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Heavy metals in the transmission spectrum of the ultra-hot Jupiter KELT-9 b

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Abstract

In a recent study we analyzed two transit observations of KELT-9 b obtained with the HARPS-N spectrograph. Using an isothermal equilibrium chemistry model, we predict the transmission spectrum for elements with atomic numbers 3 to 78, in their neutral and singly-ionized states. Of these, we identify the elements that are expected to have spectral lines in the visible wavelength range and use those as cross-correlation templates. We report on the detection of Na, Mg, Ti^+, Cr^+, Sc^+, Fe, Fe^+ and Y^+ in the transmission spectrum [1], infer that the planet is surrounded by an extended envelope and use the line positions to rule out a strong day-to-night-side wind, as well as to derive accurate values for the mass and radius of both the star and the planet.

1. Introduction

The search for transiting planets around bright stars has recently revealed a new class of *ultra-hot Jupiters* that orbit early type stars. The archetype of this class is KELT-9 b [2]. Its $T_{eff} = 10,000$K A-star heats the day-side to a temperature of over 4,000 K. At such temperatures all chemical species are vaporized and all but small amounts of the most strongly bound molecules (CO and H_2O) are dissociated into their atomic components. Therefore the entire chemical inventory of the atmosphere atomic and in the gas phase, and is visible in the transmission spectrum, free from the hindering effects of absorption by clouds. Furthermore, chemical timescales are much shorter than mixing and photo-ionization timescales, meaning that the atmosphere at the day-side and terminator regions may be assumed to consist of an atomic gas in chemical equilibrium [3, 4, 5]. This greatly simplifies the interpretation of the transmission spectrum of KELT-9 b compared to other hot-Jupiters for which aerosols and non-equilibrium chemistry are important but unknown factors. Due to these properties KELT-9 b is currently serving as a benchmark object. Through the simplified chemistry compared to other hot Jupiters, it provides unique opportunity to test the fundamental performance of retrieval techniques that are routinely applied to observations of other gas giants. The transmission spectrum of KELT-9 b serves as a litmus test for the techniques used to interpret the spectra of cooler, more complex atmospheres.

2. Metals in the transmission spectrum of KELT-9 b

Because the entire chemical inventory of the planet is expected to be atomic and in the gas-phase, the transmission spectrum is dominated by line absorption by neutral and/or ionised metals. Many atomic species have rich absorption spectra, with hundreds or thousands of lines across the optical and the NUV. This has previously motivated searches for metals in the spectrum of KELT-9 b using high-resolution ground-based spectrographs [7, 8, 9]. In a new study we have analyzed transit observations obtained with the high-resolution HARPS-N spectrograph. We analyzed these observations using the cross-correlation technique [6], using templates that we constructed for all elements in the periodic table with atomic numbers between 3 and 78. This revealed the presence of strong absorption by Na, Mg, Ti^+, Cr^+, Sc^+, Fe, Fe^+ and Y^+ at high signal-to-noise $(5 - 40\sigma)$.

The discovery of a plethora atomic species in this atmosphere at high confidence demonstrates that a detailed characterization of the chemistry of ultra-hot Jupiters is indeed possible, and that the community can move beyond the notion of *metallicity*, and instead study the chemistry of individual trace metals. The line strengths of all atoms besides neutral Fe appear to be anomalously strong (by a factor of 5 to 10) compared to the viewpoint of an atmosphere in hydrostatic equilibrium. This indicates that the atmosphere is highly inflated. This inflation of the atmosphere therefore makes KELT-9 b even better suited for transmission spectroscopy, and at the same time provides the community with the opportunity of studying atmospheric inflation in great detail.

3 Dynamics

These observations are sensitive to dynamics in the system due to the high signal to noise level at which the absorbing metals are observed, combined with the high spectral resolution of the spectrograph, which resolves Doppler velocities on the order of 1 km/s. We find that deteted absorption lines are symmetric around their mean radial velocity, which do not seem to be blue-shifted from the rest-frame of the planet. This indicates an absence of a strong day-to-night side wind. In addition, the spectrograph resolves the radial projection of the orbital velocity of the planet as it passes through transit. This allows us to measure the orbital velocity directly. Combined with the known orbital period and the parameters of the transit light curve as measured by [2], this allows us to put strong constraints on the mass and radius of both the star and the planet.

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