Meteorology

Clouds on the giant planets

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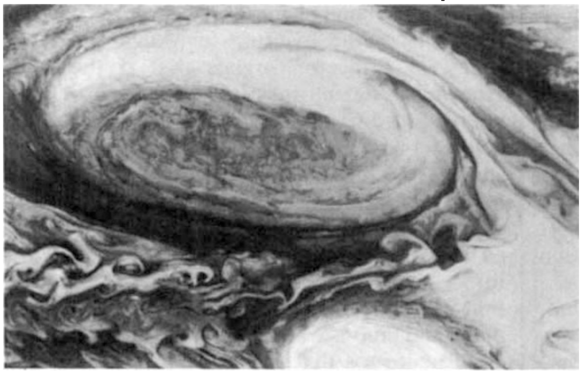
WHAT kinds of clouds exist on Jupiter and the other outer planets? The atmospheres of these planets are principally hydrogen and the trace constituents which can condense to form clouds at observable levels are NH_3, H_2O, CH_4 and possibly NH_4SH. B. E. Carlson *et al.* ask in a recent paper (*J. atmos. Sci.* **45**, 2066–2081; 1988) whether the various cloud layers are precipitating or not, and if they are, how violent the activity is. They conclude that the visible ammonia clouds on Jupiter (which is too warm for methane to condense; see figure) are not unlike thick cirrus on Earth, but that deeper clouds on Jupiter and all the clouds on Uranus and Neptune could be far more active than any that occur on Earth. These are tough issues, but are extremely important to our understanding of the outer planets. The density and temperature changes that are produced by phase changes and compositional separation within these bodies may have profound influence on the dynamics of their envelopes and on the extrapolation inward of the temperature increase that we observe in outer layers.

Even on Earth where the atmosphere is relatively well documented, the varied nature of clouds is complex and puzzling. At one extreme, there are hazes of very small, slowly growing droplets such as those of photochemically produced sulphuric acid in the stratosphere or in urban smogs. These are nonprecipitating clouds in the sense that coalescence of particles never becomes a runaway process leading to rapid fallout of material. Other clouds are produced by simple condensation of water but are also non- or only weakly precipitating. Radiation fog is an example. Finally, there are actively precipitating systems such as cumulonimbus, in which the heating that arises from the condensing phase change plays an important part in driving fluid motions, so that the existence of precipitation alters the character of the whole system.

To explain this range of behaviour one must know the composition of the atmosphere, including whether grains or ions which can serve as condensation nuclei are present; one must understand the chemistry of the mixture; and one must be able to predict the feedbacks which can occur through radiative or latent-heat effects on fluid motions. It is clear that without observational guidance, discussion of cloud structure and dynamics in remote and exotic situations is extremely difficult.

Carlson *et al.* wisely restrict themselves to the very simplest considerations. They have evaluated the timescales for the growth of crystals (or droplets), and for fallout and coalescence to occur. No attempt at detailed modelling of the processes is made. The nature of the cloud turns out to depend most importantly on the density of the condensate vapour at the base of the cloud. A low density leads to weakly precipitating clouds because particle size never becomes large enough for differential fall velocities to cause the runaway process of coalescence. A high density leads to precipitation and 'activity'.



The Great Red Spot of Jupiter and its neighbourhood, observed during one of the Voyager spacecraft fly-bys. The appearance of the ammonia clouds is consistent with cirrus behaviour, although more detailed observations are needed. The intricate patterns with sharp edges are nicely explained as condensation clouds, forming and evaporating too rapidly for diffusion to destroy the spatial gradients. These clouds occur at a level in Jupiter's atmosphere where the pressure is not far from that at the surface of the Earth and where the temperature is about 150 K. The image is two Earth diameters across and has a resolution of 40 km.

Although provocative, this exercise should be viewed with caution. Among the clouds predicted to be heavily precipitating is the Uranus methane system. In this particular case we have data from the Voyager fly-by of 1986 which shows exactly the opposite cloud behaviour. Although the temperature variation with height is nearly adiabatic and thus consistent with strong vertical mixing, a long-lived chemical tracer, the *para*-hydrogen concentration, is vertically layered (R. A. Hanel *et al. Science* **233**, 70–74; 1986), proving that mixing is not occurring. Images also reveal that the planet is covered with uniform haze and not cumulus structures as would be predicted by heavy precipitation and latent-heat release.

Uncertainties in composition are probably not sufficient to be the cause of failure of the predictions. But it is well to bear in mind that among the key condensibles, only methane on Jupiter and Saturn has a well-determined concentration, and only because it does not condense on those particular planets. The concentration is about 2×10^{-3} on both planets (Gautier, D. *et al. Astrophys. J.* **257**, 901–912; 1982; Encrenaz, T. & Combes, M. *Icarus* **52**, 54–61; 1982), or a bit more than twice what would be expected from a solar ratio of carbon and hydrogen. This and other evidence, such as the bulk densities of the outer planets (Pollack, J.B. *A. Rev. astr. Astrophys.* **22**, 389-424; 1984), are consistent with the relatively rich mixtures of condensibles asssumed by Carlson *et al.*, which lead to their prediction of strongly precipitating clouds.

There are a number of factors which could cause clouds to show different behaviour on the outer planets than on Earth. The condensible matter in the terrestrial atmosphere, H_2O, has a smaller molecular weight (18) than the bulk atmosphere (29) and therefore cannot become stably stratified within a cloud. Recall that the abundance of condensible vapour will always decrease with height in a cloud, because the temperature drops with height and the abundance is limited by the saturation vapour pressure. In contrast, the molecular weights of condensibles on the outer planets are much larger than that of the bulk atmosphere, and stable stratification can develop. Another important difference lies in the absence of a solid lower boundary analogous to the Earth's surface. On Earth, precipitation strikes the surface and cannot be removed any further from the clouds than this. On the outer planets, precipitation will fall to deeper, warmer levels and evaporate, producing a patch of gas enriched in the precipitating component and heavy relative to its surroundings. Further sinking could ensue, with the end result of removing the condensible gas from the level of mean condensation and reducing its concentration there.

These issues are similar to those encountered in other fluid systems where two constituents are mixed and buoyancy effects arise because of variable concentration. Salinity in the oceans is an example. Such systems have been examined extensively (*Buoyancy Effects in Fluids* by J. S. Turner (Cambridge University Press, 1973) is an excellent introduction). But my feeling is that the prediction from first principles of the behaviour of systems as complicated (and fascinating) as the outer-planetary atmospheres is well beyond our capability and that *in situ* observations are needed. The NASA Galileo probe to Jupiter, scheduled for launch in the autumn of 1989 and to arrive at Jupiter in 1995, may be useful. □

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