CONSIDERATION OF PROBABILITY OF BACTERIAL GROWTH FOR JOVIAN PLANETS AND THEIR SATELLITES*

D. M. Taylor
R. M. Berkman
N. Divine

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103, USA

Paper V.4.4
Joint Open Meeting of the Panel on
Planetary Quarantine and Working Group 5
17th Plenary Meeting of COSPAR
Sao Paulo, Brazil
June 17 - July 1, 1974

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

CONSIDERATION OF PROBABILITY OF BACTERIAL GROWTH FOR JOVIAN PLANETS AND THEIR SATELLITES*

D. M. Taylor
R. M. Berkman
N. Divine

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103, USA

Abstract

Environmental parameters affecting growth of bacteria (e.g. moisture, temperature, pH, and chemical composition) were compared with current atmospheric models for Jupiter and Saturn, and with the available physical data for their satellites. Different zones of relative probability of growth were identified for Jupiter and Saturn, with the highest in pressure regions of 10^6 to 10^8 N m^{-2} (10 to 100 atmospheres) and 3×10^6 to 3×10^8 N m^{-2} (30 to 300 atmospheres), respectively.

Of the more than two dozen satellites, only the largest (Io, Europa, Ganymede, Callisto, and Titan) were found to be interesting biologically. Titan's atmosphere may produce a substantial greenhouse effect providing increased surface temperatures. Models predicting a dense atmosphere are compatible with microbial growth for a range of pressures at Titan's surface. For Titan's surface the probability of growth would be enhanced if (1) the surface is entirely or partially liquid (water), (2) volcanism (in an ice-water-steam system) is present, or (3) access to internal heat sources is significant.

1.0 Introduction

An assessment of the probability that organisms can grow in extraterrestrial environments will be described here. The approach was to categorize the factors which influence growth and relate these to the environments in question. The study has been restricted to the atmospheres of Jupiter, Saturn, and their satellites, emphasizing zones where relative probability of growth (P_g), rather than mere survival, is greatest. The approach to establishing P_g values was to assess the minimal needs of bacteria and to determine whether or not atmospheric regions exist which meet these needs. Each requirement was evaluated independently in terms of its growth supporting function. Also considered was the possible existence in the atmospheres of factors which could prevent growth even in the presence of the basic growth requirements. An overall assessment in which all such factors were combined led to the establishment of zones of relatively high and low P_g.

A review of how temperature, pressure, chemical composition, and moisture affect the growth of bacteria is presented. While the maximum and minimum limits of various parameters permitting growth are described, there is no attempt to assign P_g values on the basis of the limited data. The present report derives relative P_g values as high, low, or nil. Numerical P_g values cannot be assigned reliably because large uncertainties exist in current knowledge of temperatures, pressures, abundances, turbulence, and surface characteristics for the atmospheres of Jupiter, Saturn, and their satellites.

The present P_g study used "the law of limiting factors" as a basis to calculate high, low, or nil probabilities of growth. The law states that any one factor, if limiting for growth, will affect P_g even if all other required factors are optimal.

2.0 Technical Discussion

2.1 Minimal Requirements for Bacterial Growth

The organisms considered in the study were bacteria rather than other life forms, primarily because of their greater variety, higher adaptability, comparative ease of study in the laboratory, and simple growth requirements in many cases, as well as the availability of extensive published literature on their physiological and morphological characteristics.

A concise review of the nutritional requirements of bacteria is given by Guirard and Snell [1]. For P_g purposes, the needs have been divided into 4 categories: (1) carbon source, (2) energy source, (3) salts, and (4) water.

While carbon is essential for growth, bacteria can utilize a wide variety of carbon compounds, including CO_2, CH_4, and all other naturally occurring carbon compounds. As a source of energy, the heterotrophic bacteria invariably use the same compound which serves as the carbon source, whereas autotrophs derive energy from sunlight or by oxidation of inorganic compounds.

Bacteria require a large number of inorganic salts, either in relatively large quantity $\left(SO_4^{-2}, NH_4^{+}, PO_4^{-3}, \text{etc.}\right)$, or in trace amounts ($Ni^{+2}$, Co^{+2}, etc.). Many salts are required both as structural entities and as co-factors in enzyme systems. While water is an absolute requirement, the growth of some microorganisms can occur below 80 percent relative humidity [2], and in one case growth has been measured down to 11 percent relative humidity[3].

Even with all minimal growth requirements present, other inhibitory factors including radiation, temperature, pressure, and chemical agents may still limit or prevent growth. Radiation includes both ultraviolet light and energetic charged particles. In the case of temperature, the literature indicates that the growth of Earth organisms cannot occur below about -20°C; the upper temperature extreme is generally considered to be near 100°C with few exceptions. The effect of pressure on bacterial growth has not been studied in detail; however, growth of marine bacteria has been shown to occur at depths corresponding to 10^8 N m^{-2} (1000 atmospheres) hydrostatic pressure [4]. Organisms have also been shown to grow under a pressure of 10^3 N m^{-2} (0.01 atmosphere) [5].

Chemical inhibitors of growth include those of a highly toxic nature as well as those which are toxic only when present in great abundance. The former includes various metabolic inhibitors such as azide and cyanide; the latter, compounds which are competitive inhibitors and those which cause secondary effects. An example of the latter is ammonia, which, if abundant, can raise the pH of aqueous suspensions to toxic levels. But some bacteria can grow at pH values approaching pH 13 [6, 7]; others are reported to grow under the acid conditions of pH 4 or lower [8].

Growth of bacteria can occur in a variety of atmospheres, including pure oxygen [9] and pure CO_2 [5, 10], in 50 percent NH_3 [11] and in various mixtures of NH_3, CH_4 and H_2 [11, 12].

2.2 Relevant Characteristics of Jupiter and Saturn

Available data indicate that Jupiter and Saturn (and probably other major planets) lack solid surfaces. Instead, they appear to be composed of gases whose densities decrease as a function of distance from their centers. Due to an internal heat source, large temperature gradients are predicted in their atmospheres. Although there are uncertainties in pressure-temperature relationships, models have been developed [13, 14] ranging from cool to nominal to warm (Figures 1, 2). The models also predict the locations of aqueous and ammonia clouds. The predicted abundances of the major chemical constituents are given in Table 1.

2.2.1 Probability of Growth in the Jupiter Atmosphere

The crosshatched area shown in Figure 1 indicates the temperature range compatible with bacterial growth. It also defines a pressure range from about 10^5 to 10^7 N m^{-2} (1 to 100 atmospheres). A pressure of 10^5 N m^{-2} (1 atmosphere) of pressure corresponds to an equatorial distance of approximately 71,400 km from the center of the planet. Significantly, the band in which temperature and pressure are compatible with bacterial growth is comparatively narrow, less than 300 km in depth. Considerations of P_g will be limited to this region.

While the cool, nominal, and warm models all predict aqueous clouds in the Jupiter atmosphere, only the cool model predicts the presence of liquid water. In the cool model, liquid water should be present within the band of 2×10^6 to 5×10^6 N m^{-2} (20 to 50 atmospheres) pressure. In considering water as a limiting factor, a high P_g to the 2×10^6 to 5×10^6 N m^{-2} (20 to 50 atmospheres) pressure region, and a low P_g to the remaining region between 10^5 and 10^7 N m^{-2} (1 and 100 atmospheres) can probably be assigned. However, in all three models, localized regions of high moisture content in the form of precipitation or condensation could exist even in low P_g regions.

In the region from 10^6 to 10^7 N m^{-2} (10 to 100 atmospheres), carbon is available as methane (CH_4). Ammonia is also present, although in regions below 10^6 N m^{-2} (10 atmospheres) pressure, the concentrations of methane and ammonia drop to below 0.7 and 0.2 mole m^{-3}, respectively. Based on the availability of these two compounds, one can probably assign a high P_g to the 10^6 to 10^7 N m^{-2} (10 to 100 atmosphere) pressure region, and a low P_g to regions approaching 10^5 N m^{-2} (1 atmosphere pressure).

In aqueous ammonia environments, pH can play an important growth-limiting role. A pH analysis of the growth regions was conducted, based upon abundances of water and ammonia, in relation to temperature. The calculated nominal pH is approximately 12.5, but would drop to about 10.5 in regions where temperatures are approaching 100°C. However, these values are based on average abundances and do not consider the effects of rains, turbulence, or other unknown factors.

The other chemical constituents required for growth include several inorganic compounds such as sulfur, various divalent cations, and phosphates. Although the existence of such compounds on Jupiter is not known, it is assumed they do exist along with other inorganic compounds required in trace amounts.

Radiation, chiefly in the ultraviolet wavelengths, does not pose a problem to microorganisms since most of it is dissipated before reaching the growth region. Other kinds of radiation (X-rays, cosmic rays, etc.) are not believed to be significant in considering P_g on Jupiter.

Various chemical agents inhibitory to the growth of microorganisms may or may not be present in the Jupiter atmosphere. It is assumed that such agents will not prevent growth of microorganisms. The assumption is based both on the attributes of bacteria and on the assumption that inhibitory agents, if present, are present only in low concentration.

Based on the above discussion, a high P_g zone is indicated in the crosshatched band around 3×10^6 N m^{-2} (30 atmospheres). If water were not a limiting factor, the high P_g zone could have been widened to encompass a pressure zone from 10^6 to more than 5×10^6 N m^{-2} (10 to more than 50 atmospheres). Outside the 10^5 to 10^7 N m^{-2} (1 to 100 atmosphere) range, P_g is nil.

2.2.2 Probability of Growth in the Saturn Atmosphere

Saturn and Jupiter are markedly similar in most attributes which influence probability of growth. This is evident from Figure 2 and from Table 1. However, there are some significant differences which will be addressed here. Because of the greater distance of Saturn, data obtained have greater uncertainties than those for Jupiter. Owing to its greater distance from the Sun, temperatures for Saturn are lower than those for Jupiter. Nevertheless, the internally generated heat source provides a region, as with Jupiter, in which temperatures are suitable for microbial growth. Pressures in this region are higher than pressures found in the analogous temperature zone identified for Jupiter. The higher pressures imply greater abundances of all chemical constituents.

Figure 2 indicates the temperature and pressure relationships for the Saturn atmosphere based on the three models. The cross-hatched area indicates where growth could be possible. The two horizontal lines confine the pressure regions to a range of about 3×10^5 to 2×10^7 N m^{-2} (3 to 200 atmospheres). Based on atmospheric analyses, liquid water should be present in the nominal model as well as in the cool model. The cool and warm models of both Jupiter and Saturn represent the extreme cases predicted for these environments. Since, for Jupiter, liquid water is predicted only for the cool model, a higher probability of growth should be assigned to Saturn.

2.2.3 Probability of Growth on Satellites

The satellites of Jupiter and Saturn are referred to as the "icy satellites" because of their chemical composition. While empirical measurements are relatively few, Lewis [15] has calculated the chemical composition of the icy satellites on the basis of solar chemical abundances, condensation properties of the elements, and temperatures at the time of accretion. The average calculated chemical compositions are estimated to be about 54% H_2O, 15% FeO, 13% SiO_2, 10% NH_3, 8% MgO, and less than 5% CH_4. Other compounds required for growth can be presumed present at least in trace amounts.

Surface temperatures of the satellites are generally very low, probably averaging around -150°C. The four largest Jupiter satellites, Io, Europa, Ganymede, and Callisto, are probably too cold to allow growth of microorganisms. There is some possibility, however, that growth could occur on localized regions of the Gallilean satellites if the surfaces were differentiated. Although an unlikely possibility, some surface regions could have cracks and crevices from which rich materials from the warm interiors erupt in a manner somewhat analogous to volcanic or geyser activity. This possibility is eliminated in the case of the smaller satellites which have cold interiors.

The larger satellites of Jupiter have sparse atmospheres, precluding the possibility for "greenhouse effects" in which surface heat is retained. But Titan, the largest satellite of Saturn, appears to have a dense atmosphere. Thus surface temperatures are now believed to be much higher than originally thought. However, the atmosphere prevents measurement of actual surface temperatures.

At a workshop on the atmosphere of Titan, held in July, 1973, [16] consensus was obtained on several physical parameters, namely a radius and mass considerably larger than the moon's, a gravity comparable to the moon's, and a very cold effective temperature (at 10 AU from the Sun). Intensive consideration was devoted to analysis of the spectroscopic and infrared observations, and to theoretical derivations concerning the atmosphere. The only gas molecule identifiable in the spectra is methane, but there may be other major constituents, namely hydrogen, nitrogen, or argon. Water and ammonia may occur in the warmer regions of the atmosphere inaccessible to direct observations with present techniques. The data also place various constraints on atmospheric variables; for example, that surface pressures and temperatures exceed 2×10^3 N m^{-2} and -200°C respectively.

The profiles of temperature (abscissa) and pressure (ordinate, corresponding to height above Titan's surface) shown in Figure 3 include the points and theory from the workshop. The solid line represents the nominal atmospheric model and corresponds to a pure methane atmosphere (mean molecular weight μ = 16 gram/mole). The dashed lines represent extreme atmosphere profiles ("Heavy" composition, with μ = 26, and "Light" composition, μ = 6).

In the lower atmosphere (for pressures exceeding 10^5 N m^{-2}) a shaded region is shown. This region represents the intersection of the Titan atmospheric profiles with approximate limits on pressure and temperature for survival and growth of terrestrial organisms. This region, a few hundred kilometers thick, is the one within which a high probability of growth could occur.

Note that no surface (that is, an upper bound on the pressure) is shown for this set of Titan atmosphere profiles. This occurs because present data do not establish surface pressure, but are consistent with either a thin atmosphere or a thick atmosphere; that is, surface pressures equal to or greater than 2×10^3 N m^{-2}. The profiles shown here could thus be terminated by a surface anywhere below the level at 2×10^3 N m^{-2} pressure. The growth region lies completely within those portions of the atmospheric profiles inaccessible to observation with present astronomical techniques. In this region several concerns affect growth. One of these is atmospheric dynamics (winds, weather, and other temporal and local variations), expected to be subdued on Titan because of its slow rotation (period = 16 days). Another is the likelihood of condensates. The growth region shown earlier includes only liquid ammonia as a candidate for cloud formation. However, if a surface is present, condensation of vaporized surface material, whatever it is, is likely just above the surface.

If the atmosphere profile is terminated by a surface at, for example, a pressure of 10^5 N m^{-2} and a temperature of -120°C, the surface is expected to be solid water ice with one or two major hydrates. This is the most probable surface material, and is compatible with current understanding of the structure of Titan's interior. If the surface is a solid ice crust, thermal and tidal stresses within the underlying liquid water mantle may produce the analogs of geological activity, such as volcanism, seepages, and icequakes involving water, steam, ammonia, etc.

In the case of a thicker atmosphere, liquid water is the likely surface material in the growth region. This water would have ammonia in solution, at concentrations which lead to pH values between about 11 and 12.5. Such a surface ocean might serve as a growth medium for some organisms, particularly considering the availability of carbon from atmospheric methane, along with other needed materials in solution.

The large uncertainties are apparent in these atmospheric profiles and in the surface pressure. Survival and growth of some terrestrial organisms are possible if the surface pressure falls in the range of 2×10^5 to 10^7 N m^{-2} (2 to 100 atmospheres); in this case the probability of growth on Titan exceeds that for every other outer planet satellite, according to present considerations.

3.0 Summary

Absolute probability of growth values cannot be calculated reliably for the planetary bodies discussed here. On the basis of current knowledge, a relative rank ranging from high to nil probability of growth can be assigned to each body. Such a ranking is shown in Figure 4. Saturn has been assigned the highest probability of growth in the likelihood that liquid water and relatively high concentrations of nutrients are available. Jupiter has a somewhat lower probability of growth because there is only a 10 to 20% chance that water is present as a liquid. Titan has been ranked high on the basis of its atmosphere and the accompanying greenhouse effect. The actual surface temperature of Titan cannot be ascertained at this time because radiation measurements provide data on the upper atmosphere only. Hence, the ranking for Titan is tentative. The four Gallilean satellités of Jupiter have been ranked considerably lower than Titan, and can be considered to have a very low probability of growth. Smaller satellites including the rings of Saturn, which are probably composed of ice or rock up to a few km in diameter, have essentially a nil probability of growth.

References

[1] B. M. Guirard and E. E. Snell, in: The Bacteria, V. 4, Academic Press, New York, 1962, (p. 33-92).

[2] D. J. Kushner, Adv. Appl. Microbial 10, 73-99, 1968.

[3] S. M. Siegal and K. Roberts, Proc. Nat'l. Acad. Sci. 56, 1505-1508, 1966.

[4] C. E. Zobell and R. Y. Morita, J. Bacteriol. 73, 563-568, 1957.

[5] E. J. Hawrylewicz, et al., in: Life Science and Space Research, Vol VI. Akademie-Verlag, Berlin 1968 (p. 146-156).

[6] C. S. Meek and C. B. Liman, J. Gen. Physiol. 5, 195-204, 1922.

[7] A. W. Downie and J. Cruickshank, Brit. J. Exptl, Path. 9, 171-173, 1928.

[8] M. E. Chislett and D. J. Kushner, J. Gen. Microbiol 24, 187-190, 1961.

[9] J. Caldwell, Nature 206, 321-323, 1965.

[10] J. Seckbach, F. A. Baker, and P. M. Shugarman, Nature 227, 744-745, 1970.

[11] S. M. Siegal and C. Giumarro, Proc. Nat'l. Acad. Sci. 55, 349-353, 1966.

[12] S. M. Siegal and C. Giumarro, Icarus 4, 37-40, 1965.

[13] The Planet Jupiter (1970), NASA SP-8069, 1971.

[14] The Planet Saturn (1970), NASA SP-8091, 1972.

[15] J. S. Lewis, Icarus 15, 174-185, 1971.

[16] The Atmosphere of Titan, NASA SP-340, 1974.

Table 1. Chemical compositions for Jupiter and Saturn

Constituent	Jupiter, % by weight			Saturn, % by weight		
	Cool model	Nominal model	Warm model	Cool model	Nominal model	Warm model
H_2	50.7	75.3	87.7	55.3	73.5	89.5
He	46.0	23.0	11.5	39.5	19.7	9.9
H_2O	1.60	0.80	0.4	2.5	0.83	0.28
CH_4	0.86	0.43	0.21	1.33	0.44	0.15
NH_3	0.22	0.11	0.06	0.34	0.11	0.04
Ne	0.23	0.11	0.06	0.36	0.12	0.04
Others	0.4	0.2	0.1	0.7	0.24	0.08

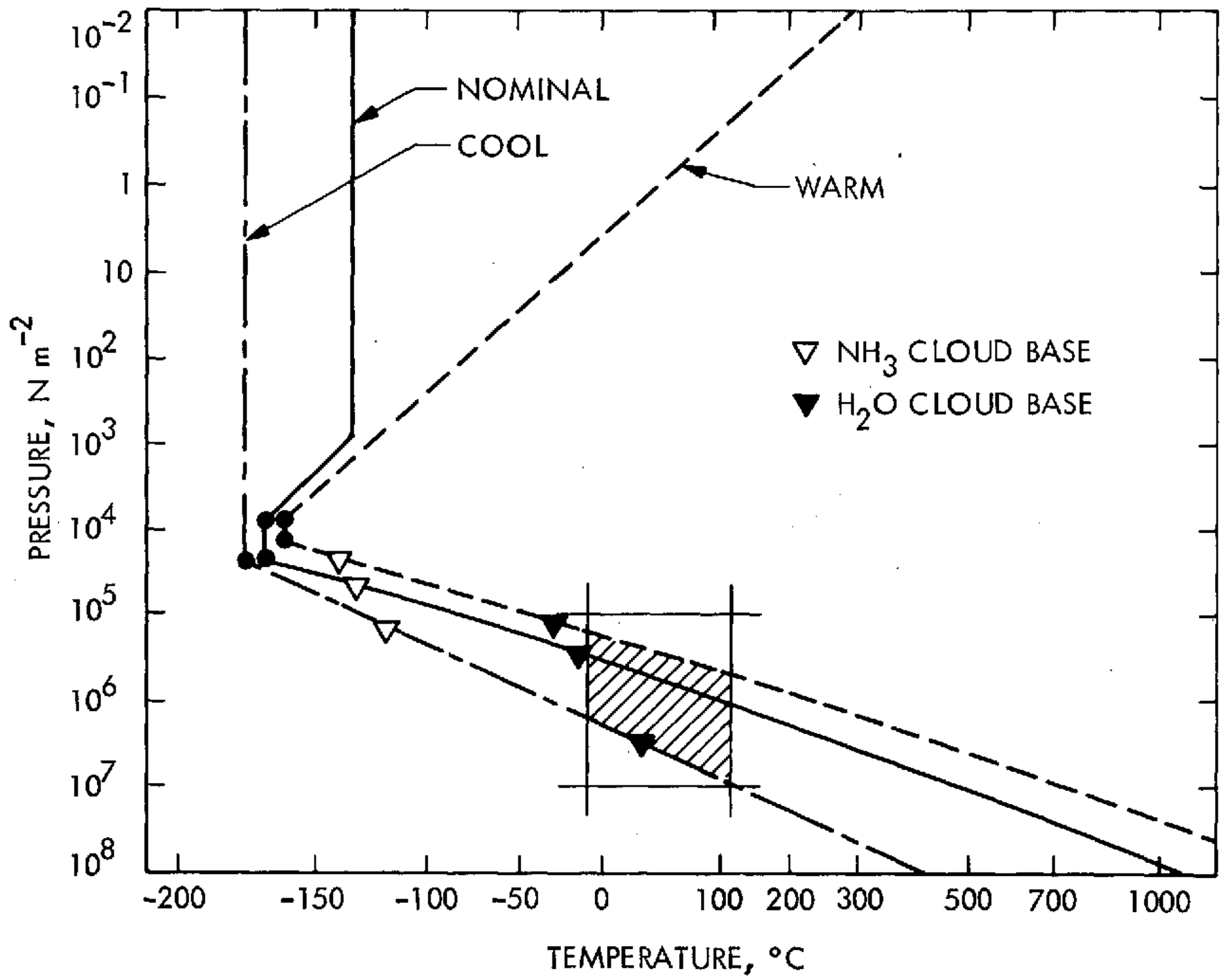

Figure 1. Pressure vs temperature for the Jupiter model atmospheres

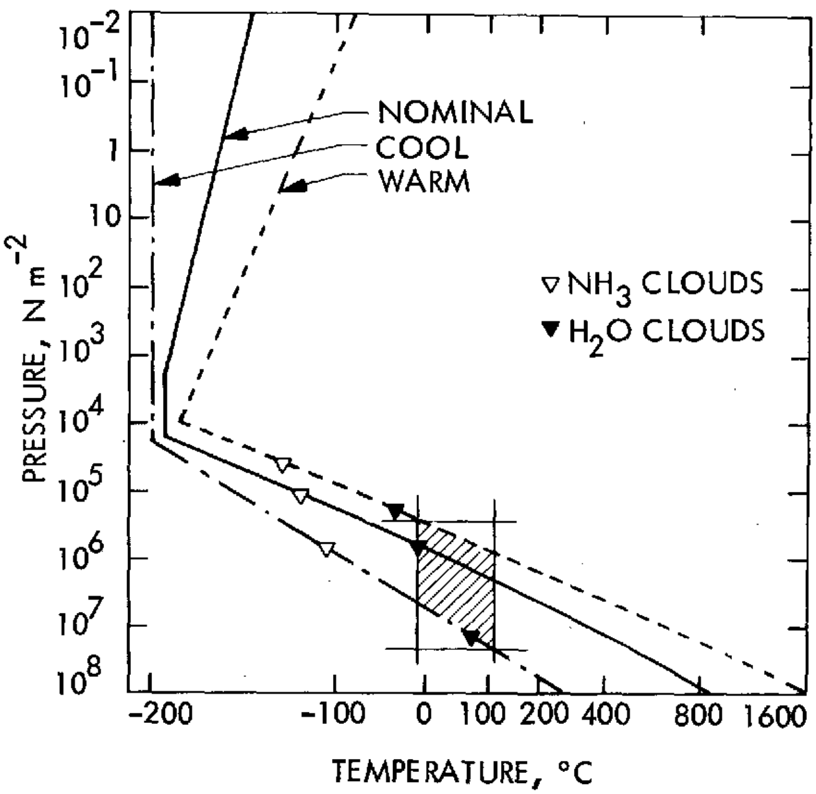

Figure 2. Pressure vs temperature for the Saturn model atmospheres

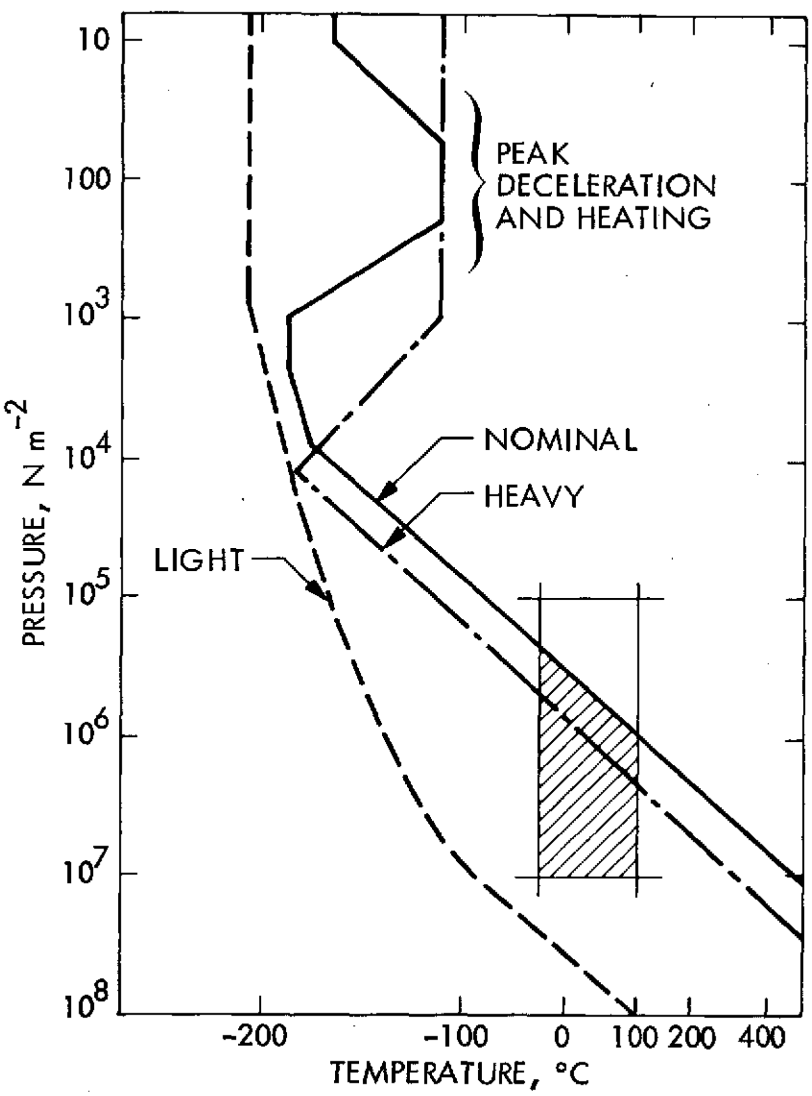

Figure 3. Pressure-temperature profiles of engineering models of Titan's atmosphere

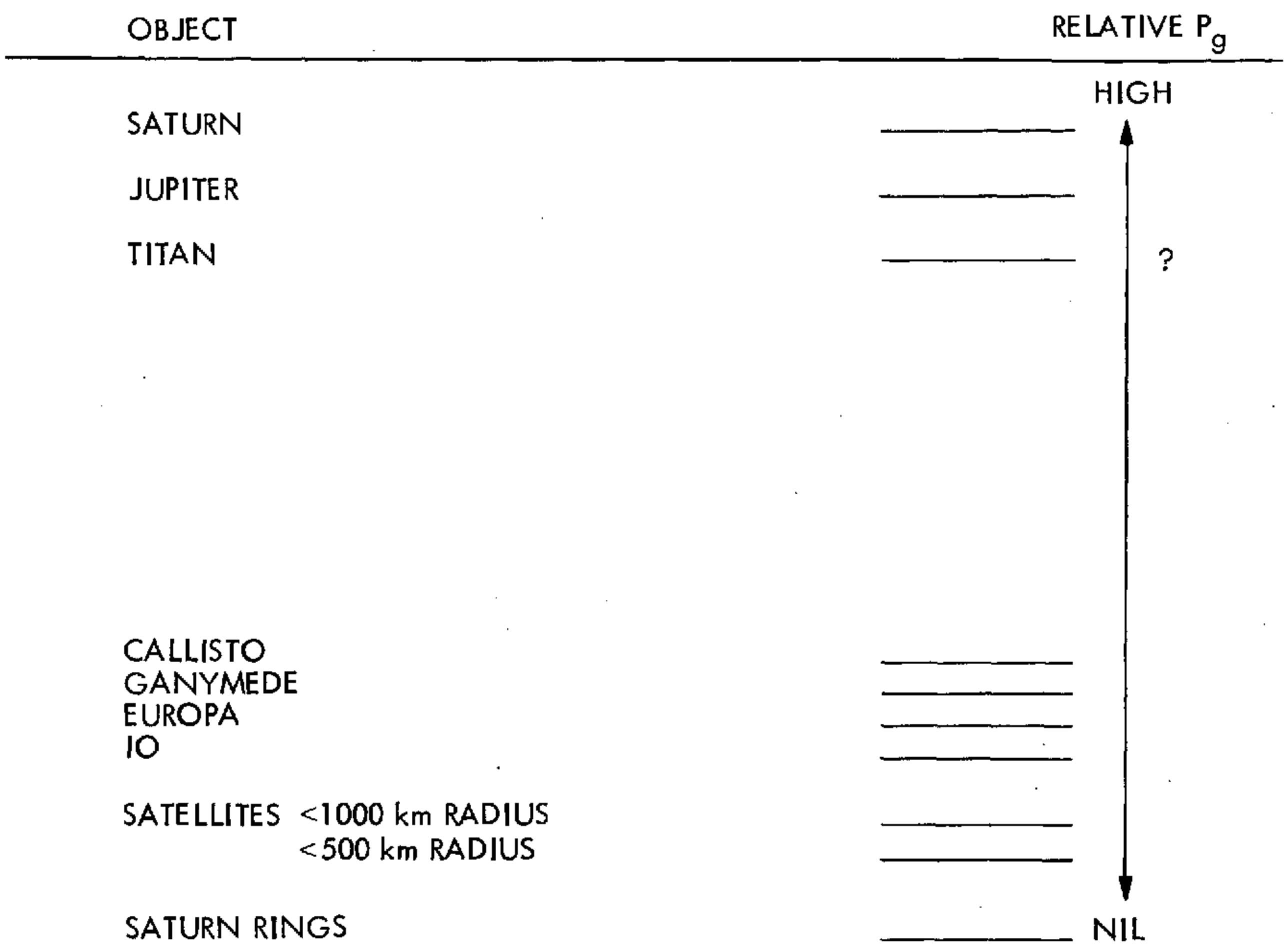

Figure 4. Relative probabilities of growth for Jupiter, Saturn, and their satellites