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TRITON'S GLOBAL HEAT BUDGET

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(NASA-CR-188178) TRITON'S GLOBAL HEAT BUDGET (JPL) 16 p CSCL 03B

N91-23018

Unclas
G3/93 0008401

Abstract

Internal heatflow from radioactive decay in Triton's interior along with absorbed thermal energy from Neptune total 5 to 20% of the insolation absorbed by Triton, thus comprising a significant fraction of Triton's surface energy balance. These additional energy inputs can raise Triton's surface temperature between ~0.5 and 1.5 K above that possible with absorbed sunlight alone, resulting in about a factor of ~1.5 to 2.5 increase in Triton's basal atmospheric pressure. If Triton's internal heatflow is concentrated in some areas, as is likely, local effects such as enhanced sublimation with subsequent modification of albedo could be quite large. Furthermore, indications of recent global albedo change on Triton suggest that Triton's surface temperature and pressure may not now be in steady state, further suggesting that atmospheric pressure on Triton was as much as 10 times higher in the recent past.

Voyager's flyby of Neptune revealed that at 38K Triton is hotter than simple thermal models predict (1-3). This conclusion was based on the assumption that absorbed insolation is the only significant energy source, and that thermal properties common to other icy satellites also apply to Triton (1). More detailed models that include volatile transport also predict surface temperatures on Triton significantly lower than those measured by Voyager, suggesting that Triton has low emissivity (4,5). Because Triton has a surface composed primarily of solid nitrogen (6,7,8), because its atmosphere is composed primarily of nitrogen gas in vapor-pressure equilibrium with solid nitrogen on its surface (2,3), and because theoretical estimates suggest solid nitrogen has low emissivity (9), this is a currently accepted interpretation.

Despite first-order success in attempts to model volatile transport on Triton, there has been some difficulty in accounting for Triton's global albedo distribution and the apparent extent of its south polar cap (4,5). Several explanations for the discrepancies have been offered, including the supposition that new ice or frost on Triton is darker than old ice or frost (4), but none are very satisfying. Accordingly, the suggestion advanced here is that difficulties encountered in modeling volatile transport on Triton may result in part because significant and previously unconsidered, non-solar energy sources are available to Triton's surface. In particular, internal heatflow, absorbed radiation from Neptune, and long-time-scale changes in bolometric bond albedo may have substantial effects on the global surface temperature and pressure of Triton. In addition, anisotropies in Triton's global internal heatflow may have substantial effects on local sublimation rates and surface volatile coverage.

That internal heatflow on Triton or absorbed thermal radiation from Neptune could have measurable effects on Triton's surface temperature and volatile transport follows partly because Triton's 38 K temperature is the lowest known of any solar-system body (2). This is due to Triton's great distance from the Sun and high albedo (1,5), resulting in absorption of only a small fraction of the incident solar energy (~1.5 W m^{-2}). Also, the ubiquitous solid nitrogen on Triton's surface is capable of efficient redistribution of absorbed energy such that Triton should be nearly globally isothermal (10). Strong seasonal changes are also now occurring on

Triton as it nears a maximum summer solstice in its southern hemisphere (11,12), resulting in substantial volatile transport (4,5,10). Further contributing (perhaps substantially) to global volatile transport on Triton are several active plumes (1).

Triton's rather high density of 2.08 gm cm^{-3}, implies that its mass is ~70% rock (1), and this in turn implies a large, current source of internal heat from radioactive decay. In addition, Triton may have been strongly heated by tidal dissipation during its hypothetical capture by Neptune (13,14), although it is doubtful that tidal heating is presently significant (14). That Triton has been strongly heated is confirmed by Voyager images showing widespread and relatively recent geological activity (1).

Triton's ~15-μbar surface pressure (2) is sufficient to buffer the temperature of the nitrogen-ice portions of Triton's surface such that they are globally isothermal (10). This allows a calculation of expected steady-state temperature given bolometric emissivity, absorbed insolation and the extent of surface ice or frost coverage. A similar calculation was carried out for Triton (1), but the result is only approximate because internal heatflow and absorbed thermal radiation from Neptune were not taken into account. A more complete expression for the global energy balance of the ice or frost on Triton is:

$$\frac{S_o(1-A_f)a}{4\pi R^2} + Ha'' + N_o\epsilon_f a' = \sigma\epsilon_f T_f^4 a'' \qquad (1)$$

where S_o is the total luminosity of the Sun, R is heliocentric distance, a is the projected area of frost illuminated by the Sun, a' is the projected area of frost illuminated by thermal radiation from Neptune, a'' is the total area of frost, H is the global average heatflow, N_o is the total thermal flux per unit area from Neptune at Triton's distance from Neptune, A_f is the bolometric bond albedo of the frost, ϵ_f is the bolometric emissivity of the frost, T_f is the temperature of the frost and σ is the Stefan-Boltzmann constant.

More detailed models of frost temperature and volatile transport on Triton (4,5) suggest that, in response to seasonal and diurnal variations of insolation, some areas on Triton could be stripped of their seasonal coating of frozen nitrogen as summer progresses in Triton's southern hemisphere. At present, however, groundbased spectroscopy suggests that the bulk of Triton's illuminated surface is covered with nitrogen ice (6,7,8). Thus, for the purposes here, we will assume that Triton is completely covered in frozen nitrogen which reduces Eq. 1 to:

$$T = \left\{ \frac{1}{\sigma\epsilon} \left[H + \frac{N_o \epsilon}{4} + \frac{S_o(1-A)}{16\pi R^2} \right] \right\}^{1/4} \tag{2}$$

We drop the subscript f here because we are referring to global properties. Equation 2 specifies the global-average temperature on Triton given bolometric bond albedo, bolometric emissivity, global-average heatflow and the total thermal luminosity of Neptune. The bolometric bond albedo of Triton was derived from Voyager images (1,12,15) and from the measurements of the Voyager 2 Photopolarimeter experiment (16). Although the bolometric bond albedo of Triton derived from the photopolarimeter data disagrees somewhat with that derived from the imaging data, the consistency of results obtained by several investigators analyzing the imaging data, including our own extensive analysis of both groundbased and Voyager imaging data, leads us to adopt a value of 0.85 ± 0.05, the approximate average of the published imaging results and of our own results (1,12,15).

Calculation of N_o, the thermal radiation from Neptune incident on Triton, can be made using Neptune's size and effective temperature, and Triton's distance from Neptune. The effective blackbody temperature of Neptune is 59.3 ± 2.0 K (3), and, ignoring the small change in incident flux due to Triton's finite size, the incident thermal flux at any distance R_t from Neptune is given by:

$$N_o = 2\sigma T^4 \left[1 - \left\{ 1 - \frac{r_n^2}{R_t^2} \right\}^{1/2} \right] \approx \sigma T^4 \frac{r_n^2}{R_t^2} \quad \text{for } r_n \ll R_t \tag{3}$$

With $r_n = 25225$ km and $R_t = 354600$ km (1), N_o is ~3.6 mW m^{-2} at Triton's orbit. The absorbed fraction of this energy is proportional to Triton's projected area and thermal absorptivity (averaged over all wavelengths of interest in Neptune's thermal spectrum) which we assume is equal to its thermal emissivity. Finally, for the moment we treat Triton's spherically averaged heatflow as a free parameter, confined to the range discussed below.

Current radiogenic heatflow on Triton depends on the total mass of silicates in Triton and the present abundance of long-lived radionuclides. Triton's silicate mass fraction probably ranges from 0.65 to 0.75 (1), corresponding to 1.4 to 1.6 x 10^{22} kg of silicates. For outer planet satellites the most common assumption is that silicates have a chondritic composition which produces about 5.45 x 10^{-12} W kg^{-1} (17) from radioactive decay. Current estimates of lunar heatflow give a heating rate of 9.20 x 10^{-12} W kg^{-1} (17), which we treat as an upper limit to the radiogenic heating in Triton. The resulting range for Triton is then about 3.3 to 6.6 mW m^{-2} or a total of 0.75 to 1.5 x 10^{11} W.

The combined contribution of internal heatflow and absorbed thermal radiation from Neptune is then ~4-7 mW m^{-2}. The relative sizes of different contributions to Triton's surface heat budget are listed in Table 1, where the sum of internal heat flux and absorbed thermal radiation from Neptune is seen to be 5 to 20% of the insolation absorbed by Triton. For a bolometric bond albedo of 0.85 ± 0.05, an emissivity of 0.6 (9) and a heliocentric distance of 30.2 AU, a temperature increase of between 0.5 and 1.5 K is achievable over that resulting from absorbed insolation alone. The significance of this is underscored because a 0.5 to 1.5 K increase in surface temperature on Triton would increase its atmospheric pressure by a factor of 1.5 to 2.5! This is shown in Fig. 1, where surface pressure versus emissivity is plotted for 3 different values of Triton's bolometric bond albedo; clearly demonstrated are the large incremental effects of internal heat flux and absorbed thermal energy from Neptune. Thus, Triton seems to be one of the few objects in the solar system whose internal heatflow may significantly affect its surface temperature and pressure.

Although the above discussion assumes that Triton's internal heatflow is isotropic, potentially more interesting is the idea that Triton's heatflow is likely to be anisotropic. Support for this comes from images of Triton's equatorial regions and low northern latitudes which show definitive evidence of large-scale volcanic and tectonic activity (1). If these regions are geologically young, as their lack of cratering suggests (1,18), heatflow in these regions could be significantly greater than the global-average value, due possibly to bodies of cryogenic magma within a few tens of kilometers of the surface. One way to concentrate heatflow on a larger scale would be for convective circulation in Triton's mantle to transport internal heat preferentially to the surface in some regions. A permanent, kilometer-thick deposit of frozen nitrogen over most of Triton's southern hemisphere (as suggested by Voyager images) may act as a heat barrier, causing Triton's internal circulation to behave in just such a way. This is conceivable because the thermal conductivity of nitrogen ice is ~50 times less than that of water ice at 38 K, thus an extensive cap of frozen nitrogen (such as seems to exist on Triton) could act as a barrier to internal heatflow in the regions under the cap material. Nevertheless, the plausibility of mantle upwelling in Triton's equatorial regions and the role played by a thermally insulating polar cap needs to be assessed by numerical models of convection in Triton's mantle.

If Triton's heatflow is anisotropic, profound effects on local sublimation rates and albedos could result, depending on the magnitude of the anisotropy. For example, at 60% albedo, areas on Triton near 20° north latitude presently receive enough diurnal-mean insolation that a 38 ± 1 K temperature can be maintained with little or no net sublimation over a Triton day (5). For an emissivity of 0.6, between 64 and 79 mW m^{-2} is radiated to space at 38 ± 1 K. Thus, if local heatflow were just a few times the global average, a substantial amount of net sublimation would occur at 20° north latitude. If the areas of enhanced heatflow were axisymmetric, the condensation front of new frost in the present season would be expected to occur substantially north of 20°. In fact, if heatflow in places were ~10-15 times the global average, enough energy would be available to prevent ice condensation in any season, regardless of albedo, even for those areas north of the present arctic circle on Triton. Thus, areas on Triton showing evidence of enhanced sublimation correlated with past or present geologic activity may be seen in Voyager images.

Up to now we have tacitly assumed that Triton's global bolometric bond albedo is constant with time. Differences in Triton's present visual and near-infrared reflectance as compared to that in 1976 and 1977 (19,20), however, suggest that Triton's global albedo may be variable on a time scale of several years. The data show that Triton was much redder 13-14 years ago than now (1), and thus had a substantially lower bolometric bond albedo. There is further evidence for a change in Triton's reflectance from infrared observations reported by Cruikshank *et al.* (21).

If a change in Triton's bolometric bond albedo has occurred, then it must have affected Triton's surface energy budget. Because Triton's atmosphere stores a large amount of latent heat, the global surface temperature and pressure on Triton require~~s~~ a finite time to respond to changes in the global energy budget, thus suggesting that the temperatures and pressures at Triton's surface recorded by Voyager 2 may only be transient values.

To estimate the time scale for the response of Triton's atmosphere to albedo changes, we assume global energy balance. Therefore, for a unit area of ice on Triton's surface interacting with the atmosphere, energy balance can be written as:

$$\sigma\epsilon T_f^4 = -\frac{d\Sigma}{dt} h_s + S^* \tag{4}$$

where h_s is the latent heat of sublimation of nitrogen (taken here as 260 J g^{-1} [22]), Σ is the total column mass density of nitrogen gas in the atmosphere, and S^* is the total of absorbed insolation, global heatflow and all other heat sources per unit area averaged over the entire surface of Triton. S^* can be expressed as:

$$S^* = \frac{S_o(1-A_f)}{16\pi R^2} + H + \frac{N_o}{4}\epsilon_f \tag{5}$$

Because the global-average sublimation or condensation rate required to maintain a temperature of ~38 K is ~10^{-7} gm cm^{-2} sec^{-1}, to a very good approximation Triton's atmosphere is in hydrostatic equilibrium (23). The surface pressure is then given by $P = \Sigma g$, where g is the mean acceleration of gravity over the atmospheric column weighted by the local number density. Equation 4 can then be written as:

$$\frac{dP}{dt} = \frac{g}{h_s}\left(S^* - \sigma\epsilon_f T_f^4\right) \tag{6}$$

If the atmosphere is always in vapor-pressure equilibrium with the surface ice, the Clausius-Clapeyron relation, $P = K \exp(-b/T)$, defines the dependence of basal atmospheric pressure on temperature, and equation 6 becomes (where we again drop the subscript f):

$$\frac{dT}{dt} = \frac{gT^2}{h_s Pb} \left(S^\star - \sigma\epsilon T^4\right) \tag{7}$$

For the mean acceleration of gravity over the atmospheric column on Triton we can use as a good approximation the surface value of 78 cm sec^{-2} calculated from the mass of Triton (3) and its radius (1). A detailed calculation of the mean acceleration of gravity weighted by the density profile of a hydrostatic atmosphere shows that the correction for Triton is only ~3%. The relation describing the vapor pressure of nitrogen as a function of temperature is taken from Brown and Ziegler (24). The global-average emissivity is assumed constant because temporal variations in emissivity are likely to have a much smaller effect on the global energy budget than albedo changes. All other parameters are as previously defined except for the time history of the global bolometric bond albedo of Triton. We have calculated the bolometric bond albedo of Triton for 1976-1977 using the approach of Hillier *et al.* (15) and the average spectrum of Triton for 1976 and 1977 as published by Cruikshank *et al.* (19) and Bell *et al.* (20). From this we find that the bolometric bond albedo of Triton in 1976-1977 was ~0.74. Because there aren't sufficient data to specify the detailed time history of Triton's albedo, we treat 2 simple cases: an instantaneous albedo change and a linear change with time. In Fig. 2 are displayed the results of a simulation of the response of Triton's atmospheric pressure to an instantaneous albedo change and a linear change over 5 years, where we have included a contribution from Triton's internal heatflow and absorbed thermal energy from Neptune.

The major aspects of the calculations displayed in Fig. 2 are the initial and final atmospheric pressure, and the time scale for relaxation to a new equilibrium state after the albedo changes have ceased. Depending on the emissivity of Triton's surface, relaxation of the atmospheric pressure in this model can take as long as 15 years. For lower emissivities, the model suggests that Triton's atmospheric pressure could have been an order of magnitude higher as recently as 10-15 years ago, and that it may be relaxing to a value half or less of the ~15 μbars found by

Voyager. To effect an increase or decrease of ~150 μbars in Triton's surface pressure, about 2 gm cm^{-2} of nitrogen must either evaporate from or condense onto Triton's surface globally. This amounts to a change in atmospheric mass and latent heat by ~4.5×10^{17} gm and 1.2×10^{20} J respectively, or an average of ~2.5×10^{11} W over a period of 15 years. Thus, it is clear that if albedo changes of the size indicated have indeed occurred on Triton, they may still be having a substantial effect on Triton's global temperature.

Figure Captions

Fig. 1. Triton's surface pressure as a function of emissivity for three values of bolometric bond albedo. The heavy line is for a model that includes solar, internal radiogenic, and Neptune energy inputs. The light line is for a model that includes only solar input, and the area between the dashed, horizontal lines is the range of pressure 15 ± 5 μbars, encompassing the range of Voyager measurements of Triton's surface pressure (2). Radiogenic heat and heat from Neptune in this model amount to 6 mW m^{-2}.

Fig. 2. Response of Triton's atmospheric pressure to a change in bolometric bond albedo from 0.74 to 0.85. The heavy curves are for a linear change in albedo over a period of 5 years and the light curves are for an instantaneous change. Curve pairs are plotted for several different emissivities, ranging from 0.55 for the top pair to 0.70 for the bottom pair in steps of 0.05. A combined contribution of 6 mW m^{-2} from internal heatflow and absorbed thermal energy from Neptune has been included, chosen so that for an emissivity of 0.55, the final equilibrium pressure is 15 μbars.

Table 1: Triton Power Comparisons

Source	Power (10^{11}W)
Incident Solar	85.5
Absorbed Solar	8.5 - 17.0
Internal Heatflow	0.75 - 1.5
Neptune Thermal	0.1 - 0.2

Note: Incident solar flux was calculated at a distance of 30.2 AU, the absorbed solar flux was calculated for a bolometric bond albedo range of 0.8 to 0.9, internal heatflow was calculated according to the description in the text and absorbed thermal energy from Neptune was calculated for the range of emissivity 0.5 to 1.0, assuming Triton's thermal absorptivity is equal to its thermal emissivity.

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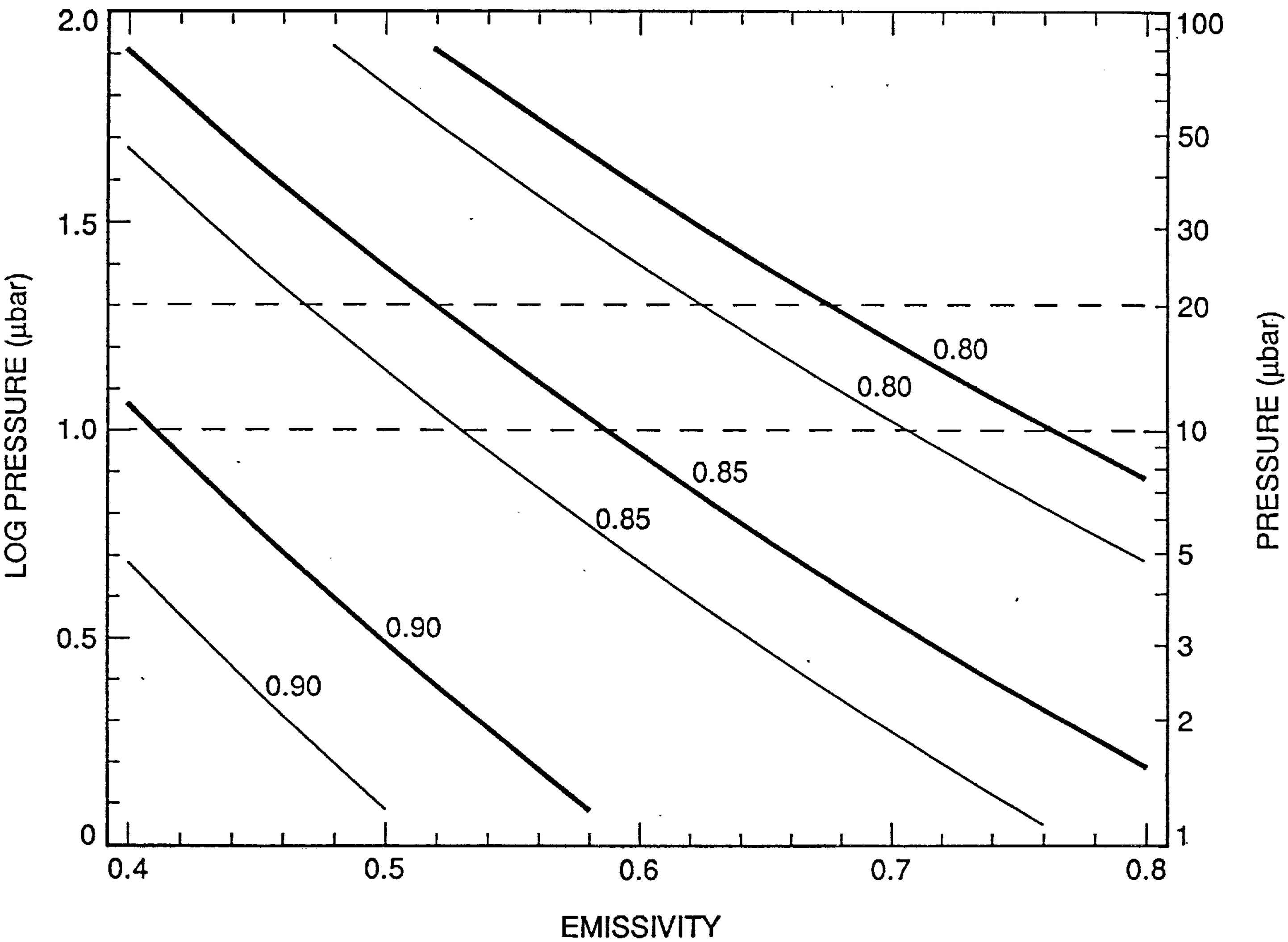
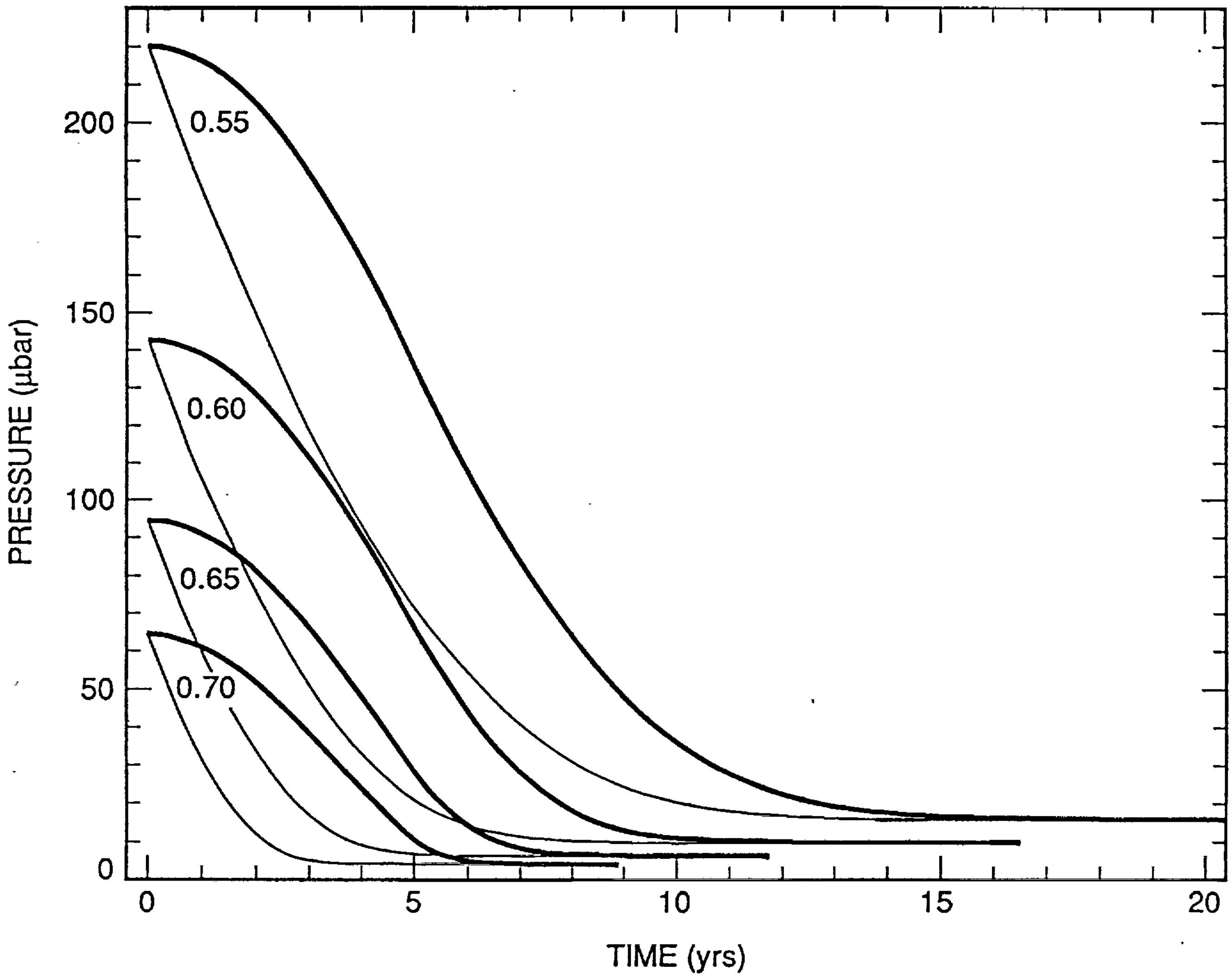
25. This work represents one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.



2.0
1.5
1.0
0.5
0
LOG PRESSURE (μbar)
100
50
30
20
10
5
3
2
1
PRESSURE (μbar)
0.80
0.80
0.85
0.85
0.90
0.90
0.4
0.5
0.6
0.7
0.8
EMISSIVITY

Fig. 2



PRESSURE (μbar)
TIME (yrs)
0.55
0.60
0.65
0.70
0
50
100
150
200
0
5
10
15
20