Atmospheric Dynamics of Giant Planets

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The giant planets constitute immense natural experiments in planetary fluid dynamics. They obey the same fluid mechanics laws as Earth and exhibit many similar phenomena, including jet streams, vortices, waves, convection, and thunderstorms. But these basic phenomena assume distinct behaviors on giant planets because of the greater sizes, faster rotation rates, lack of solid surfaces, and weaker solar-energy absorption as compared to terrestrial planets in our solar system. Here, I will review past and current research and highlight future directions in understanding giant planet dynamics at pressures ranging over 9 orders of magnitude from ~ 1 Mbar to ~ 1 millibar.

At the cloud level, the dynamics on Jupiter, Saturn, Uranus, and Neptune are dominated by multiple east-west (zonal) jet streams whose speeds range from $\sim 100\,\mathrm{m\,sec^{-1}}$ on Jupiter to $\sim 300\,\mathrm{m\,sec^{-1}}$ on Neptune. Infrared (thermal) measurements constrain how these jets vary with height above the clouds, but the depth dependence of these jets below the clouds is poorly understood. Endpoint hypotheses range from the "shallow" scenario, where the jets are confined to a few scale heights below the clouds, to the "deep" scenario, in which the jets penetrate throughout the molecular envelope along cylinders parallel to the planetary rotation axis. For Neptune, Voyager gravity observations suggest that the jets are confined to the outermost $\sim$1% of the planetary mass, but similar constraints are so far lacking for Uranus, Saturn, and Jupiter. I will review in detail the proposed formation mechanisms for these jets, which range from deep convection throughout the planetary interior to shallow turbulence interactions in the cloudy weather layer.

All four planets also exhibit numerous time-variable clouds and vortices whose details vary from planet to planet. Jupiter and Saturn sport hundreds of compact vortices ranging in size from Jupiter's Great Red Spot (dimensions 20,000 km by 10,000 km) to the resolution limit of current images (hundreds of km or less). Neptune and Uranus are less active than Jupiter and Saturn but nevertheless exhibit several interesting vortices and other cloud features. Giant planet vortices have been observed to merge, split, eject filaments, orbit other vortices, oscillate in shape and position, migrate in longitude and latitude, change color and albedo, and interact with jets in a variety of ways. Lifetimes range from >100 years for the Great Red Spot to only days for some of the smaller structures. These behaviors provide clues not only about vortex dynamics itself but about the background atmosphere in which the vortices reside. Thus, detailed numerical studies of vortex interactions holds promise for constraining the depth dependence of zonal wind, static stability, and other properties in the difficult-to-observe layer below the clouds. Vortices also hold clues about planetary energetics, since in some cases vortices form by robbing energy from the zonal jets, while in other cases short-lived eddy structures produced by convection may pump momentum upgradient into the jets, hence accelerating them. In addition to vortices, the giant planets exhibit a wealth of time variable phenomena, ranging from short-lived thunderstorms and waves to multi-year-long, quasiperiodic variations in the banded cloud patterns. I will survey this diversity and discuss its role in jovian dynamics.

All four giant planets contain stratospheres where the temperature is approximately constant or increases with height, leading to greater static stability than in the underlying tropospheres. The stratospheres exhibit few clouds, so direct measurement of winds is difficult. But Voyager, Cassini, and groundbased infrared measurements constrain the three-dimensional temperature patterns, which via balance arguments has lead to an understanding of how the zonal wind varies with height above the tropospheric cloud decks. In general, the fast zonal jets at cloud level appear to decay with altitude, although some exceptions exist. The mechanism for this decay remains poorly understood but probably involves the interaction of meridional Hadley-type circulations with wave absorption or instabilities of the jets. As with the tropospheres, the giant-planet stratospheres exhibit considerable variability as manifested in infrared spectra. On Jupiter and possibly the other planets, this variability includes the so-called "Quasi Quadrennial Oscillation," which is a quasiperiodic variation in the equatorial wind direction that (in analogy with Earth's Quasi Biennial Oscillation) is driven by absorption of waves propagating upward from the troposphere. A major area of untapped potential involves the interaction of chemistry and dynamics. The stratospheres contain trace abundances of ethane, acetylene, and other compounds whose variation in latitude and height holds clues about the stratospheric circulation patterns. Coupled modeling of stratospheric dynamics and photochemistry may help to explain the chemical observations while simultaneously unraveling many aspects of the stratospheric circulation.

Weather and climate on giant planets reflect a richness and beauty that rivals that on any terrestrial planet. The giant planets experience variability over all time and length scales that have been observed (hours to centuries and tens to tens of thousands of km). They encapsulate many atmospheric dynamics phenomena familiar from Earth, but they greatly broaden our understanding of dynamics by showing how the behavior changes when gravity, static stability, rotation rate, bottom boundary condition, and themodynamic heating rates are altered far from their terrestrial values.