

Observation and feature measurements of cloud and haze in exoplanet atmosphere based on transmission spectra

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Abstract. Clouds and hazes are important components of exoplanet atmospheres. This paper generalizes features and applications of exoplanet clouds and hazes in transmission spectra. A transmission spectrum presents a planet atmosphere's wavelength-dependent absorption ability of host star's radiation during transit. Effective transit radius model is often adopted to explain the wavelength-dependent absorption. In spectrum processing, the effect of stellar limb darkening and star spots should be taken into consideration. Clouds and hazes change features of planet transmission spectrums considerably, e.g., clouds reduce or eliminate absorption features on all bands observed. Since hazes (with small sizes) produce Rayleigh scattering, their reduction in absorption depth is greater in optical band than in infrared band. As transmission spectrum provides limited data about exoplanet atmospheres, emission and reflection spectrum during secondary transit should receive more observation. JWST will perform well in all forms of atmospheric spectrum observation. Advanced knowledge about clouds and hazes will benefit the confine of exoplanet atmospheres' chemical composition, biosignatures, meteorology as well as planet evolution model. These results shed light on guiding further exploration of exoplanets and life possibilities on them.

Keywords: exoplanet; planet atmosphere; cloud; haze.

1. Introduction

In 2002, Observers made first discovery of exoplanet atmosphere on the planet HD 209458 b. The detection was made by planet's transmission spectrum [1]. After the first detection, numerous studies about atmosphere of HD 209458 b have been done. The planet possesses a large value of $R_{planet} / R_{star} = 0.12099 \pm 0.00029$ [2], making it favorable to transit observation. Consequently, its transmission spectrum of high precision has been gained by the HST. Researchers analyzed its inconformity in Na D line depth between predicted value and observed value. They proposed several reasons for this inconformity, one of them being a high cloud deck that reflect rather light absorb light at certain wavelengths. It also proposes that stellar ultraviolet flux might cause the formation of photochemical hazes, which also affect the spectral feature of planet's atmosphere [3].

In HST observation of gas giant HD 189733b, inconformity between synthetic spectrum and observed spectrum was also detected. Scholars found that spectrum lack features and that effective transit radius (will be explained in Part 2) is about 2000 km higher than in cloudless model within wavelength range of 600nm-1000nm. Thus, they concluded that haze exists in the planet's atmosphere [4].

Apart from gas giants, super earths are also given atmospheric observations. For instance, GJ 1214b was observed by HST to have flat, featureless atmospheric spectrum, indicating an opaque atmosphere. Based on assumption that the atmosphere had high mean molecular mass, researchers estimated that the opacity is brought by cloud [5]. To sum up, clouds and hazes are important factors that substantially change the observational feature of exoplanets atmospheric spectrums. To constrain properties of exoplanet atmospheres, clouds and hazes must be studied thoroughly.

Clouds and hazes in exoplanet atmospheres have been widely studied, but there isn't a paper that summarizes their observation, which is the topic of this study. In this paper, methods in gaining transmission spectrum of exoplanets, features of cloud and haze in transmission spectrum and their applications will be discussed. In Sec. 2, methods in detecting exoplanet transmission spectrum and confounding factors in observation will be presented. In Sec. 3, features of cloud and haze in

exoplanet transmission spectrum and their applications will be explained. In Sec. 4, limits of current observation method and outlooks will be discussed. Eventually, conclusion of the results will be made in Sec. 5.

2. Methodology

2.1. Transmission spectrum

Spectrometric observation of exoplanet atmosphere can be divided into two main categories: direct imaging and eclipse observation. Application of direct imaging method requires wide angular separation between star and planet. Beyond that, planet itself has to be bright enough to reach qualified Signal to Noise Ratio (SNR) [6].

Eclipse observation of atmospheric spectrum also fall into two categories: transmission spectrum during the first eclipse (transit, when planet passes in front of the star) and emission & reflection spectrum observation during the secondary eclipse (when planet passes behind the star). The latter observation form also requires the planet to emit or reflect adequate radiation to reach qualified SNR level [7].

In transmission spectrum, the amount of stellar radiation on certain wavelength that is absorbed by planet atmosphere can be observed. It is required that the ratio R_p / R_s that is adequately large and adequate surface brightness of the star. These two requirements ensure enough value of radiation absorption pass through planet’s atmosphere and are collected by telescope.

In planet atmosphere, different chemical components possess different absorption and reflection properties, causing different relative transit depth $(1 - E_{transit} / E_0)$ at different wavelengths (E is the light flux). To explain the wavelength-dependent inconformity, astronomers use a model of effective transit radius. The radius is wavelength-dependent. At a certain wavelength, planetary body within effective transit radius is opaque to radiation at the wavelength.

Fig. 1 shows a planet’s effective transit radius at two assumed wavelengths, λ_1 and λ_2 . The two corresponding radiuses are labeled R_{e1} and R_{e2} respectively. It is supposed that $R_{e1} < R_{e2}$. Thus, the wavelength-dependent relative transit depth $\Delta h(\lambda) = (\frac{R_e(\lambda)}{R_{star}})^2$ for λ_2 is larger than that of λ_1 . As illustrated in Fig. 2, with larger relative transit depth, light curve of λ_2 radiation is deeper than light curve of λ_1 radiation during transit.

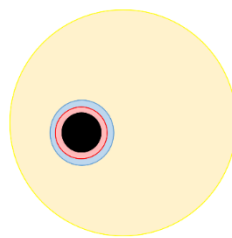


Fig. 1 A schematic diagram of effective transit radius model (proportion is not accurate). Black sphere represent intrinsic planet radius; red sphere represent effective transit radius at λ_1 ; blue sphere represent effective transit radius at λ_2 .

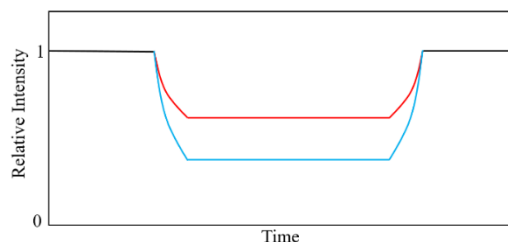


Fig. 2 A schematic diagram of wavelength-dependent transit light curve (proportion is not accurate)

Black line represents light curve of all-wavelength radiation when there's no planetary transit. Red line represents light curve of λ_1 radiation during transit; blue line represents light curve of λ_2 radiation during transit

In eliciting planet's transmission spectrum, a "subtraction" method is used. As shown in Fig. 3, stellar spectrum within the transit is subtracted by stellar spectrum beyond the transit. A third spectrum is elicited by the subtraction, representing planet's radiation shielding (reduction of stellar radiation). After processing, planet's transmission spectrum is gained. It can be seen that a deeper absorption is presented at λ_2 , where the planet possesses a larger effective transit radius,.

It should also be mentioned that effective transit radius model is only an approximation, as atmosphere is not always completely transparent or opaque to certain wavelength light. Even within the effective transit radius, a proportion of a wavelength's light flux may pass through the planet's atmosphere.

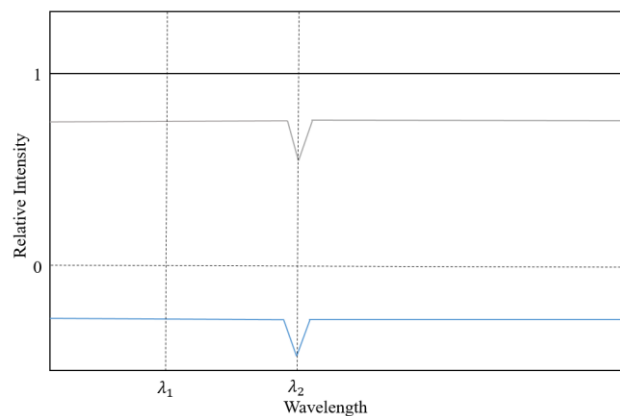


Fig. 3. A hypothetical stellar spectrum. Black line represents stellar spectrum beyond the transit; gray line represents stellar spectrum within the transit; blue line represents planet's radiation shielding (reduction of stellar radiation).

2.2. Confounding factors

Stellar radiation experiences Rayleigh scattering when passing through the stellar atmosphere, where $I_{scattering}(\lambda) \propto \frac{I_{incident}(\lambda)}{\lambda^4}$. As a result, at the limb of the stellar apparent surface, where optical depth is larger (stellar atmosphere has a larger thickness on line of sight), the long-wavelength band is brighter than the long-wavelength band. If one planet transits near the limb of the stellar apparent surface, its atmosphere will absorb a larger proportion of long-wavelength radiation [8]. This phenomenon will create a false appearance that the planet's atmosphere has a stronger absorption ability on the red end of the spectrum. This bias must be eliminated by models of stellar limb darkening.

Starspots have lower temperatures than their adjacent areas. As a result, they emit redder radiation. They can create bias in spectrum similar to what appeared in the limb darkening effect. When a planet transits across star spots, a larger proportion of red end light will be absorbed. Respectively, if a planet does not transit across star spots, more blue end light will be absorbed. Additionally, solar observation detected H₂O absorption in sunspots [9]. This characteristic may also exist on spots of other stars. When a planet transit across starspots, reduced water absorption feature will present in its transmission spectrum. Respectively, if a planet doesn't transit through star spots, increased water absorption feature will appear in its transmission spectrum. The coverage ratio of star spots is related to a star's stellar activity. When a star possesses a large ratio of star spot coverage, the effect of star spots should be taken into consideration when processing a planet's transmission spectrum.

3. Results & Discussion

3.1. Clouds

Similar to clouds in earth atmosphere, clouds in exoplanet atmospheres are composed of solid and liquid condensates. Nevertheless, their chemical composition is diverse (compared to earth clouds dominated by H₂O), which is mainly decided by planetary composition and atmosphere temperature. Generally, H₂O[l], NH₃[l] and FeS[s] exist in relatively cold, Earth or mini Neptune sized planets, while silicates (e.g., Mg₂SiO₄[s], MgSiO₃[s], SiO₂[s], Fe₂SiO₄[s]), metal oxides (e.g., TiO₂[s], Al₂O₃[s], MgO[s], FeO[s]) and other particles (e.g., Fe[s], CaTiO₃[s], FeS[s]) exist in hydrogen-poor terrestrial planets and hot, giant gas planets. These cloud particles usually condensate on condensation nuclei. It should also be mentioned that clouds don't exist in excessively hot planets, as high thermal instability breaks molecules apart [10].

Cloud condensates are larger than typical particles that produce Rayleigh scattering. As a result, clouds can be seen as grey opacity sources, which possess consistent opacity at all wavelengths [11]. In transmission spectrums, clouds reduce the depth of absorption lines or even eliminate them. In the latter condition, transmission spectrums are featureless. The degree of clouds' impact on transmission spectrums mainly depend on cloud coverage fraction of planet's surface and the cloud top height. The larger these two quantities are, the larger sheltering ratio do clouds have, the less intrinsic atmosphere spectrometric features are presented. Fig. 4 depicts influence of clouds on a hypothetical exoplanet transmission spectrum.

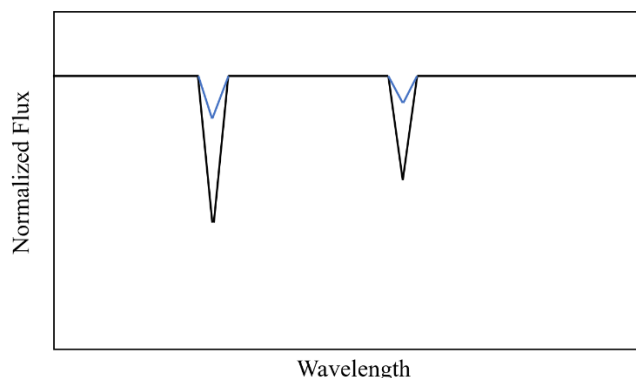


Fig. 4. Influence of clouds on a hypothetical exoplanet transmission spectrum. Black line represents transmission spectrum without clouds; blue line represents transmission spectrum with clouds

3.2. Hazes

Hazes in exoplanet atmospheres are composed of small (sub- μm size) particles [11]. It is suggested that haze particles can be caused by photochemical reaction, in which solar radiation reacts with volatile atmospheric materials. On account of the small sizes (close to visible light wavelength) of haze particles, hazes produce significant Rayleigh scattering. Scattering is high on optical band, but reduces on infrared band. Therefore, atmospheres covered by hazes (instead of clouds) are somehow opaque on optical band, presenting reduced absorption features. Atmospheres become much more transparent on infrared band, possessing richer absorption features. This feature is not only shown in exoplanets with hazes, but also in solar system objects with atmosphere, such as Venus, Titan and Triton [6].

3.3. Applications

Observers commonly find inconformity in gas abundance between observed data and theoretical models. The existence of clouds and hazes in atmospheres often accounts for this inconformity. Their opacity reduces the depth of absorption lines. As a result, the abundances of those gases that produce absorption features seem lower than their intrinsic values. By having more thorough understandings

about exoplanet clouds and hazes, researchers can better constrain chemical composition of exoplanet atmospheres.

Scholars commonly use earth's life effect on atmosphere to presume clues in exoplanet atmosphere that indicate presence of life. These clues are called biosignatures. For example, presence of O_2 is related to photosynthesis process. O_3 is formed through photochemical reactions from O_2 . CH_4 can be created through methanogenesis, a process in which anaerobic microbial discharge waste products. N_2O is produced in incomplete denitrification. Except for gases, organic haze also serves as a biosignature. These biosignatures can be detected through spectrometric observation of exoplanet atmosphere. O_2 absorption is detected on VIS/NIR band. O_3 and CH_4 absorptions are found on VIS/NIR/MIR band. Organic haze absorption is distributed in UV/blue band [12]. As mentioned, clouds and hazes reduce the depth of these absorptions. Absorption of biosignatures should be analyzed considering the presence clouds and hazes. The feature of organic hazes should also be investigated.

Certain clues (e.g., atomic hydrogen cloud) indicate gas escape in exoplanet atmosphere. By studying the escape, researchers are able to know how planets lost their mass in the presence of stellar radiation [13]. Moreover, clouds and hazes absorb and re-emit planetary radiation, contributing for the greenhouse effect. In addition, condensates in the upper atmosphere may be heated by stellar radiation (especially on the red band), causing a temperature inversion in atmosphere [14].

4. Limitations & Prospects

As an observational method, the transmission spectrum method has one significant limit. Seen from Fig. 5, during the when transit transmission spectrum is produced, only the day-night terminator part of the atmosphere is presented on the spectrum. As for some planets close to their host stars (synchronous rotation occur), heat is distributed unevenly in global range. Hence, thermal and chemical characteristics as well as features clouds and hazes are presumed to lack representativeness in global sphere. Moreover, properties (e.g., planet albedo and effective temperature) remain unknown in transmission spectrum. These properties are crucial in studying cloud and haze characteristics and formation.

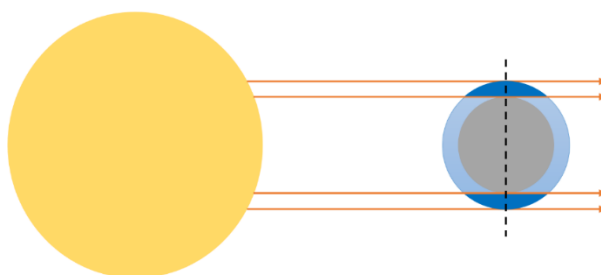


Fig. 6. Principle of transmission spectrum. Light blue part shows the part of atmosphere that doesn't produce transmission spectrum during transit; dark blue part shows the part of atmosphere that produce transmission spectrum during transit. Black dotted line shows the planet's day-night terminator.

More emission and reflection spectrum during the secondary eclipse should be observed in order to obtain more comprehensive understanding of an exoplanet's atmosphere. In this observational form, atmospheric information is shown in the scope of the whole day hemisphere. Reflection spectrum data provides knowledge about a planet's wavelength-dependent albedo (the proportion of reflected radiation in total received radiation), which is currently very unsure. Emission spectrum data gives a firsthand measurement of planet's effective temperature.

Currently, most exoplanet atmosphere transmission spectrums are taken by the HST. However, the James Webb Space Telescope (JWST), which has started its scientific mission recently, has higher spectrometric resolution, wider observational wavelength range in Infrared band (0.6-28.3 μ m,

compared to HST's 0.8-2.5 μm) and fewer disturbance at L2 point. JWST will be able to take both emission & reflection and transmission spectrum, which would substantially improve understanding about exoplanet atmospheric features. On June 21, 2022, JWST observed the transmission spectrum of exoplanet WASP-96b in the wavelength range of 0.6-2.8 μm . The observation discovered signature of water and evidence for clouds and hazes in the planet's atmosphere for the first time. Researchers also presume that JWST's 1-11 μm spectrum will well determine temperatures and molecular mixing ratios of cloudy exoplanets [15].

5. Conclusion

In conclusion, this paper summarizes the usage of transmission spectrum in exploring clouds and hazes in exoplanet atmospheres. Exoplanet clouds and hazes are both composed of tiny condensates. While cloud particles are bigger and in both solid and liquid form, haze particles have smaller sizes and are only in solid form. Clouds usually reduce or eliminate absorption features on the whole observed transmission spectrum because of its wavelength-independent opacity. Hazes, producing Rayleigh scattering, have larger reduction in absorption depth on optical band than on infrared band. Currently, atmospheric observation of exoplanets is dominated by transmission spectrum, which only partially presents atmospheric features. As a result, reflection and emission spectrum during secondary eclipse that are complementary to transmission spectrum should be paid more attention to. JWST that has higher spectral resolution and better ability to collect light in infrared band is likely to play a significant role in detecting exoplanet atmospheric spectrum in the future. Deeper understandings of exoplanet clouds and hazes would contribute to better constrains of chemical composition and other features of exoplanet atmospheres. Exoplanet astrobiology, exoplanet meteorology and planet evolution theory will also benefit from the more in-depth knowledge.

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