GIANT-PLANET ATMOSPHERES: COMPOSITION AND CHEMISTRY.

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Abstract: Our understanding of the composition and chemistry of giant-planet atmospheres has been refined and heightened from research activities carried out in the past decade. Ground-based and Earth-orbiting (e.g., HST, ISO, Spitzer, SWAS, Odin, EUVE, FUSE, HUT, ROSAT, Chandra, XMM-Newton) telescopes and *in situ* spacecraft (e.g., Cassini, Galileo, New Horizons) have supplied detailed new quantitative information, and recent laboratory investigations and theoretical models have helped place the interpretations of those observations on a more secure foundation. Major highlights in the field from recent years include: (1) better determinations of elemental abundances on Jupiter from the Galileo probe that enhance our understanding of solar-system formation, (2) new detections of oxygen and nitrogen species in giant-planet stratospheres that indicate that the atmospheric composition is influenced by external material, including a possible recent large impact on Neptune, (3) new detections of hydrocarbons in giant-planet atmospheres that improve our understanding of stratospheric chemistry and transport, (4) a better three-dimensional view of tropospheric and stratospheric chemistry that illuminates the complex and intimate connection between composition, temperatures, and dynamics, and (5) increased evidence for how global- and regional-scale chemistry changes with time. Arguably the most exciting development in astronomy in recent years is the detection of planets around other stars; by studying the diverse giant planets in our own solar system, we can learn what to expect from and perhaps how to best characterize extrasolar giant planets. I will review recent highlights in the field of giant-planet composition and chemistry and prognosticate on important future directions.

Introduction: A complete review of the chemistry and composition of Jupiter, Saturn, Uranus, and Neptune is not possible in a two-page abstract or, for that matter, a 40-minute talk. I will attempt to highlight the basics of and the latest developments in the gas-phase chemistry of giant-planet stratospheres and tropospheres. The composition of the interior, with its implications for the origin and evolution of the solar system, is discussed more fully in another talk, as are cloud and hazes, ionospheric/thermospheric chemistry, and extrasolar giant planets. For more complete reviews of giant-planet chemistry, see [1-31].

Elemental and Isotopic Abundances: The giant planets are composed largely of H_2, with a smaller amount of He [32-35], and trace amounts of heavier elements, mostly in their reduced forms. The mass spectrometer and helium-abundance detector on the Galileo probe have supplied direct measurements of elemental abundances on Jupiter [32, 35-37] and have provided a "ground truth" for remote-sensing techniques. The Galileo-probe-derived helium abundance [32,35] was found to be higher than that derived from remote-sensing from Voyager instruments [38], shedding doubt on the Voyager technique [e.g., 39]. Helium on both Jupiter and Saturn seems to be depleted relative to expected solar-nebula values, indicating that condensed helium droplets, perhaps with neon dissolved within them, are falling toward the planet centers [see 13]. The abundance of heavy elements provides critical constraints for theories of giant-planet formation [e.g., 13,36,40]. Most of the elements heavier than He are enriched relative to solar values by a factor of 2-4 on Jupiter [35-37], indicating that icy planetessimals contributed to the accretion of Jupiter, but leaving puzzles as to the source of those planetessimals [36,13,40]. A good measure of the oxygen elemental abundance in the deep atmosphere of Jupiter (not obtained by the Galileo probe), should help resolve the remaining puzzles. Isotopic ratios such as D/H can also provide clues to the contribution from icy planetessimals [e.g., 3]. On Saturn, heavier elements appear enriched relative to solar, but the error bars are large [e.g., 40]. Uranus and Neptune are much more enriched in heavier elements than either Jupiter or Saturn (~30-60 times solar) [34,41].

Thermochemistry: Thermochemical equilibrium controls the abundance of constituents in the deep, hot regions of giant-planet atmospheres [see 42,43]. The tropospheric composition is therefore expected to vary with pressure and temperature. As parcels of gas rise from the deep troposphere, thermochemical conversion between different molecular forms (e.g., CO to CH_4) occurs. However, chemical kinetics can be slow at cold temperatures, and vertical mixing time scales can becomes shorter than kinetic conversion time scales at some pressure level in giant-planet tropospheres. At that point, the composition may be "quenched", and disequilibrium abundances can prevail above the quenching region [44, 45]. Some of the assumptions of the earlier "quench" calculations have been called into question [46-48] due to recent kinetic measurements and theoretical considerations. Because the abundances of observed disequilibrium constituents can shed some light on things like the oxygen elemental abundances in the deep atmosphere [48,49] and the predicted composition of extrasolar planets [43,47], more detailed kinetic modeling is warranted.

Tropospheric Photochemistry: Upper tropospheric temperatures on the giant planets are so low that most equilibrium constituents condense in the troposphere, and only the most volatile molecules survive to reach altitudes above the cloud tops, where they can interact with solar ultraviolet radiation or (eventually) energetic electrons. Tropospheric photochemistry on the giant planets is dominated by molecules that contain nitrogen (with NH_3 as the "parent" molecule), phosphorus (PH_3), and possibly sulfur (H_2S). Ammonia can be photolyzed by relatively long wavelength UV radiation in the troposphere (Jupiter and Saturn, in particular). The physical separation of the NH_3 photolysis region from the much-higher-altitude CH_4 photolysis region limits the photochemical production of nitriles and other organo-nitrogen compounds. However, ammonia photochemistry is influenced by the presence of PH_3 [see 50,1-3,18,21 for details]. Little is known about sulfur photochemistry on the giant planets [cf. 51]. Several recent observations have increased our knowledge of the altitude, latitude, and longitude distribution of tropospheric constituents on the giant planets [52-58].

Stratospheric Photochemistry: Our understanding of the chemistry and composition of the stratospheres of the giant planets has evolved considerably in the past decade. Methane photolysis in the upper stratosphere initiates the production of more complex hydrocarbons on the giant planets, and many such hydrocarbons have been detected recently by ISO [59-62], Spitzer [63-64], Cassini [65], and ground-based observations [66-67]. These observations help us refine the details of hydrocarbon photochemistry and vertical diffusion in giant-planet stratospheres [5,60, 61,68] and help us track the effects of trace species on temperatures and climate. Methane photochemistry is now well understood qualitatively, but some of the quantitative details (especially for molecules like C_6H_6 and C_3H_4) remain to be worked out. Laboratory measurements and theoretical calculations help fill in uncertain parameters needed for photochemical models and observational abundance derivations [e.g., 69-79]. The recent detection of oxygen compounds that are unambiguously in the stratospheres of the giant planets indicates that external material from meteoritic dust, ring/satellite debris, and/or cometary impacts is continually entering giant-planet atmospheres [80-87, 65]. Interestingly, Neptune may have experienced a large cometary impact a few hundred years ago [85]. Observers have now mapped the latitudinal distribution of several stratospheric constituents [65,88-91], providing some much-needed constraints on stratospheric transport, but providing many puzzles as well [92,93]. The effects of auroral chemistry on stratospheric composition is another currently hot topic [e.g., 94].

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