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The Significance of the Sodium Detection in the Extrasolar Planet HD 209458 b Atmosphere

S. Seager

Institute for Advanced Study, School of Natural Sciences, 1 Einstein Drive, Princeton, NJ 08540

The Carnegie Institution of Washington, Dept. of Terrestrial Magnetism, 5241 Broad Branch Rd. NW, Washington, DC 20015

Abstract. The Hubble Space Telescope (HST) detection of an extrasolar planet atmosphere in 2001 was a landmark step forward for the characterization of extrasolar planets. HST detected the trace element sodium, via the neutral atomic resonance doublet at 593 nm, in the transiting extrasolar giant planet HD 209458 b. In this paper I discuss the significance of this first ever extrasolar planet atmosphere detection. I explain how the sodium measurement can be used as a constraint on HD 209458 b atmosphere models and review recent interpretations of the lower-than-expected sodium line strength.

1. Introduction

The first—and only to date—atmosphere detection of an extrasolar planet was made by Charbonneau et al. (2002) with the Hubble Space Telescope (HST). Charbonneau et al. (2002) observed the parent star HD 209458 A, during and outside of the planet transit. During a transit, some of the stellar intensity passes through the optically thin parts of the planet atmosphere. Thus the star's spectrum taken during transit is expected to contain some weak signature of the planet atmosphere. The planet atmosphere signature measured in this way is called the "transmission spectrum".

The strength of the planetary transmission spectrum can be estimated as the ratio of the planet atmosphere annulus area to the star area. We can very roughly estimate the maximum annulus area by assuming the atmosphere is 10 "pressure scale heights" thick. The atmospheric pressure scale height, H, is the characteristic vertical dimension in pressure: the e-folding distance for pressure,

$$H = \frac{P}{g\rho} = \frac{kT}{mg}, \tag{1}$$

where P is pressure, g is surface gravity, ρ is density, and m is atomic or molecular mass. With appropriate numbers for HD 209458 b ($T = 1000$ K, $g = 8.6$ m s^{-2}, m the mass of H_2), $H \sim 500$ km[1]. Ten times the pressure scale height is

[1] The scale height is constant only for an isothermal atmosphere and is otherwise depth dependent; i.e. it changes throughout the atmosphere. For our estimate it is sufficient to use an average number.

5000 km, which is 5% of the planetary radius. Note that the large scale height works to great advantage; the much cooler planet Jupiter with a higher surface gravity has a scale height of 24 km; ten times this is only 0.3% percent of Jupiter's radius.

The above estimate for atmosphere size can be used to estimate the maximum strength of the planet atmosphere transmission spectrum in the combined star + planet spectrum. This maximum estimate uses the assumption that at some wavelengths the gas is strongly absorbing (i.e., opaque) out to 10 pressure scale heights. Comparing the area of the atmosphere annulus to the stellar disk, ignoring stellar limb darkening, we get 1.5×10^{-3}.

Because the planet transmission spectrum is so weak, the planet transmission spectrum must be searched for in the residuals of the in-transit minus out-of-transit stellar observations. Furthermore, the weakness of the planet signature requires that observers are unable to take a broad spectrum to search for atomic and molecular absorption features, but instead must concentrate observations on a pre-chosen narrow wavelength region in order to get a high enough signal-to-noise. Charbonneau et al. (2002) describe a very careful analysis resulting in a measurement of the sodium (Na) line strength of $2.3 \pm 0.57\times\ 10^{-4}$. Even so, the Na detection is a 4-σ result and follow-up confirming measurements of sodium other absorption features (such as the resonance doublet of potassium (K) (767.0 nm), and near-IR H_2O, CO, and possibly CH_4) would be reassuring. Na—expected to be the strongest absorber—found to be less than the maximum estimate implies that the other species may have much smaller signatures than expected.

The planet atmospheric transmission spectrum is wavelength-dependent; at wavelengths where no absorbers are present the stellar intensity will pass through the atmosphere unimpeded, whereas at (possibly) neighboring wavelengths a strong absorber will allow no stellar intensity to be transmitted. This wavelength dependency can be thought of a planet radius being different sizes at different wavelengths. Comparing the continuum to an absorption line was used to make the Na line measurement.

2. The Significance of the Sodium Detection

The first ever atmosphere detection is a landmark in extrasolar resesarch because atmosphere studies open a whole new window to extrasolar planet characterization. Three main reasons why the sodium detection in the atmosphere of HD 209458 b is so important are described in the following subsections.

2.1. CEGPs Are What we Expect to First Order

First and foremost the detection of neutral Na confirms the very basic postulate that CEGPs have atmospheres expected for their equilibrium effective temperatures (T_{eq}). This is because HD 209458 b is a representative of the class of the close-in extrasolar giant planets (CEGPs) with semi-major axes < 0.05 AU. Physically, T_{eq} is is the effective temperature attained by an isothermal planet after it has reached complete equilibrium with its star.

$$T_{eq} = T_* \, (R_*/2a)^{1/2} \, [f(1 - A_B)]^{1/4}, \tag{2}$$

where T_* is the stellar temperature, R_* is the stellar radius, a is the semi-major axis, A_B is the Bond albedo, and f is a parameter to describe the heat redistribution from the day side where $f = 1$ if the heat is evenly distributed or $f = 2$ if only the day side reradiates the energy. With the unknown Bond albedo the CEGPs are expected to range in temperature from approximately 1000 to 1500 K; Na is expected to exist in neutral gaseous form in atmospheres for any T_{eq} in this range. In other words, for HD 209458 b, for a given distance from the parent star, star temperature, and solar composition the HD 209458 b atmosphere is to first order what is expected.

Even though at 2 x 10^{-6} solar abundance Na is essentially a trace element, the neutral Na spectral signature is extremely strong at optical wavelengths due to a very strong resonance line. In addition there are expected to be no other strong optical absorption lines; most atoms are locked into molecules which tend to have transitions at either UV wavelengths (electronic transitions) or at IR wavelengths (rotational-vibrational transitions). In fact since cool T dwarfs with similar effective temperatures to HD 209458 b have extremely deep and broad Na and K resonance lines it is not a surprise that neutral Na was measurable in the HD 209458 b atmosphere. See Figure 2 in Liebert et al. (2000) for the first observational confirmation of Na and K as the major optical absorbers in T dwarfs, from a spectrum of the T dwarf SDSS1624.

2.2. The Sodium Line was Predicted in Advance

The presence of neutral Na in the atmosphere of HD 209458 b was first predicted for transmission spectra by Seager & Sasselov (2000). Before the atmosphere detection the Na line doublet was also studied by Brown (2001) and Hubbard et al. (2001). The HST atmosphere detection of the transiting planet is reassuring because it involved a specialized observation that required advance knowledge of what atmospheric feature to look for, as described in Sec. 1. The success of the Na detection shows that applications of atmospheric physics to planets in new environments can be successful and that model results as guidelines to experimental design are reliable.

2.3. The Sodium Line Strength is Weaker than Expected

The measured value of the Na absorption line feature was lower than predicted. This is not surprising because the models did not include accurate treatment of secondary effects and inputs, almost all of which should reduce the strength of the Na line. To illuminate the significance of the low value of detected Na I used simple inputs to my atmosphere model and computed the change in transit depth in adjacent bands as was done with the real data in Charbonneau et al. (2002; see Figure 1 in this reference). The simple inputs include: solar composition, cloud-free, and that the heat from the incident stellar intensity is instantaneously redistributed around the planet. The "secondary effects" are all omitted: no photoionization, no photochemistry, no atmospheric circulation. For this reason I emphasize that the model is just one out of a large range of parameter space, but that it is sufficient for the illustrative purposes here.

The computed transit depth in the Na line from the simple model is $\sim 9 \times 10^{-4}$, 12 sigma away from the observational measurement. This simple model is therefore completely ruled out by the data. In this simple, homogeneous model the abundance of Na would have to be approximately 1000 times less than solar to match the observed line strength. In other words, the low measured value of the Na line is significant.

3. Using the Sodium Observation as a Constraint on Model Atmospheres

3.1. Transmission Spectra Models

The transmission spectrum from the transiting extrasolar planet HD 209458 b is straightforward to compute. Stellar light rays travel along the line of sight through the planet atmosphere towards the observer. These rays from the star suffer exponential attenuation due to wavelength-dependent absorption from the planetary atmosphere[2],

$$I_\lambda = I_{\lambda,0} \exp(-\tau_\lambda), \tag{3}$$

where I_λ is intensity and $I_{\lambda,0}$ is initial intensity originating from the star. τ_λ is the optical depth

$$\tau_\lambda = \int_0^L n(l)\sigma_\lambda dl, \tag{4}$$

where $n(l)$ is the number density of a given species, σ_λ is the absorption cross section, and L is the path length through the planetary atmosphere. τ_λ can include many different absorption species and $n(l)$ and σ_λ depend on T and P. For a resonance line transition where n_1 is the number density of atoms with electrons in the ground state and subscript 2 refers to the $n = 2$ state,

$$n_1\sigma_\lambda = n_1 \frac{h\nu_0}{4\pi} B_{12}\phi(\nu), \tag{5}$$

where B_{12} is an Einstein probability and $\phi(\nu)$ is the line profile.

While the transmission spectra, via exponential attenuation shown in equation (3), is straightforward to calculate, it relies on the underlying radial atmosphere structure via T, and n_1 (which is related to P and to the radiation field J); see Figure 1. This underlying radial atmosphere structure is difficult to calculate. The radiative transfer methods used to self consistently compute the atmospheric structure in proximity to the central star and results can be found in a variety of sources (e.g., Seager 1999; Barman et al. 2002; Burrows & Sudarsky 2003; Sudarsky et al. 2003a, 2003b). The atmospheric temperature-pressure structure is required to determine: the species abundance (from chemical equilibrium) that factors into the number density for the opacity in equation (4); and the temperature required for absorption coefficients, e.g. equation (5). There are many uncertainties in these atmosphere models. Most notably, none of them consider atmospheric circulation which is crucial for the redistribution of stellar irradiation (Showman & Guillot 2002; Showman & Guillot 2003; Cho et al. 2003) that determines the atmospheric temperature-pressure structure. In addition photochemistry is omitted as is non-equilibrium chemistry. Steps are being made to advance the models and this is an ongoing process.

[2]Refraction in the planet's atmosphere is negligible (Hui & Seager 2002).

Different parts of a transmission spectrum absorption line are formed at different parts in the atmosphere. The transmission spectral line is created by removing photons from the stellar beam. This absorption process can be thought of as additive over many layers of the atmosphere (see Figure 1). Deep in the atmosphere, the number density of absorbing atoms is high and at the line center all of the stellar photons will be absorbed, i.e., the part of the line formed deep in the atmosphere is saturated. In addition, deep in the atmosphere pressure broadening will be strong, causing absorption away from the line center—the line wings. High in the atmosphere there is little pressure broadening and hence little contribution to the line wings. Because the number density of absorbers is much lower compared to the deep atmosphere, the line core is not saturated and actually is formed in the upper atmosphere. Although the Charbonneau et al. (2002) measurement does not resolve the spectral line, some information can be garnered about the gross line shape because the measurement is deeper in the narrow bands than the medium bands, and is absent from the wide bands,

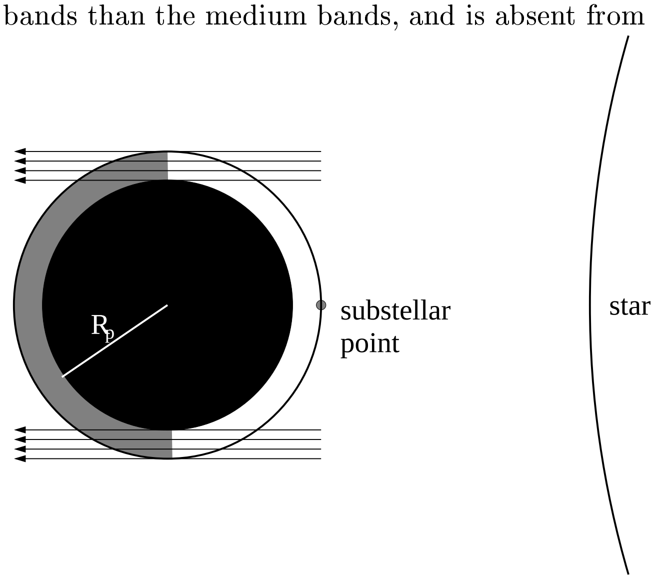

Figure 1. A schematic cross section of HD 209458 b to illustrate transmission spectrum modeling. Light rays (indicated by the lines with arrows) travel from the star through the planetary atmosphere. The total transmission spectrum is additive over the different rays. Because the rays sample different radial atmosphere depths, the underlying temperature-pressure structure is crucial to the transmission spectrum calculation. This simple day/night picture for HD 209458 b, however, is in error (Showman & Guillot 2002, 2003; Cho et al. 2003). Note that for the transmission spectrum calculation R_p—the measured planetary radius at optically thick wavelengths—must be chosen.

3.2. Possible Interpretations of the Weak Sodium Line

The Na line strength measured by Charbonneau et al. (2002) provides the first constraint on extrasolar giant planet atmosphere models. Notably the measured Na abundance is much lower than predicted. This weaker than expected Na line strength can be matched by only a few extreme cases in the parameter space modeled by Charbonneau et al. (2002). In their discovery paper, Charbonneau et al. (2002) outline four possible explanations for the weaker than expected Na line: a high cloud; photoionization; low Na abundance; or chemical equilibrum depletion of atomic Na into molecules and solids.

Many causes have been proposed since the discovery paper, with calculations to back them up, to explain the lower than expected strength of the Na line. The author finds it interesting that each group finds the reason to be what their code can calculate. The proposed explanations are described in the rest of this subsection.

Non-LTE effects could make the Na line weaker and a different shape compared to the simple model (Sec. 2.3). LTE, an abbreviation for "local thermodynamic equilibrium", is a simplification used in most extrasolar planet atmosphere models (and many stellar atmosphere models). The LTE assumption is that the state of the gas can be described by only two variables, temperature and pressure. State of the gas refers to the chemical equilibrium partitioning of molecules, the ionization states, and, most relevant for this case, the atomic level populations (used in equation (5)). In order to compute the transmission spectrum of the Na line, the ground state level population needs to be known (see equation (4)). LTE is valid at high densities and where the radiation field is a black body. In the upper layers of HD 209458 b, where part of the transmission spectrum forms, neither of these is valid and non-LTE is expected to prevail. The atomic levels must be computed under non-LTE in order to compute the line strength. Because the upper atmosphere is most senstive to non-LTE conditions, the non-LTE calculation mostly affects the line core, even producing emission in the line core with absorption in line wings. See Barman et al. (2002, 2003) for a more detailed description of the non-LTE effect.

A high cloud was first suggested in Seager & Sasselov (2000). We assumed that the cloud would be optically thick, and the cloud top would correspond to R_p in Figure 1. In this case the only part of the planet atmosphere that is probed by the transmitting stellar rays is the part of the atmosphere above the cloud tops. If the cloud is high in the atmosphere, then the stellar rays probe a small part of the atmosphere that is not very dense, with low pressure broadening. The resulting Na transmission spectrum line is expected to be fairly weak with no broad line wings. This is in contrast to the low or no cloud case where R_p is low in the atmosphere so that the stellar rays probe a large fraction of the atmosphere where the high number densities cause high pressure broadening. The resulting Na line is expected to be strong and wide from pressure broadening.

Photoionization is an obvious suggestion since due to the proximity of the planet to the parent star the planet is receiving huge amounts of stellar UV photons compared to solar system planets where photoionization is known to play a role. Detailed photoionization models have yet to be produced; in addition to Na they would involve many atoms and molecules which could serve as sinks for the UV radiation and sources of free electrons for Na^+ to recombine. Using a simple photoionization model Fortney et al. (2003) show that the weak Na line can be reproduced with photoionization together with a high cloud.

Atmospheric circulation models (Guillot & Showman 2002; Cho et al. 2003) are needed to describe the transfer of stellar radiation throughout the planet atmosphere. HD 209458 b is expected to be tidally locked (Guillot et al. 1996) to its parent star, thus one side is permanently heated while the other side is in permanent darkness. Strong winds are expected to redistribute the stellar radiation, based on a comparison of the advective and radiative time scales. Thus atmospheric circulation will determine the atmospheric structure (see Figure 1) and hence the transmission spectrum. Guillot & Showman (2002, 2003) suggest that winds could transport atomic Na from the planetary day side to the night side. They propose that temperatures on the night side could be colder, allowing Na to condense into solid NaCl where it could sink out of the atmosphere and not be available as Na for transmission spectra. In this scenario, Na is depeleted and a weak line results.

Post-accretionary extraplanetary origin of sodium has been suggested by Atreya et al. (2003). Atreya et al. (2003) propose that primordial Na is not present in HD 209458 b's atmosphere due to differentiation to the planetary interior and subsequent depletion of atomic Na into molecular species. They propose that the small amount of Na present in HD 209458 b's atmosphere comes from later influx of material from meteorite or comet impacts, planetary rings, or a volcanically active satellite.

Low sodium abundance. It could be difficult to attribute the weakness of the Na line to a low Na abundance until all of the above effects have been ruled out. As suggested in Charbonneau et al. (2002), however, if observations of H_2O and CO show "normal" abundances compared to Na, then we may be able to attribute the weak Na line to low primordial abundance.

Can anything be ruled out from the Na measurement? There is no detailed information about line shape from the Na measurement. However, based on the fact that the transit in the Na line was weaker in the medium band than the narrow band, and not detected in the wide band, we can say that a very broad absorption line is not present. Therefore we have an indication that either the deep atmosphere is not being probed or the Na atomic number density is very low. Furthermore, we know that photoionization alone is unlikely to be the only explanation of the weak Na signal. Photoionization affects only the upper atmosphere, and hence mostly the line core. In this case the line should still be broad. Emission line models (see Barman et al. (2002)) under extreme assumptions in the non-LTE scenario are also ruled out because a net increase—as opposed to a net decrease—in Na line flux during transit would have been detected.

4. Other Observational Diagnostics

The Na measurement is a very useful constraint on HD 209458 b's atmosphere. Yet it is not enough to get anywhere near a clear picture of the atmosphere. Many observations are ongoing to try to detect other atmospheric constituents. We expect the H_2O near-IR absorption bands to be prominent spectral features. CO or CH_4 or both should also be present, the relative abundance is a good temperature diagnostic (Seager, Whitney, and Sasselov 2000). HD 209458 b's albedo and orbital light curve will be measured with the upcoming space satellite

MOST (Micro Oscillations of STars)[3]. HD 209458 b's day and night side temperatures will be measured with SIRTF. Following is a table of key features that are obtainable within the next two years. The combination of all of these observational diagnostics will provide powerful constraints on theoretical atmosphere models.

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Bulk Property	Observational Diagnostic	Method
Temperature (T)	CH_4 vs. CO	ground
T of day and night side	IR photometry	ground or SIRTF
Albedo	Secondary eclipse photometry	MOST
General properties of atmospheric scattering particles	Photometry during the planet's orbit	MOST
Other spectral lines	Transit transmission spectra	ground, HST

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Sara Seager