Atmospheric Dynamics on the Outer Planets

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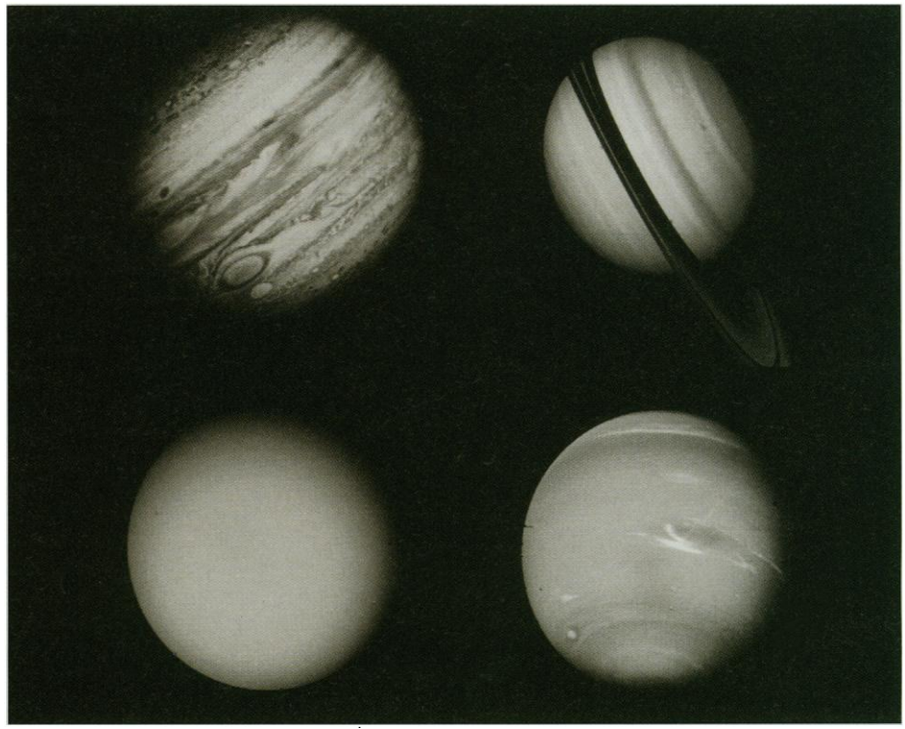
Jupiter and the other outer planets exhibit vigorous and complicated atmospheric flows (*1*). Averaged over time, the mean flows are alternating east-west jets with characteristic velocities of about 100 m s^{-1} on Jupiter and Uranus, and about 400 m s^{-1} on Saturn and Neptune. On Jupiter and Saturn there are several alternating jets in each hemisphere (see figure). On Uranus and Neptune there are westward equatorial jets and one eastward jet at high latitudes in each hemisphere. It is not known what determines the speed, the symmetry, and the magnitude of these flows. The situation can be contrasted with that on Earth, where to a first approximation the atmospheric temperature is governed by radiative balance. An equator-to-pole gradient is established in response to insolation. A dynamical regime becomes established, with one major tropospheric jet in each hemisphere. The speed and geometry of the jets are related in a straightforward way to the externally imposed heating. The jets turn out to be unstable, and quantitative details of the turbulent flow are very difficult to predict with accuracy, but the general nature of the velocity and temperature regime is well understood.

There are two possible forcings for flows on the outer planets, but it is not known which is dominant. One is the latitudinal gradient of insolation and the other is heating from below. Except possibly for Uranus, where the internal heat flow appears to be small, internal heat sources generate about the same amount of energy as insolation. For either energy source, the thermal drive for atmospheric motions is of global scale. The emergence of multiple alternating jets on Jupiter and Saturn means that an internally determined length scale arises. The general circulations on these planets are therefore responding to the external forcing in a more indirect manner than on Earth, and the fluid mechanics correspondingly is more subtle.

Our knowledge of the vertical structures and depth of outer planetary flows is very limited. Observations by remote sensing are limited to the stratospheres and the upper tropospheres where atmospheric pressures are approximately 1 bar or less. The major cloud systems, which make the atmospheric jets visible on Jupiter and Saturn, are near the 1-bar level. The deepest available information comes from the Galileo probe, which penetrated to about the 24-bar level on Jupiter (*2*), but this represents only a single profile of atmospheric properties. In the terrestrial case, experience shows that knowledge of the surface boundary condition and of the depth of the troposphere are absolutely essential to understanding the flow regime. The latitudinal temperature gradient only constrains the vertical wind shear, not the speed of the flow. As is discussed in meteorology texts (*3*), the depth of the flow regime must also be known in order to determine characteristic velocities.

Thermodynamic aspects of the outer planetary flows are also not well known. The major constituent of the atmospheres is H_2. Within the outer few hundred kilometers it behaves as an ideal gas, but at greater depths it becomes more liquidlike. In the conventional view, heat transfer from the interiors is by convection, and the thermodynamic structure of the deep atmospheres and the interiors is close to isentropic, but recent calculations of radiative opacities have led to the suggestion that there may be a substantial subadiabatic (stably stratified) layer at a depth of a few thousand kilometers (*4*), at least on Jupiter and Saturn.

In addition to the stratification, another important thermodynamic issue is the energy storage mechanism involved in heat transfers. The ultimate drive for dynamics must be buoyancy, which arises because of density contrasts that are associated with heat transfer. A wide range of temperatures exists within the envelopes of the outer planets, approximately from 100 K to a few thousand kelvin, and several constituents are candidates for phase changes. Examples include water, methane, and even silicon compounds at deeper levels where temperatures are highest. Each phase change gives a possible buoyancy effect, either through latent heat release or by precipitation and molecular weight alteration. Another possible thermodynamic effect is the conversion of para hydrogen to ortho hydrogen, which are known to be out of equilibrium on Jupiter and Neptune (*5*). Either mechanism, phase change or hydrogen conversion, could generate buoyancy



Images of Jupiter, Saturn, Neptune, and Uranus (clockwise from top left) obtained by the NASA Voyager spacecraft. The contrasts associated with cloud features are largest on Jupiter because the condensing ammonia clouds are relatively high in the atmosphere and are not obscured by overlying haze or Rayleigh scattering gas. With image enhancement, features can be identified and mean flow drifts measured even on Uranus. The resulting zonal velocity profiles are exhibited by Cho and Polvani [see figure 2 of (*6*)]. The structure of small-scale turbulent motions is clear only on Jupiter.

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contrasts of a few percent or more, which is ample to affect dynamics.

In view of all the complexities, how does one approach the question of why the outer planets have jet systems, long-lived ovals, and all the other observed richness of meteorological behavior? Cho and Polvani, in this issue (6), describe the behavior of an extremely idealized mathematical model and show that the model reproduces several features of the observed planetary circulations. The model represents a thin homogeneous "ocean" of depth H, on a planet of radius a, surface acceleration of gravity g, and rotation period P. It has no thermodynamic forcing and is initialized with a random velocity field. As Cho and Polvani discuss, other workers have studied similar models (7), but this is the first time that a series of experiments have been carried out for an unforced flow in full spherical geometry and for a range of parameter values spanning all the outer planets. The idea is to discover the key processes at work by isolating them in a very simple calculation.

The calculations represent extremely interesting fluid dynamical results. But what does one learn about the planets from qualitative agreement with observation in this model? The model has not been demonstrated to be unique in showing agreement, and therefore any conclusions must be tentative. One point of importance is the width of the jets that emerge. The model contains three scales: the planetary radius, the "deformation radius," and the Rhines scale. The deformation radius, from meteorology, is $L_D = \sqrt{gH}/\Omega$, where the rotation rate is $\Omega = 2\pi/P$. The Rhines scale (L_β) is given by $L_\beta = \sqrt{Ua}/\Omega$, where U is the magnitude of the flow speed. Rhines (8) has shown that in two-dimensional flow on a rotating sphere, an inverse turbulent cascade of energy to large scales is interrupted at scale L_β, and alternating jets can arise. The spacing of jets in the Cho and Polvani experiments, after initial transients, turns out to be on the order of L_β. But then, what sets the flow amplitude U on which the Rhines scale is based? This may depend on thermodynamics and remains an unanswered question. It is also possible that the new simulations are not based on the relevant deformation radius, and that the wrong regime, in terms of the ratio of L_β to L_D, is being explored. As Cho and Polvani point out, it is not at all clear what value of L_D (if any) is appropriate to simulate the correct planetary dynamics in a two-dimensional model.

But if the Cho and Polvani calculations have indeed captured the essential physics of jets and eddies on the outer planets, then the thermodynamic complexities described above for deep atmospheres are incidental, and fluid dynamics controls the gross structure and the visual appearance of the outer planets. If true, this would be a striking conclusion, simultaneously simplifying and complicating. The fluid dynamics is turbulent and nonlinear, yet leads to highly organized and persistent mean flows.

The simulations do not produce eastward currents at low latitudes on Jupiter and Saturn. Observations show strong eastward equatorial jets, which are particularly puzzling because they represent concentrations of angular momentum (more rapid rotation than the average). An angular momentum pumping process is needed to maintain them. Because these jets are on the equator, they cannot be produced by poleward drift of gas that conserves angular momentum, the way eastward mid-latitude jets on Earth can be produced. As Cho and Polvani remark, the fact that none of their numerical experiments produces these jets suggests that another mechanism, beyond the scope of the simple model, may be necessary. Stratification and the third dimension might be the missing ingredients.

Future progress will depend on new information from the planets. Numerical modeling has become very powerful, but the physical system is so ill-defined that modeling is not well constrained. It would be useful to have detailed maps of velocity fields within Jupiter's clouds, so that statistical properties could be compared with numerical simulations. The NASA Galileo orbiter may obtain such data during the next 2 years. It would also be useful to have more probes beneath the clouds of the outer planets, to better define the depth and the stability properties of the flows.

References and Notes

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Cuprates Fall into a Gap

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Superconductivity occurs in a metal when it is energetically favorable for the electrons to form Cooper pairs. Pair formation causes an energy gap to open in the electronic spectrum. The pairs may be destroyed in the presence of photons or thermal fluctuation energy, but only if the incident energy exceeds the energy gap. Therefore, the gap is a measure of the robustness of the superconducting state: The larger the gap, the higher the critical temperature T_c. A decade after the discovery of high-temperature superconductivity in the cuprates, persuasive evidence has been obtained for a partial gap that opens, not at T_c, but at a temperature 100 to 150 K higher. Is this higher temperature gap flagging the existence of an exotic electronic phase or merely a harbinger of superconductivity itself? How does the newly discovered gap affect the debate on the nature of electronic excitations and the origin of superconductivity in these remarkable solids? These and other issues continue to roil the field. In this issue, Loeser *et al.* (1) report photoemission spectra that bring this higher gap into sharper relief.

In a photoemission experiment, electrons are ejected when the sample is exposed to photons. In the more sophisticated technique of angle-resolved photoemission spectroscopy (ARPES), only the electrons ejected in a prescribed direction are detected (see figure). This refinement enables the energy versus momentum dispersion within the sample to be determined directly if it is two-dimensional (2). The Fermi surface (the surface enclosing all the occupied states) may be mapped by changing the detection angle.

The essential structure in all superconducting cuprates is the copper oxide layer. In the parent compound of each family, the highest $3d$ state in each copper ion is occupied by a single electron. In principle, a lattice with one electron per site should be a metal with a half-filled band. However, in the cuprates, Coulomb repulsion between two electrons on the same site is so strong that electron hopping and band formation are precluded altogether: The parent compound is an insulator. Dramatic changes occur when a small fraction of the electrons are chemically removed to create vacancies or

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