PREDICTING THE ATMOSPHERIC COMPOSITION OF EXTRASOLAR GIANT PLANETS.

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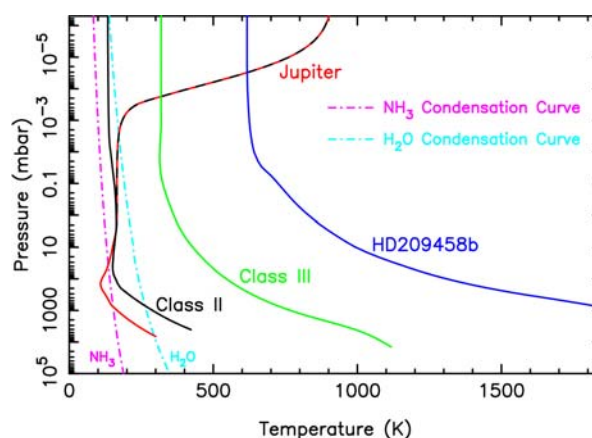
Introduction: To date, ~120 planet-sized objects have been discovered around other stars, mostly through the radial-velocity technique. This technique can provide information about a planet's minimum mass and its orbital period and distance; however, few other planetary data can be obtained at this point in time unless we are fortunate enough to find an extra-solar giant planet that transits its parent star (i.e., the orbit is edge-on as seen from Earth). In that situation, many physical properties of the planet and its parent star can be determined, including some compositional information (e.g., [1]-[6]). Our prospects of directly obtaining spectra from extrasolar planets may improve in the near future, through missions like NASA's Terrestrial Planet Finder.

Most of the extrasolar giant planets (EGPs) discovered so far have masses equal to or greater than Jupiter's mass, and roughly 16% have orbital radii less than 0.1 AU — extremely close to the parent star by our own Solar-System standards (note that Mercury is located at a mean distance of 0.39 AU and Jupiter at 5.2 AU from the Sun). Although all EGPs are expected to have hydrogen-dominated atmospheres similar to Jupiter, the orbital distance can strongly affect the planet's temperature, physical, chemical, and spectral properties, and the abundance of minor, detectable atmospheric constituents. Thermochemical equilibrium models can provide good zero-order predictions for the atmospheric composition of EGPs [e.g., 7]. However, both the composition and spectral properties will depend in large part on disequilibrium processes like photochemistry, chemical kinetics, atmospheric transport, and haze formation. We have developed a photochemical kinetics, radiative transfer, and 1-D vertical transport model to study the atmospheric composition of EGPs. The chemical reaction list contains H-, C-, O-, and N-bearing species and is designed to be valid for atmospheric temperatures ranging from 100-3000 K and pressures up to 50 bar. Here we examine the effect of stellar distance (e.g., incident ultraviolet flux, atmospheric temperature) on the chemical properties of EGPs. The model is applied to two generic Class II and III [see 8] intermediate-temperature EGPs located at 3.3 and 0.27 AU from a solar-like parent star, and the results are compared with a model for Jupiter at 5.2 AU.

Results and Discussion: The closer an EGP is to its central star, the warmer it becomes and fewer ele-

ments are tied up in condensed phases deep in the troposphere. First ammonia, then hydrogen sulfide, then water become available in the gas phase as the stellar distance decreases. Interaction between the various carbon, nitrogen, oxygen, and sulfur species can then occur, especially when the planet is being irradiated by ultraviolet light from its parent star. The UV radiation can break apart molecules, allowing chemical interactions to occur more readily.

The temperature-pressure profiles for the planets considered in this study are shown in Figure 1. Note that these planets were classified by *Sudarsky et al.* [8] based on their temperature profiles and the likely condensates in their atmospheres. Class I planets, represented here by Jupiter, are so cold that both ammonia and water will condense in the troposphere. Class II planets (from ≤ one to a few AU) are somewhat warmer such that ammonia no longer condenses, but water still does, and Class III planets (at a few tenths of an AU) are expected to be relatively cloud-free, with neither water nor ammonia condensing. Classes IV and V planets are not considered here, but they are so warm (often called "roaster planets" or "hot Jupiters") that silicate and metal-bearing clouds would be present at high-enough atmospheric levels to affect their spectral properties.
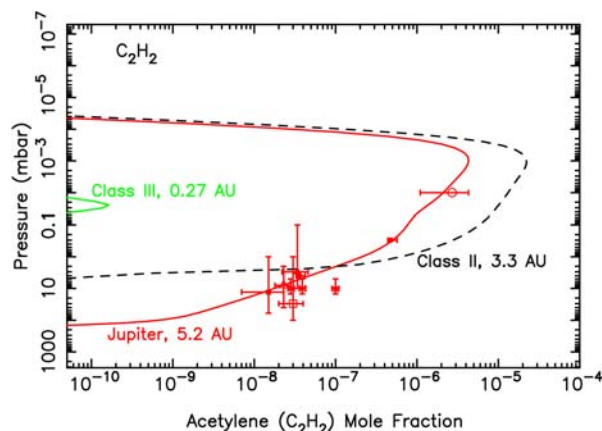

Fig. 1. Temperature profiles for Jupiter (red, 5.2 AU), the Class II planet (black, 3.3 AU), and the Class III planet (green, 0.27 AU), compared with the Class V planet HD 209458b (blue, 0.05 AU).

On Jupiter, ammonia condenses in the upper troposphere, but methane is volatile enough to diffuse past the tropopause cold trap and be transported to the up-

per stratosphere, where it interacts with ultraviolet radiation at wavelengths less than 145 nm. Methane photolysis initiates the production of complex hydrocarbons like C_2H_2, C_2H_4, C_2H_6, C_3H_4, C_4H_2, and C_6H_6. Such hydrocarbons (and CH_4) dominate the mid-infrared spectra of Jupiter and Saturn and help cool the stratosphere. Ammonia can also be photolyzed on Jupiter by longer-wavelength UV radiation that can penetrate to the troposphere; however, the physical separation between the ammonia and methane photolysis regions inhibits interaction between carbon and nitrogen species. Ammonia photochemistry leads to the production of species like N_2 and N_2H_4 rather than HCN and organo-nitrogen compounds. Water condenses so deep that tropospheric oxygen photochemistry is not important.

Class II planets have more interesting photochemistry. Increased photolysis rates due to the decreased stellar distance lead to an increased production of complex hydrocarbons (see Fig. 2). Ammonia is confined to the lower stratosphere and troposphere because of inefficient recycling, and the photochemistry of NH_3 is interesting and complex. Ammonia photolysis products can interact with hydrocarbons to produce HCN and other nitriles like CH_3CN, C_2H_3CN, and HC_3N; the formation of interesting complex "prebiotic" molecules is also likely. Water is still confined to the upper troposphere and does not play a large role in the photochemistry of Class II EGPs.

Fig. 2. The volume mixing ratio of acetylene from our photochemical model of Jupiter (red), the Class II planet (black), and the Class III planet (green). The individual data points are observational constraints for Jupiter. Note the huge sensitivity to stellar distance.

Class III planets are so close to their central stars that the photochemistry no longer resembles that of Jupiter. High-temperature reactions dominate, and atomic hydrogen is produced at a prodigious rate through photolysis of H_2O, CH_4, and NH_3 and subse-

quent catalytic destruction of H_2. Methane is depleted from the upper stratosphere by high temperature reactions (e.g., $H + CH_4 = CH_3 + H_2$) and by interactions with H_2O, NH_3, and their photolysis products (e.g., $CH + H_2O$, $CH_3 + O$, $CH_3 + OH$, $CH_3 + NH_2$). Ammonia is depleted from upper stratosphere and is not efficiently recycled; the production rate of HCN is large. Water vapor is present throughout atmosphere and is efficiently recycled, although there is a large production rate of CO and CO_2. Complex hydrocarbons become depleted in the middle and upper stratosphere (Fig. 2) due to high-temperature reactions and high H abundances; however, some hydrocarbons (e.g., C_2H_4, C_2H_6, C_6H_6) increase in troposphere due to high-temperature reactions and increased CH_3 production.

Conclusions: Stellar distance affects the physical and chemical properties of EGP atmospheres by controlling atmospheric temperatures, condensation levels, and photolysis rates. EGPs with orbital distances from ~0.8 to 3 AU for a solar-type star (also depends on stellar type) can have interesting coupled nitrogen-carbon photochemistry and may produce a wide variety of potentially observable complex molecules. As the planet resides closer and closer to the star, complex molecules are less stable, and simple molecules with strong bonds (e.g., CO, N_2, HCN, CO_2) are the big winners from a photochemical standpoint. Photochemistry can substantially perturb atmospheric composition away from thermochemical equilibrium. No candidate photochemical hazes have yet been identified in our models of "warm" giant planets.

These models will be useful for planning missions such as the Terrestrial Planet Finder and for investigating the composition of brown dwarfs. Further modeling is warranted to examine the effect of stellar type, transport effects, the photochemistry of extremely close-in objects [see 9], the chemistry of sulfur, alkalis, halides, and other common elements, and to more self-consistently calculate the temperatures and predicted spectra of EGPs, with photochemical products included in the calculations.

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