THE ATMOSPHERE OF JUPITER*

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2.0 THE ATMOSPHERE OF JUPITER

In this chapter we will set the scenario for the probe as it descends through the atmosphere of Jupiter. First we summarize some of the pertinent atmospheric data such as the Jovian temperature profile. The temperature is shown as a function of pressure in the range anticipated to be explored by the probe. Relationship between the pressure and altitude measured from a certain given reference level is also illustrated. A list of important gaseous species with their mixing ratios expected to be encountered by the probe in the relevant pressure range is generated. The scientific significance of measuring the abundances of these species is discussed and some recommendations regarding the desired accuracy of measurements and mass range are presented. So far only a handful of Jovian gases have been detected principally by visible, ultraviolet and infrared spectrometers used in ground based, aircraft, rocket, satellite and the Pioneers 10 and 11 spacecraft instruments. The abundances of the key species H_2, He, CH_4 and NH_3 have been deduced, only a few with some degree of confidence. The difficulty with the type of measurements to date is that they yield only column abundances of species above a certain effective scattering or reflecting layer which naturally varies from specie to specie and for the region of the spectra detected. The determination of the important quantity of mixing ratio in the relevant part of the atmosphere i.e., the homosphere then remains quite model dependent. The in situ mass spectrometer measurement will, to a large extent, eliminate such model dependence.

The upper abscissa scale in Figure 2-1 shows Jovian temperature as a function of pressure. Down to the ammonia cloud top (at about 1 atmosphere pressure level) the temperature is inferred from the Pioneers 10 and 11 infrared radiometer data; and radio and stellar occultation data (Hunten (1976). The temperature near the top is about 150°K and it undergoes inversion at around 100 mb pressure level and then increases to 165°K at 1 atmosphere pressure level. Continuation of the solid line T(P) curve beyond P = 1 atmosphere gives temperature as calculated by Weidenschilling and Lewis (1973). Calculations of Divine (1971) for P > 1 atmosphere are shown by the dashed curve. Divine's curve then represents the upper limit to the temperature one might anticipate in the lower atmosphere of Jupiter. Divine's calculation gives 100°K higher temperature at 10 atmosphere level than Weidenschilling and Lewis (1973). The reason for such discrepancy between the two models is choice of different boundary values and different He/H_2 abundance ratio; specific heats of helium and hydrogen are widely different. Due to gross uncertainties in the various parameters entering the thermodynamical calculations, higher temperatures may not be entirely ruled out. Thermodynamical calculations also suggest distinct cloud condensation of ammonia (at 168°K), ammonium hydrosulphide (at 230°K) and water (at 300°K) at the levels where the partial pressures of these gases exceed their saturation vapor pressure. The water cloud merges with water ice cloud at lower temperature. Also shown in Figure 1 is a plot of altitude vs. pressure Z(P) with altitude scale drawn on the lower abscissa. The reference height, Z = 0 km is taken at the 1 atmosphere pressure level. In order to arrive at the altitude vs. pressure curve temperature profile shown by the solid line T(P) curve was assumed.

Escape of even the lightest gases from the atmosphere of Jupiter appears improbable due to Jupiter's great gravitational potential barrier and low exospheric temperature. As a result, the atmospheric composition of Jupiter is suspected to represent conditions of primordial solar nebula. Figure 2-2 taken from Cameron (1968) shows solar system abundances as a function of increasing mass number. In this figure the standard of normalization is taken to be the element silicon, assigned a value 10^6. One notes that mixing ratio of species with $m > 50$ is quite low with only a few peaks occurring at larger masses. The upper atmosphere of Jupiter consists mostly of H_2, He, and several hydrocarbons: CH_4, CH_3, C_2H_4, C_2H_2, C_2H_6 etc. Figure 2-3 taken from Atreya and Donahue (1976) shows the distribution and these gases as a function of height for several variations of the eddy mixing coefficient K. The altitude is referenced from the level where the atmospheric number density is 10^{16} cm^{-3}, so that the ammonia cloud top is 150 km below the reference level on this scale. The composition of the upper atmosphere of Jupiter would have been determined reasonably well by several optical devices on-board MJS'77 spacecraft. The Jupiter Orbiter Probe mass spectrometer will then provide a smooth transition from the region already explored by MJS'77 to the lower depths. Combining the results of the two missions will result in a significant and comprehensive picture of the atmosphere of Jupiter and possibly the solar system evolution.

We list in Table 2-1 gaseous species most likely to be encountered in the pressure regime beyond 100 mb. The table is arranged in order of decreasing volume mixing ratios of species relative to H_2. The mass numbers m/e in AMU are given in the third columm of the table. Wherever important mass numbers of the corresponding isotopes are listed in the parentheses. The mixing ratios of species listed are mostly what one would expect for a Jovian atmosphere reflecting solar type composition. Some of the species have been definitely detected and their abundances measured while others have only been marginally identified as stated in the last column of the table. Particular attention will be devoted to the isotopes a little while later in this chapter, as the accuracy with which their abundances and/or ratios of abundances may be measured is critical to the understanding and modeling of the solar system evoluation. At the moment we will make some remarks about the other species entered in Table 2-1

The most abundant gases in the atmosphere of Jupiter are H_2 and He. Column abundance of hydrogen has been deduced from the ground based spectroscopic observations of the (4-0) quadrupole lines of H_2, while helium has only been recently detected by the ultraviolet photometer on-board Pioneers 10 and 11. The helium to hydrogen mixing ratio derived from the UVP measurements is, however highly inprecise. Therefore, until this important quantity is measured accurately, possibly on the JO Probe, solar abundance ratio of 0.11 remains our best guess. The next most abundant specie is oxygen. It is suspected that oxygen in Jupiter is present in the form of water with trace quantities in the form of several oxides mainly CO and CO_2. Interpretation of the recent measurements in the 5μ window of Jupiter indicate water abundance to be 10^{-6} relative to H_2, some three orders of magnitude smaller than expected. CO and CO_2 whose mixing ratios are on the order of 10^{-9} do not contribute appreciably to the oxygen abundance on Jupiter. Therefore a precise in situ measurement of H_2O abundance in Jupiter will be very significant in solving the puzzle of oxygen. Most of the carbon in the reducing atmosphere of Jupiter would be found in the form of methane. Several UV and IR measurements of CH_4 give its mixing ratio close to the solar value. Hydrocarbons such as ethane (C_2H_6), acetylene (C_2H_2), ethylene (C_2H_4) and methyl radicals (CH_3) will also be formed as a result of the photochemical reactions involving methane. C_2H_6 and C_2H_2 have been identified by Ridgway and a French group. However the two groups deduce widely different abundances of these species. Measurement of the hydrocarbon mixing ratios with some confidence is highly desirable. In particular infrared active species such as C_2H_6 and C_2H_2 influence the thermal structure of the atmosphere of Jupiter, in particular in the thermal inversion regime. Next, we come to nitrogen which is expected to be found in the form of NH_3 in the Jovian atmosphere. Thermodynamic calculations indicate the presence of an NH_3 cold trap around 1 atmosphere pressure level. Below this level NH_3 mixing ratio is expected to be solar (i.e., 2×10^{-4} relative to H_2) while just above it, NH_3 saturation vapor pressure determines the mixing ratio to be nearly 10^{-6}. Extensive calculations carried out by Atreya et al., (1976) indicate that NH_3 nearly 40 km above the cloud top may be depleted by as much as a factor of 10^4 from the saturation mixing ratio value just above the cloud top. The photochemical conversion of NH_3 above the clouds may result in the formation of hydrazine (N_2H_4) and nitrogen (N_2) in particular. Figure 2-4 taken from Atreya et al., (1976) shows realistic distributions of the various products of NH_3 photochemistry for a model atmosphere in which eddy coefficient K varies inversely as the square root of atmospheric number density. The curves labeled as -···- show the 'true' N_2H_4 and N_2 mixing ratios expected in the troposphere and stratosphere of Jupiter. The solid line N_2H_4 and N_2 curves in Figure 2-4 show the distributions of these species only if all of N_2H_4 were present in the 'gaseous' state. However, under conditions of low temperatures prevalent in this regime of the Jovian atmosphere maximum possible N_2H_4 in gaseous state is the one shown by the -···- label. Measurements of NH_3 mixing ratio both above the cloud top and below it will be highly revealing since NH_3 poses an unsolved challenge. Photochemical calculations with transport indicate that Jupiter's atmosphere should have been entirely devoid of ammonia in less than 1% of the geologic time i.e., in 60 million years. Presence of ammonia on Jupiter in solar mixing ratio therefore implies some as yet undecided recycling mechanism. Since N_2H_4 may play a major role in recycling ammonia, measurement of its mixing ratio, specially near the cloud tops and below them where measurable quantities of N_2H_4 may be found in the gaseous phase, will be highly revealing. Measurement of N_2 is also very desirable since its mixing ratio will be determined directly from N_2H_4's in the gaseous phase. Measurement of altitude profiles of ammonia and its photochemical products, specially N_2H_4 and N_2, will be extremely helpful in forming a composite picture of the photochemistry and possibly recycling mechanism of ammonia on Jupiter. Next, we have deuterium which is expected to be present mostly in the form of HD with small amounts in the form of CH_3D. Measurement of HD is important from the point of view of determining an astrophysically significant quantity H/D ratio about which we shall write a little more while discussing isotopes. Spectroscopic identification of phosphine on Jupiter has been recently reported by Ridgway and Larson _et al_. Since triclinic red phosphorus which is a photochemical product of PH_3 may account for the coloration of the Great Red Spot and possibly zones and belts, PH_3 is a useful specie to measure on the probe. One can learn something about the large scale dynamics of Jupiter's atmosphere by studying the GRS and zones and belts. Actually several suggestions have been made for the coloring agent of the clouds of Jupiter and one of them is H_2S also. H_2S has never been observed spectroscopically on Jupiter, perhaps because it is frozen out at lower levels in the form of NH_4SH. Suggestions have been made that H_2S may undergo photochemical decomposition by the solar UV radiation penetrating through holes in the clouds and produce a form of sulfur which has color resembling that of the clouds. There are several difficulties with both the PH_3 and H_2S hypotheses, it would therefore be important to measure these species to settle the question of the coloration of the GRS and clouds. Radicals formed in the photochemistry of ammonia may undergo reactions with methane and its products in the reducing atmosphere of Jupiter. One suspects formation of several trace organics such as cyanides, cyanogens, methyl amines, nitriles etc. In addition, under compression several higher order hydrocarbons such as butylene, propylene and in general 'dirty gasoline' may be formed. The mixing ratios of the trace organics are suspected to be rather small, $\leq 10^{-7}$ relative to H_2. If at all possible, their measurements would be desirable since the trace organics play an important role in the chemical evolution of the atmosphere. Furthermore, some trace organics are suggested to be responsible again for the coloration of the clouds. Formation of hydrides such as hydrogen fluoride, silane, germane, arsane and selamium hydride is entirely possible in the high temperature, high pressure regimes of Jupiter's interior. The gaseous abundances of most these compounds in the region to be explored by the probe, are however suspected to be quite low. Their detection is important from the viewpoint of understanding the interior structure of Jupiter. Some effort toward detection of these species in the final few moments of the probe descent may be in order.

The contents of Table 2-1 are displayed in Figure 2-5 . This cartoon shows mixing ratios of species on the lower abscissa as a function of pressure (right ordinate) and as a function of atmospheric number density (left ordinate). The species are identified on the top abscissa scale. All species with uncertain but less than 10^{-7} mixing ratios are lumped together between the parentheses signs. The location of distinct 'thermodynamic'cloud layers is illustrated by heavy horizontal bars. Only ammonia cloud top has been identified so far. The merging of water clouds into water ice clouds at low temperatures is illustrated by a field of dots.

Much of the discussion regarding isotopes has been presented by Cameron (1968 and 1973) and we see little point in repeating the various cosmogonic considerations in which isotopes play an important role. An accurate determination of the isotope ratios in the atmosphere of Jupiter will provide important constraints for these various theories regarding planetary and solar system origin and evolution. In general, an absolute measure of the isotopic abundances may not be as critical a quantity as the measure of the ratios of abundances. This criterion then relaxes somewhat the constraint on the accuracy of measurement since some of the uncertainties in an absolute measurement may be cancelled out when taking the ratio of this measured quantity relative to another quantity with similar uncertainties. We present in Table 2-2 important isotope ratios to be measured by the JOP mass spectrometer. Mixing ratios relative to H_2 of the compounds in which these isotopes may be found in the Jovian atmosphere are given in Table 2-1. The precisions with which these isotope ratios can be determined using a mass spectrometer with dynamic range of 10^7:1 are shown in the last column of Table 2-2 . A specie with mixing ratio of 10^{-7} will then produce 10^3 ions per second (see Carignan, Donahue and Atreya, 1975) on the detector of such a mass spectrometer. It should be pointed out that the estimate of precision of measurement given in Table 2-2 assumes only statistical uncertainties of measurement. In a well designed system these fluctuations dominate the isotope ratios in many cases. In some cases mass interferences limit precision as at mass 3 where HD and He^3 have the same mixing ratio.

Finally in this chapter we wish to point out that most species listed in Tables 2-1 and 2-2 have mass m/e ≤ 52 except GeH_4(77), AsH_3(78), SeH_2(81), Kr(84) and Xe(131). Also the hydrides are not expected to be abundant in the pressure region to be explored by the probe. Thus, for obtaining statistically significant results most observational effort should be directed toward covering the nominal mass range. The exploratory nature of this mission encourages the acquisition of a small amount of data up to higher masses, however presence of higher masses is likely to be manifested in the lower mass range by ion source fragmentation.

TABLE 2-1

IMPORTANT NEUTRAL GASEOUS SPECIES IN THE JOVIAN ATMOSPHERE

(Pressure $\gtrsim$ 0.1 Atmosphere)

Species X_i	Mixing Ratio X_i/M	Mass AMU	Remarks	Reference
H_2	0.9	2 (1,3)	Ground based measurement	(a)
He^4	0.1	4 (3)	Solar mixing ratio. P-10 & P-11 measurements imprecise	(b)
H_2O	10^{-3} TO 10^{-12}	18 (17,16)	Mixing ratio variation from below the H_2O clouds to above them. 5μ measurements give $H_2O/M=10^{-6}$	(c)
$C^{12}H_4$	7×10^{-4}	16 (17,18)	Ground based measurement	(a)
NH_3	2×10^{-4} TO 8×10^{-7}	17 (18)	Mixing ratio variation from below the NH_3 clouds to above them. UV & IR measurements	(d)
Ne^{20}	1.1×10^{-4}	20 (22)	Planetary mixing ratio. Isotope	(e)
C_2H_6	$\leq 8 \times 10^{-5}$	30	Measured	(f)
He^3	4.2×10^{-5}	3 (4)	Solar mixing ratio. Isotope	(e)
HD	4.0×10^{-5}	3 (1,2)	Solar mixing ratio. Isotope	(e)
H_2S	3×10^{-5} TO 10^{-12}	34	Mixing ratio variation from below the NH_4SH clouds to above them	(h)
Ne^{22}	1.2×10^{-5}	22 (20)	Planetary mixing ratio. Isotope	(e)
$C^{13}H_4$	7×10^{-6}	17 (16,18)	Measured	(m)

TABLE 2-1 (CONT)

Species X_i	Mixing Ratio X_i/M	Mass AMU	Remarks	References
Ar^{36}	5×10^{-6}	36 (38)	Solar Mixing ratio Isotope	(e)
C_2H_2	$\leq 1.5 \times 10^{-6}$	26	Measured	(f)
Ar^{38}	1×10^{-6}	38 (36)	Solar mixing ratio Isotope	(e)
PH_3	4×10^{-7}	34	Possible detection	(g,i)
CH_3D	1.5×10^{-7}	17	Measured. Isotope	(j)
N_2	$\leq 10^{-9}$	28	Estimate	(l)
Kr	3.6×10^{-9}	84	Solar mixing ratio (all isotopes combined)	(e)
N_2H_4	$\leq 10^{-10}$	30	Calculated May be condensed out	(l)
CO	$\leq 10^{-9}$	28	Measured. Highly imprecise result	(k)
CO_2	$< 10^{-9}$	44		(k)
Xe	4×10^{-10}	131	Solar mixing ratio (all isotopes combined)	(e)
HCN	$\leq 10^{-7}$	27,28	These products may be formed as a result of photochemical reactions involving NH_3 and CH_4 in the reducing atmosphere of H_2.	
CH_3NH_2	$\leq 10^{-7}$	31,32		
CH_3CN	$\leq 10^{-7}$	41,42		
C_2N_2	$\leq 10^{-7}$	52		
C_2H_4	$\leq 10^{-7}$	20		
C_3H_4	$\leq 10^{-7}$	40		
C_3H_6	$\leq 10^{-7}$	42		
C_3H_8	$\leq 10^{-7}$	44		

TABLE 2-1 (CONT)

Species x_i	Mixing Ratio x_i/M	Mass AMU	Remarks	REFERENCES
HF	$\leq 2 \times 10^{-6}$	20		
SiH_4	5×10^{-10}	32		(i)
GeH_4	$\leq 7 \times 10^{-9}$	77		(i)
SeH_2	$\sim 6 \times 10^{-9}$	81		
AsH_3	$\sim 4 \times 10^{-10}$	78		(i)

References:

(a) see McElroy (1969)
(b) Carlson and Judge (1974)
(c) Treffers et al (1974)
(d) see Anderson et al (1969)
(e) Cameron (1973)
(f) Ridgway (1974a)
(g) Ridgway (1974b)
(h) see Lewis and Prinn (1970)
(i) Larson et al (1976)
(j) Beer and Taylor (1972)
(k) Beer and Taylor (1976)
(l) Atreya et al (1976)
(m) Fox et al (1972)

TABLE 2-2

IMPORTANT ISOTOPE RATIOS

Isotope	Ratio	Remarks	Mass Spectrometer† Measurement Precision
H/D	6.8×10^4	Solar ratio	0.15%
He^4/He^3	5.0×10^3	Planetary Ratio	
	2.4×10^3	Solar Ratio	0.15%
C^{12}/C^{13}	9.0×10^1	Solar ratio	0.43%
N^{14}/N^{15}	2.7×10^2	Solar Ratio	0.45%
O^{16}/O^{18}	4.9×10^2	Solar Ratio	0.63%
Ne^{20}/Ne^{22}	8.0	Planetary Ratio	
	1.2×10^1	Solar Ratio	0.4%
Ar^{36}/Ar^{38}	5.0	Planetary & Solar Ratios are within 5% of each other	1.5%
Ne^{20}/Ar^{36}	2.2×10^1	Solar Ratio	0.55%
S^{32}/S^{34}	2.2×10^1	Solar Ratio	1.2%
S^{32}/S^{33}	1.2×10^2	Solar Ratio	2.5%

†See Text

FIGURE LEGENDS

Figure 2-1 Temperature (top abscissa) as a function of pressure in the atmosphere of Jupiter. The solid line $T(P)$ curve shows temperature as a function of pressure (Hunten, 1976) down to 1 atmosphere pressure level and continuation of this curve to higher pressures is according to Weidenschilling and Lewis' (1973) calculations. The broken line curve represents temperature in $P > 1$ atmosphere region according to Divine's (1971) calculations. Also drawn on this Figure is altitude (lower abscissa) as a function of pressure. The reference altitude $z = 0$ km is taken at $P = 1$ atmosphere level. The cross marks refer to the pressure levels at which ammonia, ammonium hydrosulfide and water clouds are formed.

Figure 2-2 The solar system abundances plotted as a function of mass number (Cameron 1968).

Figure 2-3 Models of the upper atmosphere of Jupiter (Atreya and Donahue, 1976). The height scale refer to altitude measured from the 10^{16} cm^{-3} density level. On this scale, the ammonia cloud top will be 150 km below the reference level. Models are shown for the eddy coefficient $K = 10^5$ cm^2 s^{-1} and constant throughout the entire altitude range; $K \propto 1/M$ and $K \propto 1/\sqrt{M}$ cases.

Figure 2-4 Volume mixing ratio of ammonia and its photochemical products NH_2, H, N_2H_4 and N_2 (Atreya *et al.*, 1976) are shown by solid lines for the atmospheric model in which eddy diffusion coefficient K varies inversely as the square root of atmospheric number density M. The height scale refers to altitude above the 1 atmosphere pressure level. The curve illustrated by ----- for N_2H_4 gives the saturation vapor mixing ratio of N_2H_4 as a function of altitude (or temperature). This is the maximum allowed N_2H_4 in the 'gaseous' phase in the atmosphere of Jupiter.

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Figure 2-4 (Cont.)

The resultant N_2 mixing ratio profile is shown by ----- N_2 curve. N_2H_3 mixing ratio profiles are shown for two values of rate constant of the reaction ($N_2H_4 + H \xrightarrow{k_4} N_2H_3 + H_2$). The new measurements of Stief and Payne, (1976) give a value of k_4 up to a factor of 35 lower than Francis and Jones (1971) measurements in the temperature range pertinent to the NH_3 photochemistry region.

Figure 2-5 Mixing ratios as a function of pressure and atmospheric number density, of the various gaseous species anticipated to be present in the atmosphere of Jupiter. Some of these species have been detected (see text) and others expected on the basis of solar system composition. Various products of ammonia radical and methane chemical reactions and several hydrides likely to be formed in the atmosphere are trace constituents and are thus lumped together with mixing ratios $\leq 10^{-7}$. The pressure levels of where the NH_3, NH_4SH and H_2O clouds are formed are shown by heavy horizontal bars. The water clouds merge into water ice clouds at lower temperatures (hence at lower pressures).

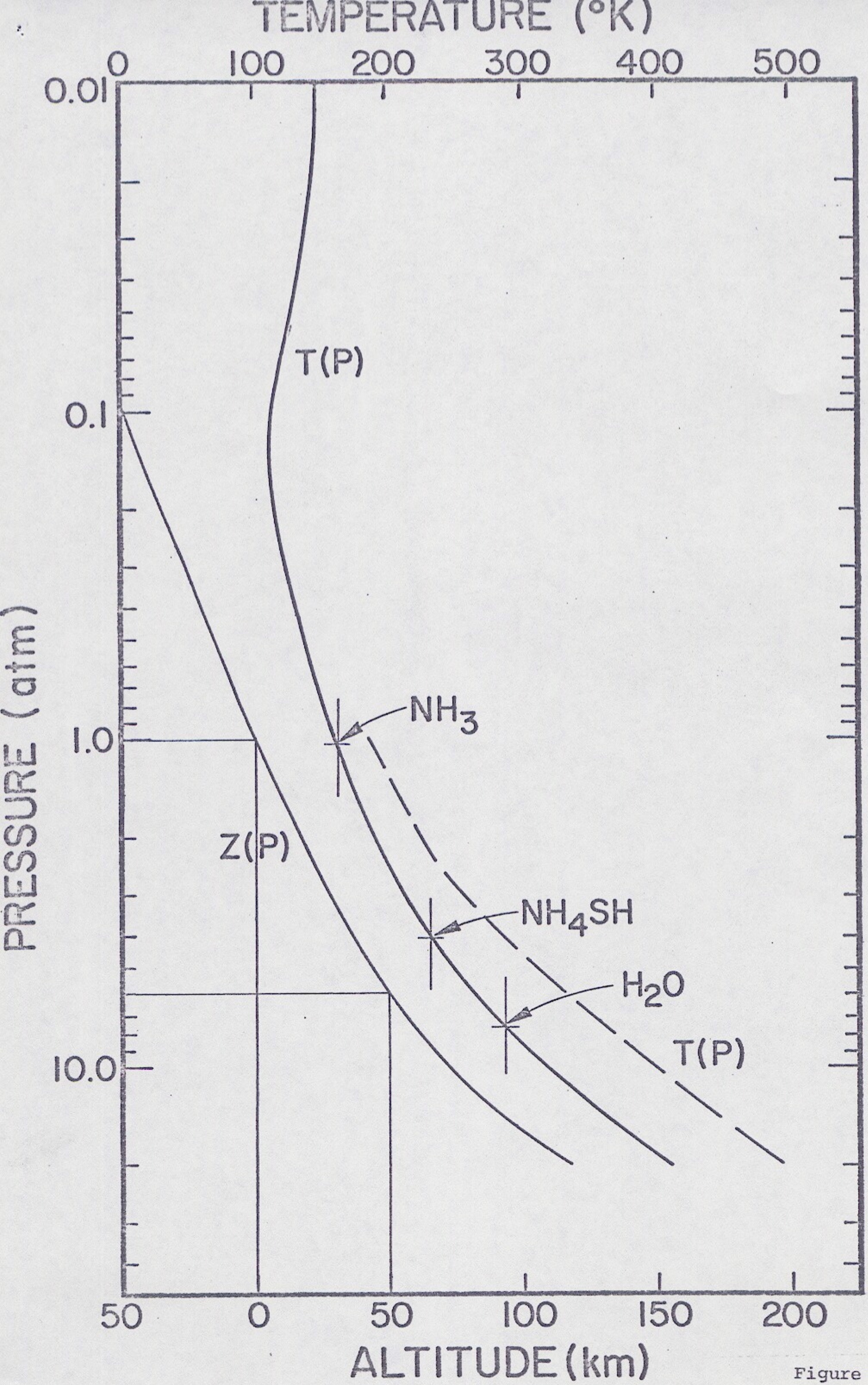
TEMPERATURE (°K)
0
100
200
300
400
500
0.01
0.1
1.0
10.0
PRESSURE (atm)
T(P)
NH_3
Z(P)
NH_4SH
H_2O
T(P)
50
0
50
100
150
200
ALTITUDE (km)

Figure 2 - 1

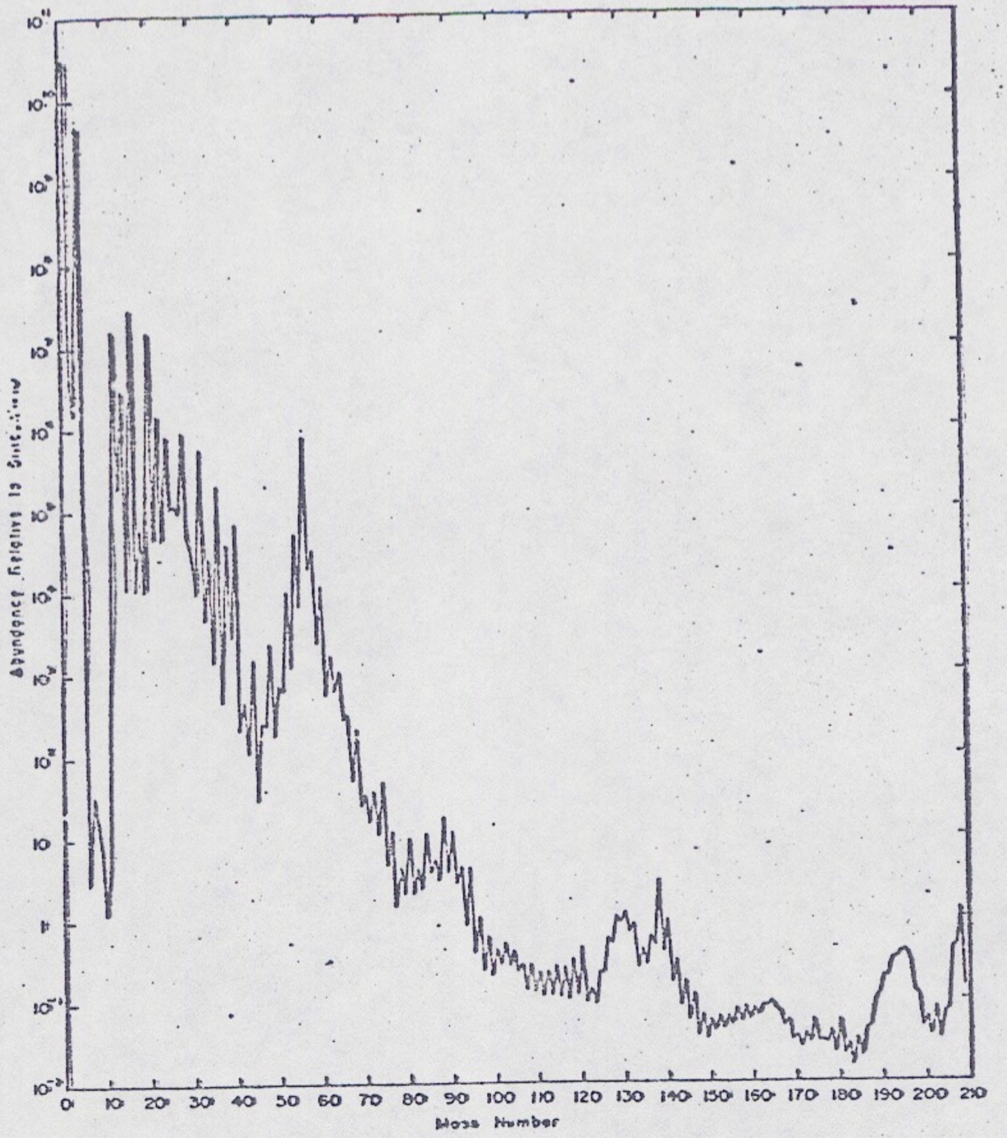
Abundance Relative to Silicon
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
Mass Number

Figure 2 - 2

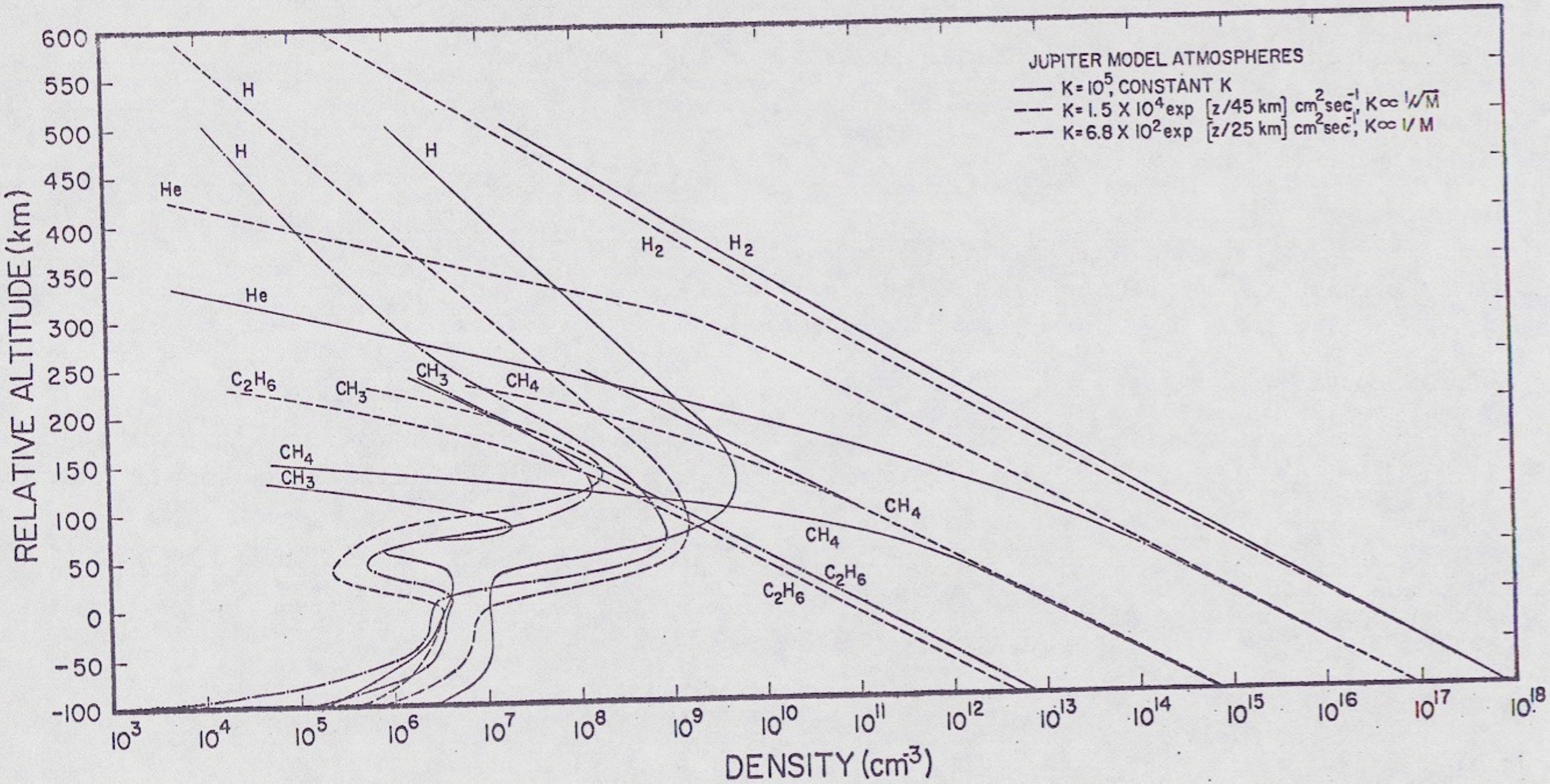
JUPITER MODEL ATMOSPHERES
K=10^5, CONSTANT K
K=1.5 X 10^4 exp [z/45 km] cm^2 sec^-1, K∝ 1/√M
K=6.8 X 10^2 exp [z/25 km] cm^2 sec^-1, K∝ 1/ M
H
H
H
He
He
H2
H2
C2H6
CH3
CH3
CH4
CH4
CH3
CH4
CH4
C2H6
C2H6
RELATIVE ALTITUDE (km)
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
-100
DENSITY (cm-3)
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18

Figure 2 - 3

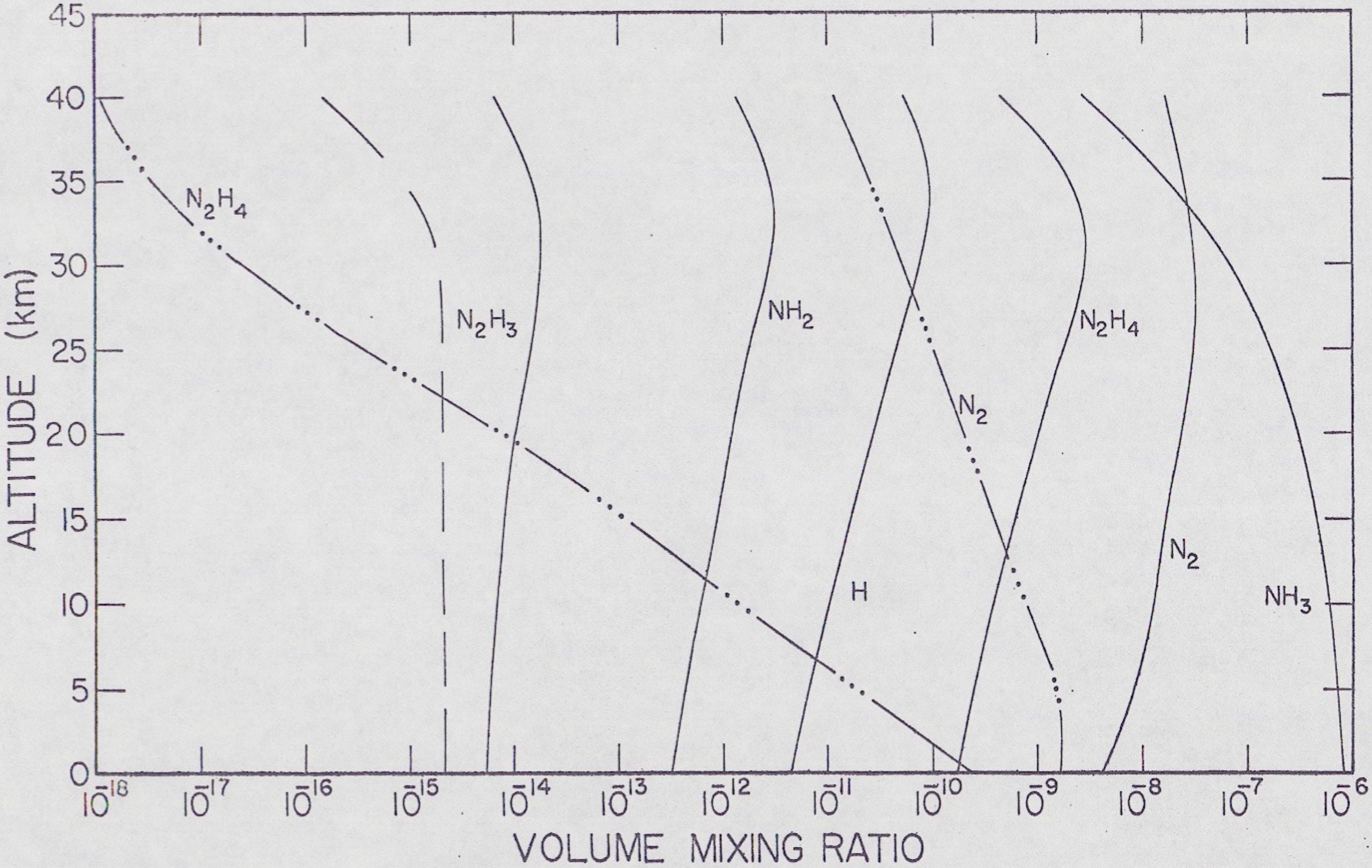
ALTITUDE (km)
0
5
10
15
20
25
30
35
40
45
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
VOLUME MIXING RATIO
N_2H_4
N_2H_3
NH_2
N_2
N_2H_4
H
N_2
NH_3

Figure 2 - 4

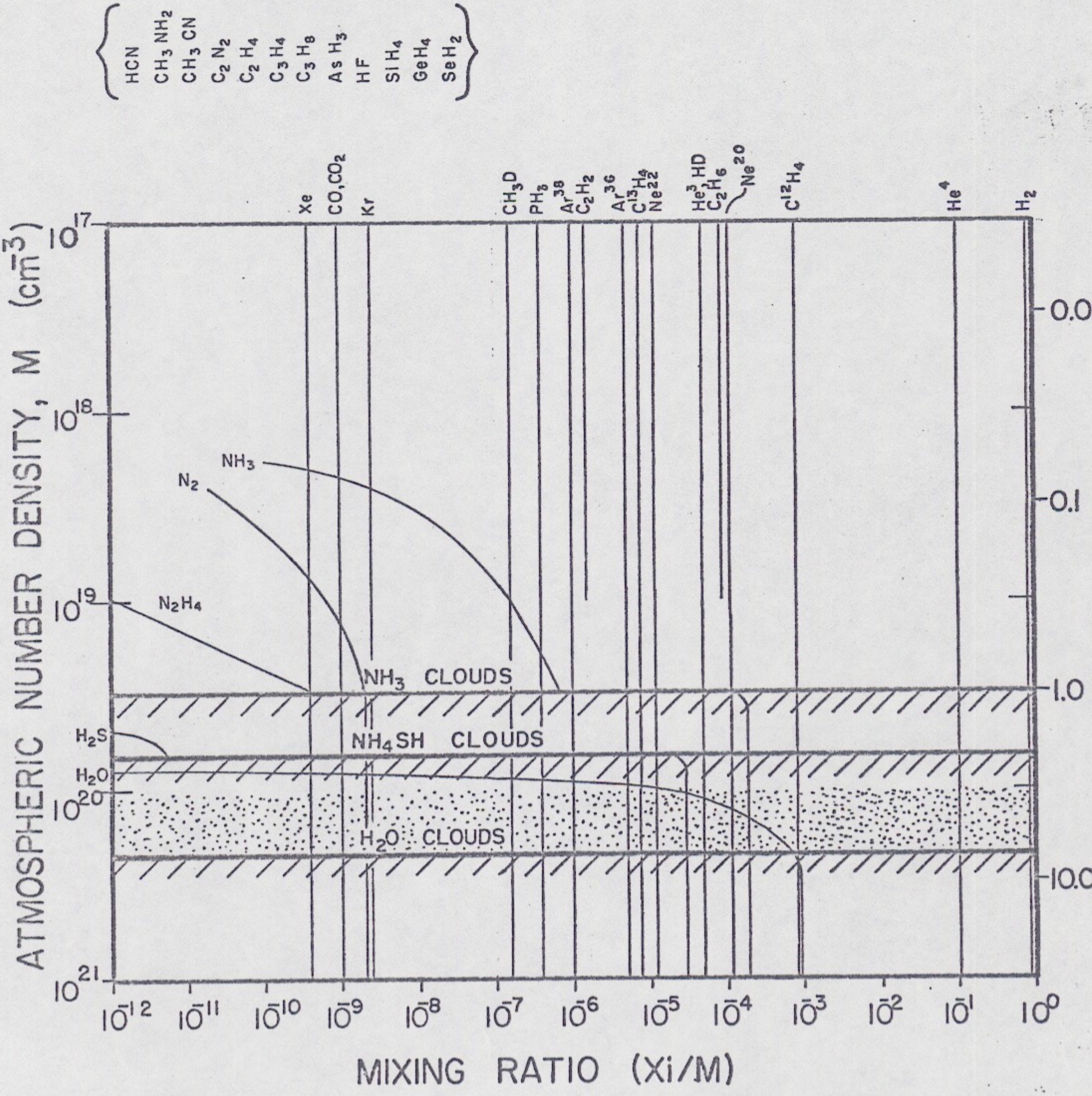HCN
CH₃NH₂
CH₃CN
C₂N₂
C₂H₄
C₃H₄
C₃H₈
AsH₃
HF
SiH₄
GeH₄
SeH₂
Xe
CO,CO₂
Kr
CH₃D
PH₃
Ar³⁸
C₂H₂
Ar³⁶
C¹³H₄
Ne²²
He³ HD
C₂H₆
Ne²⁰
C¹²H₄
He⁴
H₂
ATMOSPHERIC NUMBER DENSITY, M (cm⁻³)
10¹⁷
10¹⁸
10¹⁹
10²⁰
10²¹
NH₃
N₂
N₂H₄
NH₃ CLOUDS
H₂S
NH₄SH CLOUDS
H₂O
H₂O CLOUDS
0.0
0.1
1.0
10.0
10⁻¹²
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
MIXING RATIO (Xi/M)

Figure 2 - 5

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