Habitability of an exoplanet based on stellar wind

Changseok Lee

UWC Changshu, Suzhou city, 215500, China.

changseoklee9@gmail.com

Abstract. This paper aims to investigate the influence of stellar winds on the atmosphere of exoplanets. Stellar winds, which consist of charged particles produced by stars, can heavily alter and affect the evolution and composition of exoplanet atmospheres. This paper will provide an overview of stellar wind characteristics and their interactions with exoplanets. It will also investigate the consequences of such interactions, such as atmospheric erosion, atmospheric escape, and the exoplanet's habitability. In order to develop a more sophisticated and accurate method for identifying habitable planets that may host life, it is necessary to better understand the mechanisms of stellar wind to build more accurate models of stellar wind.

Keywords: Stellar Wind, Exoplanet, Habitability, Atmosphere, Magnetosphere

1. Introduction

There has been a steady rise in the discovery of exoplanets in the past 20 years, primarily due to the launch of the Kepler Mission and the Transiting Exoplanet Survey Satellite (TESS) Missions. The first atmospheric detection of an exoplanet occurred in 2002 when high-precision spectrophotometric measurements were made of the transiting planet HD 209458, a gas giant with a mass of 1.35 [1]. Ever since this discovery, there have been continuous attempts to obtain spectrophotometric measurements of the atmospheres of smaller and smaller planets. As the technical capabilities of telescopes improve, the search for an exoplanet with a habitable environment has felt increasingly within our reach. With the successful launch of the James Webb Space Telescope (JWST), there has been an increasing precision in the measurements we can make. In June 2023, traces of water were found in the atmosphere of WASP-18b, a brief period gas giant [2]. With such discoveries, atmospheric composition observations became a field of interest to determine a planet's habitability.

One significant phenomenon determining a planet's habitability is how its atmosphere interacts with its host star. Specifically, stellar wind from the star can increase atmospheric escape rates [3]. This, in turn, affects whether the atmosphere is retained [4]. A contained atmosphere is necessary for liquid water to exist under the required pressure and temperature conditions, providing a sufficient shield from deadly radiation [5]. Furthermore, stellar wind activity also needs to be studied indirectly due to the problematic nature of observing it. These limitations mean that simulations and models are the best methods of study at the current moment. Although the newer updated stellar wind models can fully consider three dimensions and better consider mass loss rates, they still rely on assumptions [6].

DOI: 10.54254/2753-8818/43/20241135

2. Stellar Winds: Characteristics

Stars are incredibly dynamic and active objects. Due to the pressure caused by internal nuclear fusion or the star's magnetic field, stars emit particles such as protons, electrons, and atoms. Stellar winds from low to medium-mass stars, including our sun, are primarily powered and affected by their magnetic activity. The star's magnetic activity gives particles in the outer layer sufficient energy to escape gravity. This generates stellar wind, which only causes stars to lose a small percentage of the star's mass throughout the stable period of their lifetime.

It should also be noted that hot stars tend to have a tight correlation in the mass loss rate due to stellar wind and the star's luminosity. Usually, the terminal velocities of the stellar winds emerging from hot stars are a few times the escape velocity. On the other hand, cooler stars seem to not correlate with the mass loss rate and the stellar parameters [7].

Two significant parameters describe a stellar wind: terminal velocity (v) and the mass loss per rate of time (m) [7]. The mass loss rate of the star is significant in determining the star's evolution. Furthermore, the amount of kinetic energy deposited by a stellar wind is determined by $\frac{1}{2}\,\dot{m}v_{\infty}^{2}\tau$ Therefore, to be able to study the surrounding environment of the star, it is necessary to be able to determine the value of the two parameters.

3. Exoplanet Atmospheres

The exoplanet atmosphere is an essential field of study for the search for life or habitable worlds. Liquid water cannot be thermodynamically stable without an atmosphere due to low pressure. Furthermore, there would be no barrier to deadly radiation and cosmic rays [5]. This means that the magnetosphere is necessary for a planet to be habitable. The only way to determine habitability indicators such as temperature and biosignature gases is by studying the atmosphere [5]. Using this, we can see that the necessary parameters for habitability are that the exoplanet lies within the habitable zone and has a magnetosphere sufficient to shield the atmosphere [6].

The most straightforward way to observe an exoplanet's atmosphere would be by direct imaging. However, this method is currently only applicable to planets that are large, bright, and far from the host star. With current technology, studying large exoplanet atmosphere samples is impractical. The method that has yielded the best results has been the transit method. The discovery of large numbers of short-period gas giants enabled a process by which the atmosphere can be studied from the eclipsing nature between the host star and the planet.

The process when the exoplanet passes in front of the star is called primary transit. During this transit, light from the star can pass through the planet's atmosphere. ("Using this light, the planet's spectral emission can be obtained by comparing this spectrum to the spectrum obtained when the planet is not blocking the star [5].") An obvious drawback to the transit method is that the studied sample focuses on short-period gas giants when terrestrial planets are more "interesting" for studying habitability.

4. Stellar Wind-Exoplanet Interactions

Interactions between the stellar wind and exoplanets can change depending on the distance between the star and the planet. For planets that are far out, the exchanges can be one-sided, where only the planet is affected; however, for close-in planets, magnetospheres of both the planet and the star interact with each other. The tidal force can also impact the stellar flow [8]. Previous studies have even shown that planets closest to the stars can have an ion escape rate 50 times that of the outmost planets, strongly suggesting that closer planets would have little to no atmosphere, whereas further ones can guarantee atmosphere retention [9].

Interactions between a planet and its host star can include atmospheric escape caused by sputtering, magnetic storms, and stellar wind impacts [3]. Therefore, a magnetosphere is necessary to protect a planet from such activity. One interesting case study on this is our neighbor Mars. It is believed that 1.5 billion years ago, Mars had an atmosphere with habitable conditions: it was warm and moist [3]. However, as Mars' core cooled, the magnetosphere was lost. Without a magnetosphere, the atmosphere of Mars would have been exposed to solar radiation and solar wind impacts, resulting in atmosphere losses [6]. Therefore, it can be concluded that the importance of a stable atmosphere means a sufficient magnetosphere is also necessary.

Evaporative outflow or atmosphere escape inhibits the retention of a planet's atmosphere. Therefore, it is necessary to determine the evaporative outflow to determine habitability. Atmospheric escape is usually classified into thermal and nonthermal processes, also known as "suprathermal" [4]. The temperature of the exosphere determines the thermal escape rate. Mechanisms of the nonthermal process include charge exchange, photochemical reactions, sputtering, ion escape, and ion pickup. The interaction with the stellar wind causes the ion pickup process. Ion pickup occurs when neutral elements of the upper atmosphere become ionized and are accelerated due to the electric fields of the plasma streams from the stellar winds [10]. More specifically, it relies upon whether the stellar wind is strong enough to make magnetic reconnections with the magnetosphere. The ram pressure of the wind further determines where this reconnection can occur. If the ram pressure is higher, it will make the planetary magnetopause smaller. The unshielded atmosphere outside the magnetosphere becomes ionized and then taken away by the stellar wind [11]. This mechanism is highly effective at atmospheric escape for planets without the protection of a magnetosphere. Most mechanisms of nonthermal escape depend on the conditions of the upper atmosphere (density, temperature, and particles) and the stellar wind conditions [10].

A stellar wind's strength also significantly affects the direction of the evaporative outflow [9]. Furthermore, the orbital position affects the direction of the evaporative outflow of a planet. The impact of stellar wind on the planet's directional outflow suggests a necessity for a simulation model that considers its orientation. For this reason, Magnetohydrodynamic (MHD) models are more suitable for simulations of this interaction than Hydrodynamic (HD) models. MHD simulations can consider the strength and orientation of the star's magnetic field.

Results from previous studies show a high degree of correlation between stellar winds and nonthermal atmospheric loss [10, 12,13]. A denser stellar wind increases the atmospheric loss rate [10]. This is because a stellar wind with higher density increases the number of charge exchanges between the atmosphere and the wind. This produces heat, which consequently speeds up the escape process of the ions in the atmosphere [10].

5. Models & Simulations

5.1. Star-planet Interaction Models

Close star-planet interactions have been shown to affect both the star and the planet [8]. Therefore, for a model to be accurate, both bodies must be considered. On the contrary, due to the interaction, only the planet's magnetic fields will be altered for far-out planets. Therefore, the stellar wind can be independent [11]. Since most planets of interest (habitable ones) are relatively "far-out," such as the Earth being 1 AU away, models tend to take on the approach where the interaction is one-sided and only affects the planet's magnetic activity. Models used to simulate Star Planet Interaction (SPI) interactions tend to use MHD equations. Center of Excellence Space Studies India – Star Planet Interactions Module (CESSI-SPIM) simulates SPI interactions using an MHD code – PLUTO [11]. This model is specific for the SPI for far-out planets like Earth. Therefore, the model disregards the magnetic effect on the star. The model was initially created to analyze magnetic reconnections based on different star-planet configurations [11]. The equations for the plasma simulations are given as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} + \frac{1}{4\pi\rho}\vec{B} \times \left(\nabla \times \vec{B}\right) + \frac{1}{\rho}\nabla P = \vec{g} \quad (2)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P)\vec{v} - \vec{B}\left(\vec{v} \cdot \vec{B}\right) + \left(\eta \cdot \vec{J}\right) \times \vec{B}\right] = \rho \vec{v} \cdot \vec{g} \quad (3)$$

$$\frac{\partial \vec{B}}{\partial t} + \nabla \times \left(\vec{B} \times \vec{v}\right) + \nabla \times \left(\eta \cdot \vec{J}\right) = 0 \quad (4)$$

Where $\rho, \vec{v}, \vec{B}, P, \vec{g}, \mathcal{E},$ and $\vec{J}$ denote the density, velocity, magnetic field, total thermal and magnetic pressure, acceleration due to gravitational strength, total energy density, and current density. In-situ observations can support the CESSI-SPIM results.

Another frequent model is the Block Adaptive-Tree Solar-Wind Roe-type Upwind Scheme (BATS-R-US), developed by the University of Michigan Computational MHD group. This model solves MHD equations using a block-adaptive grid. This model uses solar wind plasma and magnetic field parameters to solve for parameters relating to magnetospheric plasma and chemical reactions in the ionosphere [10].

5.2. Stellar Wind Models

Stellar wind models can be complex due to the need for observational data [6]. Furthermore, the mechanism responsible for stellar wind acceleration still needs to be fully understood, making it difficult to model it accurately. Although more representative models using MHD codes are available with the most up-to-date models, it is impractical to use complete MHD codes on large data samples [6]. More applicable for large samples are simpler one-dimensional models such as the Parker Wind Model and the Cranmer and Saar Model [14,15]. Nonetheless, it is only possible to accurately depict the winds' behaviors with a more sophisticated understanding of stellar wind and a more extensive database of stellar wind measurements. Therefore, more stellar wind must be studied to understand better its characteristics, such as the mechanisms responsible for acceleration.

6. Conclusion

A core aspect of exoplanet study has been discovering a habitable planet that can hold life. For this reason, a framework for assessing habitability has been developed named the habitable zone. The habitable zone considers whether liquid water can sustain itself on the surface of an Earth-like planet. However, it neglects another essential aspect of deeming a planet's habitability: the atmosphere. Liquid water can become thermodynamically unstable without a sufficient atmosphere due to low pressure. Furthermore, without a sufficient magnetosphere, the planet's surface is vulnerable to hazardous radiation, affecting habitability.

A star's interaction with the planet can severely affect a planet's atmosphere. The interaction can include sputtering, ion escape, and more. These interactions affect the atmospheric escape of the planet, which in turn has a strong effect on the atmosphere retention of the planet. Models have been made using MHD equations to study such interactions. Simpler stellar wind models have been more favorable due to the complexity of three-dimensional models, such as ones using MHD equations. The described stellar wind models contain significant underlying uncertainty, such as the precise mechanism of stellar wind acceleration.

Due to these reasons, to develop a more sophisticated and accurate method of identifying habitable planets with potential for life, it is necessary to create a better understanding of the mechanisms of stellar wind to construct a more precise model of stellar wind.

References

[1] Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. (2002). Detection of an Extrasolar Planet Atmosphere. *The Astrophysical Journal*, *568*(1), 377–384. https://doi.org/10.1086/338770

[2] Coulombe, L.-P., Benneke, B., Challener, R., Piette, A. A. A., Wiser, L. S., Mansfield, M., MacDonald, R. J., Beltz, H., Feinstein, A. D., Radica, M., Savel, A. B., Dos Santos, L. A., Bean, J. L., Parmentier, V., Wong, I., Rauscher, E., Komacek, T. D., Kempton, E. M.-R., Tan, X., … Wheatley, P. J. (2023). A broadband thermal emission spectrum of the ultra-hot Jupiter WASP-18b. *Nature*, *620*(7973), 292–298. https://doi.org/10.1038/s41586-023-06230-1

[3] Nandy, D., Martens, P. C. H., Obridko, V., Dash, S., & Georgieva, K. (2021). Solar evolution and extrema: Current state of understanding of long-term solar variability and its planetary impacts. *Progress in Earth and Planetary Science*, *8*(1), 40. https://doi.org/10.1186/s40645-021-00430-x

[4] Catling, D. C., & Kasting, J. F. (2017). *Atmospheric Evolution on Inhabited and Lifeless Worlds* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781139020558

[5] Grenfell, J. L. (2021). Habitability, Role of the Atmosphere. In M. Gargaud, W. M. Irvine, R. Amils, H. J. Cleaves, D. Pinti, J. Cernicharo Quintanilla, & M. Viso (Eds.), *Encyclopedia of Astrobiology* (pp. 1–6). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-27833-4_5098-2

[6] See, V., Jardine, M., Vidotto, A. A., Petit, P., Marsden, S. C., Jeffers, S. V., & Nascimento, J. D. do. (2014). The effects of stellar winds on the magnetospheres and potential habitability of exoplanets. *Astronomy & Astrophysics*, *570*, A99. https://doi.org/10.1051/0004-6361/201424323

[7] Lamers, H. J. G. L. M., & Cassinelli, J. P. (1999). Introduction to Stellar Winds. In *Introduction to Stellar Winds*. https://ui.adsabs.harvard.edu/abs/1999isw..book.....L

[8] Strugarek, A. (2016). ASSESSING MAGNETIC TORQUES AND ENERGY FLUXES IN CLOSE-IN STAR–PLANET SYSTEMS. *The Astrophysical Journal*, *833*(2), 140. https://doi.org/10.3847/1538-4357/833/2/140

[9] Harbach, L. M., Moschou, S. P., Garraffo, C., Drake, J. J., Alvarado-Gómez, J. D., Cohen, O., & Fraschetti, F. (2021). Stellar Winds Drive Strong Variations in Exoplanet Evaporative Outflow Patterns and Transit Absorption Signatures. *The Astrophysical Journal*, *913*(2), 130. https://doi.org/10.3847/1538-4357/abf63a

[10] Luo, J., He, H.-Q., Tong, G.-S., & Li, J. (2023). Quantifying the Key Factors Affecting the Escape of Planetary Atmospheres. *The Astrophysical Journal*, *951*(2), 136. https://doi.org/10.3847/1538-4357/acd330

[11] Das, S. B., Basak, A., Nandy, D., & Vaidya, B. (2019). Modeling Star–Planet Interactions in Far-out Planetary and Exoplanetary Systems. *The Astrophysical Journal*, *877*(2), 80. https://doi.org/10.3847/1538-4357/ab18ad

[12] Gronoff, G., Arras, P., Baraka, S., Bell, J. M., Cessateur, G., Cohen, O., Curry, S. M., Drake, J. J., Elrod, M., Erwin, J., Garcia-Sage, K., Garraffo, C., Glocer, A., Heavens, N. G., Lovato, K., Maggiolo, R., Parkinson, C. D., Simon Wedlund, C., Weimer, D. R., & Moore, W. B. (2020). Atmospheric Escape Processes and Planetary Atmospheric Evolution. *Journal of Geophysical Research: Space Physics*, *125*(8). https://doi.org/10.1029/2019JA027639

[13] Lichtenegger, H. I. M., Kislyakova, K. G., Odert, P., Erkaev, N. V., Lammer, H., Gröller, H., Johnstone, C. P., Elkins-Tanton, L., Tu, L., Güdel, M., & Holmström, M. (2016). Solar XUV and ENA-driven water loss from early Venus' steam atmosphere: WATER LOSS FROM EARLY VENUS. *Journal of Geophysical Research: Space Physics*, *121*(5), 4718–4732. https://doi.org/10.1002/2015JA022226

[14] Parker, E. N. (1958). Dynamics of the Interplanetary Gas and Magnetic Fields. *The Astrophysical Journal*, *128*, 664. https://doi.org/10.1086/146579

[15] Cranmer, S. R., & Saar, S. H. (2011). Testing a Predictive Theoretical Model for the Mass Loss Rates of Cool Stars. *The Astrophysical Journal*, *741*, 54. https://doi.org/10.1088/0004-637X/741/1/54