Dynamics of the Atmospheres of the Outer Planets

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Abstract

Current knowledge about dynamics and thermal structure on the outer planets is reviewed with the aim of identifying important measurements which should be made in the post- Voyager era. The existence of jets and cloud bands is the puzzle that underlies all others. Discussion focuses on the particular case of Jupiter because documentation is most complete. Recent dynamical work has successfully reproduced much of the behavior of jets and spots with simple models that contain few parameters. It is argued that the gross dynamical parameters of the outer planetary atmospheres are the keys to their behaviors, rather than the particular specifics of radiative forcing, cloud distributions, or thermodynamic transformations. Voyager data has shown that the jet systems decay with height in the region above the visible clouds. Therefore the highest priority must be given to establishing dynamical parameters that characterize levels within and beneath the clouds. These require determination of the deep structure of the jets, of the density stratification, and of the horizontal density contrasts. The deep regions are not easily accessible and these measurements present challenging opportunities. Indirect inferences about the controlling processes may sometimes be possible by observing waves and other activity in the more easily accessible stratosphere, and some of these issues are also discussed.

Introduction

The study of the dynamics of the atmospheres of the giant planets is motivated by a number of different considerations. The visible appearances of the planetary disks are manifestations of dynamical processes. An understanding of atmospheric chemistry and the distribution and transport of atmospheric constituents require a knowledge of atmospheric structure and dynamics. Cloud microphysics is strongly coupled to the basic structure and dynamic regime. The study of the deep, rapidly rotating atmospheres of the outer planets represents an important limiting case in comparative planetary meteorology. The investigation of Jovian dynamics can lead to new insight in certain areas of basic geophysical fluid dynamics. While these are all important reasons for studying Jovian atmospheric dynamics, perhaps the most compelling motivation is the intrinsic interest of the subject itself as exemplified by a few simple but basic questions asked by layman and specialist alike. Why are there cloud bands and jets on the outer planets? Why are there equatorial currents? What parameters are responsible for the planet-to- planet variations in jet amplitudes and latitudinal scales? What are the spots and "storms"? What are the mechanisms of heat transport from the interiors? More detailed questions can also be asked if one has access to detailed information, but these very general questions underlie all others. The two Voyager spacecraft gathered vast amounts of new data during the decade between 1979 and 1989, and our purpose here is to discuss the post-Voyager status of these questions, and to outline the new observational goals for the next steps toward reaching their answers.

To set the general context Figure 1 displays selected radio occultation temperature profiles for the outer planets. This data provides the best available vertical resolution for temperatures but only exists at a few locations where flyby spacecraft passed behind the edges of the planets. All four planets show stable stratospheres above less stable tropospheres, where cloud formations exist. Patterns and motions are apparent in the cloud formations and form the subject of dynamical work. At great depth, approximate adiabatic extrapolations from the measurements are sketched in Figure 1. The detailed stratification and the wind shear below the clouds are among the key pieces of missing information at present, as will be discussed below.

Most of the questions treated in this review are typified by Jupiter, and we will use that planet as the primary example. However, reference to the other three planets will be made from time to time since intercomparisons may ultimately lead to a better understanding of some aspects of the atmospheric structure and dynamics. Since all of of the above questions are exemplified by the single question "Why are there cloud bands and jets?", we will focus the discussion on this point. Although other issues are equally interesting, and undoubtedly involve different and important sets of physical processes for explanation, the fundamental observational needs are exposed by discussing the jets.

In the following section, the parameters needed to characterize the cloud bands and jets are reviewed, and the current state of observational knowledge is summarized. Next, certain theoretical and modelling concepts are discussed with emphasis on "shallow water" theory, and specific questions are formulated that can be addressed by measurements. Both global and local energy balance are discussed within the context of dynamical processes. Properties of the upper troposphere and stratosphere that may be diagnostic of the dynamics at the deeper levels are then considered. These include atmospheric waves, cloud structure and properties and distributions of minor gaseous constituents. Finally, the basic observational strategy needed in order to make further progress toward understanding the basic nature of the cloud bands and jets is summarized.

Characterization of bands and jets

The Voyager spacecraft greatly improved our knowledge, for all thè outer planets, of exactly what the belts are. To describe them, one needs the following zonal and temporal mean quantities:

$u(r, \theta)$, the zonal velocity as a function of radius and latitude;

$T(r, \theta)$, temperature;

$n_c(r, \theta)$, cloud particle density;

$f_p(r, \theta)$, fraction of hydrogen in para state;

$\mu(r, \theta)$, composition, here summarized by molecular weight μ;

$w(r, \theta), v(r, \theta)$, radial and meridional velocities.

This list is oversimplified, of course. For example, cloud particles exist with a spectrum of sizes and compositions. But it is detailed enough to serve as a framework for discussion.

Zonal velocity profiles have been determined with excellent spatial resolution, probably on the order of a few hundred kilometers, by measuring the displacement of cloud features in images (Ingersoll *et al.*, 1981; Limaye *et al.*, 1982). A profile produced by Limaye (1986) is displayed in Figure 2. There is very little difference between the Voyager 1 and Voyager 2 zonal mean velocities, with a time separation of four months. In fact, features of the Jovian jet system are apparent throughout the historical record (Peek, 1958), extending back about a century, suggesting that the jets are permanent.

It is not known at exactly what height the tracked cloud features exist, nor even whether they are all at the same height. West *et al.* (1986) review the inferences from spectroscopy and imaging. Ammonia clouds are located near the p = 700 mb level, and their thickness varies in latitude in a manner that is correlated with the jets (Gierasch *et al*, 1986), with thickest cloud at the equatorward edge of prograde (faster than the planetary rotation) jets. Some of the dynamical cloud tracers may be associated with this level, the "ammonia cloud base". But West *et al.* point out that there is a layer of haze extending at least from the ammonia cloud base up to the p = 200 mb level, and that this haze is also spatially variable. Thus cloud features detectable in visible light might reside anywhere in the approximately two scale height thick layer between 200 and about 800 mb. Magalhães *et al.* (1990) find slightly different velocities using violet filter and orange filter images and suggest that a vertical shear is being detected. A method of directly measuring flow velocities at different (and known) heights is sorely needed. Only then will the three dimensional structure of the circulation become accessible in a straightforward way.

The Voyager infrared spectrometer was able to determine $T(r, \theta)$, at least to some extent, for all the outer planets. Hanel *et al.*, 1979 report the first Jupiter flyby data; further analysis and discussion can be found in Flasar (1986). The spatial resolution is much less than that of imaging information, but in all cases it is good enough to delineate the general jet structure. Temperature can be retrieved at levels between about 400 mb and 2 mb, by using H_2 and CH_4 opacities. Deeper than 400 mb, cloud opacity introduces another variable and unambiguous retrieval is not possible with the Voyager data.

Over the Jovian jets there is a consistent thermal pattern, illustrated by Figure 3. There are latitudinal temperature variations whose amplitude is largest at about the height of the tropopause ($p \sim 100$ mb), and correlated with jets in such a way that maximum temperature is located over the poleward edges of prograde jets. These horizontal temperature gradients show that there is a vertical shear in the zonal wind, as a consequence of hydrostatic and geostrophic balance. Except within a few degrees of the equator where Coriolis forces become weak, large scale motions (those with small Rossby number) satisfy:

$$\frac{\partial p}{\partial r} = -\rho g, \quad 2\Omega \sin\theta\, u + \frac{1}{\rho r}\frac{\partial p}{\partial \theta} = 0. \tag{1}$$

The notation is standard. The partial derivative with respect to latitude is at constant radius, and we assume spherical geometry with constant acceleration of gravity. Taking the ratio of the two equations and rearranging gives

$$2\Omega \sin\theta \frac{\partial u}{\partial r} = \frac{g}{r\rho}\left(\frac{\partial \rho}{\partial \theta}\right)_p, \tag{2}$$

where it is important that the latitudinal derivative is at constant pressure. In the region near the tropopause on Jupiter, the ideal gas equation holds and the composition is very close to uniform, so that the molecular weight is constant. The density derivative with latitude is due entirely to temperature variation, and the "thermal wind equation" is obtained.

As illustrated in Figure 4, it is found from the observed thermal structure that the zonal winds are decaying with height throughout the layer from the upper troposphere into the lower statosphere. The rate of decay is such that the tropospheric jets are largely attenuated three or four scale heights above the tropopause on Jupiter, and a bit higher on the other planets. Thus the Voyager data has given us a three dimensional picture of the top portion of the jet systems on all the outer planets, and we have learned that the jets are decaying with height above the clouds.

Composition varies in the Jovian jet system. The Voyager infrared spectra show that near the 700 mb pressure level, where the temperature is about 145 K, the ammonia abundance is well correlated with the cloud opacity (Gierasch, Conrath and Magalhães, 1986). This suggests that the clouds are thickest where the gas abundance is high, rather than where low temperatures have caused condensation. de Pater (1986) presents evidence from ground-based VLA radio observations that the latitudinal variations of ammonia concentration extend down at least to the two bar pressure level. Water vapor also is variable (Bjoraker *et al.,* 1986) but a detailed mapping to reveal correlations with jets is not available. Finally, the ortho-para ratio of the molecular hydrogen is not in equilibrium in Jupiter's upper troposphere, and is variable from place to place on the planet (Conrath and Gierasch, 1984), but a relationship to the jet structure is unclear.

The mean vertical and poleward velocities associated with the jets are unknown. The cloud tracking results of Ingersoll *et al.* (1981) show that mean poleward velocities of cloud tracers are less than about 5 m s^{-1}, and in fact they may be very much less. Indirect inferences, for example from composition, are uncertain. High ammonia abundance does not necessarily imply zonal mean upwelling.

In summary, characterization of the Jovian belts and jets improved dramatically during the Voyager era. The zonal velocity profile at Voyager flyby at the visible cloud level was determined with a spatial resolution of a few hundred kilometers. The zonal mean temperature cross section above the clouds was determined with a spatial resolution sufficient to resolve the belts, and it implies through hydrostatic and geostrophic balance that the jet system decays with height above the clouds. The cloud structure and the ammonia abundance have a characteristic correlation with the jets, with the densest cloud and highest abundance on the equatorward edges of prograde jets. But a large number of key quantities are not yet determined, and in particular, we do not know the structure of the jets beneath the visible clouds.

Dynamical developments

At about the time of the Voyager launch, numerical studies of very simple fluid dynamical systems were beginning to show behaviors with remarkable similarities to the

Jovian belts and spots. Williams (1978) experimented with random forcing of a single layer of fluid of constant depth on a rotating sphere, and found that a system of jets developed. They are explained by the inverse cascade of kinetic energy to larger length scales, which is a well known property of two dimensional turbulence, until a large scale (and low frequency) is reached at which Rossby wave production occurs instead of further inverse cascade. The coupling to waves has been called the "Rhines effect", and occurs at a scale L given by

$$\beta \sim U/L^2, \tag{3}$$

where $\beta = (2\Omega\cos\theta)/r$ is the latitudinal gradient of the planetary vorticity (Coriolis parameter) and U is the amplitude of motions of scale L. This is also the scale that is set by the shear instability criterion for zonal jets in the same system, $u_{yy} = \beta$, where y measures northward distance.

More recent work has focused on the dynamics of vortices, and on a single fluid layer whose depth is not constrained by a lid but is determined by a free surface condition. This is a "shallow water" system. Near a vortex, streamlines cross latitude circles, and vorticity changes along the streamline can in principle reveal the latitudinal change in height of fluid columns. Dowling and Ingersoll (1988) use Voyager measurements of the vorticity field in and around the Jovian great red spot to deduce the thickness profile near the spot. It varies with latitude, and the conclusion is that a single layer of fluid on a smooth sphere is not an adequate dynamical model, but that a sloping lower boundary is needed.

Even a simple fluid dynamical model is capable of a rich variety of behavior. Setting aside the sloping lower boundary, the one layer shallow water models have three parameters. Williams and Wilson (1988) discuss these systems in terms of the Rossby number, $Ro = U/fL$, the ratio L_D/L, of the deformation radius L_D, given by $L_D^2 = gH/f^2$, to the scale L, and a dimensionless beta parameter $\beta L/f$. Here f is the local Coriolis parameter at the vortex location and H is the depth of the fluid layer. As Williams and Wilson show, many different regimes in the three dimensional space defined by these parameters can support vortices; different processes act in different regimes to provide competing constructive and destructive tendencies. The shallow water system, with the added flexibility of a bottom surface whose depth varies with latitude, is capable of producing jets and spots for a wide range of parameters. In fact, the system is of interest in itself, and a great deal has been learned about its subtlety from the numerical experiments that have been motivated by Jupiter (Marcus, 1988; Ingersoll and Cuong, 1981; Dowling and Ingersoll, 1989; Williams and Wilson, 1988).

Notice that of the three parameters discussed by Williams and Wilson, only the one involving the deformation radius is observationally unconstrained. For the largest scales of motion, the Rossby number is small, and the beta parameter is fixed by the observation that $U/L^2 \sim \beta$. The appropriate deformation radius is ill defined from direct observation because of the unclear relationship between the one layer model and the real three dimensional atmosphere, and because the stratification of the atmosphere beneath the clouds is unknown. The question arises whether detailed analysis of the observational velocity fields can discriminate between flows produced by numerical models with different deformation radii. Marcus (1988) and Dowling and Ingersoll (1989) argue that such a discrimination is possible for the great red spot, but there is debate.

Latitude- dependent bottom topography in a one layer hydrostatic dynamical model is equivalent to a two layer model in which the bottom layer is very deep and contains a latitude- dependent zonal flow (Ingersoll and Cuong, 1981). Because the bottom layer is very deep, the flow there is steady. Although no claims are made that specific locations in Jupiter's atmosphere correspond to any particular part of the one layer dynamical model, this "one and one- half layer" interpretation is often made, because it is known that no solid sloping boundary exists in Jupiter. The models are simple abstractions that contain a small subset of the physical processes that act on the outer planets, and their value lies in the understanding that they can give about the interactions within the subset of processes. They are not "models" in the sense that astronomers sometimes use the term; that is, as a first approximation to an actual physical configuration.

At the present time, the observed Jovian velocity scales and length scales, the theoretical work by Williams and Marcus, and the data analysis by Dowling and Ingersoll point to several general conclusions about Jupiter from these models.

1. The one layer hydrostatic model with sloping lower boundary demonstrates behavior remarkably similar to that of Jupiter on large scales. The implication is that Jupiter's belts and zones may exist because of, and depend on, only a small number of dynamical parameters that characterize a certain region of the atmosphere.

2. A corollary is that the exact nature of the forcing may be unimportant. It may be random and at small scales, with an inverse cascade, or it may be at large scales, perhaps thermal.

3. The planetary vorticity gradient β is important; $U/L^2 \sim \beta$. There is also an influence, probably of a deeper flow, acting like a latitudinally varying bottom surface, which has an effect of the same order as β.

4. A corollary of the preceding point is that the jet system, as abstracted by the one layer model with bottom, appears to be constrained by $U/L^2 \sim \beta$. This sets one relation between U and L. One other condition is required in order to determine the system. This other condition is unknown.

Jovian questions

Why should a three dimensional planetary fluid envelope behave like two dimensional flow in a one layer shallow water system? The shallow water system develops pressure gradients because there is a density discontinuity at the fluid surface, and a slope at the surface leads hydrostatically to a pressure gradient within the fluid. Likewise the three dimensional Jovian atmosphere must have density contrasts (relative to a well-mixed adiabatic configuration) in order to develop pressure gradients. But are these density contrasts concentrated at interfaces, making Jupiter literally similar to the one layer model? Or are they distributed smoothly? Are the density gradients primarily vertical? Or are they primarily horizontal?

These are the questions that Jovian observations must address. It is well to bear in mind while contemplating observations that the shallow water models are not likely to be direct analogies to the outer planets. They produce behavior similar to observed large scale motions, but this only means that they possess certain processes in common with the planets. Much of the smaller scale activity on Jupiter has not yet been seen in a shallow water model. Examples are the wavey turbulence just west of the red spot, the small scale herring-bone- like turbulence at the edges of many jets, and the mesoscale waves on jet cores (Flasar and Gierasch, 1986). It seems probable that Jupiter's three dimensional atmosphere contains a hierarchy of dynamical phenomena, of which only the largest scales resemble the one layer models. But these are the scales that control the planet's appearance, so they are of special interest. Consequently, we would like to know the location and nature of the density contrasts that cause the large scales of motion to behave two dimensionally.

What is the other relation between U and L that sets the scale and amplitude of the jet system? Comparisons among the outer planets may provide additional constraints on this question. The characteristics of their jet systems are compared in Figure 5. Is the basic mechanism that establishes and maintains the jet structure the same on all four planets? The amplitude and scales of the jets do not appear to depend on external planetary parameters in any simple way. Despite its relatively great distance from the sun, Neptune's wind speeds are much greater than those of Jupiter. The relative latitudinal scale of the jets on Uranus and Neptune is much larger than on Jupiter and Saturn, and the equatorial currents on the former pair are retrograde while they are prograde on the latter pair. The jet structures of Uranus and Neptune are qualitatively similar, even though their obliquities and internal heat fluxes are quite different, supporting the suggestion that details of the forcing may not be important. It is not clear that the shallow water models contain the required relationship between amplitude and scale, unless it arises through the deformation radius. A possibility is that the shallow water dynamical analogy breaks down at a certain scale on each planet and this sets the remaining relation between U and L. The discussion below will illustrate possible mechanisms.

Figure 6 illustrates the application of the thermal wind equation to a hypothetical Jovian jet system with a level of no motion at some great depth. The figure is marked as if density variations were due to temperature variations, but molecular weight variations are also a possibility. The important point is that horizontal density contrasts are necessary if a geostrophic current is to exist at cloud top level and yet not exist at some deeper level. A scaled version of (2) is

$$\frac{2\Omega \sin\theta U L}{gH} = \frac{D}{H}\frac{\Delta T}{T}. \tag{4}$$

Here D is the depth of the system and ΔT is the horizontal temperature contrast. We have also divided both sides by a scale height H for nondimensionalization; meteorologists will recognize the quantity on the left as the quotient of a Rossby number and a Burger number. Ingersoll and Cuzzi (1969) pointed out that the quantities on the left side are all known or observable, and with the data then available on the profile of $u(\theta)$, found that the combination was nearly constant from jet to jet. They concluded that a specific density difference and depth are characteristic of the Jovian jets. This would provide the second relation between U and L to determine the system completely. Barcilon and Gierasch (1970) pointed out that the depth to the water clouds and the temperature differential available from latent heat give a correct value for the combination (4).

In Figure 7 more recent estimates of L and U from Voyager wind profiles are shown, and it is seen that the combination (4) is not a constant, but appears perhaps even to vary from jet to jet in a systematic way. If density contrasts control the jet strengths, it is not quite in the simple manner previously envisioned. Nevertheless, this illustrates an important point; it is possible that the missing factor needed to explain the jet system is a limiting horizontal density contrast. The contrast could be thermal in origin, it could be due to compositional separation, or it could be due to a thermodynamic transformation such as H_2 ortho- para conversion.

Numerically, the magnitude of the left side of (4) is about 10^{-2} if we use a scale height of 20 km, appropriate for the upper troposphere on Jupiter. Useful observational determination of density variations beneath the clouds therefore must be to within about 1%. Note that it is the density gradient along a constant pressure surface that is the important quantity.

Another dynamical possibility is that the vertical density contrast introduces a controlling scale. The local Brunt frequency in a continuously stratified medium is given by

$$N^2 = -\frac{g}{\rho}\left[\left(\frac{\partial\rho}{\partial r}\right) - \left(\frac{\partial\rho}{\partial r}\right)_a\right], \tag{5}$$

where the subscript a denotes the adiabatic derivative. The Brunt frequency is the highest frequency that an internal gravity wave can exhibit, and is of great importance in itself. It is difficult to determine at deep levels because the density gradient becomes close to the adiabatic, but it is a crucial objective. In general it would be useful to determine the difference to within 10%. The local deformation radius in a continuously stratified fluid is given by

$$L_D = H\frac{N}{2\Omega\sin\theta}, \tag{6}$$

where H is the local scale height. At the tropopause on Jupiter, where $\partial T/\partial z = 0$, one finds that $N \sim 2 \times 10^{-2}$ s^{-1}, and $L_D \sim 4000$ km. Figure 7 displays deformation radii at the latitudes of the different jets, ratioed against the width scales of the jets, L. It is interesting that the deformation radius at tropopause height is indeed of the order of magnitude of L, but there are variations in the ratio from jet to jet. It seems unlikely that the stratification at the tropopause controls the jet scales, and we would like to have information from greater depths.

The thermodynamics and microphysics of the fluid is also important because of possible influences on the fundamental dynamical parameters. For example, equation (5) is oversimplified; the Brunt frequency is itself a function of time scale. The important quantity is the difference in density gradient between the mean for the atmosphere and that of a parcel moving through pressure surfaces. The latter depends on chemical reactions, phase changes or precipitation processes that occur during the displacement, and may depend on the speed of the displacement because of finite reaction rates. The hydrogen ortho-para conversion is a particularly difficult problem on the outer planets because rates are uncertain. It becomes more important at lower temperatures, and may be unimportant at levels within Jupiter where $p > 500$ mb. Other difficulties on the outer planets are raised by condensation of the various compounds, from methane through water and on to silicates at still higher temperatures, that are expected on grounds of cosmic abundance to exist within the tropospheres and lower atmospheres (Gierasch and Conrath, 1985). It is conceivable that the density interfaces in the one and one- half layer models have real counterparts in the planets, in the form of thin sheets where composition jumps.

The highest priority post-Voyager desiderata are those quantities that define the mean dynamical configuration beneath the cloud tops.

1. The jet structure $u(r, \theta)$, to within 10% (or about 10 m s^{-1}, with ± 1 m s^{-1} desirable.
2. The gravitational layering, determined by $\partial T/\partial r$, $\partial \mu/\partial r$. where μ is the mean molecular wieght. These quantities should be determined sufficiently well to fix the Brunt frequency to within 10% or so. This will usually impose not very stringent requirements on trace constituents, since a determination of abundance will fix μ with precision enhanced by the inverse of the concentration. The temperature requirement is indeed challenging. It will typically require accuracy of a degree or so.
3. Horizontal buoyancy contrasts, determined by density gradients along surfaces of constant pressure, to within about 1%. This requires $\partial T/r\partial\theta$, $\partial\mu/r\partial\theta$. Again the temperature is the most difficult, and will require accuracy of probably a degree or so.

The foregoing parameters determine the dynamical configuration and probably underlie the existence of the jet system and its general properties. The configuration may, of course, be interactive and controlled by feedbacks, with the dynamical configuration itself a function of the dynamics. Nevertheless the first observational objective should be to determine the configuration.

Energy balance

The global energy balance of Jupiter has been established by Voyager to within a few percent (Hanel *et al.,* 1981). The remaining uncertainties have to do with angular variations in the reflected sunlight, which were incompletely sampled during the Voyager flyby. Roughly, Jupiter emits about twice as much thermal energy to space as it absorbs from the sun. The extra heat is associated with cooling of the planet as a whole. The mode of heat transport from interior to atmosphere is not yet known.

The energy balance as a function of latitude has been determined from Voyager infrared data by Pirraglia (1984). Spatial resolution is good enough only to resolve the widest belts at low latitudes. The belt- zone variations are displayed in Figure 8. They are about 5%, and are in a compensating sense; where absorbed solar radiation is highest, so is the emission to space. A causal relationship cannot be assumed, however. In fact, the significance of heat balance details is questionable. It is undoubtedly important that the atmospheric system receives energy at a higher temperature than it rejects it, both through the internal heat and through solar radiation that is deposited beneath the level of emission to space. The system thus can operate as an engine, generating kinetic energy. But the detailed latitudinal variations of, for example, absorbed solar radiation may be secondary, depending on cloud formations whose feedback to the general circulation is negligible.

Nevertheless the distribution of heating and cooling is important and remains an objective of observations. Comparisons among the four planets may provide indications of the relative importance of solar radiation and internal heat. For example, the behavior of Neptune and Uranus suggests that the distribution of the total heating between these two sources may not be particularly significant. Dynamical models will be needed to determine what aspects of the heating distribution are of fundamental importance. The current one layer models, which work so well, do not contain any thermodynamic influence on density, and it will be a future generation of models that can address questions of energetics and thermodynamics.

Clouds

A great deal of effort has gone into characterization of clouds and aerosols on the outer planets. There are excellent recent reviews of the Jovian case by West *et al.* (1986), focusing on the aerosol distribution and properties, and by Beebe *et al.* (1987) focusing on long- term changes in color and pattern. It is of clear importance to understand the nature of these clouds. The visual impact of the cloud system is, for many, the principal motivation for asking questions about the planet Jupiter. The clouds are of interest in the context of structure and dynamics for two reasons. First, cloud particles, along with gaseous absorption, determine the levels of deposition of solar energy in the atmosphere. Second, their distribution and behavior can potentially yield diagnostic information on dynamical processes.

As discussed in the preceeding section, knowledge of the distribution of radiative heating and cooling near and below the cloud top level is an important objective. Present uncertainties in this area are, to a large extent, due to a lack of complete characterization of the clouds and aerosols. Knowledge of the particle spatial distribution, size, and optical properties is needed to permit estimates of heating and cooling to be made. Also, the particulate properties must be known in order to properly interpret remotely sensed data on gas abundances in and below the clouds; the latter is also required for the heating and cooling estimates.

It is difficult to point to particular properties of the clouds as being definitive diagnostics of key dynamical processes. For example, it has classically been assumed that the bright zones on Jupiter are regions of upwelling (Hess and Panofsky, 1951). But this may not be true; convection can control the moisture and cloud distribution, and convection may indicate low stability, not upwelling. Even if the inference of upwelling is valid, it does not lead to conclusions that discriminate among physical processes. The Lagrangian mean meridional circulation is a response to eddy processes as well as the mean heating distribution. In fact, the circulation can be thermally indirect and is known often to be so in the Earth's atmosphere (Andrews *et al.,* 1987). The composition and distribution of aerosols and condensates is important information, but future observations will be most useful if simultaneous gas abundances and temperatures can be obtained, and if spatial patterns and correlations are determined, so that underlying processes can be elucidated.

Waves

Waves can be diagnostic of mean structure. Flasar and Gierasch (1986) infer the existence of an internal gravity wave duct beneath Jupiter's clouds from the observation of numerous mesoscale wave trains. In this particular case, however, lack of temporal sampling hinders unique interpretation, and shear instability is another possibility. Waves can also be diagnostics of excitation processes that are of interest. Magalhães *et al.* (1990) find slowly moving patterns in thermal maps of Jupiter from Voyager infrared data, at locations where jets are strong, and conclude that stationary disturbances have influence that extends through the jets. Allison (1990) argues that apparent stratospheric temperature fluctuations in Voyager occultation data from Jupiter indicate vertically propagating waves that are diagnostic of dynamical activity at deeper levels. Magalhães and Hinson (1991) examine Neptune occultation data and draw similar conclusions. Finally, in some situations waves can carry sufficient energy or momentum to be the principal drive for flows. A case involving the Jovian stratosphere will be mentioned in the next section.

Flasar (1987) discusses the general topic of time- variable phenomena on Jupiter. Simple inferences are usually possible only in the case of linear wave phenomena with clear periodicities in both space and time. But when such information is available, an observation can be unambiguous in its identification of a physical phenomenon and therefore is extremely valuable. On Jupiter, the upper troposphere and stratosphere are the prime targets for observations of waves in the temperature field, and experience shows that sensitivity of a degree or so is sufficient. Frequency and both horizontal and vertical wavelengths are needed for unambiguous identification of modes.

Upper stratosphere

This region is particularly accessible to observation because it is not obscured by dense clouds. It is complicated because its dynamics and structure may not be determined by the local heat sources and sinks. The density is very small relative to that in the troposphere, and consequently a small penetration of tropospheric activity can overwhelm other processes. But this is at the same time a complication and an asset, since diagnosis of tropospheric activity is a prime objective.

There are now several lines of observational evidence showing that the statospheres of the outer planets are horizontally inhomogeneous and temporally variable. Orton *et al.* (1991) report on a decade of monitoring Jupiter at 7.8 μm. Raster scans were used to construct images of the thermal emission, which originates near the 20 mb level. The sensitivity to relative brightness temperature variations is about 0.3 K. The maps show a banded structure in latitude, with smaller longitudinal variability. There is an extremely interesting oscillation in temperature near 20° north and south latitude, displayed in Figure 9. The temperature at these latitudes rises and falls, with both hemispheres in step, with a period that appears to match half the Jovian orbital period and an amplitude of about 2 K. There are also longitudinal temperature variations apparent in the data, of the order 1 K, which vary over times of two months. Leovy *et al.* (1991) propose that there are vertically propagating waves, and that the oscillation of the mean temperature is caused by the same wave propagation switching mechanism that controls the terrestrial quasi-biennial oscillation (Andrews, Holton and Leovy, 1987).

There are latitudinal gradients in composition on the outer planets which also are probably dynamical in origin. Again the best data are from Jupiter. Wagener and Caldwell (1988), with data from the International Ultraviolet Explorer, find that C_2H_2 is depleted in the Jovian south polar region relative to midlatitudes and northern regions. Kim *et al.* (1985) and Maguire *et al.* (1985) using Voyager IRIS data, find indications of latitudinal gradients of C_2H_2, C_2H_6. Deductions from infrared spectra are difficult, however, because of the necessity to retrieve temperatures simultaneously.

It is also now well known by observers that near infrared imaging of Jupiter and the other outer planets reveals latitudinal variations in aerosol abundance (Nicholson, 1992). In the strong methane bands these gradients refer to the middle and upper stratosphere, although quantitative retrievals have not been done.

A prime objective of stratospheric observations is to determine the aerosol and gas state well enough so that radiative heating and cooling can be evaluated. Once the local drives are known, modeling can be used to determine the configuration, both thermal and compositional, that the local processes would establish. Differences between this configuration and the actual one then may determine the momentum and energy fluxes from below.

Summary

The primary measurements required to address the nature of the Jovian cloud bands and jet structure are summarized in Table 1. Zonal mean values of the parameters are needed from the cloud tops down to pressures of several bars, and deeper if possible, with a latitude resolution of 5° or better. We have indicated the precision and vertical resolution required in order for the parameters to provide useful information. Where appropriate we have also indicated desired goals. The primary purpose of the gaseous abundance measurements is to obtain the mean molecular weight as a function of position, which is needed, along with the temperature, to obtain the density field. It should be emphasized that we have chosen measurements of the temperature and composition as one means of obtaining the density; however, any method of obaining horizontal density contrasts and vertical stratification with the necessary precision, either directly or indirectly, will serve the purpose. Since we are concerned with horizontal and vertical gradients, the relative precision of the measurements is of greater concern than absolute accuracy. Note that only the abundances of those species capable of undergoing phase changes within this part of the atmosphere are of interest since they can be spatially inhomogeneous.

The reader may well comment that these demands are unrealistic because they seem to require an extremely expensive undertaking that includes large numbers of probes. We hope that this is not true. At radio wavelengths is is possible to extract thermal and compositional information from levels on Jupiter where the pressure is several bars (see de Pater (1986) for example), and the difficulties are in separating ammonia concentration from temperatures. Perhaps these techniques can be improved. Perhaps also there will be innovations that lead to different methods altogether.

In Table 2, a set of measurements in the upper troposphere and stratosphere are summarized. The emphasis here is on the possible diagnostic properties of the parameters in inferring information on the atmosphere below the cloud tops. It is assumed that the zonal mean wind field can be obtained from the temperature field and knowledge of the wind velocity at the deeper levels. Alternatively, direct wind measurements in this portion of the atmosphere could be used. A latitude resolution of 5° or better is needed in all cases. For the temperature measurements, a resolution of 5° or better in longitude is also required to facilitate wave analyses. Cloud particle properties and the distribution of hydrocarbons are included because of their potential diagnostic value, although the relationship of the motion field to these parameters is probably rather indirect. This information is also required for the calculation of atmospheric heating and cooling.

While we have concentrated primarily on Jupiter, the general measurement strategy is similar for the other giant planets. We have addressed only the broadest issues; there are clearly many other aspects of the structure and dynamics of the atmospheres of the giant planets that are of great interest and require the measurement of other parameters. However, the measurements outlined here, along with an active theoretical modelling program, would provide extensive new insight into the basic questions about the cloud bands and jets that are, at present, unanswered.

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Table 1. Primary Parameters Required Below Cloud Tops for Study of Jovian Atmospheric Dynamics

Parameter	Precision	Vertical Resolution (Scale Heights)	Purpose
Zonal Wind Velocity	± 10 m s^{-1} (useful) ± 0.1 m s^{-1} (desired)	1.0	Jet characterization.
Temperature	±1 K (useful) ±0.1 K (desired)	1.0 (useful) 0.1 (desired)	Vertical stratification and horizontal density gradients.
Gaseous Abundances	±20% (useful) ±5% (desired)	0.25	Mean molecular weight for vertical stratification and horizontal density gradients.

Table 2 Parameters Required in the Upper Troposphere and Stratosphere for the Study of Jovian Dynamics

Parameter	Precision	Vertical Resolution (Scale Heights)	Purpose
Temperature	±1 K (useful) ±0.1 K (desired)	1.0 (useful) 0.1 (desired)	Mean structure, thermal winds, waves.
Hydrocarbon abundances	±30% (useful) ±5% (desired)	0.3	Determination of heating and cooling.
Particle number density	±20%	0.5 (useful) 0.1 (desired)	Diagnostics of deep atmosphere. Calculation of heating and cooling.
Particle size	±50%	0.5	Calculation of heating and cooling.

Figure captions

Figure 1. Temperature profiles. From Lindal *et al.* (1981, 1985, 1987, 1990). Displayed are the Jupiter Voyager 1 ingress, Saturn Voyager 2 ingress, Uranus Voyager 2 ingress and Neptune Voyager 2 egress. The data extends only as far as the solid lines. The dashes are approximate adibatic extrapolations. Approximate condensation temperatures are indicated for a mixture enriched above solar by a factor of two in oxygen and nitrogen and a factor of ten in carbon neglecting differences in helium abundance between the planets). Intersections with temperature profiles give a rough indication of the expected locations of cloud bases.

Figure 2. Jovian velocity profile from cloud tracers, from Limaye (1986).

Figure 3. Zonal mean temperatures, from Gierasch *et al.,* (1986). The bars indicate root mean square variations from the longitudinal mean. Note that they are particularly large near ± 18 degrees of latitude. These are the locations of the strongest westward jets.

Figure 4. Vertical wind shear calculated from observed latitudinal temperature gradients at the 270 mb pressure level, compared with a smoothed version of the mean wind profile from Figure 2. Smoothing was used to reduce the resolution of the wind profile to that of the temperature observations. From Gierasch *et al.,* (1986).

Figure 5. Comparison of the zonal wind velocities at the cloud top level on the four giant planets. The curves represent approximate fits to measurements based on cloud feature motion.

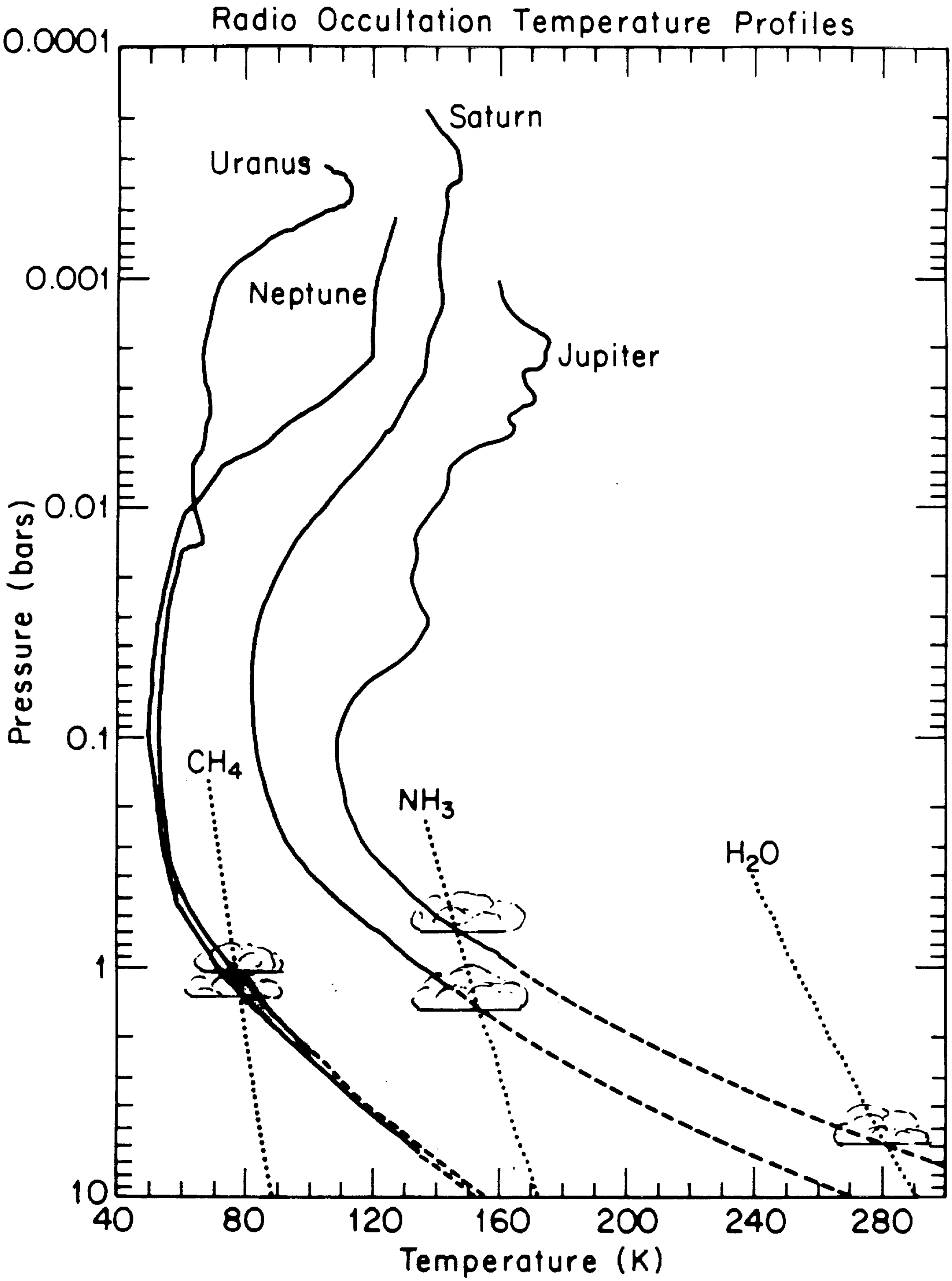
Figure 6. Illustration of creation of horizontal pressure gradients by hydrostatic columns of different density. Any vertical shear in a balanced geostrophic system (one with large Coriolis forces) requires horizontal density gradients along surfaces of constant pressure. In this example a level of no motion is assumed; this may not exist in the zonal mean on Jupiter. Instead there may be (as in the one and one- half layer models) a merging into a deep steady flow. But dynamical activity in the upper layer still requires horizontal density gradients. In this conceptualization these gradients

are distributed. They could instead be concentrated in a sloping compositional or thermal interface, as in the simple dynamical models.

Figure 7. Scaling estimates for the Jovian jets. U is taken to be half of the velocity difference between adjacent extrema. πL is taken to be the distance between positions of the extrema.

Figure 8. Local energy balance as a function of latitude on Jupiter. From Pirraglia (1986).

Figure 9. Temporal variation of Jovian stratospheric temperature, from Orton *et al.*, (1991). Notice the oscillation,with a period of about five years, of the equatorial temperature relative to its surroundings.



Radio Occultation Temperature Profiles
Pressure (bars)
Temperature (K)
0.0001
0.001
0.01
0.1
1
10
40
80
120
160
200
240
280
Saturn
Uranus
Neptune
Jupiter
CH4
NH3
H2O

Fig 1

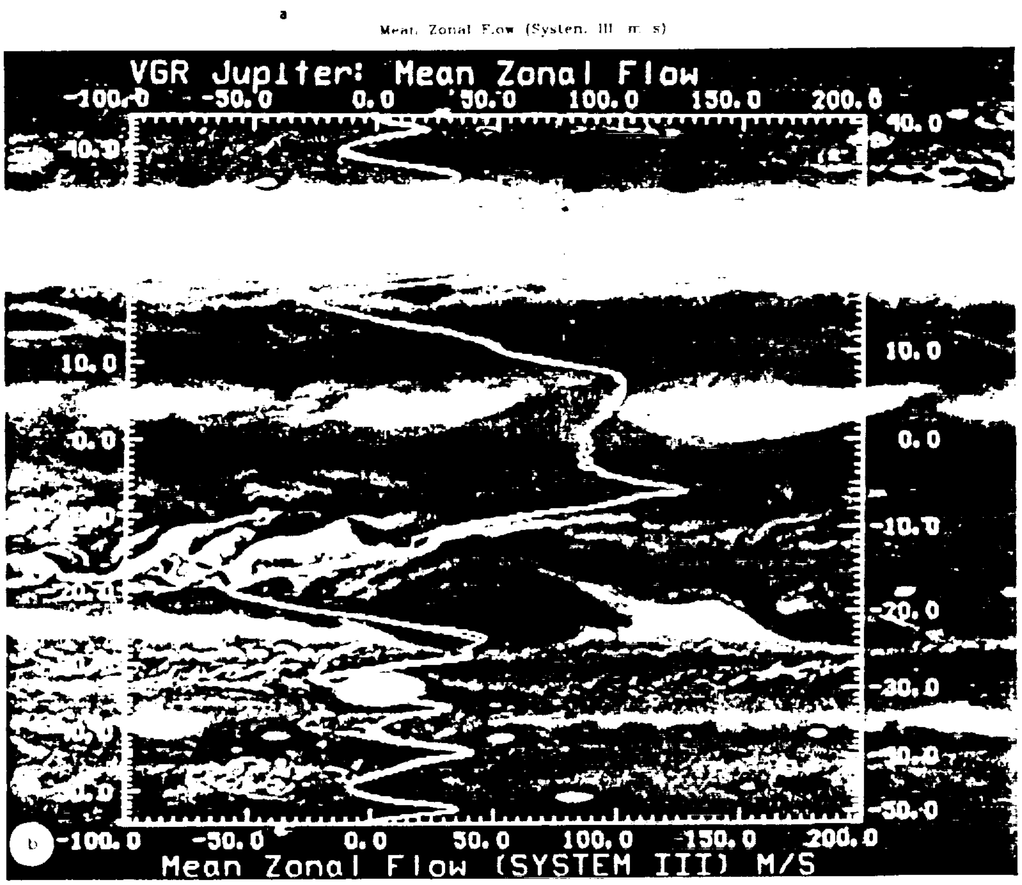
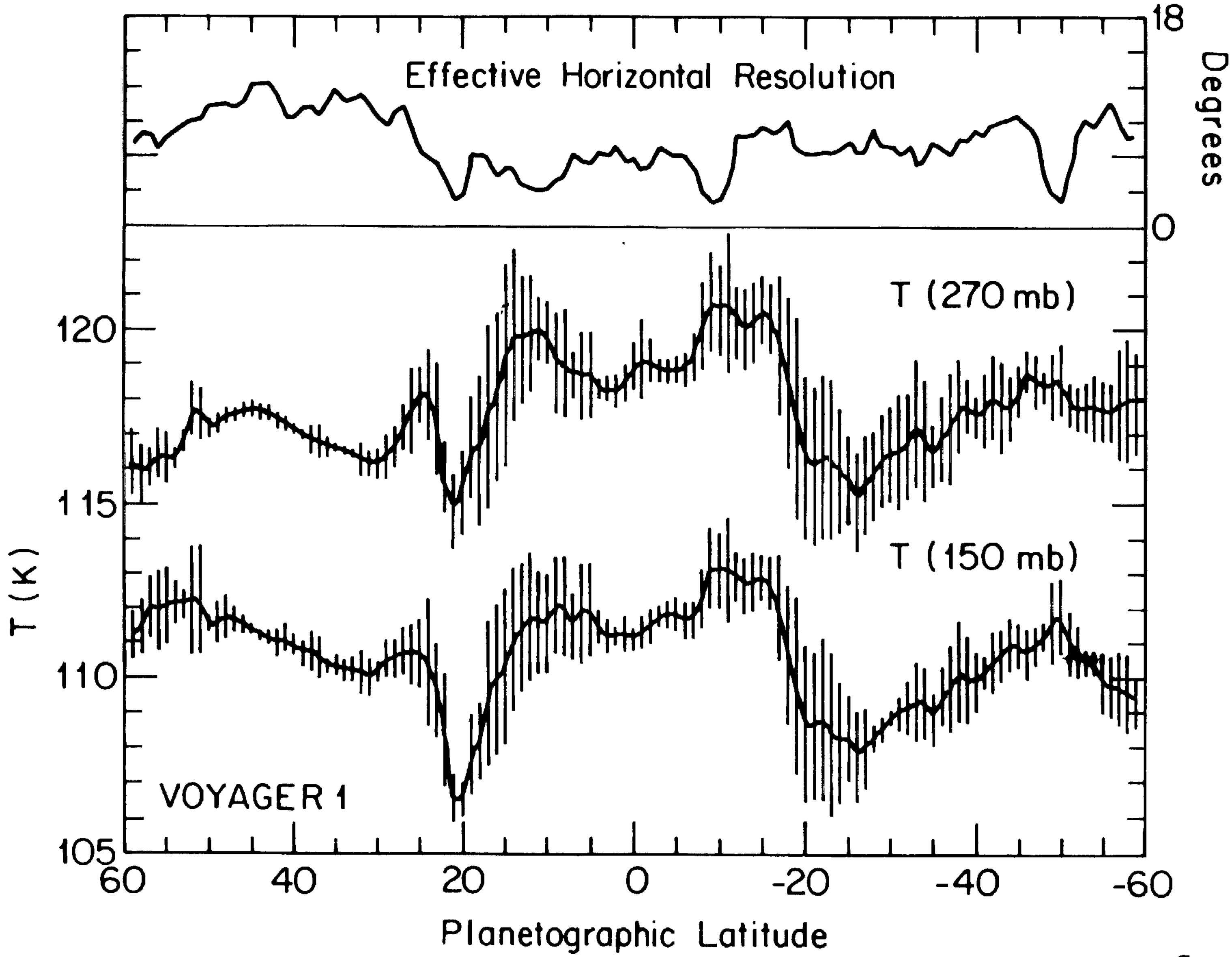


FIG. 2. (a) Average of mean zonal component profile calculated from analysis of 56 Voyager 1 mosaic pairs as a function of planetographic latitude. The RMS deviation for each latitude scan is shown by the thin line while the standard error of the mean at each latitude is shown by the width of the $\langle u \rangle$ profile (= twice the standard error of $\langle u \rangle$). (b) Voyager 1 and Voyager 2 average zonal mean zonal component are shown overlaid on a section of a mosaic image with the exact same latitude scale. Note the different morphology on either side of the dark belt. The jet peak is south of this dark belt by a considerable distance.

FIG. 2



Effective Horizontal Resolution
Degrees
18
0
T (270 mb)
T (150 mb)
VOYAGER 1
T (K)
120
115
110
105
60
40
20
0
-20
-40
-60
Planetographic Latitude

Fig 3

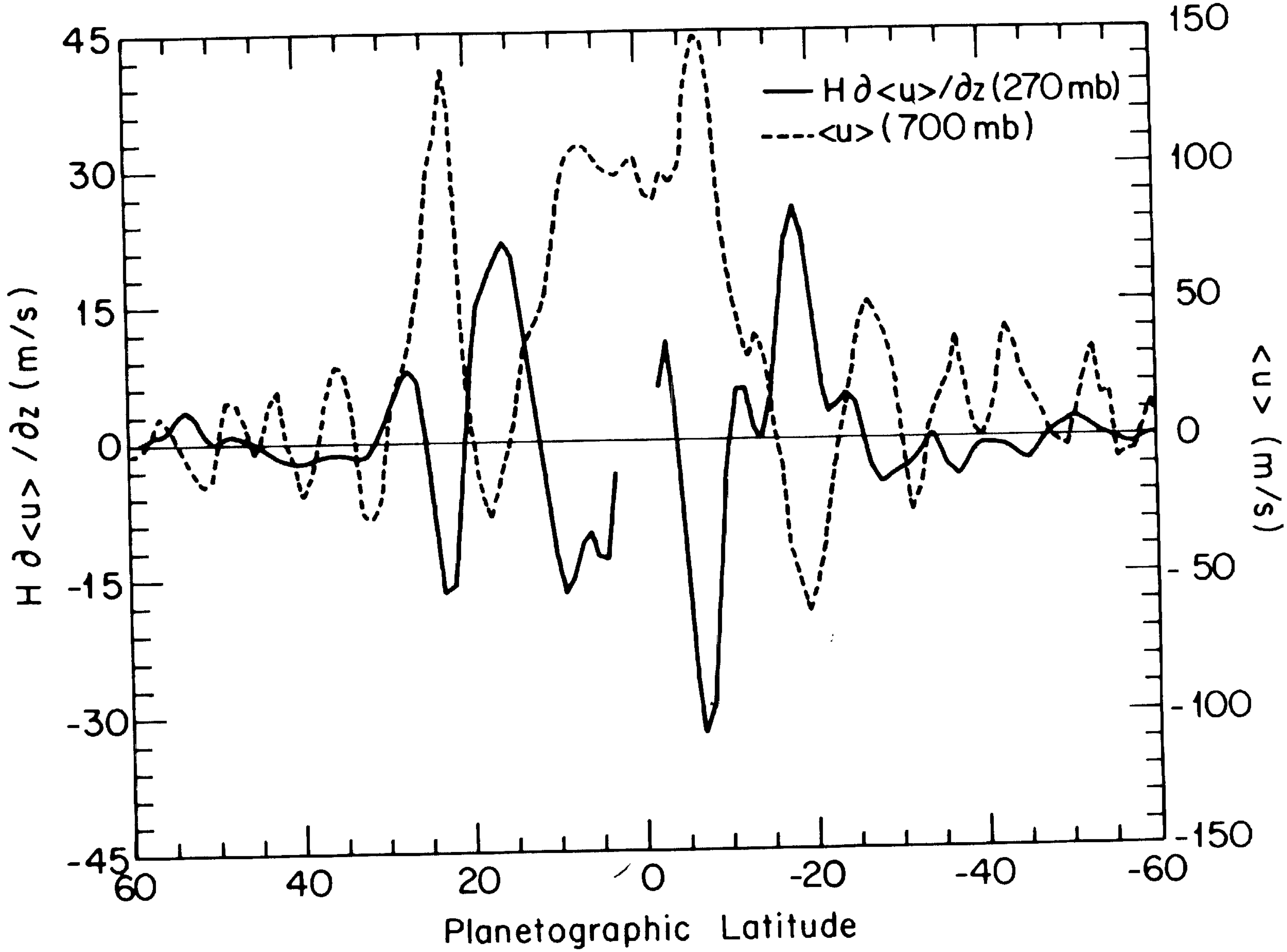
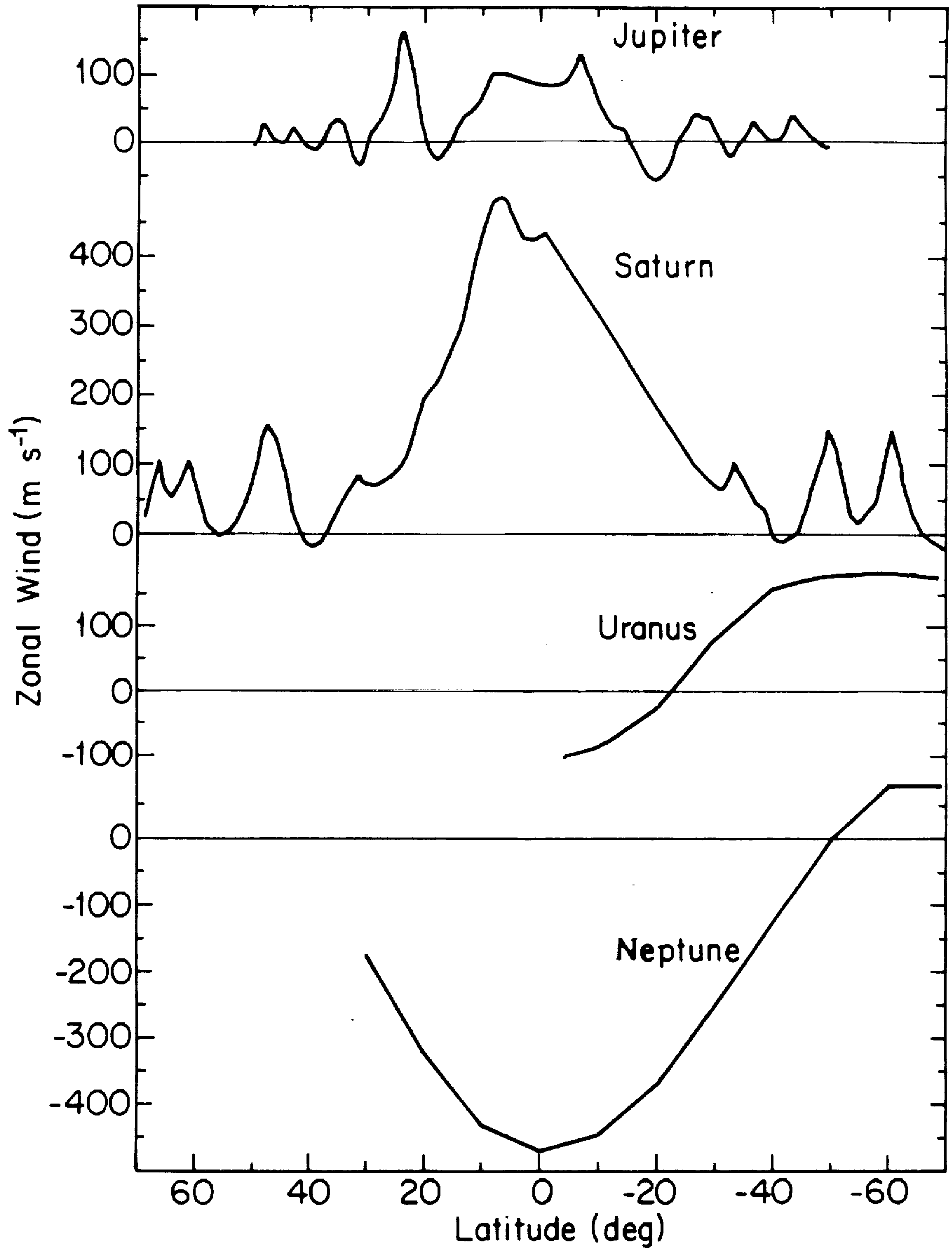

45
30
15
0
-15
-30
-45
150
100
50
0
- 50
- 100
-150
60
40
20
0
-20
-40
-60
H ∂<u>/∂z (270 mb)
<u> (700 mb)
H ∂<u> /∂z (m/s)
<u> (m/s)
Planetographic Latitude

Fig 4



Jupiter
Saturn
Uranus
Neptune
Zonal Wind (m s-1)
Latitude (deg)
100
0
400
300
200
100
0
100
0
-100
0
-100
-200
-300
-400
60
40
20
0
-20
-40
-60

Fig. 5

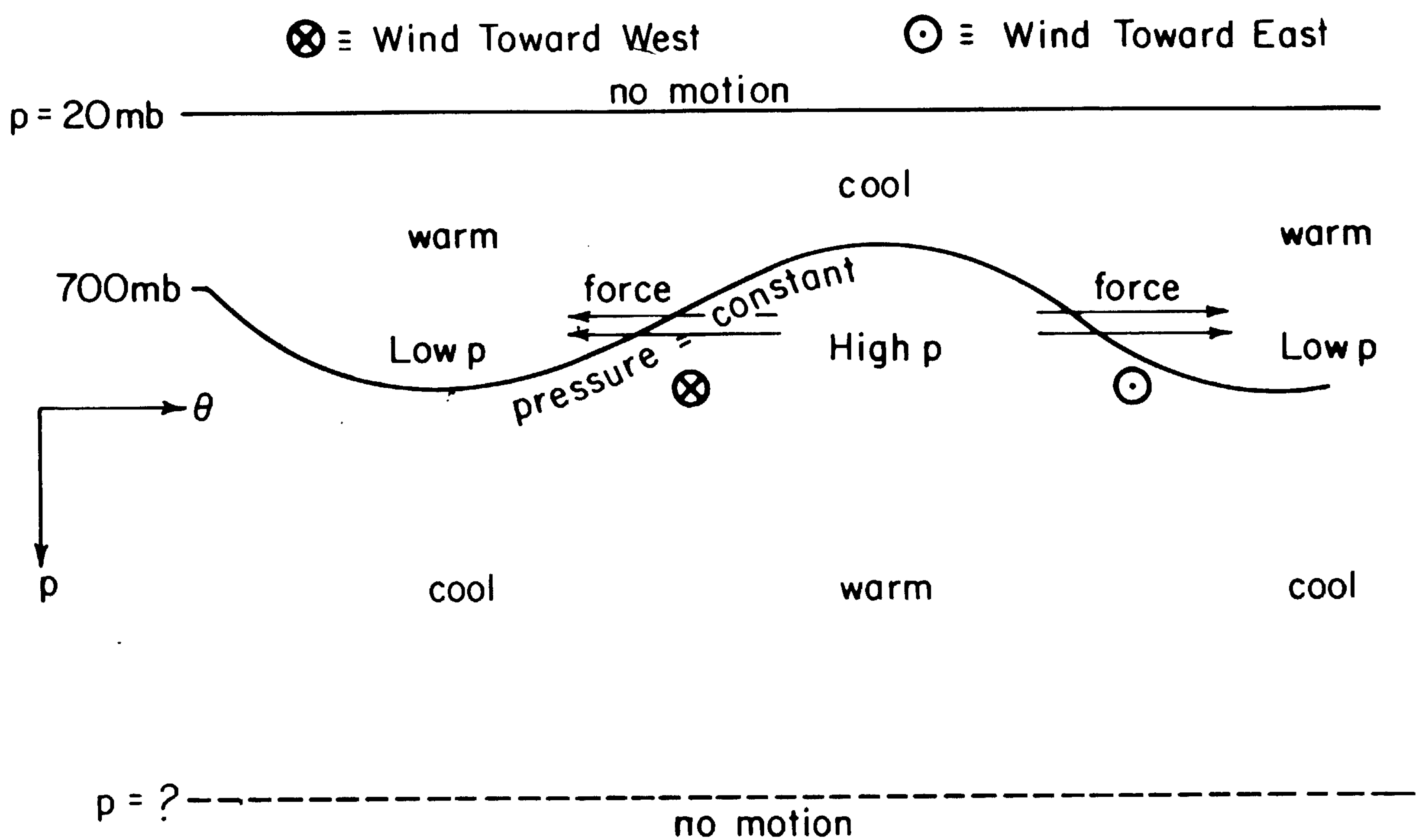
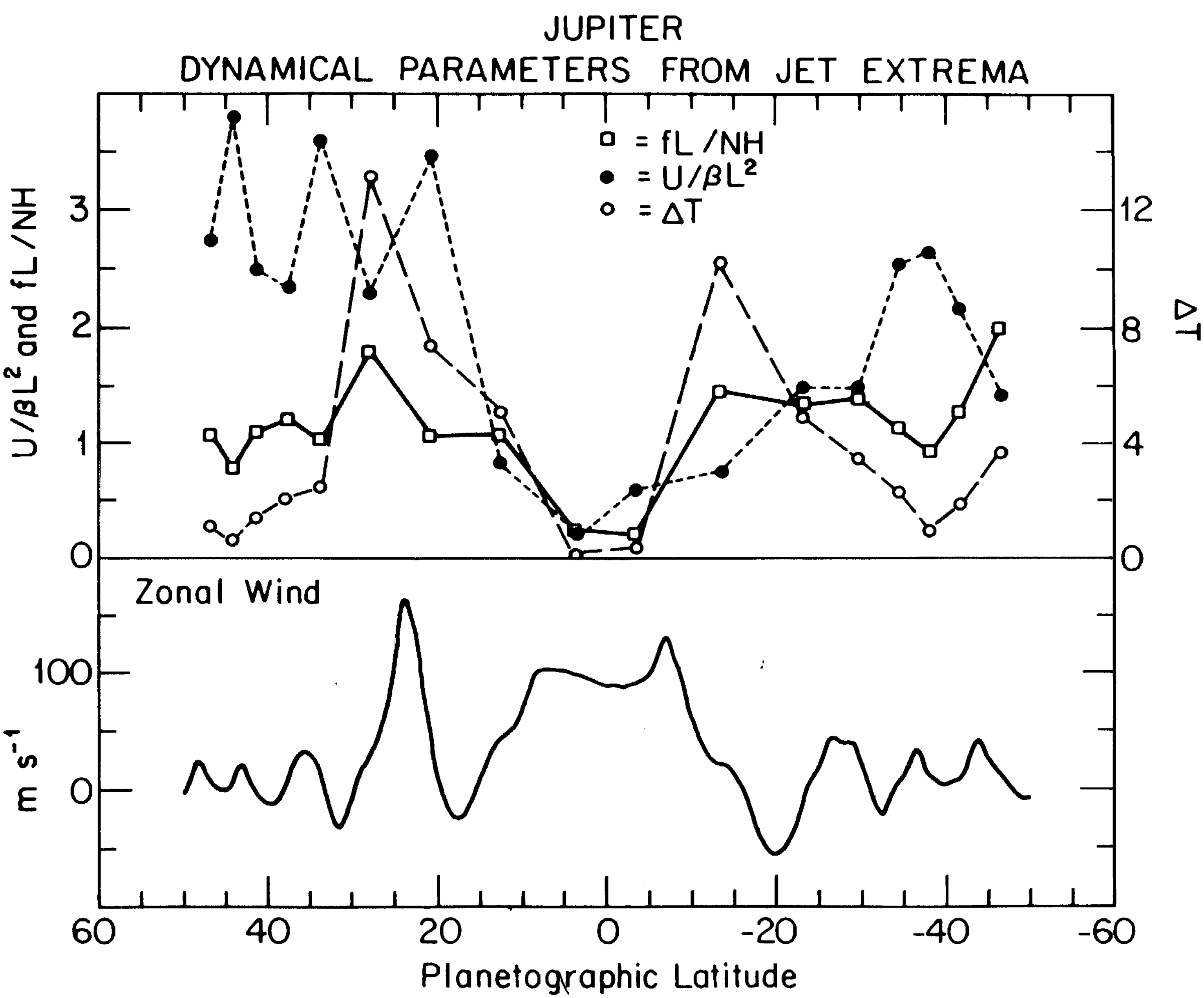
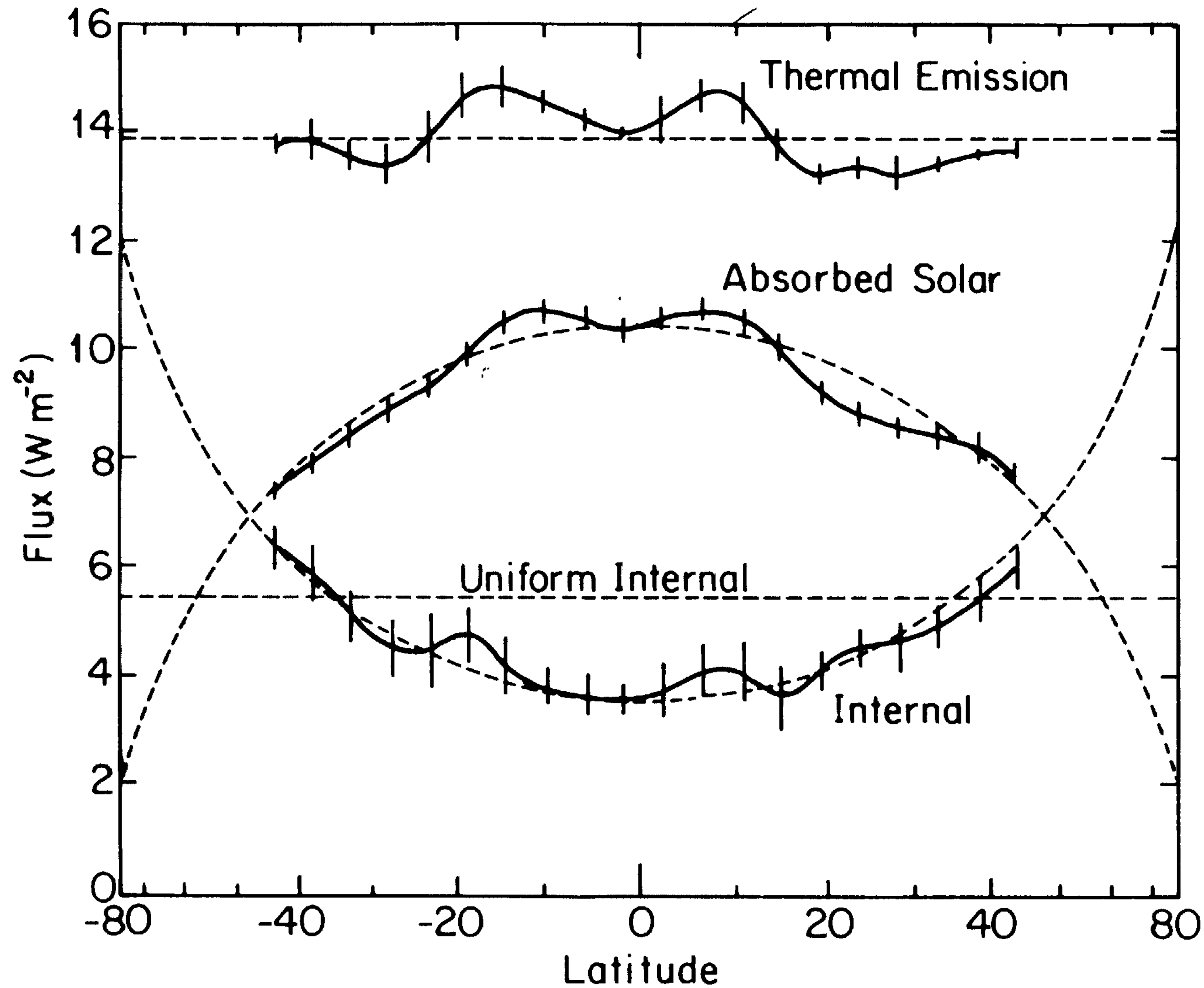

⊗ ≡ Wind Toward West
⊙ ≡ Wind Toward East
no motion
p = 20 mb
cool
warm
warm
700mb
force
force
Low p
High p
Low p
pressure = constant
θ
p
cool
warm
cool
p = ?
no motion

Fig. 6



JUPITER
DYNAMICAL PARAMETERS FROM JET EXTREMA
□ = fL/NH
● = U/βL²
○ = ΔT
U/βL² and fL/NH
ΔT
Zonal Wind
m s⁻¹
Planetographic Latitude

Fig 7



Thermal Emission
Absorbed Solar
Uniform Internal
Internal
Flux (W m^{-2})
Latitude
16
14
12
10
8
6
4
2
0
-80
-40
-20
0
20
40
80

Fig. 8

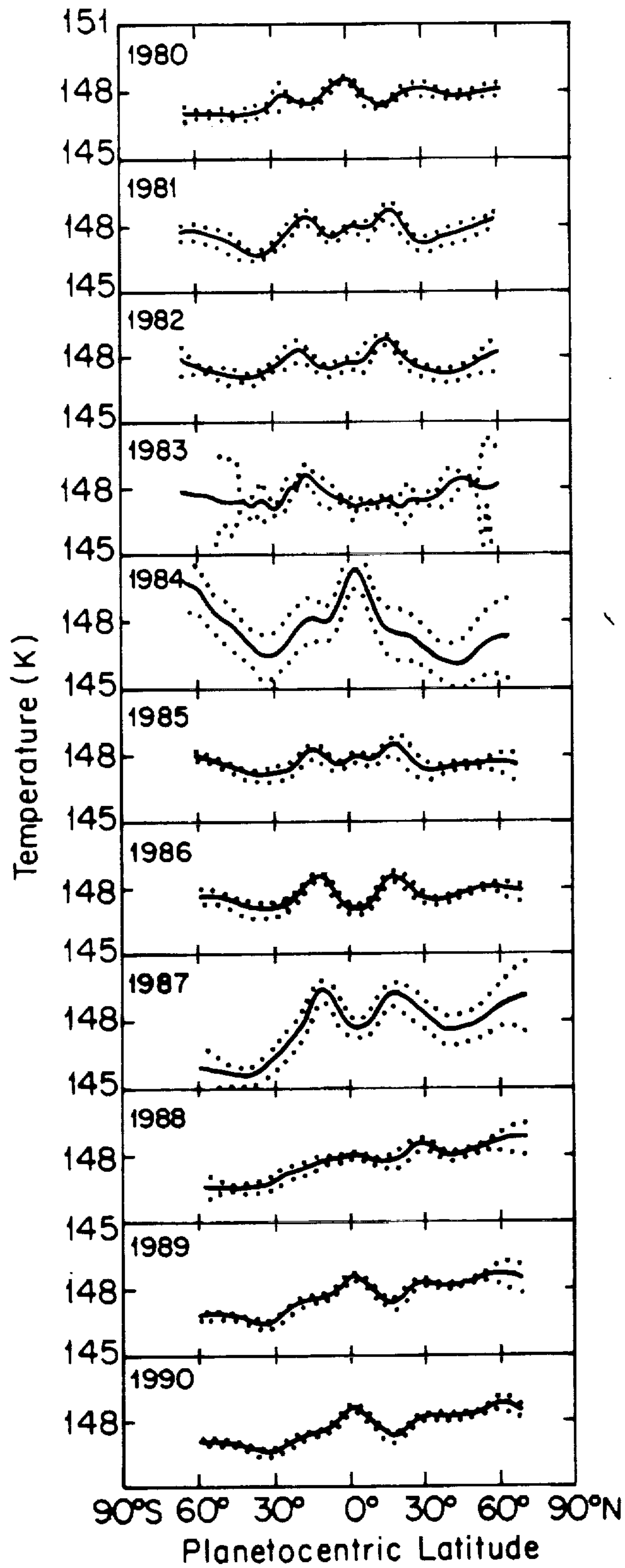

151
148
145
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
Temperature (K)
90°S 60° 30° 0° 30° 60° 90°N
Planetocentric Latitude

Fig 9