry and other data show that there is relief of \( \sim 700 \) m.
or more in Titan’s North polar lakeland terrain, as in a few other areas on Titan. Thus a characteristic depth of 70 m would be implied, in good agreement with the 10–300 m range suggested by area scaling above.

[9] A final, and completely independent, measure is radiometric. The darkest parts of some lakes, generally the largest ones, are ‘black holes’, offering no measurable radar return down to the instrument noise floor of ~26 dB [Stofan et al., 2007]. This requires not only that the surface reflection be very small (consistent with a smooth surface of a low dielectric constant material, such as a liquid hydrocarbon surface unroughened by waves) but also requires that the liquid be deep and/or lossy enough to suppress a bottom reflection. Lake bottoms with sediment density increasing smoothly with depth could also suppress bottom reflections via gradient-index impedance matching: however, there are morphological indications such as dark channels incised in almost-as-dark lakes that suggest that at least in some places bottom reflections are seen. Assuming then that such lakebed features are being hidden in ‘black’ areas by column absorption, a minimum depth can be inferred: the lower the assumed loss tangent δ, the deeper the lake must be. Clean liquid hydrocarbons have δ = 10^-4 to 10^-3 [Sen et al., 1992; Rodriguez et al., 2003] although suspended or dissolved polar molecules such as nitriles and small tholin particles could increase these values. A penetration depth (1/e one-way absorption - see e.g. similar calculations elsewhere in the Saturnian system [Ostro et al., 2006]) of λ/2πδ√ε, with λ the radar wavelength of 2.2 cm and ε the real part of the dielectric constant (∼2), would therefore be 2–20 m - lakes with nonzero reflectivity or visible lakebed features are therefore likely shallower than this range.

[10] In summary, several lines of evidence point towards smaller lakes on Titan (∼100 km²) having a depth of the order of 10 m, and the handful of large ‘seas’ having depths ten or more times greater. It is noteworthy, that dozens of Titan’s lakes individually contain ∼200 km³ of liquid methane/ethane, an amount equal to the ∼130 billion tonnes of proven natural gas reserves on Earth. Indeed, Titan’s total inventory of liquids exceeds terrestrial oil and gas reserves of proven natural gas reserves on Earth. Indeed, Titan’s total inventory of liquids exceeds terrestrial oil and gas reserves [Lorenz et al., 2006a; Radebaugh et al., 2007], correlating with areas seen to have a distinct dark near-infrared spectral type [e.g., Soderblom et al., 2007], although very few are found poleward of 30°. As on Earth, a range of dune size and interdune sand depth is observed. First, when the radar illumination is broadside-on to large dunes and interdune sand is thick enough that the intrinsic radar albedo of the surface is uniform, topographic shading is the major contributor to brightness variation in the scene. This permits a radarclinometric estimate of dune height of the largest dunes of ∼150 m [Lorenz et al., 2006a]. The typical dune width to interdune distance ratio is 1–4, so we can assign an area-average sand dune thickness (assuming a triangular cross-section with height) of 15–50 m. To this must be added the thickness of sand in the interdune areas, estimated below as ∼5 m, and thus we adopt a typical area-averaged sand thickness for thick-sand areas of 30 m.

[11] More typically, with off-broadside observations, smaller dune height and especially with thinner interdune sand, the duneform is seen only as a dark streak, against a brighter exposed or thinly-covered interdune background (as for many radar observations of dunes on Earth). In these cases, radarclinometric measurement of height is impossible. However, field data of Earth dunes show [Lancaster, 1995] that longitudinal dunes have height:width of 0.01–0.2, implying Titan dune heights of 10–400 m (similar heights result from considering the height:spacing ratios).

[12] We can also apply a radiometric constraint, namely that the dunes appear dark against the bright interdune material by obscuring it. Rodriguez et al. [2003] determine loss tangent δ of tholin of between 0.001 and .05. The corresponding penetration depths as above (∼λ/10δ) are 2 m and 0.04 m. Thus a minimum thickness of dark streaks (and dark interdune areas where topographic shading is seen) of a meter or so seems likely, although is in this case less constraining than the morphological similarity range of >10 m above. Again adopting a local dune coverage fraction of 20–50%, we therefore find an area-average sand thickness of 2–200 m and adopt 10 m as a working value.

[13] Assuming roughly equal areas of thick and thin sand (noting that particular resolution and viewing azimuth is needed to identify the former - although dark streaks are more commonly seen in data so far, better imagery of the same areas might show topographic shading), the sand seas (i.e. 40% of the half of Titan’s surface that lies between ±30° latitude) have an average sand depth of 20 m, which corresponds to a to a total inventory of some 3.2 × 10⁵ km³ of material. This corresponds to about 400 times the ~900 billion tonnes of proven coal reserves on Earth [BP, 2007], a material which has some superficial similarities with the likely dune sand on Titan. The figure above is perhaps more likely to underestimate the inventory than to overestimate it: a reasonable range is therefore 2–8 × 10⁵ km³.

4. Discussion and Conclusions

[14] The results reported here must be considered preliminary, not least since they are based on only 20% coverage of Titan’s surface, of which most is in the northern hemisphere and the equatorial regions. However, the hemispheres would have to be very different to give results that diverge widely from the estimates presented here. The
inventory is substantial, exceeding in absolute terms the biospheric, oceanic and fossil fuel reservoirs on Earth; see Table 1. In terms of column abundance (mass/area) Titan’s carbon inventory may approach Earth’s non-carbonate reservoirs.

[17] The total inventory we measure is substantially smaller than the reservoir estimated to be produced throughout the age of the solar system if methane photolysis were to have occurred continuously at its present rate. The apparent dearth of material (compared to these model predictions - a summary is given by Lunine et al. [2004].) supports such a picture. A final more speculative possibility is that some process has destroyed or subducted the deposits, such that they no longer exist at the surface.

[18] Note that the volume of sand considerably exceeds the amount of sand-sized material produced in impact ejecta for the known craters. Applying the sediment productions of Lorenz et al. [1995] for the known Titan craters yields only ~500 km$^3$ of mm-sized material. It is possible that the larger volumes of bigger ejecta particles could have been broken down into sand by other processes. The observed river channels, covering perhaps 0.1% of the surface and having incision depths of 100 m or less, are only able to account for ~10$^4$ km$^3$ of material. In sum, geological processes cannot account simply for the large volume of sand-sized material on Titan, supporting a photochemical origin for much of it [Lorenz et al., 2006a].

[19] The uncertainty in lake volume compared to dune volume spans a liquid:solid ratio of 0.03-1. Allowing for half of the liquid to be methane (e.g., see the ocean:atmosphere equilibrium discussion by Lunine et al. [1983] and Lorenz et al. [1999]), solid materials must dominate over liquid ethane. This contrasts with the predictions of photochemical models which indicated a converse relationship, that acetylene and other solids would amount to less than a third of the amount of liquid ethane (e.g. the acetylene:-

### Table 1. Titan Carbon Inventory Compared With Other Planetary Reservoirs$^a$

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Inventory (a), km$^3$</th>
<th>Inventory, GT carbon</th>
<th>Column Mass, kg/m$^2$</th>
<th>Pressure, mbar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Titan</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane in Atmosphere</td>
<td>800,000</td>
<td>360,000</td>
<td>4000</td>
<td>60</td>
</tr>
<tr>
<td>Ethane/Methane Lakes</td>
<td>30,000–300,000</td>
<td>16,000–160,000</td>
<td>200–2000</td>
<td>3–30</td>
</tr>
<tr>
<td>Sand Dunes</td>
<td>200,000–800,000</td>
<td>160,000–640,000</td>
<td>2000–6400</td>
<td>40</td>
</tr>
<tr>
<td>Fine Impact Ejecta</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erosion from River channels</td>
<td>8000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Earth Carbon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>140$^a$, 132$^e$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>230$^a$, 356$^e$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>3500$^a$, 900$^d$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmosphere</td>
<td>720</td>
<td></td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Biosphere</td>
<td>2000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>38,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithosphere (Kerogens)</td>
<td>1.5 × 10$^7$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithosphere (Carbonates)</td>
<td>6 × 10$^7$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Earth Water</strong></td>
<td></td>
<td>20</td>
<td>~2</td>
<td></td>
</tr>
<tr>
<td>Oceans</td>
<td>1.3 × 10$^9$</td>
<td>2.4 × 10$^6$</td>
<td>240,000</td>
<td></td>
</tr>
<tr>
<td>Lakes</td>
<td>125,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Icecaps</td>
<td>&gt;3 × 10$^7$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mars</strong></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>27,000</td>
<td>5900</td>
<td>150$^d$</td>
<td></td>
</tr>
<tr>
<td>Seasonal Frost Caps</td>
<td>7000</td>
<td>1600</td>
<td>40$^d$</td>
<td>1.5</td>
</tr>
<tr>
<td>Polar Layered Deposits</td>
<td>4000</td>
<td>900</td>
<td>23$^d$</td>
<td></td>
</tr>
<tr>
<td>Permanent Polar Caps</td>
<td>900,000</td>
<td>200,000</td>
<td>5000$^{a,e}$</td>
<td>185</td>
</tr>
<tr>
<td>Regolith</td>
<td>180,000</td>
<td>40,000</td>
<td>1000$^d$</td>
<td>37</td>
</tr>
<tr>
<td><strong>Venus</strong></td>
<td>5.8 × 10$^8$</td>
<td>1.25 × 10$^8$</td>
<td>10$^8$</td>
<td>90,000</td>
</tr>
</tbody>
</table>

$^a$Indirectly-determined quantities shown in italics; expressed as volume of condensed species.

$^b$Falkowski et al. [2000].

$^c$BP [2007].

$^d$Read and Lewis [2004].

$^e$May be much less [see Byrne and Ingersoll, 2003].
ethane production in three models reviewed by Lorenz and Lunine [1996] ranged from 0.2 to 0.8). Unless strong assumptions are made about the relative amounts of unobserved material such as subsurface ethane aquifers, models of photochemical production (and perhaps subsequent chemical processing in lakes) need to explain the predominance of solid materials. We note in this context that a major surprise from Cassini has been the complexity of the organic species formed, even in the ionosphere. Benzene has been detected in some abundance even at 1000 km altitude and some polycyclic aromatic hydrocarbons (PAHs) like anthracene and its derivatives have been inferred [Waite et al., 2007]. This unexpectedly rapid synthesis of heavy (solid) organics may be the reason there is more sand than liquid.

[20] Finally, the liquid inventory, while extending over a large enough area to permit evaporation fluxes to match photochemical depletion on short timescales [Mitri et al., 2007], is not enough in volume terms to sustain the concentration of this greenhouse gas in the atmosphere on geological timescales. But another way, there is an order of magnitude less liquid in the lakes than there is methane in the atmosphere, and photochemical models predict that inventory to be depleted in ~10 Myr. This makes the present climatic situation somewhat precarious - the observed surface reservoir, even if mostly methane, is unable to buffer the atmospheric methane for long, and unless volcanic resupply matches methane loss at just the right rate, significant climate change is likely in the future and by implication in the past [Lorenz et al., 1997, 1999]. Stronger volcanic fluxes of methane might lead to wetter conditions, perhaps producing flood features that cannot be readily explained in the present climate. Periods without resupply might lead initially to conditions dryer than present, but then (as the greenhouse warming of methane is lost) cooling and condensation of some of the nitrogen atmosphere onto the surface - a partial collapse [Lorenz et al., 1997].

[21] The apparent ocean-atmosphere equilibrium is very different on Earth, where the condensable greenhouse gas (water) in the air has a global equivalent depth of only ~2 cm, tiny compared to the ~2.4 km global average depth of its surface reservoir. The situation on Mars may be intermediate (Table 1) - if the permanent polar caps and regolith contain tens of times the atmospheric inventory of CO₂ [Read and Lewis, 2004], but recent work [e.g., Byrne and Ingersoll, 2003] suggests the caps have only a veneer of a few m of CO₂ ice, making Mars rather like Titan from a volatile inventory perspective. On Titan, if the liquid in the lakes participates in a seasonal cycle [e.g., Stevenson and Potter, 1986; Mitri et al., 2007], it has only a small influence on the overall meteorology and climate, since the liquid inventory (~200 kg m⁻², or 3 mbar or perhaps a few times higher than this) is small compared with the ~60 mbar of methane in the atmosphere, in contrast to the ~30% Mars seasonal pressure cycle. Further study would be needed to consider how the methane reservoir could influence seasonal changes in cloud patterns [e.g., Mitchell et al., 2006; Rannou et al., 2006].

[22] Future Cassini observations will help make a more complete inventory, notably in the Southern hemisphere, and indications of surface composition from near-infrared spectroscopy will be useful to understand the chemical species involved in the global carbon cycles. Indirectly, the changing patterns of methane clouds on Titan, especially in the equinox period 2009–2011 during Cassini’s proposed extended mission may show the participation of surface methane moisture in the climate system. Beyond this, important goals for a possible future mission might be to assess sediment and liquid depths directly with ground-penetrating radar, and to search in-situ for isotopic and other indications of chemical processing and volatile release from the interior.

[23] Acknowledgments. This work was supported by the Cassini Project, managed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Cassini is a joint project of NASA, the European Space Agency (ESA) and the Italian Space Agency (ASI). We thank our colleagues on Cassini, and in particular the RADAR team, for making this work possible.

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