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Interpreting low spectral resolution data of transiting exoplanets

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Abstract

During primary transit transmission spectra of the exoplanet's limb are recorded as the planet passes in front of the star. During secondary eclipse, measurements yield the planetary emission spectra. Photometry and spectroscopy of transiting exoplanets indicate the presence of water, methane, carbon monoxide and potentially carbon dioxide in a number of extrasolar planets [1, 2, 3, 4, 5, 6]. Observations at different points in an exoplanet's orbit also reveal variations in the planet's temperature field with longitude, which manifest the planet's dynamical redistribution of heat [7]. Yet even for the brightest systems, molecular abundances are constrained only to within 3-5 orders of magnitude and temperatures as a function of pressure to roughly 300 K. A large part the uncertainties stem from the range of models that fit the data. Here we explore the degeneracies in the solution sets with the aim to better constrain and measure planetary characteristics.

1. Introduction

We focus on measurements of a "hot Jupiter" exoplanet, for which there is a little data, i.e. not so much data that one might get entangled in gnarled questions such as that of the star's variability, which requires considerable data to unravel. In particular, we examine primary transit and secondary eclipse data of XO-2b, a Jupiter-sized (0.996 R_J and 0.5 M_J) planet, with a 2.6 day period. This exoplanet orbits a K0 V star 0.0369±0.002 AU away, which forms a binary system with a companion star roughly 4600 AU away [8]. XO-2b is one of perhaps a dozen planets with Hubble Space Telescope (HST) primary transit spectrum, which ranges from 1.2-1.8 μm [9]. It is also one of the roughly two dozen exoplanets with photometric measurements from the space-based Spitzer Space telescope [10]. Currently XO-2b, one of the better observed transiting exoplanets, is not as well measured as the brighter system HD209458b, which we will also consider in this discussion.

A number of different techniques are used to extract compositional and thermal information from secondary eclipse near-IR data. All models start with basic assumptions regarding the number and identity of gases and the temperature parameters that characterize the thermal profile. Radiative transfer models generally assume LTE, and include the opacity of H_2O, CO, CH_4, CO_2 and pressure-induced H_2. In this work, instead of using the elegant Optimal Maximization inversion technique, or the faster Markov chain Monte Carlo (MCMC) methods, we use the crudest of all approaches. The temperature profile is parametrized using 6 parameters [2], and the composition assuming thermochemical equilibrium, or constant mixing ratios [2]. With 4 major molecules, considering the temperature profile, there are 10 parameters that are explored by calculating millions of spectra and comparing these to the data. The advantage of this seemingly uninspired approach is that all of the solution set is calculated, thereby elucidating the correlations in the parameters that define the solution set.

This investigation determines the degenerate solutions that match not only XO-2b's emission data, but also its transmission data. The aim is to break the degeneracies of each measurement, that recorded during primary transit and that of secondary eclipse, through the joint analysis of both data sets. Analyses of emission data indicates [5, 2] that the opacity of the atmosphere correlates with the temperature profile; the emission derives from the pressure levels where temperature matches the measured brightness temperature. The conflicting effects of the temperature, radius and gas abundances of the primary transit data are not as straightforward [11]. However, these effects can be estimated by analytical approximations, which assume that the atmosphere is homogeneous and isothermal in the region of the atmosphere that is probed during the primary transit. In this case, the transmission of the atmosphere through a cord a distance R away from the planet's center can be expressed as:

$$T(R) = \exp(-N(r)\ (2\pi RH)^{1/2}\ \kappa_e). \quad (1)$$

where $N(R)$ is the atmospheric density at a radius, r, R is the gas constant, H is the atmospheric scale height and κ_e is the atmospheric extinction. The predictions of the analytical derivations for the sensitivity of the derived gas abundances are compared to calculations from full models to better understand the measurements that are needed to infer abundances from low spectral resolution measurements of transiting exoplanets.

2. Summary and Conclusions

Our analysis indicates that for primary transit measurements the derived gas abundances are extremely sensitive to the assumed radius, and somewhat sensitive to the temperature profile. The resultant uncertainties can be estimated analytically, because only a small pressure region (roughly 4 scale heights) is probed at each wavelength. We find that the transmission spectrum is most affected by uncertainties in the radius. Assuming a jovian-sized exoplanet with T_{eff}=1000 K, a 1% error in the planet's radius causes a factor of 100 to 10,000 uncertainty in the derived abundances, depending on whether the absorption lines are in the weak or strong line limit [12]. Temperature degeneracies are smaller: for the same planet an uncertainty in the temperature by 300 K causes an uncertainty in the derive abundance of a factor of 4 [12].

This study indicates a great need to determine the radii of exoplanetary atmospheres corresponding to specific pressure levels. Such observations can be conducted with photometric measurements from modest sized telescopes. We find that primary transit and secondary eclipse data considered together can, with greater spectral coverage, lead to strong constraints on the characteristics of exoplanet atmospheres. Spectroscopy of exoplanets will be particularly productive when a single observation spans a large wavelength region with redundant molecular features as needed to better understand the data and errors. Once atmospheric observations are possible for a large number of systems we will begin to understand the effects of different stars and orbital configurations on planetary atmospheres, and thereby glean the physical processes underlying their structures.

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