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Observational constraints on the composition of exoplanets

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Abstract

Two forms of exoplanetary spectra can be measured. The primary eclipse provides a transmission spectra of the exoplanet's limb as the planet passes in front of the star. The secondary eclipse measures the emission of mainly the planet's dayside atmosphere from the planet plus star's emission minus the emission of star alone, when it eclipses the planet. In the past 3 years, infrared transmission and emission spectroscopy have revealed the presence of the primary carbon and oxygen species (CH_4, CO_2, CO, and H_2O). Yet, efforts to constrain the abundances of these molecules are hindered by degenerate effects of the temperature and composition in the emission spectra, and the composition and assumed radius in the transmission spectrum. These degeneracies lead to derived mixing ratios that span several orders of magnitude. This talk will discuss the correlations in the degenerate solutions that result from the radiative transfer analyses of both emission and transmission spectroscopy. We present an analysis of primary and secondary transit observations of HD209458b's optical to infrared spectra, and correlate the degenerate effects of the atmospheric parameters using a principal components analysis to better constrain the atmospheric composition of the exoplanet. The derived oxygen and carbon composition of the HD209458b's atmosphere are considered in conjunction with the primary star's composition in order to start to address questions regarding the evolution of the exoplanet.

1. Introduction

Currently over 500 extrasolar planets have been detected, a number which still grows exponentially with each year. Of these, over 100 planets transit their host stars thereby enabling measurements of the exoplanets' atmospheres. The two brightest transiting systems, HD189733b and HD209458b, have been measured with both transmission and emission spectra that range from UV to mid-IR wavelengths.

We will focus on the exoplanet HD209458b. Efforts to constrain the composition of this exoplanet are hindered by difficulties in separating degenerate effects of the temperature and composition in the emission spectra [1,2]. For example, the most extensive investigation of the composition of HD209458b's atmosphere from the emission spectrum led to methane mixing ratios that ranged 10^{-2} to 10^{-7} [1]. Similarly, there is a strong degeneracy in the exoplanet's size and composition in spectra of the primary eclipse. For example, investigations of transmission spectra of explanet XO-1b indicate that a 1% difference in the estimate of the planetary radius at the 1 bar pressure level results in a difference in the derived H_2O abundance of a factor of 10 [3].

An additional complication arises from the fact that most of the brightest transiting exoplanets are expected to be locked in a synchronous orbit about their primary star, such that one hemisphere is in perpetual daylight and another in perpetual night. Therefore the two transmission and emission spectra obtained from an exoplanet likely probe different atmospheric conditions, and a combined analysis of transmission and emission spectra must consider the increased number of parameters introduced by the heterogeneity.

2. RT Analysis of Emission Spectra

Here, we discuss an analysis of both the emission and transmission spectra of HD209458b. We start with the emission spectra measured during the secondary eclipse. The temperature profile is parameterized with 5 free parameters: the temperature and pressure of the coolest level, T_T and P_T, the temperature of the upper atmosphere, T_S which quantifies temperature inversions, and the temperature and pressure that establish the upper boundary layer of the lower isothermal layer, T_C and P_C [1].

We consider the main sources of opacity, CH_4, H_2O, CO, and CO_2, and, since a small pressure region is sampled, assume a constant abundance for each. (Over the pressure range sampled, this is an approximation only for CO_2 and CH_4, since H_2O and CO likely have constant abundances.) We have thereby added 4 more parameters to the model. Using correlated k-coefficients and parallel processors so that that the analysis can be completed in our lifetime, we calculate over a million models, and evaluate which combinations of temperature profiles and compositions fit the data.

A great range of water, methane and carbon dioxide abundances work. In addition, several correlations pop out, such as that between the methane and water abundances [1,2]. It is not yet clear entirely what are the strongest correlations in the gas abundances with the free parameters defining the temperature profiles, or the other gas abundances. Therefore we resort to a Principal Component Analysis to ascertain which correlations are most important.

3. PCA Analysis

Principal Components Analysis (PCA) is a technique for searching for correlations when many variables are present. For our purposes, we can search for correlations between the 9 free variables of the atmospheric models that fit the emission spectrum of a particular exoplanet. In practice, to determine the principal axes one calculates the eigenvalues and eigenvectors of the covariance matrix. The covariance matrix is an $n \times n$ matrix that enables one to treat the correlations between n measurements. The matrix is defined such that the (i, j) entry is the covariance between the i and j measurements, i.e. $C_{i,j} = cov(M_i, M_j)$, and the diagonal elements are the variance.

We can see how this method works by performing a PCA analysis of the pilot study of 8 free variables (eliminate CO from the 9 above) considering the 600 models that best fit the data. We find through the eigenvalues of the covariance matrix that the significant correlations are contained in the corresponding 3 eigenvectors.

We consider here, for brevity, only the first principal component. This first eigenvector indicates that the strongest correlations occur among the parameters [H_2O], [CH_4] and P_T (Fig. 1). This correlation becomes apparent in a plot of the 600 best fit models and the principal component axis, which indicates clearly the correlation (Fig. 1). Here we see essentially the family of solutions that we detected previously [2].

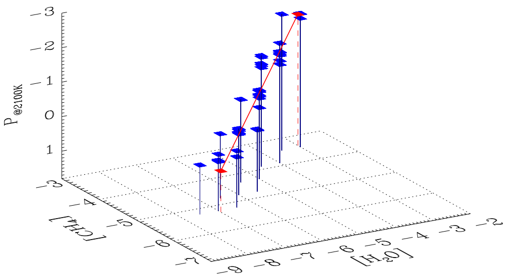

Figure 1: The mixing ratios, [H_2O] and [CH_4], for the 600 models that best fit the data (blue diamonds) correlate with the pressure level where the temperature equals 2100 K, which is established mainly by the pressure at the temperature minimum, P_T. The detected correlation is nicely indicated by the principal component of these models, shown by the red line.

4. Implications

We find, as will be discussed, that the transmission spectrum is most sensitive to the water abundance. In addition we find that the exoplanet's 0.4 μm spectrum can be used to establish an lower limit of the planet's 10 bar radius (independent of the planet's composition). These constraints, combined with the correlations established from the emission spectrum allow us to constrain the water abundance, as well as that of the other three constituents. The implied elemental composition, will be discussed in consideration with high spectral resolution measurements of the primary's C and O abundances.

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References

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