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Microphysical Modelling of Exoplanet Aerosols

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Abstract

Aerosols are common in exoplanet atmospheres, where they strongly affect observations and likely also the atmospheric state. We present case studies of exoplanet aerosols using the Community Aerosol and Radiation Model for Atmospheres (CARMA), which takes into account microphysical processes that shape the size and spatial distributions of aerosols.

1. Introduction

Observations of exoplanet atmospheres have revealed the existence of aerosols across a wide expanse of parameter space (e.g. Sing et al. 2016). These aerosols greatly affect our ability to interpret the spectral signatures of important molecular species (Barstow et al. 2016). As such, understanding how and where these aerosols form is vital to understanding exoplanet atmospheres as a whole, as well as using observations of atmospheres to infer how planets form. In this invited talk, I will present our ongoing effort to model exoplanet aerosols by taking into account microphysical processes that control the spatial and size distributions of aerosols. I will describe how we use our microphysical model, CARMA, to simulate aerosols of various compositions, including mineral dust, salts, and photochemical haze particles in an effort to predict how exoplanet clouds vary longitudinally, investigate why some exoplanets' transmission spectra are flat, and how a single framework for aerosol evolution can explain the observed diversity in near-infrared exoplanet transmission spectra.

2. CARMA

We use the Community Aerosol and Radiation Model for Atmospheres (CARMA) for our exoplanet aerosol modeling. CARMA is a 1D time-stepping model that explicitly calculates the rates of microphysical processes and transport velocities, and has been applied to a variety of aerosol processes on Earth and in the atmospheres of other solar system bodies (e.g. Toon et al. 1979; Colaprete et al. 1999; Barth et al. 2006; Gao et al. 2014; Gao et al. 2017). We have now applied CARMA to exoplanets by including condensates that have been predicted to form in hot atmospheres, including KCl, ZnS, Na_2S, MnS, Cr, Mg_2SiO_4, Fe, TiO_2, and Al_2O_3. Importantly, CARMA discretizes the aerosol size distribution so that it can take on random shapes, rather than assuming an analytic distribution (e.g. lognormal). Below, we present several case studies of exoplanet aerosols that we have done using CARMA.

3. Result

1.1 Explaining flat spectra

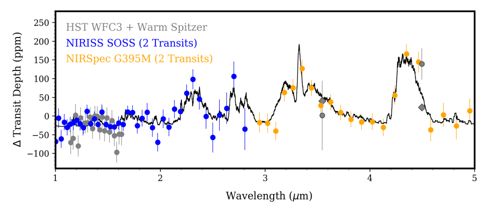

Figure 1: Synthetic observations of the transmission spectrum of GJ 1214 b by James Webb Space Telescope instruments NIRISS and NIRSpec derived using our best fit model to existing observations by the Hubble and Spitzer Space Telescopes (Gao & Benneke 2018).

Kreidberg et al. (2014) showed that the super-Earth GJ 1214 b has an extremely flat transmission spectrum that can only be explained by high altitude aerosols. In Gao & Benneke (2018) and Adams et al. (2019), we explored what kind of physical conditions are needed to loft aerosol particles to such heights. Gao & Benneke (2018) considered KCl and ZnS clouds, and found that, in order to reproduce the data, the atmospheric metallicity would need to be 1000 x Solar, and the eddy diffusivity would have to be 10^{10} cm^2 s^{-1}, ~2 orders of magnitude larger than predictions from general circulation models (Charnay et al. 2015). Adams et al. (2019) solved this issue by considering photochemical hazes that form at high altitude. By assuming fractal aggregate particles, sufficiently high aerosol opacity resulted at high altitude, producing a flat spectrum. Both Gao & Benneke (2018) and Adams et al. (2019) predicted that the transmission spectrum longward of 2 μm should contain molecular features (Figure 1), and thus observations of GJ 1214 b by the James Webb Space Telescope may tell us much more about the composition of this enigmatic super-Earth.

1.2 Longitudinal aerosol distributions

Hot Jupiters are expected to be tidally locked to their host stars, creating a large longitudinal temperature gradient. Powell et al. (2018) used CARMA to simulate exoplanet clouds at the east and west limbs and the subsolar and antisolar points of hot Jupiters, and found extensive spatial variations in cloud opacity. For example, at equilibrium temperatures greater than 1600 K the east limb becomes clear, while the west limb can remain cloudy to ~2100 K, thus necessitating the consideration of patchy clouds in interpretations of observations (Figure 2).

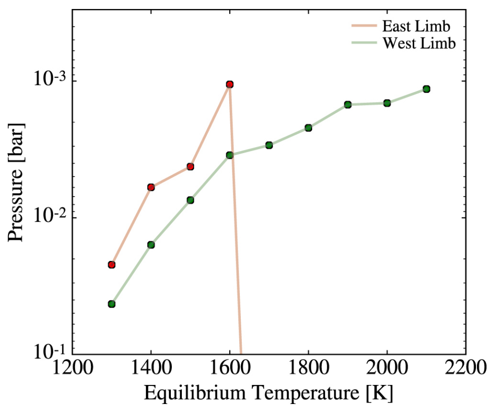

Figure 2: Opaque cloud level at 3 μm for the east and west limbs as a function of equilibrium temperature (Powell et al. 2018).

1.3 Aerosol evolution

Trends in the cloudiness of exoplanets are beginning to emerge from ever enlarging sets of observations. For example, Fu et al. (2017) derived the amplitude of the 1.4 μm water feature for 34 exoplanets with equilibrium temperatures from 600 to 2800 K and surface gravities from 4.5 to 50 m s^{-2}, and found possible nonlinear trends in exoplanet cloudiness with temperature. By considering the full set of exoplanet condensates and photochemical hazes, we have found that we can reproduce the observed trends by simply varying the atmospheric metallicity between solar and 10 x solar.

4. Summary and Conclusions

We have discussed several studies conducted using the aerosol microphysics model CARMA that focus on simulating the distribution and evolution of aerosols in exoplanet atmospheres. We have shown that, by including processes that control aerosol distributions, we can gain powerful insights into how aerosols contribute to transmission spectra, phase curves, and trends in observables across parameter space. As observations improve in quality, quantity, and wavelength coverage, more sophisticated aerosol models, such as CARMA, will be needed to fully interpret the data.

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