Variations in the Jovian Atmospheric Composition and Chemistry

Pierre Drossart†, Régis Courtin†
Sushil Atreya‡ and Alan Tokunaga§

† Département de Recherches Spatiales
Observatoire de Paris-Meudon
92195 Meudon Principal Cedex
France

‡ Department of Atmospheric and Oceanic Science
University of Michigan
Ann Arbor, MI 48109
USA

§ Institute for Astronomy
University of Hawaii
2680 Woodlawn Drive
Honolulu, HI 96822
USA
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 (NH₃), chemical reactions (PH₃), or stratospheric photochemistry (C₂H₂, C₂H₆). 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 10⁴ and 10⁸ sec, or long term secular variations on times scales of 10⁸ sec or larger. We attempt to identify theoretical 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 ± 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 H₂O 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 \(\mu\)m 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) \textit{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 \((C_2H_2 \text{ and } C_2H_6)\). Correlations with auroral observations (cf. Clarke \textit{et al.}, this issue) are needed to advance this field.

2) \textit{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 \((\text{Great Red Spot, plumes, barges, etc.})\). Gierasch \textit{et al.} \,(1986) predict values of radiative time constant and \textit{para}-hydrogen relaxation time between \(10^8\) and \(10^9\) sec, and argue that momentum transport in the upper troposphere \((P \leq 700 \text{ mbar})\) 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 stationary 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 \((\text{GeH}_4, \text{PH}_3,\ldots)\) 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 $\mu$m 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)

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Mole fraction</th>
<th>Approximate uncertainty (%)</th>
<th>Pressure level (bar)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>0.90</td>
<td>2</td>
<td>—</td>
<td>Gautier et al. (1981)</td>
</tr>
<tr>
<td>He</td>
<td>0.10</td>
<td>20</td>
<td>—</td>
<td>Gautier et al. (1981)</td>
</tr>
<tr>
<td>CH₄</td>
<td>$2.5 \times 10^{-3}$</td>
<td>20</td>
<td>—</td>
<td>Gautier and Owen (1983)</td>
</tr>
<tr>
<td>NH₃</td>
<td>$2.5 \times 10^{-4}$</td>
<td>20</td>
<td>$\geq 2$</td>
<td>De Pater (1986)</td>
</tr>
<tr>
<td>H₂O</td>
<td>$3.0 \times 10^{-5}$</td>
<td>60</td>
<td>6</td>
<td>Bjoraker, Larson and Kunde (1986b)</td>
</tr>
<tr>
<td>PH₃</td>
<td>$5.0 \times 10^{-7}$</td>
<td>50</td>
<td>2</td>
<td>Kunde et al. (1982)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bjoraker, Larson and Kunde (1986a)</td>
</tr>
<tr>
<td>CO</td>
<td>$1.5 \times 10^{-9}$</td>
<td>30</td>
<td>2</td>
<td>Bjoraker, Larson and Kunde (1986a) Noll et al. (1987)</td>
</tr>
<tr>
<td>HCN</td>
<td>$2 \times 10^{-9}$</td>
<td>100</td>
<td>$\geq 1$</td>
<td>Tokunaga et al. (1981)</td>
</tr>
<tr>
<td>GeH₄</td>
<td>$7.0 \times 10^{-10}$</td>
<td>50</td>
<td>2</td>
<td>Bjoraker, Larson and Kunde (1986a)</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>$2.0 \times 10^{-8}$</td>
<td>200</td>
<td>$\leq 1$</td>
<td>Maguire et al. (1985)</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>$3.0 \times 10^{-6}$</td>
<td>100</td>
<td>$\leq 1$</td>
<td>Maguire et al. (1985)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kostiuk et al. (1987)</td>
</tr>
</tbody>
</table>
2 Observations

Only some variability has been documented (NH$_3$, H$_2$O, C$_2$H$_2$ and C$_2$H$_6$). 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**

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

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$_2$O lines are present, and there is a possible contribution from H$_2$O 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 2ν$_2$ 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$_2$O was observed on Jupiter from airborne observations on the Kuiper Airborne Observatory at 5 and 2.7 $\mu$m (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$_2$O 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$_2$O in the deep troposphere is found to be 3 \times 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$_2$O 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$_2$O 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$_2$O) and small plumes (10 to 100 km) of rising saturated gas. The different scales can explain the observation of an apparently low H$_2$O abundance. Observational tests of this model could be achieved by recording spectra of different regions (plumes compared to dryer areas), but H$_2$O 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 $\mu$m). Although recorded variations of PH$_3$ are only tentative, 5 $\mu$m 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$_4$O$_6$ dissolved in H$_2$O). Its presence in the troposphere implies disequilibrium phenomena. The vertical profile of PH$_3$, as inferred from 10$\mu$m and 5$\mu$m spectroscopy by Voyager IRIS (Kunde et al. 1982), gives a satisfactory fit to the spectrum in both regions. From 5 $\mu$m 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 5$\mu$m 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 the Io torus) and CH₃ radicals produced in the CH₄ photochemistry (OH + CH₃ → CO + 2H₂) (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 CH₄ 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 ν₃ branch of germane can be seen in Voyager IRIS spectra, but Bjoraker (1986a)
recorded several other groups of lines of GeH₄. 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 ν₂ + ν₄ branch of PH₃, high resolution spectra would be useful to study such variations.

2.8 Acetylene and Ethane

Spatial variations in the UV absorption of C₂H₂ 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 C₂H₂ (but with a nearly-uniform abundance in the northern hemisphere), and an increase of C₂H₆ with latitude. The resulting effect is an increase of the C₂H₂/C₂H₆ 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 (Wagner and Caldwell, 1987). It is hypothesized that a depletion of C₂H₂ 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 C₂H₆ emission lines in the ν₀ band near 12 μm with ultra-high resolution (10⁶) heterodyne spectroscopy. Mole fractions retrieved at various locations on the jovian disk are not very different from the average equatorial value of 2.8 ± 0.6 × 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 C₂H₂ 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: C₂H₂/H₂ = 1.1 × 10⁻⁷
Drossart et al., 1986: C₂H₂/H₂ = 1 × 10⁻⁸.

Although different radiative transfer models and atmospheric profiles were used, there appear to have been genuine changes in the C₂H₂ 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
observations and to correlate them with stratospheric temperature studies.

2.9 Other minor constituents

New molecules have been detected (C$_2$H$_4$, C$_6$H$_6$) or tentatively detected (C$_3$H$_4$) 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 mechanisms (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 $T_e$ 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.
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$_3$NH$_2$, 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$_2$H$_2$ (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.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>$T_q$</th>
<th>$X_{equil.}$</th>
<th>$X_{obs.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH$_3$</td>
<td>1300 K</td>
<td>$4\times10^{-7}$</td>
<td>$5\times10^{-7}$</td>
</tr>
<tr>
<td>CO</td>
<td>1100 K</td>
<td>$2\times10^{-9}$</td>
<td>$1.5\times10^{-9}$</td>
</tr>
<tr>
<td>GeH$_4$</td>
<td>800 K</td>
<td>$8\times10^{-10}$</td>
<td>$7\times10^{-10}$</td>
</tr>
<tr>
<td>HCN</td>
<td>1100 K</td>
<td>$\approx10^{-12}$</td>
<td>$\approx10^{-9}$</td>
</tr>
</tbody>
</table>

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$_2$H$_2$ in the region of zenographic latitude, 58$\pm$ 10° and longitude 178$\pm$10° (System III, 1965). For the corresponding longitude, the Voyager UV aurora were detected at latitudes of 56(+4,-3) degrees (Broadfoot et al., 1979, 1981). Due to the finite dimension of the UV Spectrometer slit on this polar limb aurora, the auroral zone is uncertain by a few degrees. In any event, the UV auroras are virtually in the same zenographic locations as the infrared bright spots – giving rise to a speculation that both are triggered by the same mechanism. The UV auroras result from the precipitation of energetic charged particles, principally electrons and heavy ions. The range of electrons in the Jovian atmosphere would be greater than of ions with corresponding energy. From the Voyager measurement of the intensities of auroral H$_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$_2$H$_2$ 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$_2$H$_2$.

The above reasoning taken a step further predicts a decrease in the ethane (C$_2$H$_6$) production as larger quantities of the CH$_3$ radicals would be consumed by the increased flux of the H-atoms. C$_2$H$_6$ 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$_2$H$_2$ and CH$_4$ infrared bright spots, a decrease in the C$_2$H$_6$ 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$_4$H$_2$, and beyond, i.e., C$_{2n}$H$_2$ where n=2,3...etc.). The polyacetylenes are produced subsequent to the dissociation of C$_2$H$_2$ by either the charged particles (e) or the solar photons (h$_\nu$):

$$C_2H_2 + e (or \ h_\nu) \rightarrow C_2H + H$$

followed by

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

and

$$C_4H_2 + e (or \ h_\nu) \rightarrow C_4H + H$$

or

$$C_4H_2 + e (or \ h_\nu) \rightarrow 2C_2H$$

followed by

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

or

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

The polyacetylenes absorb sunlight to longer wavelengths (\( \leq 4000 \, \text{Å} \)) than CH\(_4\), C\(_2\)H\(_2\), C\(_2\)H\(_4\) or C\(_2\)H\(_6\) (\( \leq 1800\, \text{Å} \)). 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 \textit{Voyager 1} and \textit{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 \textit{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 ≥ 10m) dedicated to millimetric and sub-millimetric observations have recently become or are about to become operational, with improved wide-band receivers (Δν ≈ 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$_2$S, 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 $\mu$m 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 $\mu$m, 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 $\mu$m 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 $\leq 0.1$ 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 occurring 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 10⁶ (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 H₂CO 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 H₂ 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: NH₃, C₂H₂, C₂H₆, possibly C₃H₄ (allene) and C₃H₆ (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, λ/Δλ = 10⁵, 2×10⁴ or 2×10³, f.o.v. = 0.25×0.25 or 2×2 arcsec²).

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 achieved 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

<table>
<thead>
<tr>
<th>AMU</th>
<th>Species</th>
<th>AMU</th>
<th>Species</th>
<th>AMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>51</td>
<td>NH$_3$SH</td>
<td>101</td>
</tr>
<tr>
<td>2</td>
<td>H$_2$</td>
<td>52</td>
<td>C$_2$N$_2$</td>
<td>102</td>
</tr>
<tr>
<td>3</td>
<td>$^3$He; HD</td>
<td>53</td>
<td></td>
<td>103</td>
</tr>
<tr>
<td>4</td>
<td>$^4$He</td>
<td>54</td>
<td></td>
<td>104</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>55</td>
<td></td>
<td>105</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>56</td>
<td></td>
<td>106</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>57</td>
<td></td>
<td>107</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>58</td>
<td></td>
<td>108</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>59</td>
<td></td>
<td>109</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>60</td>
<td></td>
<td>110</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>61</td>
<td></td>
<td>111</td>
</tr>
<tr>
<td>12</td>
<td>C (from CO cracking)</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>CH</td>
<td>63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>N$_{14}$</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>N$_{16}$; CH$_3$</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>CH$_4$; NH$_2$</td>
<td>66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>$^{13}$CH$_4$; CH$_3$D; NH$_3$</td>
<td>67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>$^{15}$NH$_3$; H$_2$O</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>F (from HF cracking); $^{17}$OH$_2$</td>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>HF; $^{20}$Ne; $^{18}$OH$_2$</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>$^{21}$Ne</td>
<td>71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>$^{22}$Ne</td>
<td>72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>B$_2$H (from B$_2$H$_6$ cracking)</td>
<td>73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>B$_2$H$_2$ (from B$_2$H$_6$ cracking)</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>B$_2$H$_3$ (from B$_2$H$_6$ cracking)</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>B$_2$H$_4$ (from B$_2$H$_6$ cracking)</td>
<td>76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>B$_2$H$_5$; C$_2$H$_3$; HCN</td>
<td>77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>B$_2$H$_6$; N$_2$; CO; C$_2$H$_4$</td>
<td>78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>HCHO; C$_2$H$_6$</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>CH$_3$NH$_2$</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>SiH$_4$</td>
<td>82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>$^{31}$SiH$_2$; CH$_3$NH$_4$</td>
<td>83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>$^{32}$SiH$_2$</td>
<td>84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Cl (from HCl)</td>
<td>85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>$^{34}$SiH$_2$; HCl; $^{36}$Ar</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td></td>
<td>87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>$^{38}$Ar</td>
<td>88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td></td>
<td>89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>$^{40}$Ar</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>CH$_3$CN</td>
<td>91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>C$_2$H$_4$N (from C$_2$H$_4$N)</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>C$_2$H$_4$N</td>
<td>93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>C$_2$H$_6$ (propane); CO$_2$</td>
<td>94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td></td>
<td>96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>CH$_3$S</td>
<td>97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td></td>
<td>98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td></td>
<td>99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 NH₃, H₂O, PH₃ and probably GeH₄. 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 10⁸s 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 (H₂O, NH₃), others are only suspected (PH₃, GeH₄). In the stratosphere, the interpretation of the observations is difficult; variations of C₂H₂ and C₂H₆ 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 (C₂H₂ ?). 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.

Acknowledgments: S. K. Atreya acknowledges support received from the Planetary Atmospheres Program of NASA's Solar System Exploration Division.
Figure captions

Figure 1: NH$_3$, PH$_3$ and H$_2$O 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$_2$O between NEB and SEB. (after Bjoraker et al., 1986b).
Figure 4: Variations of C$_2$H$_6$ 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$^2$sec$^{-1}$ (constant);
— $T(z)$, $K\propto 1/M^{1/2}$;
- - - $T(z)$, $K\propto 1/M$;
— —, $T(z)$, $K\propto 1/M^{1/2}$, 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 $\nu_2$ band of NH$_3$. 
References


\[ w \left(10^{-9} \text{ scale heights s}^{-1}\right) \]

- \( \text{NH}_3 \) ABUNDANCE (full scale 0 to 2, units as in Fig. 3)
- ORANGE REFLECTIVITY (full scale 0.5 to 1)

PLANETOGRAPHIC LATITUDE