Variations in the Jovian Atmospheric Composition and Chemistry

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Abstract

After the *Voyager* observations, a mean atmospheric composition model has become available from a combination of spacecraft and ground-based measurements, and this model can be used as a reference for future studies on the spatial and temporal variations of atmospheric composition. A further step for understanding the Jovian atmospheric structure is therefore the study of departures from this "standard atmosphere".

We first review the existing observational evidence for variations of atmospheric composition. Although the major constituents are expected to remain constant throughout the atmosphere, physico-chemical phenomena can induce vertical as well as horizontal variations. Such variations are documented only for a few constituents, and they can be accounted for by several mechanisms: condensation (NH_3), chemical reactions (PH_3), or stratospheric photochemistry (C_2H_2, C_2H_6). Search for temporal variations should be based on a thorough knowledge of the spatial and vertical variations in the atmosphere.

Temporal variations can be expected: 1) from external driving mechanisms, such as the UV or energetic particle fluxes for photochemistry in the stratosphere, or the obliquity for seasonal effects. 2) from internal dynamics, which can induce meteorological changes on time scales between 10^4 and 10^8 sec, or long term secular variations on times scales of 10^8 sec or larger. We attempt to identify theroretical ideas that will need to be developed in the near future.

Although most of these time variability phenomena remain hypothetical, it seems possible to begin constructing an observational data base by which these ideas can be tested. Furthermore, since spatial and temporal variations must be disentangled, the first goal is to achieve high spatial resolution observations. We describe some observations that could be made throughout the electromagnetic spectrum between now and the onset of the *Galileo* observations.

1   Introduction

Since we are concerned with variations in the composition of the Jovian atmosphere, it may be useful to define a "standard composition" to which measurements at a given time and over a particular region of the disk can be compared to. Such a model will of course be somewhat arbitrary, because all the available observations that can be used to determine it do not correspond to the same period or the same portion of the disk. Whether or not this exercise will prove interesting for the study of compositional variations, we cannot tell at the moment. At least, we hope that it will provide a clear picture of where we stand in terms of the accuracy of composition determinations. In Table 1, we list the mole fractions of the Jovian atmospheric constituents that have been identified through more than one set of measurements (*i.e.* we have excluded estimates resulting from a tentative detection). All determinations correspond to regions whose center coincides with the center of the disk, but whose extent in latitude greatly varies (up to $\pm 40°$). The period of reference is roughly centered around the *Voyager* encounters (1975–83), and the pressure level of reference in the atmosphere is just below the intermediate condensation cloud around 2 bar, except for H_2O whose mole fraction is given at the 6 bar

level, and for hydrocarbons (C_2H_2, C_2H_6) which are abundant only in the stratosphere. For NH_3, PH_3 and H_2O, vertical distributions are given in Figure 1.

It is rather gratifying that for the three most abundant species after H_2, that is for He, CH_4 and NH_3, the relative uncertainty on the mole fraction is down to the 20 % level approximately. Obviously, the situation is much less satisfactory for other minor constituents of great interest like H_2O, PH_3 or GeH_4, and it is rather embarrassing for the hydrocarbons such as C_2H_2. For some of these molecules, in fact, we cannot rule out the possibility that spatial or temporal variations have contributed significantly to the large uncertainty, for example in the case of PH_3. For other constituents, the large error bar partially reflects the inaccuracy of the spectroscopic data, or of the thermal structure. For instance, both problems were encountered in the case of C_2H_6, which is observed in emission at altitudes where the temperature profile is poorly known, and for which values of the band strength at 12 μm were until recently only based on medium resolution measurements.

The methodology for recording temporal variations of atmospheric consituents is not simple: some constituents vary with altitude as well as on a horizontal scale, and it is hopeless to try to understand variations of the disk-averaged composition, without a knowledge of spatial variations. Horizontal variations are only roughly documented and uncertainties in the vertical profiles will probably not be reduced until *Galileo* observes Jupiter.

Temporal variability within the atmosphere could occur in several ways:

1) *Externally driven time variations*: the solar cycle and the orbital motion could induce cyclic variations in constituents. These effects are expected only in the upper part of the atmosphere, since solar UV variation affects only the stratospheric photochemistry, and seasonal effects (if any) are attenuated by the radiative time and are also expected to be confined to the stratosphere. Stratospheric constituents are the most obvious candidates for studies of these effects (C_2H_2 and C_2H_6). Correlations with auroral observations (cf. Clarke *et al.*, this issue) are needed to advance this field.

2) *Dynamical time variations*: The characteristic time scales of the atmospheric motions can induce variations in the abundance of constituents on a hierarchy of time scales. The apparent stability of the atmosphere seems to imply very slow secular variations in the global composition, but meteorological effects could superimpose smaller scale variations in the features of the atmosphere (Great Red Spot, plumes, barges, etc.). Gierasch *et al.* (1986) predict values of radiative time constant and *para*-hydrogen relaxation time between 10^8 and 10^9 sec, and argue that momentum transport in the upper troposphere ($P \leq 700$ mbar) is weaker than radiative processes. Variations in the upper troposphere could thus take place only on time scales longer than 10^8 sec. The atmosphere of Jupiter is in a global state of apparent stability and it can be thought that large scale spatial variations of the true composition are stationnary in time. The spatial scale of these variations could therefore give some constraints on the dynamics (or more precisely, the kinematics) of the atmosphere, from advection terms in the equations of evolution. Disequilibrium species (GeH_4, PH_3,...) are the candidates for such research.

The first step to observe temporal variations in the atmosphere is to record the spatial

variations on the disk. This has important consequences for the methodology of observations: in particular, high spatial resolution is definitely needed to separate local variations at the smallest possible scale. Spectral resolution is no less important, to discriminate between lines of various constituents, or to ultimately retrieve the line shapes to get information on the vertical profiles. In the infrared, *Voyager* IRIS data are limited to medium spectral resolution ($\Delta\sigma$=4.3 cm^{-1}). Moreover, the spatial resolution for individual spectra, although much better than for any ground-based infrared observation, often has to be reduced by averages to increase the signal-to-noise, especially in the 5 μm window. Spectroscopy with imaging capabilities seems then the best way to observe spatio-temporal variations of Jupiter constituents. A field of view of 1 or 2 arcsec is required to characterize the large scale features of the atmosphere (Great Red Spot, barges, plumes). If we take for the evolution of these features a dynamical time scale of a few days, this gives also the smallest scale of time variation. Other time scales are expected on a Jovian year or a solar cycle.

Table 1. Standard Jovian composition (equatorial region)

Molecule	Mole fraction	Approximate uncertainty (%)	Pressure level (bar)	Reference
H_2	0.90	2	—	Gautier *et al.* (1981)
He	0.10	20	—	Gautier *et al.* (1981)
CH_4	2.5×10^{-3}	20	—	Gautier and Owen (1983)
NH_3	2.5×10^{-4}	20	≥ 2	De Pater (1986)
H_2O	3.0×10^{-5}	60	6	Bjoraker, Larson and Kunde (1986b)
PH_3	5.0×10^{-7}	50	2	Kunde *et al.* (1982) Bjoraker, Larson and Kunde (1986a)
CO	1.5×10^{-9}	30	2	Bjoraker, Larson and Kunde (1986a) Noll *et al.* (1987)
HCN	2×10^{-9}	100	$\geq .1$	Tokunaga *et al.* (1981)
GeH_4	7.0×10^{-10}	50	2	Bjoraker, Larson and Kunde (1986a)
C_2H_2	2.0×10^{-8}	200	$\leq .1$	Maguire *et al.* (1985)
C_2H_6	3.0×10^{-6}	100	$\leq .1$	Maguire *et al.* (1985) Kostiuk *et al.* (1987)

2 Observations

Only some variability has been documented (NH_3, H_2O, C_2H_2 and C_2H_6). The observations being very disparate, we do not attempt here to give a global approach of the variations in the atmospheric composition of Jupiter, but we describe, molecule by molecule, the results and the conclusions which can reasonably be made. As an aid for the comprehension of the following sections, Table 2 shows the variation of the mean atmospheric level sounded as a function of wavelength.

Table 2. Atmospheric levels sounded at selected wavelengths

Wavelength	Wavenumber (cm^{-1})	Pressure level (bar)	Reference
20.5 cm	0.05	10	De Pater, 1986
6.1 cm	0.2	4.1	" "
2.0 cm	0.5	0.76	" "
1.3 cm	0.8	0.32	" "
44.2 μm	226	0.8	Gierasch et al, 1986
16.6 μm	602	0.15	" "
7.7 μm	1306	0.01	Kunde et al, 1982
4.8 μm	2100	4 to 6	" "
0.22–0.3 μm		0.01–0.1	Atreya, 1986
8900 Å		0.4 to 0.5	West, 1979
3000 Å		0.2	" "
1500–1750 Å		0.003 to 0.04	Gladstone and Yung, 1983
1000 Å		0.8×10^{-6}	Atreya, 1986

2.1 Hydrogen

From an analysis of the *Voyager* IRIS spectra in the H_2 pressure-induced absorption range between 300 and 700 cm^{-1}, Conrath and Gierasch (1984) have shown first, that the *para*-hydrogen fraction near the 300 mbar pressure level is not in thermodynamic equilibrium, and second, that this fraction varies from equator to pole, with values closer to equilibrium at high latitudes. The recent study of Gierasch *et al.* (1986) correlates these variations to those of the temperature at the 270 mbar level (cf. Flasar, this issue).

2.2 Ammonia

The VLA observations of Jupiter at 1.3, 2, and 6 cm (De Pater, 1986) reveal an atmospheric zonal structure with bands roughly positioned on the NEB and SEB. The spatial resolution of these observations is about 1.5 arcsec (1/30 of the disk). Since the opacity at these wavelengths is mostly due to NH_3, at pressure levels between 0.5 and 10 bar, and since the thermal structure is thought to be rather uniform in the deep troposphere, the conclusion is that ammonia abundance varies between zones and belts. The NH_3 mixing ratio in belts is about half the one measured in zones.

At 5 μm, NH_3 and H_2O lines are present, and there is a possible contribution from H_2O to the variations in the 2050 cm^{-1} opacity. A complete analysis remains to be done at 5 μm: it would require high spectral resolution, and the use of a multiple scattering model for the radiative transfer analysis. New spectroscopic measurements of the $2\nu_2$ band of NH_3 allow a re-analysis of the 5 μm window from *Voyager* IRIS spectra in the 1880–2000 cm^{-1} range (Lellouch *et al.*, 1987). Preliminary results from this work also suggest a depletion in the belts by a factor of 2 compared to the zones.

The *Voyager* infrared observations have been used by Gierasch *et al.* (1986) to study the variations of ammonia over the Jovian disk and of its correlations with the variations of the thermal profile, the cloud opacities, and the *para*-hydrogen ratio. A three parameter model (Conrath and Gierasch, 1986) is used to retrieve the gaseous ammonia abundance and cloud opacities at 45μm and 5μm from the IRIS spectrum at 217 cm^{-1}, 225 cm^{-1} and 2050 cm^{-1}; the level sounded for the ammonia abundance determination are about 680 mbar. A correlation is found between ammonia variations, orange reflectivity and the vertical velocity field, w, as estimated from a scale equation of the heat flux (see Figure 2). This correlation would imply vertical motions extending through a scale height of the atmosphere.

Comparing now to the centimeter and 5μm observations, the same variations in latitude are roughly found, at lower spatial resolution. If the same mechanism can be invoked, this would imply an extension of the vertical velocity field to the deep troposphere too.

Ammonia is photodissociated below about 2300 Å and it is not expected in detectable amounts above the tropopause where solar UV photons can easily penetrate. This was confirmed by IUE observations between 1900 and 2300 Å (Combes *et al.*, 1981; Wagener *et al.*, 1985) which are best interpreted with a distribution of NH_3 rapidly decreasing in the lower stratosphere. However, an interesting result has been reported by Wagener and Caldwell (1987) who found that NH_3 absorption bands near 2000 Å are stronger in the Great Red Spot than at neighboring longitudes. They conclude that rapid vertical transport in the GRS is a plausible mechanism for the origin of this enhancement. It should be noted that no significant differences were found for PH_3, neither in the same IUE spectra, nor in *Voyager* IRIS spectra recorded over the GRS and neighboring regions (Kim and Owen, 1985).

Infrared heterodyne measurements by Kostiuk *et al.* (1977) showed possibly stratospheric emission lines of NH_3 in the North and South polar auroral regions.

2.3   Water

H_2O was observed on Jupiter from airborne observations on the Kuiper Airborne Observatory at 5 and 2.7 μm (Larson *et al.*, 1975; 1984; Bjoraker *et al.*, 1986b) and by *Voyager* IRIS (Kunde *et al.*, 1982; Drossart and Encrenaz, 1982; Bjoraker *et al.*, 1986b). Weak H_2O lines between 2020 and 2090 cm^{-1} originate in the pressure range between 4 and 7 bar (Bjoraker *et al.*, 1986b). From the analysis of these lines the abundance of H_2O in the deep troposphere is found to be 3 10^{-5}. Moreover, comparison of zones and belts abundances (Figure 3) imply spatial variations (depletion in the NEB hot spots, constant values in the SEB and zones between 2 and 4 bars). This abundance of H_2O seemed to imply a depletion of oxygen compared to the solar value by a factor of 50. However, new measurements (Noll *et al.*, 1987) of another oxygenated compound, CO, (see below) suggest a nearly solar O/H (Fegley and Prinn, 1987).

An attempt to model the puzzling distribution of H_2O was made by Lunine and Hunten (1987). In this model, derived from a model for equatorial plumes by Stoker (1986), moist convection is supposed to have large (100 to 10,000 km) cells of sinking air (with undersaturation of H_2O) and small plumes (10 to 100 km) of rising saturated gas. The different scales can explain the observation of an apparently low H_2O abundance. Observational tests of this model could be achieved by recording spectra of different regions (plumes compared to dryer areas), but H_2O line observations are presently possible only from airborne observations.

2.4   Phosphine

PH_3 is a disequilibrium species and its variations could give important information on the vertical motions on Jupiter. Phosphine has been observed in the infrared (10 and 5 μm). Although recorded variations of PH_3 are only tentative, 5 μm spectroscopy can give in the next few years new information on PH_3. PH_3 was an unexpected constituent, when observed by Ridgway *et al* (1976), since the stable chemical state of phosphorus at tropospheric temperatures is an oxidized compound (P_4O_6 dissolved in H_2O). Its presence in the troposphere implies disequilibrium phenomena. The vertical profile of PH_3, as inferred from 10μm and 5μm spectroscopy by *Voyager* IRIS (Kunde *et al.* 1982), gives a satisfactory fit to the spectrum in both regions. From 5 μm CVF observations of the Jovian disk in 1982 at IRTF, Drossart *et al.*, (1983) tentatively concluded that there were variations of PH_3 between belts and zones. These observations should be repeated at higher spectral resolution to discriminate fully between continuum effects related to cloud opacities and variations of abundances. IRIS spectra in the region of 2000 cm^{-1} could be used for that purpose, since new spectroscopic measurements of PH_3 combination bands (Tarrago et al., 1987) allow the full interpretation of this spectral region. Preliminary reanalysis of *Voyager* IRIS data at 5μm do not show large variations of the phosphine abundance over the Jovian disk (Drossart, priv. comm.).

2.5 Carbon Monoxide

In the case of CO, an ambiguity has existed since the publication of two contradictory analyses of near-infrared observations by Beer and Taylor (1978) and by Larson *et al.* (1978). Beer and Taylor favored a stratospheric distribution, whereas Larson *et al.* proposed a well-mixed tropospheric profile to interpret their airborne measurements. Both distributions have their justification. In the first case, CO is formed by reactions involving exogenic OH molecules (produced from oxygen bearing constituents, such as water from meteorites or oxygen atoms from th Io torus) and CH_3 radicals produced in the CH_4 photochemistry ($OH + CH_3 \rightarrow CO + 2H_2$) (Prather *et al.*, 1978; Strobel and Yung, 1979). In the second case, CO would be brought up by strong convective motions from the deeper and hotter regions of the troposphere, and in that process, reducing reactions that tend to convert CO to CH_4 are quenched (Prinn and Barshay, 1977).

Subsequent infrared airborne observations of Jupiter in the 5 μm spectral window by Bjoraker *et al.* (1986a) led to the detection of 18 lines of CO in the 1–0 vib-rotational band. These authors attempted to reproduce the CO lines with two different models, one assuming a mole fraction of 4×10^{-8} in the stratosphere, the other a well-mixed value of 1×10^{-9}. The overall agreement reached in the latter case is significantly better and suggests that the presence of CO in the Jovian atmosphere is indeed a consequence of deep mixing processes.

Recent ground-based observations in the same region of the spectrum, but with a higher spectral resolution by Noll *et al.* (1987) confirm this tentative conclusion and provide a more accurate determination of the CO distribution. The analysis of six fully resolved lines clearly excludes a high concentration of CO in the stratosphere. For a well-mixed distribution, a mole fraction of 1.6×10^{-9} is found, but a hybrid case with most (1×10^{-9}) of the CO in the troposphere and the rest in the stratosphere is also possible. Furthermore, no spatial variation in the CO abundance is seen between the NEB, the NTrZ and the GRS after correction is made of the haze plus cloud optical depth variation.

2.6 Hydrogen cyanide

HCN has been observed at 13 μm (Tokunaga *et al.*, 1981). Its formation is not well understood, however the fact that it appears in absorption indicates that it is abundant in the troposphere. Recent measurements of the same spectral region seem to imply a lower abundance of HCN (Drossart *et al.*, in preparation). If HCN is produced by photochemistry, variations can be expected with solar irradiance (during the solar cycle). But such an interpretation remains speculative, since we do not understand exactly the formation of HCN. Tokunaga *et al.* argue that photochemical production is the most likely source.

2.7 Germane

Germane was first detected by Fink *et al.* (1978) in the atmosphere of Jupiter. Only the Q branch of the ν_3 branch of germane can be seen in *Voyager* IRIS spectra, but Bjoraker (1986a)

recorded several other groups of lines of GeH_4. Some variations are seen between various samples of IRIS spectra, the Q branch being stronger in zones than in belts, according to Bjoraker *et al.* (1984). It must be noticed that since the Q branch of germane is blended with the $\nu_2 + \nu_4$ branch of PH_3, high resolution spectra would be useful to study such variations.

2.8 Acetylene and Ethane

Spatial variations in the UV absorption of C_2H_2 have been observed by Clarke *et al.* (1982). The high altitude abundance of acetylene seems to be larger at higher latitudes. On the other hand, from an analysis of *Voyager* IRIS spectra, Maguire *et al.* (1985) report a North-South asymmetry for C_2H_2 (but with a nearly-uniform abundance in the northern hemisphere), and an increase of C_2H_6 with latitude. The resulting effect is an increase of the C_2H_2/C_2H_6 ratio from South to North. Note that the UV measurements are sensitive to absorbers in the 3–40 mbar range, whereas the IR observations probe the 10–100 mbar region. Thus, the determination of spatial variations from these measurements is further complicated by the altitude dependency of the hydrocarbon distribution, although the IRIS data for ethane and acetylene near 740 cm^{-1} (with a resolving power of 4.3 cm^{-1}), are sensitive to the 1–40 mbar range too. In the case of acetylene, a strong north-south asymmetry has been observed for Jupiter's polar regions (Wagener and Caldwell, 1987). It is hypothesized that a depletion of C_2H_2 occurs in the Jovian stratosphere over the south polar region, as a consequence of enhanced production and condensation of polyacetylenes.

Kostiuk *et al.* (1987) recently reported the results of several measurements of individual C_2H_6 emission lines in the ν_9 band near 12 μm with ultra-high resolution (10^6) heterodyne spectroscopy. Mole fractions retrieved at various locations on the Jovian disk are not very different from the average equatorial value of $2.8 \pm 0.6 \times 10^{-6}$, except inside the auroral oval, and within the footprint of the Io flux tube (Figure 4). Higher values (5×10^{-6}) are observed near the boundaries and some very low values are found over the north auroral "hot spot". On the contrary, the south auroral region exhibits substantial ethane enhancements. These facts, together with the above-mentioned results, suggest that acetylene is preferentially formed at the expense of ethane in the north polar region, although there is still some uncertainty as to how much of the observed variations can be attributed to temperature changes in the stratosphere.

Observations of C_2H_2 were made at 13 μm by Noll *et al.* (1986) and Drossart *et al.* (1986). The abundances derived by these authors are very different:

Noll *et al.*, 1986: $C_2H_2/H_2 = 1.1 \times 10^{-7}$

Drossart *et al.*, 1986: $C_2H_2/H_2 = 1 \times 10^{-8}$.

Although different radiative transfer models and atmospheric profiles were used, there appear to have been genuine changes in the C_2H_2 stratospheric abundance. Temperature variations are observed in the stratosphere at a level of a few degrees (Orton, 1986), and it seems to low to account for the observed differences in the synthetic calculations.

Year to year measurements of both ethane and acetylene are necessary to improve these

10

observations and to correlate them with stratospheric temperature studies.

2.9 Other minor constituents

New molecules have been detected (C_2H_4, C_6H_6) or tentatively detected (C_3H_4) by Kim *et al.* (1985) in a small active area in the stratosphere of the North polar region (Caldwell *et al.* 1980). This region is a zone of intense auroral activity (these phenomena are studied in the paper by Clarke *et al.*). Observations of this region have been done by Drossart *et al.* (1986), showing acetylene enhancement and by Kostiuk *et al.* (1987), showing ethane depletion.

3 Theoretical aspects

3.1 Disequilibrium species in the Jovian troposphere

During the past decade or so, a number of theoretical pathways have been proposed, and to a different extent worked out, for the synthesis of disequilibrium species in the lower troposphere of Jupiter:

- quenching of equilibrium thermochemical reactions through rapid vertical mixing

- shock heating synthesis and

- electrical discharge synthesis during thunderstorms

- hot atom chemistry

All of these processes exhibit, to various degrees, a character of variability in space or in time. Therefore, they are interesting phenomena from the point of view of the compositional variations. However, there seems to exist opposite trends between the efficiency of each of these mechanism (measured by their ability to explain the observed abundances) and their degree of variability.

Lewis and Fegley (1984) have reviewed the sources mentioned above, with a particular emphasis on deep-mixing processes. Figure 5 is a schematic representation of the vertical distribution of gases assuming quenching in the lower troposphere with (curve labelled P) or without (curve labelled Q) photochemical production at higher altitudes. T_q denotes the quenching temperature below which the chemical lifetime of the species is longer than the characteristic time for mixing H^2/K (where H is the atmospheric scale height and K is the eddy diffusion coefficient). In the absence of photochemical synthesis, the distribution of the species follows a curve similar to the curve labelled Q, in which T_c represents the temperature below which condensation may occur (dashed line). Photodissociation by solar UV photons may also take place above that level (dot-dashed line). On the other hand, if the species results from both deep mixing *and* photolysis, then its distribution will look like the curve labelled P.

11

Table 3 compares the predictions of the deep-mixing model with the observed abundances of PH_3, CO, GeH_4 and HCN. The model assumes solar composition below the 300 K level and a coefficient of turbulent diffusion $K=2\times10^8$ cm^{2}sec. An excellent agreement exists for PH_3, CO and GeH_4, although it may be fortuitous in some cases, like PH_3 for which chemical kinetics are still poorly known. For HCN, the model fails, although an alternative explanation could be the production of HCN as a photolytic product of CH_3NH_2, which could itself result from quenching at the 1500 K level. This is probably much less likely than the direct photochemical production from NH_3 and C_2H_2 (Tokunaga *et al.*, 1981; Kaye and Strobel, 1983; Ferris and Ishikawa, 1987).

Table 3. Abundances of disequilibrium species predicted by the deep-mixing model, compared to observed values.

Molecule	T_q	$X_{equil.}$	$X_{obs.}$
PH_3	1300 K	4×10^{-7}	5×10^{-7}
CO	1100 K	2×10^{-9}	1.5×10^{-9}
GeH_4	800 K	8×10^{-10}	7×10^{-10}
HCN	1100 K	$\approx10^{-12}$	$\approx10^{-9}$

Spatial and temporal variations in the abundances of disequilibrium species brought up in the observable atmosphere by convective flow will necessarily reflect changes in the characteristics of the latter phenomenon (for instance the vertical profile $K(z)$). As indicated by the near-uniformity of the radiative output measured by *Voyager* IRIS (Pirraglia, 1983), the convective flow must vary with latitude on Jupiter, to compensate the latitudinal gradient of the solar heat input (Ingersoll and Porco, 1978). Hence, it is possible that the abundances of such dynamic tracers as PH_3, CO or GeH_4, might exhibit latitudinal gradients with an opposite trend to that of the solar illumination. Theoretical estimates for these gradients need to be made. The recent observations of CO by Noll *et al.* (1987), which yield constant mixing ratios of CO at the 2 bar level in the NEB, NTrZ and GRS, are not really conclusive because they do not extend to high latitudes. Observations of that type, however, extended to higher latitudes and to other tracers, would be extremely valuable.

Seasonal and secular variations, on the other hand, are not likely to be significant because of the large value of the radiative time constant at the altitudes of the lower troposphere (p $\geq$ 600 mbars) and because intrinsic variations of the convective flow are not expected to be important, at least on time scales that are small compared to the age of the solar system.

Shock heating synthesis appears to be another plausible source of HCN or CO during Jovian thunderstorms (Bar-Nun and Podolak, 1985). However, it is unlikely that the global abundance of hydrogen cyanide results from this highly localized mechanism, given the large dilution of the products in the atmosphere. On the other hand, this component would certainly exhibit significant temporal variations.

Similar remarks apply to the two other proposed mechanisms. Production rates of organic material in electrical discharges or by hot atom chemistry, for example, appear to be negligible compared to the photochemical yields, when proper scaling is applied to the results of laboratory experiments (Lewis and Fegley, 1984).

3.2   Chemical, physical and dynamical processes affecting the composition change

In this section, certain processes are discussed that are responsible for inducing changes in the composition with time and latitude. Broadly speaking, these changes fall into two categories – those driven by an external stimulus, and those which are caused by the changes in the planet's own internal structure and dynamics.

An example of the externally driven variation of the composition is the abundance of the hydrocarbons in the high latitude region of Jupiter. Infrared "bright spots" have been detected for C_2H_2 in the region of zenographic latitude, $58\pm 10°$ and longitude $178\pm10°$ (System III, 1965). For the corresponding longitude, the *Voyager* UV aurora were detected at latitudes of 56(+4,-3) degress (Broadfoot *et al.*, 1979, 1981). Due to the finite dimension of the UV Spectrometer slit on this polar limb aurora, the auroral zone is uncertain by a few degress. In any event, the UV auroras are virtually in the same zenographic locations as the infrared bright spots – giving rise to a speculation that both are triggered by the same mechanism. The UV auroras result from the precipitation of energetic charged particles, principally electrons and heavy ions. The range of electrons in the Jovian atmosphere would be greater than of ions with corresponding energy. From the *Voyager* measurement of the intensities of auroral H_2 Lyman and Werner bands and the H Lyman- alpha, the power input into the auroral zone is calculated to be 10^{12}-10^{13} W. This translates into an energy flux of 1-10 erg cm^{-2} s^{-1} into the auroral zone. The energetic sulfur and oxygen ions (see later) would deposit their energy in the vicinity of the homopause, the electrons deeper. (At the *Voyager* epoch the homopause was found to be located at a pressure level of 1 microbar in the equatorial region). It is therefore quite feasible that the infrared bright spots of C_2H_2 are caused by an enhanced abundance of this constituent, resulting from an increased dissociation of CH_4 and the subsequent chemistry (see Atreya (1986, pp. 98-105) for the latest details of the hydrocarbon chemistry). If the UV aurora are caused by electrons (rather than ions), it is likely that an increase in the abundance will be associated with an increase in the stratospheric temperature as well. The increased dissociation of CH_4 does not necessarily imply a decrease in the CH_4 abundance either. On the contrary, an enhancement in the CH_4 abundance is most likely. This is due to the fact that the charged particles would dissociate H_2 as well, resulting in large downward flux of the H atoms.

The hydrogen atoms play a dominant role in the CH_4 chemistry in the Jovian atmosphere. For example, they react with CH_3 to produce CH_4, i.e.,
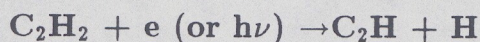
$$H + CH_3 + M \rightarrow CH_4 + M$$

(CH_3 is produced on reaction between CH_2 and H_2. CH_2 is produced on dissociation of CH_4). The greatly increased flux of H atoms would thus produce large abundance of CH_4. In fact infrared bright spots of CH_4 have been detected in the same region as bright spots of C_2H_2.

The above reasoning taken a step further predicts a decrease in the ethane (C_2H_6) production as larger quantities of the CH_3 radicals would be consumed by the increased flux of the H-atoms. C_2H_6 is produced primarily by the self-reaction between the CH_3 radicals, i.e.,
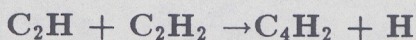
$$CH_3 + CH_3 + M \rightarrow C_2H_6 + M$$
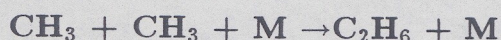
Indeed, in the region of the C_2H_2 and CH_4 infrared bright spots, a decrease in the C_2H_6 has been detected (Kostiuk *et al*, 1987). The above-mentioned hypothesis is presently being modeled quantitatively.
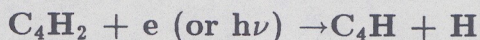
The charged particle precipitation is expected to result also in the increased production of the heavier hydrocarbons, particularly polyacetylenes (diacetylene, C_4H_2, and beyond, i.e., $C_{2n}H_2$ where n=2,3...etc.). The polyacetylenes are produced subsequent to the dissociation of C_2H_2 by either the charged particles (e) or the solar photons (hν):
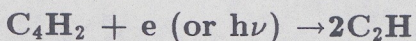
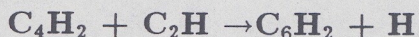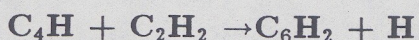$$C_2H_2 + e \ (\text{or } h\nu) \rightarrow C_2H + H$$

followed by

$$C_2H + C_2H_2 \rightarrow C_4H_2 + H$$

and

$$C_4H_2 + e \ (\text{or } h\nu) \rightarrow C_4H + H$$

or

$$C_4H_2 + e \ (\text{or } h\nu) \rightarrow 2C_2H$$

followed by

$$C_4H_2 + C_2H \rightarrow C_6H_2 + H$$

or

$$C_4H + C_2H_2 \rightarrow C_6H_2 + H$$

14

etc.

The polyacetylenes absorb sunlight to longer wavelengths (≤ 4000 Å) than CH_4, C_2H_2, C_2H_4 or C_2H_6 (≤ 1800Å). They could be the source of the aerosols that might influence the Jovian stratospheric thermal structure.

The nature and characteristics of the above-mentioned infrared bright spots and the polyacetylenes is expected to be highly variable, not only with zenographic latitude, but also with time. This is due to the fact that the charged particles responsible for them are modulated by Io and its plasma torus. The origin of the energetic ions is in the volcanoes of Io. Even between the epochs of *Voyager* 1 and *Voyager* 2 that were six months apart, large changes in the volcanic activity of Io were measured. Vulcanism tends to be highly episodic and unpredictable, even for Io. It is, therefore, expected that depending upon the volcanic activity of Io, the charged particle power input into the auroral region of Jupiter will go up or down. This would result in corresponding changes in the composition of the Jovian atmosphere at the high latitudes.

In addition to the hydrocarbons discussed above, it is expected that the influx of the atoms or ions of sulfur and oxygen would result in the production of CO, HCHO (formaldehyde), CS and COS (carbonyl sulfide). With the exception of CO, none of these other species have yet been detected, perhaps because of their low abundance. It should be noted that the source of CO could either be indigenous to Jupiter, or extraplanetary (see Sec. 2.5 for additional details). An extraplanetary oxygen bearing constituent (such as water from the meteoritic ablation, or oxygen atoms or ions from the Io torus) would subsequently react with the Jovian hydrocarbons, thus producing the CO. Both the internal and the extraplanetary sources of CO are expected to exhibit temporal as well as latitudinal variation in CO.

Unlike the abovementioned particle induced changes, "regular" temporal and latitudinal variations in the abundance and the distribution of the photochemically active constituents are expected due to the change in the solar UV flux. An example of such a variation for ammonia is shown in Figure 6. Also shown in this figure is the effect of change of atmospheric vertical mixing which is characterized by the eddy diffusion coefficient, K. Our experience with the terrestrial atmosphere indicates that temporal as well as latitudinal variations in K are expected. So far K has been determined at only the equatorial region of Jupiter by *Voyager*. Although the eddy mixing is expected to be the dominant dynamical factor in the stratospheric chemistry, one should not ignore the possibility of stratospheric winds redistributing the constituents on a short time scale. No data on such winds are available.

Internal dynamics that may be responsible for rapid upwelling of certain disequilibrium species, such as PH_3, GeH_4, SiH_4, SeH_2, AsH_3 and perhaps CO, is expected to exhibit less of a temporal than a latitudinal change.

Although many of the physical, chemical and dynamical processes affecting the atmospheric composition and its temporal and latitudinal variation are not directly measurable either now or from the planned spacecraft or the earth-based observations, one can learn a great deal about them by monitoring the compositional changes on a regular basis.

4 Prospects for future observations

In this section, we examine the observations which could be done during the next decade to improve our knowledge of spatio-temporal variations of the gaseous composition of Jupiter. Although such a study is by no means a new idea (Vogel, 1895), precise records of variations have only begun, and there is a need for simultaneous observations at different wavelengths to discriminate between temperature, cloud opacities and compositional aspects. Therefore, it is important to review the present "state of the art" to allow a broad diffusion of the Jupiter's observational programs.

4.1 Earth-orbit and ground-based observations

4.1.1 Centimeter range

The high resolution mapping of Jupiter's thermal radiation at 1.3, 2.0, 6.1 and 20.5 cm with the Very Large Array, by De Pater and Dickel (1986), provides a solid basis for a survey of the distribution of ammonia absorption. Such a program should be carried out between now and the beginning of the *Galileo* measurements. The maximum resolution presently available at 2 cm (1.5 arcsec) is adequate to characterize variations of the ammonia abundance between belts and zones (De Pater, 1986), as can be seen from Figure 2. Ammonia vertical profiles can be retrieved between 0.5 and a few bar.

4.1.2 Millimeter and sub-millimeter ranges

Apart from filtered radiometric measurements (Hildebrand *et al*, 1985, Griffin *et al.*, 1986), very little has been done for the study of the Jovian atmospheric composition at these wavelengths. The main reasons for that were the lack of large antennas devoted to that region of the spectrum, as well as the difficulty in building wide-band receivers appropriate for the measurement of weak, broad spectral features seen in absorption against a thermal background. These difficulties are being reduced. At least five large antennas ($D \geq 10$m) dedicated to millimetric and sub-millimetric observations have recently become or are about to become operational, with improved wide-band receivers ($\Delta\nu \approx 1$ GHz). Remaining problems, specific to the measurement of pressure-broadened absorption signatures in Jupiter's spectrum, are still important, however, because of the large fluctuations of the spectral baseline in the presence of a significant continuum signal. On the other hand, provided that the optical depth in the center of a line is large enough, extremely narrow features may be observed in emission. Millimetric instruments then become very powerful tools for probing the distribution of atmospheric constituents in the stratosphere and their variation in time.

Several studies have looked at the potential information that could be gained from millimeter and sub-millimeter observations concerning the composition of the Jovian atmosphere (Bézard, Gautier and Marten, 1986; Lellouch and Destombes, 1986). Figure 7 shows, for example, the numerous transitions calculated between 10 and 100 cm^{-1} (λ=0.1 to 1 mm). HCN

and PH_3, in addition to NH_3, have strong absorption features in this range. CO is probably not detectable, even with "state of the art" detectors. We are not considering here molecules that have not yet been detected but are predicted to have observable transitions (H_2S, HCP, ...) since this would be the objective of a highly sensitive search rather than that of a temporal survey. However, should they be detected in the future, these species should be included in a temporal survey, because they are convenient tracers of the deep atmospheric chemistry.

From the ground, only wavelengths longer than 300 μm are accessible because of the telluric water vapor absorption. At the present time, one can foresee systematic studies of NH_3, PH_3 and HCN using either coherent or non-coherent receivers with a spectral resolution between 10^{-3} cm^{-1} (a few MHz) and 1 cm^{-1}. With the advent of large millimetric arrays (IRAM, Nobeyama) it will be possible to repeat the kind of work that is being done for NH_3 with the VLA, but with a slightly higher spatial resolution (0.5 to 1 arcsec at 1 mm with IRAM, for example). The first high resolution millimeter maps of Jupiter may be reasonably expected for just a few years before the onset of *Galileo* measurements. In terms of vertical sounding of the atmosphere, there would be a good complementarity with the results of the PPR experiment on *Galileo*, in addition to the advantage of extended time coverage. To interpret such observations, however, laboratory measurements are needed for the pressure-broadened line shape of ammonia at wavelengths of a few millimeters (De Pater and Massie, 1985).

4.1.3   Far-infrared range

Between 30 and 300 μm, observations have to be made at high altitudes with airborne or balloon-borne instruments, or from earth orbit. Because of the high cost of operation inherent to these observations, it is difficult to warrant (or maybe even justify) their systematic use for repeated measurements. However, Jupiter being a strong source and because of the huge advance in sensitivity expected with forthcoming facilities, like the NASA airborne observatory SOFIA or the ESA satellite ISO, it is possible to envisage that a very small amount of their time could be regularly devoted to a well targeted survey program of a few molecular lines (NH_3, PH_3, HCN, $(H_2)_2$). Such observations could in fact be useful for the calibration of other spectroscopic measurements made with these facilities.

4.1.4   Near- and medium-infrared

The region between 1 and 25 μm offers many possibilities for observations of Jupiter from the ground. Historically, it is in this part of the spectrum that most of the atmospheric constituents known to date have been discovered. Very high spectral resolution (10^4–10^6) can be achieved with the use of post-dispersed Michelson interferometers, Fabry-Pérot spectrometers and heterodyne receivers. Furthermore, relatively high spatial resolution can be attained with large telescopes (diffraction limit ≤ 0.1 R_J). It is therefore a region of choice for the study of compositional variations.

The 5 μm region and the 7–14 μm windows are particularly important because of the numerous molecular transitions occuring there. Interference from Jovian cloud and haze particles will however hopelessly complicate the inference of temporal variations, if the spatial and spectral resolution are too low. There is also a strong need for simultaneous studies of the thermal structure to avoid an ambiguous interpretation on the origin of the observed variations.

Opportunities for further ground-based observations of Jupiter in the next six years include astronomical facilities in Hawaii, California, Arizona, and Texas. During the next few years, spatially resolved spectra of Jupiter at 5 μm will be obtained at Mauna Kea. The CGAS spectrometer at the NASA Infrared Telescope Facility (Tokunaga et $al.$, 1987) will be used to map Jupiter at 2.5 arcsec spatial resolution and at medium spectral resolution (1 cm^{-1}) as has been done for PH3 at lower spectral resolution (CVF) (Drossart et $al.$, 1983). The variations of phosphine, ammonia, or germane bands at such spatial resolution will provide a global map of possible spatial variations for these constituents, and a complete study of major atmospheric features (the Great Red Spot mostly).

The FTS spectrometer built by J.-P. Maillard at the Canada-France-Hawaii Telescope (Maillard and Michel, 1982) will provide high spectral resolution spectra (0.1 cm^{-1}) and a spatial resolution in some features (although a global mapping will not be possible in a reasonable time of observation). Some spectra were already recorded in 1986. Although the telluric atmospheric conditions do not allow a full scientific exploitation of these spectra, the techniques (pointing on atmospheric features, spectral range, etc.) have been tested.

Another productive instrument has been the 1-5 μm Fabry-Pérot spectrometer at the United Kingdom Infrared Telescope. This instrument has been applied to studies of CO on Jupiter (Noll et $al.$, 1987). With a resolving power of up to 30,000 it is well-suited for the study of line profiles at thermal wavelengths, especially at 5 μm.

Ultra-high resolution spectra of Jupiter with heterodyne spectrometers at 10 μm is likely to continue at Mauna Kea. Such techniques can provide spectral resolution as high as 10^6 (Kostiuk et $al.$, 1987) and with spatial resolution of about 2 arc-sec with a 3-meter telescope. The study of the stratospheric emission lines is well suited to this high spectral resolution, indeed it is possible to resolve the Doppler-broadened lines. While such spectrometers are limited in the spectral coverage and wavelength choice, the development of heterodyne spectrometers with tunable lasers as the local oscillator is likely to change the field dramatically.

The Kitt Peak National Observatory FTS has also been successfully used for the study of the Jovian atmosphere. One of the earlier spectra obtained at 10 μm was extremely fruitful (Tokunaga et $al.$, 1979). Recently, this spectrometer was outfitted with a cryogenic grating post-disperser which greatly increased its sensitivity at thermal wavelengths (3-25 μm) (Jennings, priv. comm.). Such a development has the potential of expanding the quantity and quality of infrared spectroscopy at 5-14 μm. Searches for minor constituents such as H_2CO for example can be effectively carried out with this instrument at 8–14 μm.

A 10 μm cryogenic echelle spectrometer has been constructed at the Univ. of Texas by J. Lacy. With a resolving power of 10,000, this instrument also has the potential of obtaining new 10 μm spectra of Jupiter, especially in the search for new molecular species.

A cryogenic echelle spectrograph for 1-5 μm is also being constructed for the NASA Infrared Telescope Facility. With a resolving power of up to 40,000 and a slit of up to 30 arc-sec in length, this instrument will be particularly powerful for studying line profiles, abundances, and spatial variations simultaneously. Completion of this instrument is for 1990, well in time to make observations of Jupiter before *Galileo* begins observations.

The observations of the types described above, if repeated during the next decade could provide a data base for long term observation of secular variations in the atmosphere of Jupiter. Well recorded positions are needed for a long term comparison with *Galileo* observations, however the *Galileo* observations will result in a revision of all previous analyses since a new interpretation of these data will be possible from the knowledge of the exact atmospheric structure. On the other hand, rapid revision of such data during the first few months of the Galileo experiment could increase the scientific return of the mission, by reprogramming some atmospheric observations.

4.1.5   Visible

The visible part of the spectrum is affected largely by atmospheric scattering and by the cloud physical properties (West, 1979) and these aspects are reviewed elsewhere (Beebe *et al.*, this issue). The effect of the hydrogen quadrupole lines have been studied by Cunningham *et al.* (1986), and show variations due to thermodynamics variations in the atmosphere (o/p H_2 variations). Correlations between cloud opacities and gaseous ammonia variations are clearly demonstrated in Gierasch *et al.* (1986).

4.1.6   Ultraviolet

IUE observations of Jupiter extend now over a period of more than nine years, covering the spectral range 1100–3200 Å. They have allowed the detection and/or the study of a number of atmospheric constituents above the temperature minimum: NH_3, C_2H_2, C_2H_6, possibly C_3H_4 (allene) and C_3H_6 (cyclopropane), and also the determination of upper limits for several hydrocarbons (Wagener *et al.*, 1985; Gladstone and Yung, 1983; Clarke, Moos and Feldman, 1982; Combes *et al.*, 1981; Owen *et al.*, 1979).

The remaining lifetime of IUE is short, however. The Hubble Space Telescope is the long-hoped facility that will perform similar studies with a much higher sensitivity as well as higher spatial and spectral resolution. It should undoubtedly be possible to observe time variations in the chemistry of the Jovian stratosphere with such a powerful instrument. The HST instrument that is the most suited to these studies is the High Resolution Spectrograph (λ=1100–3200 Å, $\lambda/\Delta\lambda$= 10^5, 2×10^4 or 2×10^3, f.o.v.=0.25$\times$0.25 or 2$\times$2 arcsec^2).

Among the difficulties that observers will face, is the fact that the solar spectrum, therefore the reflected spectrum that is measured on Jupiter, is strongly variable below 1900 Å. There must be a simultaneous check on these variations. There is also a crying need for low temperature measurements of absorption spectra in the laboratory, at resolutions comparable

to that acheived by the HRS. Last, but not least, is the fact that HST will be heavily over-subscribed during the next decade. An observational framework such as the one proposed by the Space Telescope Scientific Working Group for Solar System Science (Belton *et al.*, 1985) is a must if full advantage is to be obtained from the amazing potential offered by this unique facility.

4.2 *Galileo* composition measurements

4.2.1 Mass spectrometer

Direct in-situ composition measurements will be carried out by the Neutral Mass Spectrometer on the Probe. Simultaneous, supporting data on the atmospheric structure (pressure, temperature, density and mean molecular weight), cloud structure, net flux, and the atmospheric electrical activity will be obtained by other instruments on the Probe payload. Important complementary information of the visible troposphere will be provided by the solid state imager or camera on the Orbiter. Some information on the upper atmospheric gases (i.e., beyond the tropopause) is likely from the ultraviolet spectrometer whose range is 500-4000 Å. Unlike *Voyager*, however, the stellar or solar occultations will not be possible because of the spinning mode.

The Probe will enter the atmosphere in the near equatorial region (approximately 5°S latitude). Its nominal lifetime of 40 minutes will provide information to a depth where the pressure is 10 bars. It is, however, expected that useful data to a pressure level of 25 bars (descent time 60 minutes) will be transmitted to the *Galileo* Orbiter for relay to the Earth. The Neutral Mass Spectrometer will measure species beginning at the 100 mb level, and in the mass range 2-152 AMU. One channel will be devoted to all masses greater than 126. The dynamic range of the quadruple mass analyzer is 10^8. Many constituents with mole fractions as low as 10^{-10} are expected to be detected with the help of gas enrichment cells. This will be particularly valuable for the measurement of the rare gases and the isotopes. A list of the gaseous species likely to be encountered in the region of the Probe descent and expected to be detected by the Neutral Mass Spectrometer is given in Table 4. Prior to the *Galileo* measurement, long term monitoring from 1 AU (ground-based, orbital and sub-orbital) of several key species (such as hydrocarbons, NH_3, disequilibrium species, etc.) will be essential to study their temporal and latitudinal variability. A comparison of the 1-AU data with the *Galileo* data will be critical for such study, it will also provide cross calibration of the instruments.

Table 4.*

Species arranged according to their Mass Numbers

AMU	Species	AMU	Species	AMU	Species
1		51	NH_4SH	101	
2	H_2	52	C_2N_2	102	$^{34}S_3$
3	^3He; HD	53		103	
4	^4He	54		104	
5		55		105	
6		56		106	
7		57	N_2H (from N_2H_4)	107	
8		58	N_2H_2 (from N_2H_4); C_4H_{10} (butane)	108	
9		59	N_2H_3	109	
10		60	N_2H_4	110	
11		61		111	
12	C (from CO cracking)	62	P_2	112	
13	CH	63		113	
14	N^{14}	64	P_2H_2; S_2	114	
15	N^{15}; CH_3	65	P_2H_3	115	
16	CH_4; NH_2	66	P_2H_4; S_2	116	
17	$^{13}CH_4$; CH_3D; NH_3	67		117	
18	$^{15}NH_3$; H_2O	68	S_2	118	
19	F (from HF cracking); $^{17}OH_2$	69		119	
20	HF; ^{20}Ne; $^{18}OH_2$	70		120	
21	^{21}Ne	71		121	
22	^{22}Ne	72	C_5H_{12} (pentane)	122	$(C_2H_5S)_2$
23	B_2H (from B_2H_6 cracking)	73		123	
24	B_2H_2 (from B_2H_6 cracking)	74		124	P_4; ^{124}Xe
25	B_2H_3 (from B_2H_6 cracking)	75		125	SbH_3
26	B_2H_4 (from B_2H_6 cracking)	76	GeH_4	126	^{126}Xe
27	B_2H_5; C_2H_3; HCN	77		127	I (from HI)
28	B_2H_6; N_2; CO; C_2H_4	78	AsH_3; C_6H_6 (benzene); ^{78}Kr	128	^{128}Xe; HI
29		79		129	^{120}Xe
30	HCHO; C_2H_6	80	Br; ^{80}Kr	130	^{130}Xe
31	CH_3NH_2	81	SeH_2; HBr	131	^{131}Xe
32	SiH_4	82	C_6H_{10} (from hexane); ^{82}Kr	132	^{132}Xe
33	$^{31}SH_2$; CH_3NH_4	83	C_6H_{11} (from hexane); ^{83}Kr	133	
34	$^{32}SH_2$	84	C_6H_{12} (hexane); ^{84}Kr	134	^{134}Xe
35	Cl (from HCl)	85		135	
36	$^{34}SH_2$; HCl; ^{36}Ar	86	^{86}Kr	136	^{136}Xe
37		87		137	
38	^{38}Ar	88		138	
39		89		139	
40	^{40}Ar	90		140	
41	CH_3CN	91		141	
42	C_2H_4N (from C_2H_5N)	92		142	
43	C_2H_5N	93		143	
44	C_3H_8 (propane); CO_2	94		144	
45		95		145	
46		96	$^{32}S_3$	146	
47	CH_3S	97		147	
48		98		148	
49		99		149	
50		100		150	

4.2.2 NIMS and PPR

The Near Infrared Mapping Spectrometer (Hunten *et al*, 1986) will provide spectral maps of Jupiter with 0.025 μm spectral elements and spatial resolution between 100 and 1000 km (depending of proximity), in the 0.7 to 5.2 μm range. Synthetic spectra will be calculated for comparison to the NIMS observations at various wavelengths. The infrared Jovian windows at 2.7 and 5 μm allow abundance measurements for NH_3, H_2O, PH_3 and probably GeH_4. The short wavelength range (0.7 to 3 μm) is adapted to joint determinations of abundance and cloud observations. Temperature profiles are retrieved from the Photopolarimeter and Radiometer experiment (Hunten *et al*, 1986). A calibration of the full procedure would be possible by observing the Probe entry site of Galileo with NIMS. Global mapping of the equatorial regions of Jupiter would be devoted to the study of variations at planetary scales. Close observations of smaller features could allow the first local study of small scale composition variations. The *Galileo* mission will have about 20 orbits around Jupiter. This will allow time record variations in the upper troposphere, according to an estimate of a time constant of 10^8s by Gierasch *et al.* (1986).

4.3 General remarks on observational techniques and data analysis

Techniques for mapping spectroscopy from ground based observatories are presented here. The comparison of several datasets (for example, IRIS spectra, compared to ground based observations) requires accurate position measurements on the Jovian disk, and the choice of standard coordinates. When a single aperture or linear array is used, the precision of the position measurement on the disk is hardly better than 2 arcsec when compared to the limb position. A better accuracy (at least *a posteriori*) can be achieved by a comparison with the position of the Galilean satellites, whose geocentric positions are known to 0.05 arcsec (Arlot, 1982; Chapront *et al*, 1986).

The interpretation of spectra is often limited by the lack of laboratory spectroscopic measurements: this has been the case for the 5 μm region. Figure 8 shows the comparison of synthetic spectra with old data (1982) and with new ammonia spectroscopic data (1987).

The method for studying variations of the composition requires:

- Use of a standard model of the thermal structure of the atmosphere of Jupiter (*Voyager* IRIS temperature profiles should be used for each region of interest).

- Use of a structure model of the atmosphere

- Using standard profiles of variations of known constituents

5 Conclusions

The study of composition temporal variations on Jupiter remains very fragmented today. The interpretation also is incomplete, and the question of the origin of several components (HCN,

CO) is controversial. As spatial variations of some tropospheric constituents begin to be documented (H_2O, NH_3), others are only suspected (PH_3, GeH_4). In the stratosphere, the interpretation of the observations is difficult; variations of C_2H_2 and C_2H_6 are observed, in auroral regions, but thermal as well as abundance variations are probably both present.

Up to now, temporal variations are only suspected for stratospheric constituents (C_2H_2 ?). The need for a long term observational study of this problem is therefore strong, before the *Galileo* mission, to improve our knowledge of the compositional variations on Jupiter.

The recent development of new ground-based instruments with spatial resolution similar to the major features of the Jovian atmosphere give new opportunities to study this field. The theories invoked to explain composition variations in the stratosphere are related to photochemical and auroral processes; in the troposphere, the dynamics of the atmosphere as well as non equilibrium chemistry are probably important. The study of temporal variation in composition is thus central to the understanding of many key problems of the Jovian atmosphere.

Figure captions

Figure 1: NH_3, PH_3 and H_2O vertical distributions. after Bjoraker (1986), Kunde *et al*, 1982.

Figure 2: Comparison of NH_3 variations, orange reflectivity and vertical velocity. (after Gierasch, Conrath and Magalhaes, 1986).

Figure 3: Variations of H_2O between NEB and SEB. (after Bjoraker *et al.*, 1986b).

Figure 4: Variations of C_2H_6 over the disk. (after Kostiuk *et al.*, 1987).

Figure 5: Vertical distributions of gases (after Lewis and Fegley, 1984). (see text for explanations).

Figure 6: Variation of the ammonia mixing ratio with height for the various atmospheric models. Altitudes are above the cloud top. —··— $T(z)$, $K=2\times10^4$ cm^2sec^{-1} (constant);
— $T(z)$, $K\propto1/M^{1/2}$;
- - - $T(z)$, $K\propto1/M$;
— —, $T(z)$, $K\propto1/M^{1/2}$, latitude$=75°$;
···· Strobel (1973).
(after Atreya *et al.*, 1977).

Figure 7: Molecular transitions in the sub-millimeter spectrum of Jupiter (after Bézard *et al.*, 1986).

Figure 8: Comparison of the 5 μm spectrum of Jupiter (IRIS spectrum averaged on the NEB) with synthetic spectra computed with previous (Drossart and Encrenaz, 1982) and new (Lellouch et al, 1987) spectroscopic data for the 2 ν_2 band of NH_3.
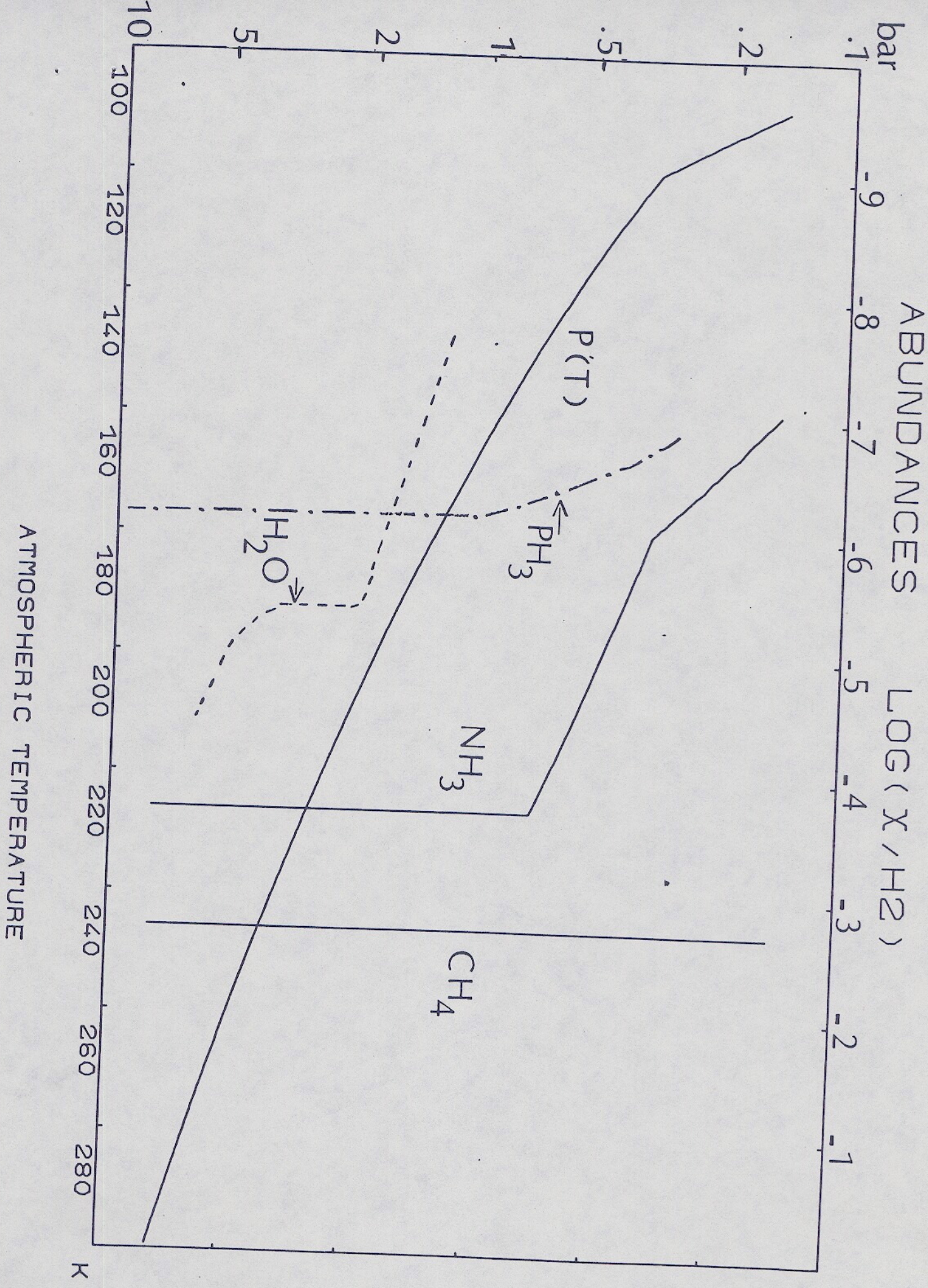
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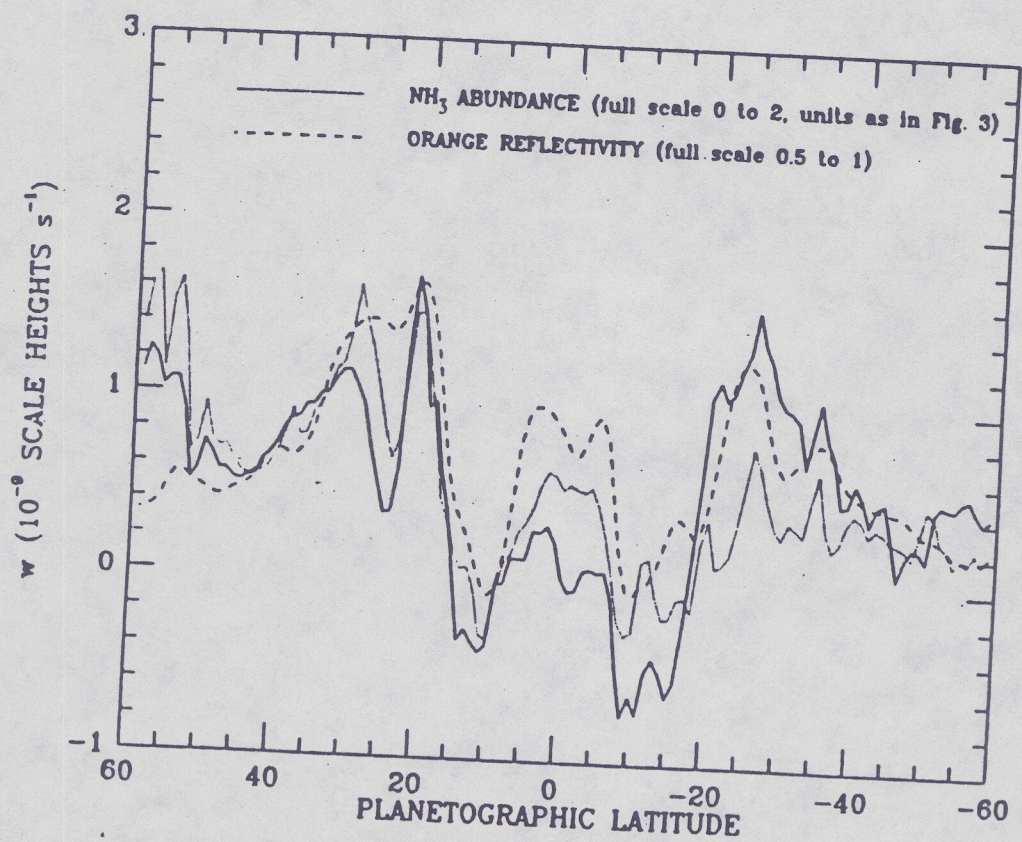
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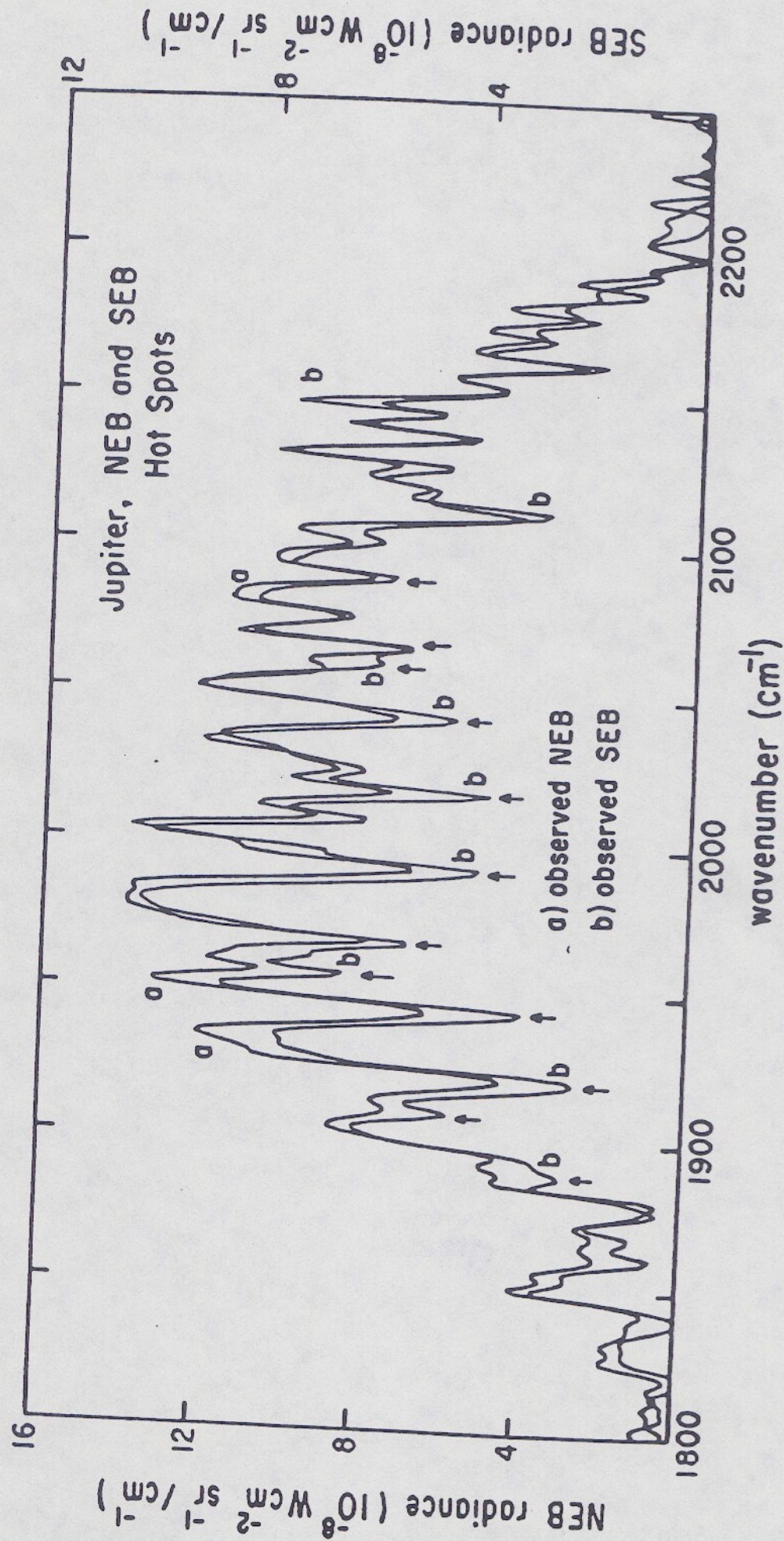FINK, U., H .P. LARSON, AND R. R. TREFFERS (1978). Germane in the atmosphere of Jupiter. *Icarus* **34**, 344–354.

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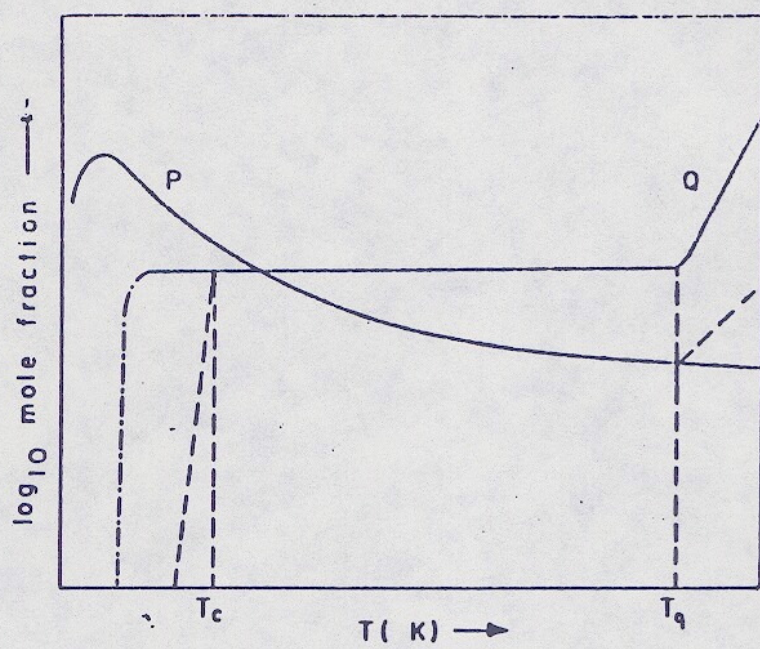
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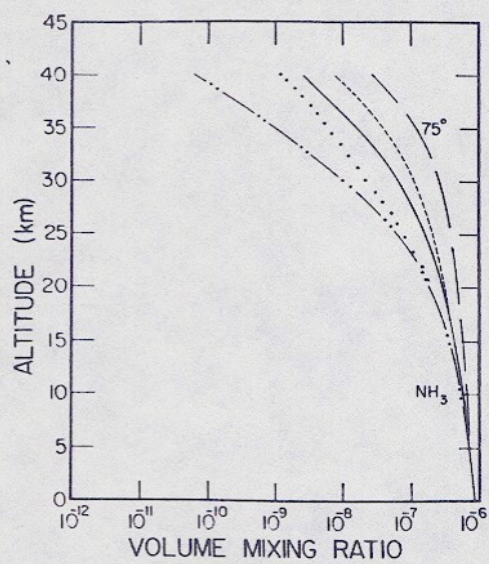
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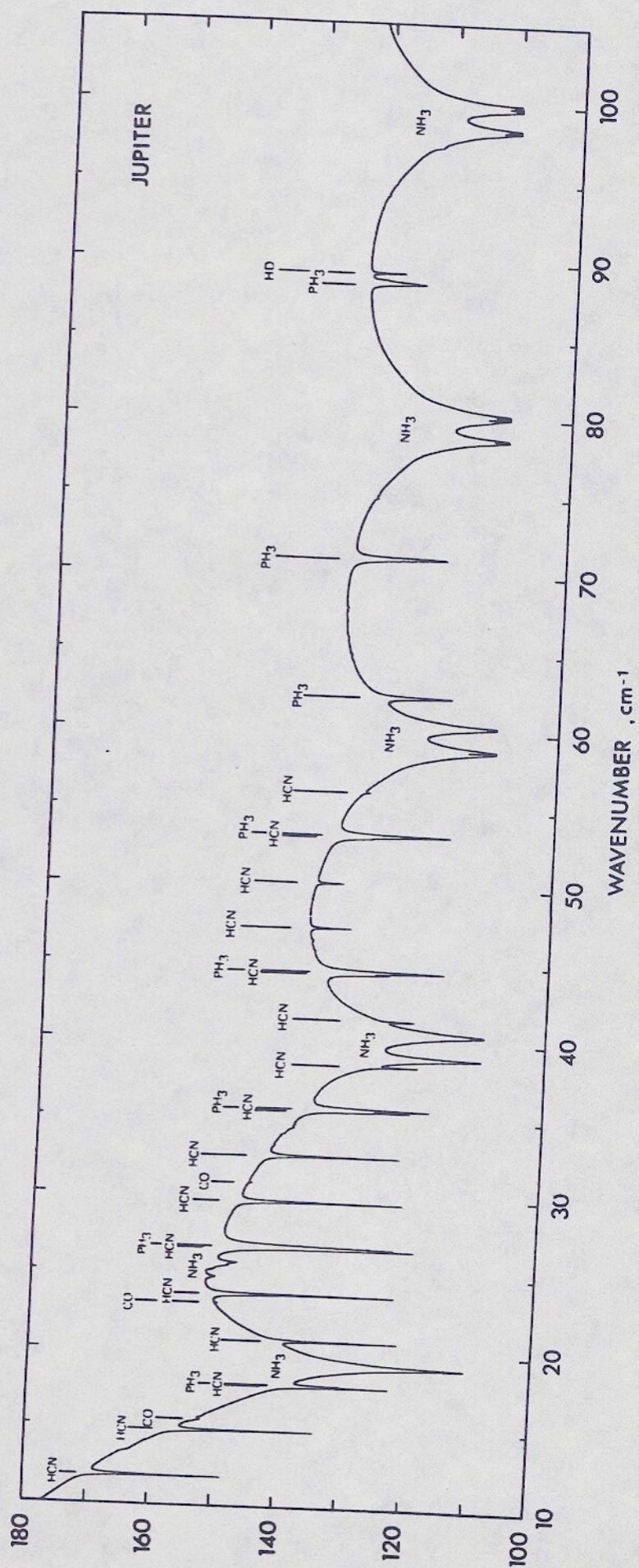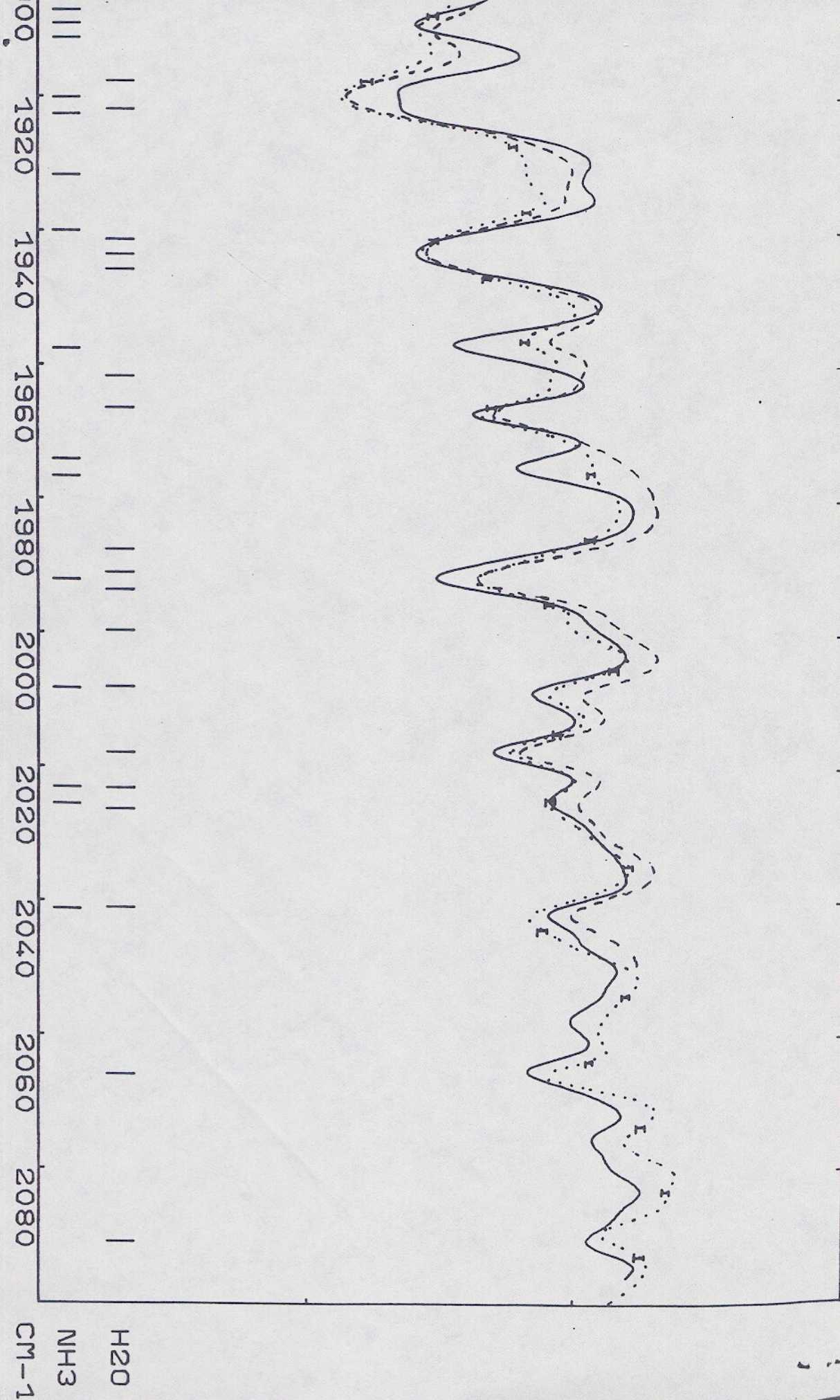
Fig. 2

F, 3

Jupiter, NEB and SEB
Hot Spots

a) observed NEB
b) observed SEB

SEB radiance (10^{-8} Wcm^{-2} sr^{-1}/cm^{-1})

NEB radiance (10^{-8} Wcm^{-2} sr^{-1}/cm^{-1})

wavenumber (cm^{-1})

MOLE FRACTION OF C_2H_6 ON JUPITER
$(x \ 10^{-6})$

LATITUDE

SYSTEM II (1965) LONGITUDE

• APRIL 1982
▲ MAY 1982
■ APRIL 1983

JUPITER

WAVENUMBER

1900 1920 1940 1960 1980 2000 2020 2040 2060 2080 CM-1

H2O   NH3