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Characterizing Cool Giant Exoplanet Clouds and Hazes with Direct Imaging

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Abstract

The WFIRST Space Telescope CoronaGraph Instrument (CGI) and the extremely large telescopes with specialized instruments, such as TMT/PSI or GMT/GMagAO-X, planned for the next decade will have the capability to detect and characterize giant planets in reflected light. Cool giant planets, particularly those in 1 to 3AU orbits make for excellent, relatively bright targets. Future large space telescope mission concepts, such as LUVOIR or HabEx, would have the capability to detect and study many more such planets. Because reflected light from a planet, particularly a gas or ice giant planet, depends upon the balance of absorption and scattering in the atmosphere, such observations are extremely sensitive to atmospheric aerosols. Here we briefly review this topic and highlight the new, open source, tool PICASO, for computing planetary reflection spectra.

1. Introduction

The atmospheres of cool gas giant planets are predominantly H_2-He with a few percent sprinkling of other notable gasses, notably CH_4, NH_3, H_2O, and – for warm planets – Na and K. These gases and their condensates sculpt the optical reflected-light spectra. Of particular interest to observers and theorists alike is the abundance of these gases relative to that of their primary stars. In the solar system, Jupiter is enhanced by a factor of about 4 and Saturn a factor of 10 in C for example. The specific fingerprint of gas abundances is understood to provide insight into the reservoir of material that impacted the growing planets during their formation (e.g., [2]). Early trends in transiting planets show some evidence that the metallicity enhancement may be inversely proportional to planet mass. Whether such trends continue for colder giants that potentially formed farther from their stars and did not migrate is of particular interest.

The major species detected in reflected light spectra of the gas giant planets will almost certainly be those predicted by chemical equilibrium, as their atmospheres are dense and well mixed (trace amounts of disequilibrium species, such as CO or PH_3, are unlikely to be detectable for the cool giants that will be characterized by direct imaging). Thus, optical to near-IR spectroscopy has the potential to measure true C, N, and O abundances, if the complicating effects of atmospheric aerosols can be properly accounted for. Figure 1 shows some of the diversity of reflected light spectra expected from various cool giant planets.

2. Clouds

Clouds and hazes in planetary atmospheres both inside and outside of the solar system critically shape reflected-light spectra. The influence of clouds on planetary spectra is notoriously difficult to predict. Furthermore, with their onion-skin-like atmospheric structure, giant exoplanets offer a continuous array of cloud types to scatter incident flux. The cloud layers present in any given planet will depend upon atmospheric mixing ratios and temperature, but certainly water and ammonia clouds will be prominent in many planets with relatively cool atmospheres.

Figure 1 highlights the impact of H_2O clouds on the reflected-light spectrum of a giant planet somewhat warmer than Jupiter. In fact, giant exoplanets in the habitable zones well outside the tidal locking distance of their host stars will provide some of our first opportunities to understand the formation of water clouds and their effect on global energy budgets in exoplanet atmospheres. The robustness with which we are able to constrain the properties of clouds (e.g., cloud top pressures, degree of partial cloudiness, single scattering albedos, and scattering asymmetry factors) will critically impact our ability understand clouds and extract the planetary thermal and chemical structure of both terrestrial and giant planets.

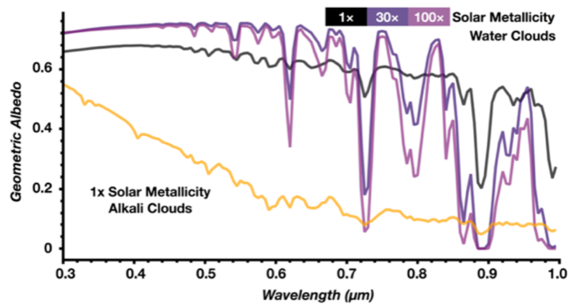

Figure 1: Collection of model reflected light spectra of cool giant planets. Top three spectra show albedo changes as the global water cloud deck responds to changes in atmospheric. The yellow curve reveals the remarkable change in reflectivity when water clouds are not present, as here in a slightly warmer planet at 1AU.

3. Photochemistry

Photochemical processes also play key roles in shaping the atmospheres and observed spectra of all solar system planets. In the stratospheres of solar system giant planets, CH_4 photochemistry generates hydrocarbons such as C_2H_6 and C_2H_4, and these can polymerize into more complex hydrocarbon species, some of which form aerosols. These hydrocarbons strongly absorb UV and blue light on Jupiter and Saturn. In addition, giant exoplanets somewhat warmer than Jupiter will likely host an array of photochemical S, N, and O species. Sulfur hazes in particular can radically alter albedo spectra, making planets bright in the red and very dark in the blue to UV [3].

Lab results point to the likely ubiquity of photochemical hazes under diverse conditions [4]. Any complete characterization of an exoplanet atmosphere thus must account for the presence of hazes. Studies of hazy giant planets in reflected light would provide a valuable proving ground for understanding photochemical processes in atmospheres that differ from those found in the solar system and would give insight into habitable exoplanet haze processes.

4. A New Tool for Computing Albedos

We have recently presented [1] the first open-source radiative transfer model for computing the reflected light of exoplanets at any phase geometry, called PICASO: Planetary Intensity Code for Atmospheric Scattering Observations. This code, written in Python, has heritage from a decades old, well-known Fortran model used for several studies of planetary objects within the Solar System and beyond [6]. We have adopted it to include several methodologies for computing both direct and diffuse scattering phase functions to enable study of a broad diversity aerosol properties, and have added several updates including the ability to compute Raman scattering spectral features.

5. Summary and Conclusions

Clouds and hazes have a dramatic impact on the reflected light spectra of extrasolar planets. Retrieval studies [5] have even shown that the presence or absence of clouds will be easier to recognize than the presence of specific gaseous absorbers. To evaluate the impact of varying atmospheric parameters, including clouds and photochemical hazes, we have developed an open source tool, PICASO, for computing albedo spectra. Using this tool we will discuss the impact of various types of atmospheric aerosols on the reflected light spectra and discuss opportunities for constraining clouds and hazes with the tools becoming available in the next decade.

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