Towards a Universal Taxonomy of Planetary Atmospheres

A major theme in talks, posters, and discussions throughout the conference was different approaches to classification of planetary atmospheres. Taxonomies have been considered previously for solar system planetary atmospheres as a way of challenging our fundamental understanding of what physical processes differentiate the atmospheres of planets from each other and as a way of placing our own planet into a larger context. With the advent of exoplanet discovery and tentative but incomplete characterization, taxonomies are taking on a new importance as we try to infer whether the conditions on these planets might be conducive to habitability in the absence of detailed information.

Several different approaches to atmospheric classification were discussed at the conference. The most basic is the issue of what determines whether a planet can retain an atmosphere over time. Historically, this has been viewed as solely a matter of the escape velocity and thus the planet size, atmospheric temperature, and atmospheric composition. Within our own solar system the examples of the similar size satellites Titan, which has a thick atmosphere, and Ganymede, which has virtually no atmosphere, indicate that additional processes must be important. It was proposed that a clue to this difference is the larger gravitational potential well of Jupiter relative to that of Saturn. This causes larger impact velocities on Ganymede that erode the atmosphere to a greater extent than the volatiles that they deliver to it. Modeling of impact velocities for a wide variety of solar system objects and exoplanets suggests empirically than a median impact velocity greater than ~5-6 times the escape velocity results in a planet that cannot retain its atmosphere.

Given an atmosphere, the relative abundances of different elements control the nature of the chemistry, the dominant molecular constituents, the types of condensation clouds and photochemical particulate hazes that form, and thus ultimately the magnitude of the greenhouse and anti-greenhouse effects that exert the first-order influence on whether a planet might be habitable. It was proposed that the two key factors that differentiate atmospheres from a purely chemical standpoint are the H abundance and C/O ratio. Gas giants are defined by their large H abundance. For intermediate H abundance, low vs. high C/O ratios separate water-rich from hydrocarbon-rich atmospheres, whereas H-deficient atmospheres will vary from being oxygen-rich to CO_2/CO-dominated as the C/O ratio increases.

Beyond this basic chemical taxonomy, the relevant question is whether spectra of a planetary atmosphere can provide evidence of biosignatures. The degree of chemical disequilibrium, defined as the Gibbs free energy difference between the actual composition and the minimum value that would characterize an equilibrium composition, was proposed as a first step in such a classification. By this metric Earth's atmosphere is in disequilibrium by many orders of magnitude more than any other solar system atmosphere. However the nature of the disequilibrium must be examined to differentiate biotic from abiotic (e.g., photochemical, external injection) sources of disequilibrium free energy. Mars, e.g., has a modest degree of disequilibrium, but due to photochemistry. Thermo-chemical equilibrium has traditionally been used to anticipate the existence and location of cloud layers, especially on the giant planets. However, the presence of dynamics, and in particular moist convection, can cause the abundance of a condensable to be significantly subsaturated and the cloud fraction to be small above the nominal equilibrium condensation level, the best example being water on Earth. Thus future planetary cloud classification might have to take both chemistry and thermodynamic stability into account.

A different approach to creating a possible taxonomy of atmospheres for exoplanet habitability purposes is to use only easily-observed external parameters. One such example was presented, based solely on planet mass and incident stellar flux. This type of classification has the most in common with previous attempts to define habitable zone limits. It is bounded at the low mass end by hydrodynamic escape and at the high mass end by hydrogen/helium accretion or escape, both limits being increasing functions of incident stellar flux. Inside these limits, the atmosphere is strongly influenced by the incident stellar flux. At low fluxes, even an N_2 atmosphere collapses. As the flux increases, an N_2 atmosphere with other constituents such as CH_4 or CO might be maintained but would be too cold to support liquid water. At some point an outer edge habitable zone threshold is crossed beyond which a sufficiently strong greenhouse effect due to gases and/or clouds allows an H_2O water-vapor equilibrium to exist. Eventually, as stellar flux increases, the inner edge of the habitable zone is reached, most likely because a “water-loss” limit is reached as water vapor builds, the tropopause is eroded, and significant water vapor reaches what was previously the stratosphere, at which point water is photodissociated and lost to space. A simple analytic model presented at the conference suggests that the location of the tropopause is above the radiative-convective boundary and determined by the altitude at which the gray infrared optical thickness is ~0.1, which for a wide variety of planets occurs near the 0.1 bar level. The presence of a significant stratosphere is then determined by the ratio of the shortwave absorption optical depth to the infrared optical depth. A less restrictive inner edge definition can be based on the concept of a runaway greenhouse and dominant H_2O “steam” atmosphere, although it is not clear whether this limit can be reached in practice. Finally, for very high stellar fluxes, surface melting takes places and atmospheres can contain significant amounts of silicate gases and clouds; this may be typical of “hot Jupiters” with orbits very close to their stars.

Finally, several presentations emphasized atmospheric classifications based on dynamical considerations. Several such taxonomies have been suggested in the literature over the years. Necessarily, planet rotation rate is fundamental to any such classification. The simplest separation is between rapidly rotating planets with quasi-geostrophic dynamics (based on a zeroth order balance between Coriolis and pressure gradient forces) and baroclinic waves that dominate heat transport, and slowly rotating planets with quasi-cyclostrophic dynamics (in which centrifugal forces replace the Coriolis force as the leading order balancing term for the pressure gradient force) and heat transport primarily by a Hadley cell. The dimensionless Rossby number, which goes from small to order unity as rotation rate decreases, captures this transition. More generally, the transition occurs when baroclinic waves increase in spatial scale to the point that they effectively do not fit on the planet. This then introduces other factors such as planet size, gravity, and static stability, which can be summarized in terms of a dimensionless thermal Rossby number. Such classifications are useful for purely dynamical purposes, e.g., to distinguish atmospheres with significant superrotation (slow rotation, high static stability) from those without (rapid rotation and/or low static stability). Another relevant factor highlighted at the conference was the degree of seasonality, with increasing seasonality suppressing superrotation because of cross-equatorial transport of low-angular momentum air and hemispheric asymmetries in zonal wind.

However, dynamics also has a central role to play in considerations of habitability, because of heat transport. Planets that might seem prone to atmospheric collapse due to cold polar or nightside temperatures may nonetheless remain habitable if dynamical heat transport from the tropics or dayside is sufficiently efficient. Likewise, the onset of the water-loss or runaway greenhouse inner edge limit might be mitigated by heat transport away from the tropics or subsolar point. Results from simulations with a simplified GCM showed how equator-pole heat transport decreases with increasing rotation rate as the spatial scale of baroclinic eddies decreases, and how the transport increases with increasing atmospheric mass.