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Star-exoplanet interactions: A growing interdisciplinary field in heliophysics

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Traditionally, heliophysics is characterized as the study of the near-Earth space environment, where plasmas and neutral gases originating from the Earth, the Sun, and other solar system bodies interact in ways that are detectable only through *in-situ* or close-range (usually within ~10 AU) remote sensing. As a result, heliophysics has data from the space environment around a handful of solar system objects, in particular the Sun and Earth. Comparatively, astrophysics has data from an extensive array of objects, but is more limited in temporal, spatial, and wavelength information from any individual object. Thus, our understanding of planetary space environments as a complex, multi-dimensional network of specific interacting systems may in the past have seemed to have little to do with the highly diverse space environments detected through astrophysical methods. Recent technological advances have begun to bridge this divide. Exoplanetary studies are opening up avenues to study planetary environments beyond our solar system, with missions like Kepler, TESS, and JWST, along with increasing capabilities of ground-based observations. At the same time, heliophysics studies are pushing beyond the boundaries of our heliosphere with Voyager, IBEX, and the future IMAP mission.

The interdisciplinary field of star-exoplanet interactions is a critical, growing area of study that enriches heliophysics. A multidisciplinary approach to heliophysics enables us to better understand universal processes that operate in diverse environments, as well as the evolution of our solar system and extreme space weather. The expertise, data, theory, and modeling tools developed by heliophysicists are crucial in understanding the space environments of exoplanets, their host stars, and their potential habitability. The mutual benefit that heliophysics and exoplanetary studies offer each other depends on strong, continuing solar system-focused and Earth-focused heliophysics studies. The heliophysics discipline requires new targeted funding to support inter-divisional opportunities, including small multi-disciplinary research projects, large collaborative research teams, and observations targeting the heliophysics of planetary and exoplanet systems. Here we discuss areas of heliophysics-relevant exoplanetary research, observational opportunities and challenges, and ways to promote the inclusion of heliophysics within the wider exoplanetary community.

KEYWORDS

heliophysics, exoplanets, space weather, multidisciplinary, stellar wind, magnetosphere, ionosphere, stellar activity

1 Introduction

Heliophysics is the study of fundamental processes of plasma and neutral gas dynamics within the solar system, in regions ranging from the Sun to the edge of the heliosphere and extending into the upper atmospheres of planets. These processes are primarily driven by the Sun's magnetic activity and by the unique properties of the planetary magnetic fields and atmospheres and their interaction with the surrounding space environment. Analogous fundamental physical processes occur in the space weather environments of other stars, and these processes impact and interact with the associated exoplanets. The study of heliophysics processes in exoplanet system contexts provides a unique parameter space that can complement the knowledge of our present-day Earth-Sun system, as well as inform us about our past and future.

Known exoplanet systems span a wide range of host star ages, magnetic activity levels, and frequency of extreme space weather events. This variety of exoplanet systems provides a more complete parameter space that allows us to explore concepts beyond those developed specifically for the Sun's interactions with the Earth (and other solar system planets), in order to derive more universal, self-consistent relations and understanding of fundamental processes. Extending our understanding to higher stellar activity levels will help constrain the possible impacts of extreme solar storms on the Earth as well as on Mars and the Moon, which are the focus of human space travel. Similarly, studying young solar-type stars can provide vital information about the young Sun to understand the evolution of solar drivers and corresponding atmospheric and magnetosphere/ionosphere/thermosphere (M-I-T) processes early in the Earth's history.

The field of exoplanets is becoming a major area of interdisciplinary research that considers the full complexity of planets in the Universe. It is essential that researchers from across the heliophysics community participate in exoplanet studies so that important insights gained from heliophysics are brought to the table by experts in the field. Such interdisciplinary studies have been recognized as crucial in the decadal surveys and community white papers of other divisions and past heliophysics decadal surveys (e.g., National Research Council, 2003; National Research Council, 2013; Kopparapu et al., 2021; National Academies of Sciences, 2021) as well as overview books on exoplanets and their stars (e.g., Deeg and Belmonte, 2018; Linsky, 2019; Basri, 2021). This recognition provides an opportunity to expand the contribution of heliophysics, raising its profile to be acknowledged as a field with universal impact. It will also build intra-disciplinary collaborations that tie together heliophysics subfields, yielding scientific applications well beyond exoplanet studies.

We recommend a greater investment of efforts and funding in the cross-disciplinary study of fundamental heliophysics and space weather processes in exoplanet systems. This investment should take the form of both greater participation in existing programs and the creation of new programs. For instance, a larger contribution from Heliophysics to NASA's Exoplanets Research Program (XRP) and Habitable Worlds (HW) programs would bring further heliophysics expertise to the interdisciplinary questions of exoplanet habitability and star-planet interaction. Additionally, the Living with a Star (LWS) program could include more solicitations with Focused Science Topics concerning the heliophysics of exoplanet systems by incorporating partnered support from other Divisions. Exoplanet-related heliophysics research should also include the creation of new programs, such as an interdisciplinary mission of opportunity or an early solar system research program. Existing advisory groups with the inclusion of heliophysicists such as NexSS and ExoPAG could be utilized in providing innovative strategies for implementing such developments. The recommendations here should not be taken as recommendations to replace any current or planned heliophysics research, but rather to expand and build upon it, as the strength of our physics-based understanding of the heliosphere and the space environments of the Earth and other planetary bodies depends on the strength and continuation of our current heliophysics program. More broadly, this paper calls for wider recognition of the connections between the Sun-Earth system and exoplanetary science and the value of interdisciplinary work in applying heliophysics to the exoplanet context and *vice versa*.

2 Research areas

2.1 Stellar activity/Sun as a star

An obvious connection between exoplanetary science and heliophysics exists when considering the Sun as a star, or conversely, examining populations of other G-type stars as "solar analogs'. Stellar observations and theory tell us that stars spin down as they age and shed angular momentum to their stellar winds; thus, the Sun must have been more rapidly rotating and more magnetically active in its past. In order to understand the space weather environment and solar driving that led to present-day conditions on Earth and other solar system planets, we must study the Sun's past by applying data-constrained, multidimensional heliophysics models of the solar corona, the wind, and solar transient events (Airapetian et al., 2021). Multi-wavelength observations and empirical Sun-as-a-star models of other solar analogs provide constraints on the modeling of the magnetic environments of the Young Sun (Toriumi and Airapetian, 2022; Toriumi et al., 2022). Solar twins—or G type stars with similar properties (such as temperature, age, and composition) to the present-day Sun—play an important role in comparative studies of the Sun and other stars (Porto de Mello et al., 2014). They can be used to calibrate stellar evolution models or investigate the rotational history of the Sun, among other applications (Galarza et al., 2016; do Nascimento et al., 2014). Other G-type stars at different stages of their lifetimes can provide clues to the solar system's past and future (e.g., Ribas et al., 2005). Cool stars of other types including F, K, and M stars are also of interest in providing points of comparison such as different levels of coronal emission, stellar wind fluxes, flaring output, and other stellar drivers such as coronal mass ejections (CMEs) and stellar energetic particles (SEPs). A more detailed understanding of stellar energetic output is needed to assess the influences that lead to both the Earth's present-day habitability, and the possible habitability of exoplanets through their lifetimes.

There are several key differences in the observational capabilities between studying our solar system (including Heliophysics and Planetary missions) and studying other stars. A large gap exists between the methods and outcomes of solar system observations–typically *in-situ*, spatially-resolved, and/or continuous in time–and astronomical observations of exoplanets and their host stars–typically point-source and intermittent in time, and by necessity remote. Though these differences can present obstacles in communication between the exoplanet and heliophysics communities, we also emphasize that these approaches can complement one another. This can be done by developing Sun-as-a-star empirical models of solar flares and CMEs. Better constraints on how stars spin down, and how their flaring and coronal emission outputs evolve over the lifetime of their planetary systems, are required to contribute directly to understanding the behavior of the Sun over the history of the Solar system.

2.2 Astrospheres

Analogous to our heliosphere, the region of space surrounding other main sequence stars and dominated by the stellar magnetic field and the ionized stellar wind is called the astrosphere. The solar/stellar wind is an important mediator of interactions, carrying charged particles and magnetic field lines out to the planets, where it influences the atmospheric composition and drives atmospheric erosion. From an astrophysics perspective, the stellar wind properties are of interest because they determine shedding of stellar mass and angular momentum. The resulting impact on stellar spin-down rates in turn affects how one might use gyrochronology to estimate stellar ages. However, the winds of other cool stars are difficult to constrain observationally. Preliminary success in constraining stellar wind mass loss rates *via* Ly-α emission from hydrogen buildup at the hydrogen wall beyond the astropause (analogous to the heliopause) is a promising avenue of research in understanding universal heliophysics processes in other stellar systems. Additional observations and modeling will aid our ability to interpret Ly-α emission in terms of stellar wind pressures and speeds (Wood et al., 2005; Wood et al., 2021), particularly for other planet-hosting systems (Hussain et al., 2016; Edelman et al., 2019). An understanding of the relationship between host star magnetic field strength, resulting wind speed, and spatial distribution is key to determining the solar wind as a driver of past M-I-T processes at solar system planets (including Earth).

From the heliophysics perspective, Parker Solar Probe is opening a new era of *in-situ* observations of the very inner heliosphere, including the regime within about 20 solar radii where the solar wind is sub-Alfvénic, that is, having a bulk plasma velocity less than the local Alfvén speed, $v_A = B/\sqrt{4\pi\rho}$, where ρ is the mass density and B is the magnetic field magnitude (e.g., He et al., 2021; Bandyopadhyay et al., 2022). This achievement in heliospheric observations is directly relevant to the exoplanet context, since many terrestrial exoplanets orbiting M stars are expected to fall within their host stars' Alfvén surfaces (the boundary between sub- and super-Alfvénic wind flow) for part or all of their orbital periods (e.g, Garraffo et al., 2016; Farrish et al., 2019). Outside the Alfvén surface, upstream-directed interactions from the planets to the Sun cannot occur. The solar wind forms a bow shock ahead of any planetary obstacles. This bow shock slows and redirects the solar wind, influencing the interaction of the solar wind with the planet's magnetosphere, ionosphere, and atmosphere. Inside the Alfvén surface, by contrast, the flow of energy may occur in both directions, toward and away from the star, allowing direct interaction between the planet and its host star [e.g. (Cohen et al., 2014; Saur et al., 2013)]. Though some close-in planets on extremely short orbital periods may be moving fast enough to produce a bow shock ahead of the planet as its Keplerian speed exceeds the local sound speed [for example, WASP-12b (Vidotto et al., 2011)], still other close-in planets are expected to experience sub-Alfvénic interaction with their host star winds for some or most of their orbits [for example, TRAPPIST-1e (Harbach et al., 2021) or AU Mic b Cohen et al. (2022)], even when the orbital speed of the planet is accounted for. It is therefore important to understand the interaction of planetary magnetospheres and atmospheres with their host star winds under a variety of conditions. *In-situ* data of solar wind speeds and magnetic features such as switchbacks and shocks provide a better picture than ever before of the behavior of the Sun's very inner heliosphere. As a complement, the extension of solar wind and magnetospheric models to the sub-Alfvénic regime, and the transition between sub- and super-Alfvénic regimes, can provide more context for possible interactions between M stars and their extremely close-in planets. These cases of sub-Alfvénic interactions or transitions between sub- and super-Alfvénic conditions demonstrate an area where heliophysics observations are uniquely poised to help answer scientific questions in exoplanet systems, and where solar missions and heliophysics modelers can provide expertise to researchers in other exoplanet-related disciplines.

The "superflare" extremes of stellar activity, and their potential planetary and exoplanetary consequences, have garnered considerable interest from heliophysics, planetary science, and astrophysics. By analogy with energetic solar flare events, stellar flares are expected to be associated with stellar CMEs, shocks, and stellar energetic particles (SEPs) whose properties are a critical factor of exoplanet habitability (Airapetian et al., 2020). The search for these astrospheric counterparts of stellar superflares along with stellar prominence and filament eruptions is a growing area of research and requires coordinated multi-observatory, multi-wavelength observations of active stars. Recent studies report several potential detections of stellar CMEs associated with (super-)flares on G, K and M-dwarfs. The observational signatures are based on detection of the Doppler shifted absorption/emission of optical/UV/X-ray emissions lines, coronal XUV/FUV dimming, radio bursts, and continuous absorption of X-rays due to eruptive filaments or passing CMEs (Veronig et al., 2021; Namekata et al., 2022). While past studies so far have relied on a single observational technique, coordinated studies to search for multiple signatures are required to constrain the properties of these ejections. Such coordinated observational campaigns are strongly encouraged, as they would provide criticial constrains for modeling efforts of stellar CMEs in various coronal environments of active stars (see review by Lynch et al., 2022). Hu et al. (2022) modeled the extreme energetic particle events accelerated by superflare-associated CMEs from solar-like stars. Our knowledge so far depends on such data-constrained modeling capabilities, with the same tools used for our own space weather research as for exoplanetary space environments over a range of stellar activity assumptions. These modeling activities provide knowledge of not only astrospheric environments but also of our own solar system under a range of possible circumstances, and of the uniqueness of our situation among the broad populations of extrasolar systems.

2.3 Exoplanet magnetospheres

Planetary magnetic fields are generated within planetary interiors by magnetic dynamos. As such, their presence can provide constraints on planetary interiors. Further, the extent to which exoplanets retain their atmospheres over geological time scales depends in part upon whether they are exposed directly to the host stars' stellar winds. In the Solar System, data from instruments on the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft have captured the erosion of Mars' atmosphere when a coronal mass ejection (CME) impacted it. Some of these topics are synergistic with those addressed in Section ("Exoplanet Atmospheres").

Some exoplanets are found in close-in orbits (<0.05 au) to their host stars. These close-in planets experience persistent extreme space weather conditions, due to stellar wind and interplanetary magnetic field parameters that can be 1–3 orders of magnitude stronger than the typical values near Earth (e.g., Garraffo et al., 2016). Moreover, depending upon the characteristics of the stellar winds and the eccentricities of their orbits, close-in exoplanets can transition between very different plasma sectors within short time intervals during their orbits, mimicking transient conditions (e.g., CMEs) (Cohen et al., 2014). More distant exoplanets (>0.1 au) present more direct analogs to Solar System planets, but potentially offer a greater diversity of planetary interiors, operative dynamos, and magnetospheric geometries than those found in our own solar system. For both close-in and more distant exoplanets, magnetospheres potentially shield the planets from their host stars' stellar winds, as well as control energetic particle access to their atmospheres (including both magnetospheric- and stellar-origin particles). Magnetospheres play an important role in redirecting stellar wind and CME energy and escaping ions to influence atmospheric escape.

Stellar XUV-driven atmospheric heating produces the significant expansion of the upper atmospheres of rocky and giant exoplanets that in some cases can transition into hydrodynamic escape (Johnstone et al., 2018; Johnstone et al., 2019). The interaction between the expanding upper atmospheres of rotating hot Jupiters within their large-scale (dipole-like) magnetic fields drives the formation of a magnetodisk located outside the "Alfvénic surface" from the planet (Khodachenko et al., 2021). For close-in exoplanets, the tidal force and XUV driven heating are strong contributors to drive the expansion of planetary atmosphere beyond the Roche lobe and to accelerate its material in the form of a double stream planetary wind at the day- and night-sides of the planet (Shaikhislamov et al., 2019).

Knowledge about and accurate modeling of exoplanetary magnetic fields could constrain our understanding of planetary responses to their space environment and evolutionary path (Dong et al., 2019; Dong et al., 2020). In the Solar System, planetary magnetic fields can be probed *via in-situ* measurements from spacecraft. For exoplanets, one of the few means of constraining the presence of exoplanetary magnetic fields is by their interactions with the host stars' stellar winds. Electron cyclotron masers operating in the polar regions of planets with planetary-scale magnetic fields and sourced by magnetic field-stellar wind interactions may be detectable over interstellar distances. Two potential observations of radio emission resulting from exoplanet magnetospheric processes have been found to date, from the hot Jupiter τ Boo b (Turner et al., 2021) and an otherwise unconfirmed Earth-size planet (Vedantham et al., 2020). However, in dense plasmaspheres of close-in hot exoplanets around young G and K type stars, where plasma (Langmuir) frequency, f_L, gets close to the electron gyrofrequency, f_c, traditional ECMI generation mechanisms are likely not efficient (Weber et al., 2017). The account of plasmasphere cut-off (i.e., breaking of the ECMI condition $f_L < 0.3 f_c$) constitutes the specifics of exoplanetary radio emission problem, as compared to similar cases in the Solar System. In these cases, plasma maser mechanism of exoplanetary radio emission can be efficient in dense and weakly magnetized (or even non-magnetized) plasma (Zaitsev and Shaposhnikov, 2022). Similar mechanisms are known to play an important role in the generation of radio emission in solar corona, as well as in magnetospheres of the Solar System planets.

There have been numerous estimates of the radio powers generated by exoplanetary auroral emissions due to electron cyclotron masers (e.g., Laneuville et al., 2020), but the lack of many detections to date likely reflects both the limited sensitivity of many current telescopes and the relatively high frequencies observed compared to the radio frequencies at which Solar System planets emit.

The importance of these questions is recognized on an interdisciplinary basis, and continued collaboration between heliophysics modelers and radio astronomers to predict the conditions necessary for detection and interpret any future detections is crucial. The report of the Panel on Exoplanets, Astrobiology, and the Solar System, from the *Pathways to Discovery* Astronomy & Astrophysics Decadal Survey, stated, "For terrestrial planets, surface/atmosphere exchange mechanisms mediate atmospheric composition, and planetary magnetic fields can illuminate processes occurring deep in a planet's interior, while providing critical insights into how the planet's atmosphere interacts with the space environment." In the *Origins, Worlds, and Life* Planetary Science & Astrobiology Decadal Survey report, two Priority Science Question Topics had elements involving the existence of planetary magnetic fields and their interactions with the solar wind, Question 6: "Solid body atmospheres, exospheres, magnetospheres, and climate evolution" and Question 12: "Exoplanets." Further, the recommendation for the Uranus Orbiter & Probe as the next Planetary Science Flagship mission was based on the importance of studying its magnetosphere and its interaction with the solar wind as "ground truth" for ice giants in other planetary systems.

2.4 Exoplanet ionospheres

Ionizing Extreme Ultraviolet (EUV) flux and particle flux incident on the upper atmosphere creates the ionosphere, which modulates magnetospheric responses to stellar winds, provides protection from stellar winds in the case of unmagnetized planets, and provides a source of atmospheric escape. The extreme space weather conditions at many observable exoplanets may lead to high ionospheric escape rates and heavy ion loss (Airapetian et al., 2017; Garcia-Sage et al., 2017), as well as large Joule heating (Cohen et al., 2014). The Joule heating influences the upper atmospheric density and expansion and may further enhance escape. This heating depends on ionospheric conductance, which is determined by many parameters, some of which are unknown, including EUV flux, atmospheric composition, planetary field, particle precipitation, and stellar wind properties. Comprehensive, detailed modeling is required to determine the impact of these parameters on the ionospheric conductance and the consequent modulation of atmospheric loss and atmospheric observables.

Testing our ionospheric models on observables is key. At Earth and other solar system planets, the ionosphere and ionospheric activity are remotely observable with airglow and the aurora, but these processes are expected to be too faint to be observed at exoplanets. However, the auroral radio emission mentioned above is influenced by the ionosphere, resulting in potentially observable ionospheric effects. The modulating effects of the ionosphere must be taken into account for predicting or analyzing observations of auroral radio emission (Sciola et al., 2021). Radio emission may only be observable under certain planetary and astrospheric conditions, but testing models on observable planets will provide key constraints and validation of our models.

Finally, it should be noted that under extreme conditions of hydrodynamic escape within the region of strong tidal forces, as discussed in the previous section, the star-ward and tail-ward expansion of the atmosphere results in an ionopause that also extends in both directions, with a complex shape that should be taken into account in the interpretation or prediction of Ly-α observations.

2.5 Exoplanet atmospheres

As explained in the previous section, a star's activity has a major impact on the atmospheres of any planets orbiting it, and close-in exoplanets are subjected to more extreme conditions than any observable in our Solar System. This gives a unique opportunity to understand the impact of extreme events on the chemistry and climate of rocky exoplanets, the critical factors for their habitability. For example, stellar energetic particles (SEPs) - a source of ionizing radiation - from young solar-like stars during extreme space weather events could have modified planetary atmospheric compositions and may explain the formation of potent greenhouse gases and prebiotic molecules on early Earth and Mars (Airapetian et al., 2016; Jolitz et al., 2017; Lingam et al., 2018). Analogously, stellar activity, including photons and particles emitted during CMEs and Stellar Proton Events (SPEs), and cosmic rays (both stellar and galactic) could affect the chemical composition of the atmosphere including biosignatures. The extent to which a particular biosignature might be detectable would depend upon the stellar activity level, the specific molecule under consideration, and the endogenous production rate of that molecule on the planet (e.g., Segura et al., 2005; Grießmeier et al., 2016; Tabataba-Vakili et al., 2016). Potential biosignature molecules can be directly destroyed by energetic particles or their downstream photochemical products, reducing their abundance and thus detectability at a given rate of planetary production (Tabataba-Vakili et al., 2016). Particles could have enough energy to split the nitrogen molecule, N_2, producing NO_x (NO and NO_2), which can destroy the potential biosignature O_3 (Segura et al., 2005; Segura et al., 2010; Tilley et al., 2019) or could contribute to create biosignature "false positives" by catalyzing the abiotic generation of biosignature molecules such as N_2O (Airapetian et al., 2016; Airapetian et al., 2020). Potential false positive scenarios could be predicted by extensive characterization of the host star or identified by searching for the spectrally active non-biosignature gases that are predicted to form in combination with the putative biosignatures (e.g., Tabataba-Vakili et al., 2016; Schwieterman et al., 2022). For example, abiotic production of N_2O would be accompanied by more robust production of NO_2, HNO_3, and/or HCN (Ibid.). The abiotic production or destruction of greenhouse gas molecules such as nitrous oxide *via* stellar activity could impact planetary climate, depending on the abundances of the produced or destroyed gases and their endogenous production rates (e.g., Airapetian et al., 2016; 2020; Tian et al., 2020). For hot Jupiters, photons and particles can influence detectable chemical species (e.g. NH_3, HCN). In general, the photochemistry driven by all phenomena associated with stellar activity should be considered when predicting or analyzing the spectra of exoplanets (Venot et al., 2016; Barth et al., 2021).

The effect of the space environment on atmospheric evolution, both within and outside of our solar system, is also of major importance to understanding space weather effects on habitability and on the observed trends for exoplanet radii vs. insolation (Fulton et al., 2017; Ketzer and Poppenhaeger, 2022). An overview of atmospheric escape processes by Gronoff et al. (2020) identified ten escape processes, most of which have been observed within our Solar System. These processes can broadly be categorized as thermal escape (Jeans and hydrodynamic escape), photochemical escape, and ion escape. The primary drivers of these loss processes are stellar XUV heating and stellar wind, but the properties of the planet, including mass, atmospheric composition, and intrinsic magnetic field, determine the response to these drivers and the mechanisms that can most effectively induce atmospheric loss. The specifics of the loss mechanisms affect not only the total mass loss rates but also atmospheric species or isotopes that undergo the greatest loss (e.g. Garcia-Sage et al., 2017; Gronoff et al., 2020). In some cases, such as that of Mars, atmospheric evolution may be drastic, leading to loss of water and nearly complete loss of the atmosphere (Dong et al., 2018b; Jakosky et al., 2018) from a combination of thermal, photochemical, and ion escape processes. Atmospheric escape at Earth is often compared to that at Mars, leading some to claim that Mars lost its atmosphere because it has no magnetic field. Both planets would have been subjected to nearly the same stellar wind and XUV fluxes, resulting in increased mass loss early in the planets' histories. While the magnetic field of the planets would have influenced this mass loss, some studies suggest atmospheric escape would have been enhanced, not suppressed, by a strong intrinsic field (e.g. Lazio et al., 2019; Gronoff et al., 2020; Lee et al., 2021). The observations of exoplanets, which in some cases have included detectable atmospheric escape (e.g., Lecavelier Des Etangs et al., 2010), allow the study of a greater parameter space of planetary mass, stellar impacts, and atmospheric losses, which enables us to better characterize the reasons why a planet retains or loses its atmosphere.

Overall, heliophysics facilitates our understanding of how an exoplanet atmosphere evolves with its host star, which allows us to better delineate the history of the planets in the solar system. Conversely, studying exoplanet atmospheres has the potential to highlight the activity of their host stars. With the planet acting as a detector for the star's particles and fields, we may be able to study stellar activity regimes that are rarely seen on our Sun.

3 Observational opportunities and challenges

Heliophysics observations generally fall into two categories - *in-situ* measurements of space plasmas, and remote sensing from spacecraft instruments and ground-based facilities, mostly of the Sun or aurora. In contrast, astronomical observations rely on integrated flux observations in different spectral bands, spectroscopy, polarimetry, and radio observations. Thus, while limited to one star and planetary system, heliophysics observations provide details that cannot be obtained by astronomy. These approaches are complementary: while astronomical observations provide broad statistics of systems, heliophysics observations provide a fine, realistic, and complex picture of the current solar system.

Ongoing and future heliophysics missions are making ground-breaking *in-situ* observations of processes that influence stellar and exoplanetary space environments. One potential approach to making use of these observations is to analyze solar system objects as astrophysical objects - predicting what would be observed if, e.g. an Earth-like or Venus-like planet or a Sun-like star were observed by current or future astrophysical instruments and missions. As mentioned in Section 2.2, the Parker Solar Probe (PSP) is contributing the first *in-situ* observations of the very inner heliosphere within the sub-Alfvénic solar wind, with implications for exoplanetary space environments. The encounter of PSP with a comet-like object 322P around 0.025 AU may also offer fresh insights concerning the habitability of close-in exoplanets (0.03–0.05 AU) around M dwarfs (He et al., 2021). At the same time, through collaborative missions with planetary science, such as Juno at Jupiter and MAVEN at Mars, we are able to test our understanding of how universal heliophysics processes, including atmospheric and ionospheric escape, energetic particle acceleration and propagation, and solar wind interactions with magnetospheres and ionospheres apply to diverse planetary systems.

The coming decade will bring an increased understanding of the upper atmosphere and ionosphere of Earth, in unprecedented detail, with the GDC (Geospace Dynamics Constellation) and DYNAMIC (Dynamical Neutral Atmosphere-Ionosphere Coupling) missions, which together will allow us to better understand the transition from the middle atmosphere into the magnetosphere and the many dynamic processes that influence energy and mass transfer between these regions. A strong interdisciplinary collaboration is needed in order to utilize these and other heliophysics observations as detailed case studies for exoplanet research. Of particular interest across science divisions are questions of atmospheric escape. Opportunities similar to the MISTE mission recommended by the previous Heliophysics Decadal Survey (National Research Council, 2013; Moore et al., 2016; Parsay et al., 2021) would shed light on the basics physics of ion escape processes, which is necessary to move past Earth-based phenomenology and accurately predict exoplanet escape. On the astrophysical side, UV imaging similar to the proposed ESCAPE mission (France et al., 2022) would provide the necessary knowledge of stellar fluxes at wavelengths that drive a multitude of escape processes.

Astronomical observations are increasingly expected to make measurements that are highly relevant to the stellar and exoplanetary space environments, providing the crucial measurements needed to test understanding of basic heliophysics processes. Studies of the radio emission generated by CMEs from other stars or the magnetospheric emissions from exoplanets or both would be enabled by space-based observations at a few Megahertz and below, e.g., as a successor to the Sun Radio Interferometer Space Experiment [SunRISE, Kasper et al. (2021)]. The TESS mission provides extensive data from nearby star systems, including observations of stellar flares (Günther et al., 2020). JWST has already reported a detection of a CO_2 atmosphere (JWST Transiting Exoplanet Community Early Release Science Team, 2022) and can be expected to vastly extend our knowledge of exoplanet atmospheric compositions.

4 Modeling opportunities and challenges

With growing computer power and capabilities, heliophysics models increase in resolution and physical complexity, allowing them to realistically reproduce phenomena in much finer detail and accuracy. Nevertheless, heliophysics models commonly operate under known limitations that are filled in with empirical fitting or simplifying assumptions. These empirical constraints and other Earth- or solar system-based assumptions may not be appropriate for other systems. As a result, the modeling of exoplanetary plasma environments can present significant challenges to established heliophysics models.

Heliospheric magnetosphere models typically assume that the upstream stellar wind is supersonic and super-Alfvénic, (the transition boundary is called the Alfvén surface) which allows for one-way, supersonic boundary conditions on the upstream side of the magnetosphere. This assumption is not valid for many detected exoplanets. Changing this boundary condition presents a significant challenge to the modeling efforts. In many cases, the planet finds itself inside the Alfvén surface of the host star, allowing feedback to the host star (e.g., Garraffo et al., 2017). Even in the case of supersonic stellar winds, the conditions can be so extreme that the magnetopause boundary is close to the planetary surface (Dong et al., 2017b; Slavin et al., 2019). This also presents significant numerical challenges because the larger intrinsic wave speeds in the region of the stronger magnetic field near the planet require a much smaller timestep for numerical stability, making the computations quite expensive (e.g., Sciola et al., 2021). The adaptation of sophisticated heliophysics models for exoplanet applications requires acknowledgment of areas where we are missing basic physics in our models and so may help us to better understand the limitations of our knowledge, to better define our computational needs, and to incorporate new or different physics in the models.

While the above examples detail a few of the many cases where exoplanetary systems with extreme conditions may require extensive new physics to model, the considerable expertise in sophisticated and validated models that have been developed or are becoming available within the heliophysics community serves as an excellent starting point for development of exoplanetary models even in extreme conditions. These models not only include the important magnetic coupling of planetary magnetic fields to a dynamic stellar wind, but also include the equally important effects of the ionosphere and atmospheric outflow (e.g. Brambles et al., 2011; Garcia-Sage et al., 2015; Garcia-Sage et al., 2015; Glocer, 2016; Dong et al., 2017a; 2018a; Airapetian et al., 2017; Airapetian et al., 2020). In addition, there is a considerable amount to be learned from applying heliophysics models to less extreme situations, which are likely to be of more interest in addressing the question of habitability.

Because astrophysics generally works in population-level statistics, another way to bring together heliophysics with exoplanetary system observations is by carrying out extensive heliophysics modeling to develop space environment statistics that can be compared to astronomical observations. The latter may also provide independent constraints on heliophysics models.

5 Collaboration opportunities, challenges, and recommendations

Heliophysics observations and models provide constraints to any attempt to understand a realistic stellar system and exoplanets within it. It is imperative that heliophysics expertise is used to inform a realistic, complex view of exoplanet systems. A strong interdisciplinary collaboration is needed to integrate such expertise into exoplanet research. Recognizing the need for interdisciplinary research, NASA has begun extending its funding opportunities for more interdisciplinary proposals. Specifically, the Exoplanets Research Program (XRP), Habitable Worlds (HW), and Interdisciplinary Consortia for Astrobiology Research (ICAR) programs have provided the opportunity to propose “heliophysics of exoplanets” projects. The XRP program is funded by all four NASA divisions, and most of the funding still comes from the Astrophysics Division and Planetary Science Division. In 2020, only 2 out of 26 selected proposals were heliophysics projects. We recommend augmenting Heliophysics funding to both the XRP and HW programs to allow broader participation of heliophysics researchers in exoplanets and comparative planetology research. Funding from Heliophysics for exoplanetary topics facilitates ties between divisions. We also recommend the creation of interdisciplinary opportunities within the Heliophysics programs, e.g., LWS, and the creation of interdisciplinary review panels to review explicitly interdisciplinary Heliophysics proposals. Finally, we recommend having relevant heliophysics opportunities such as LWS as paths to join the Nexus for Exoplanet Systems Science (NExSS) and other Research Coordination Networks. Such networks and collaborations - and interdisciplinary collaboration in general - improve our ability to conduct our technical work, and help us exchange best practices for open science and strategies for creating diverse, inclusive, equitable, and accessible environments in the field. These advances are important and especially critical for interdisciplinary research where the incorporation of different perspectives is required to advance the field.

Author contributions

KG-S organized and led the discussions that gave rise to this paper and that developed the recommendations therein. KG-S and AF organized the writing of the paper, wrote major portions of the paper, and revised the entirety of the paper for scientific content and scope. VA, DA, OC, SD-G, CD, GG, AH, JL, JGL, ES, ASc, ASe, FT, and JV contributed to the conception of the paper and generated crucial content, references, and revisions to the scientific content and scope. MA, KB, and GR contributed text and revisions of the scientific content of the paper.

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Conflict of interest

Publisher’s note

References

Airapetian, V. S., Barnes, R., Cohen, O., Collinson, G. A., Danchi, W. C., Dong, C. F., et al. (2020). Impact of space weather on climate and habitability of terrestrial-type exoplanets. *Int. J. Astrobiol.* 19, 136–194. doi:10.1017/S1473550419000132

Airapetian, V. S., Glocer, A., Gronoff, G., Hébrard, E., and Danchi, W. (2016). Prebiotic chemistry and atmospheric warming of early Earth by an active young Sun. *Nat. Geosci.* 9, 452–455. doi:10.1038/ngeo2719

Airapetian, V. S., Glocer, A., Khazanov, G. V., Loyd, R. O. P., France, K., Sojka, J., et al. (2017). How hospitable are space weather affected habitable zones? The role of ion escape. *Astrophysical J. Lett.* 836, L3. doi:10.3847/2041-8213/836/1/L3

Airapetian, V. S., Jin, M., Lüftinger, T., Saikia, S. B., Kochukhov, O., Güdel, M., et al. (2021). One year in the life of young suns: Data-constrained corona-wind model of κ 1 ceti. *Astrophysical J.* 916, 96. doi:10.3847/1538-4357/ac081e

Bandyopadhyay, R., Matthaeus, W. H., McComas, D. J., Chhiber, R., Usmanov, A. V., Huang, J., et al. (2022). Sub-alfvénic solar wind observed by the parker solar probe: Characterization of turbulence, anisotropy, intermittency, and switchback. *Astrophysical J. Lett.* 926, L1. doi:10.3847/2041-8213/ac4a5c

Barth, P., Helling, C., Stüeken, E. E., Bourrier, V., Mayne, N., Rimmer, P. B., et al. (2021). Moves–iv. modelling the influence of stellar xuv-flux, cosmic rays, and stellar energetic particles on the atmospheric composition of the hot jupiter hd 189733b. *Mon. Notices R. Astronomical Soc.* 502, 6201–6215. doi:10.1093/mnras/staa3989

Basri, G. (2021). *An introduction to stellar magnetic activity*. Bristol, UK: IOP Publishing, 2514–3433. doi:10.1088/2514-3433/ac2956

Brambles, O. J., Lotko, W., Zhang, B., Wiltberger, M., Lyon, J., and Strangeway, R. J. (2011). Magnetosphere sawtooth oscillations induced by ionospheric outflow. *Science* 332, 1183–1186. doi:10.1126/science.1202869

Cohen, O., Alvarado-Gómez, J. D., Drake, J. J., Harbach, L. M., Garraffo, C., and Fraschetti, F. (2022). Space-weather-driven variations in lyα absorption signatures of exoplanet atmospheric escape: MHD simulations and the case of AU mic b. *Astrophysical J.* 934, 189. doi:10.3847/1538-4357/ac78e4

Cohen, O., Drake, J. J., Glocer, A., Garraffo, C., Poppenhaeger, K., Bell, J. M., et al. (2014). Magnetospheric structure and atmospheric Joule heating of habitable planets orbiting M-dwarf stars. *Astrophysical J.* 790, 57. doi:10.1088/0004-637X/790/1/57

Deeg, H. J., and Belmonte, J. A. (2018). *Handbook of exoplanets*. Switzerland: Springer International Publishing. doi:10.1007/978-3-319-55333-7

do Nascimento, J., J. D., García, R. A., Mathur, S., Anthony, F., Barnes, S. A., Meibom, S., et al. (2014). Rotation periods and ages of solar analogs and solar twins revealed by the kepler mission. *Astrophysical J. Lett.* 790, L23. doi:10.1088/2041-8205/790/2/L23

Dong, C., Huang, Z., and Lingam, M. (2019). Role of planetary obliquity in regulating atmospheric escape: G-Dwarf versus M-dwarf earth-like exoplanets. *Astrophysical J. Lett.* 882, L16. doi:10.3847/2041-8213/ab372c

Dong, C., Huang, Z., Lingam, M., Tóth, G., Gombosi, T., and Bhattacharjee, A. (2017a). The dehydration of water Worlds via atmospheric losses. *Astrophysical J. Lett.* 847, L4. doi:10.3847/2041-8213/aa8a60

Dong, C., Jin, M., Lingam, M., Airapetian, V. S., Ma, Y., and van der Holst, B. (2018a). Atmospheric escape from the TRAPPIST-1 planets and implications for habitability. *Proc. Natl. Acad. Sci.* 115, 260–265. doi:10.1073/pnas.1708010115

Dong, C., Jin, M., and Lingam, M. (2020). Atmospheric escape from TOI-700 d: venus versus earth analogs. *Astrophysical J. Lett.* 896, L24. doi:10.3847/2041-8213/ab982f

Dong, C., Lee, Y., Ma, Y., Lingam, M., Bougher, S., Luhmann, J., et al. (2018b). Modeling martian atmospheric losses over time: Implications for exoplanetary climate evolution and habitability. *Astrophysical J. Lett.* 859, L14. doi:10.3847/2041-8213/aac489

Dong, C., Lingam, M., Ma, Y., and Cohen, O. (2017b). Is proxima centauri b habitable? A study of atmospheric loss. *Astrophysical J. Lett.* 837, L26. doi:10.3847/2041-8213/aa6438

Edelman, E., Redfield, S., Linsky, J. L., Wood, B. E., and Müller, H. (2019). Properties of the interstellar medium along sight lines to nearby planet-hosting stars. *Astrophysical J.* 880, 117. doi:10.3847/1538-4357/ab1f6d

Farrish, A. O., Alexander, D., Maruo, M., DeRosa, M., Toffoletto, F., and Sciola, A. M. (2019). Characterizing the magnetic environment of exoplanet stellar systems. *Astrophysical J.* 885, 51. doi:10.3847/1538-4357/ab4652

France, K., Fleming, B., Youngblood, A., Mason, J., Drake, J. J., Amerstorfer, U. V., et al. (2022). Extreme-ultraviolet stellar characterization for atmospheric physics and evolution mission: Motivation and overview. *J. Astronomical Telesc. Instrum. Syst.* 8, 14006. doi:10.1117/1.JATIS.8.1.014006

Fulton, B. J., Petigura, E. A., Howard, A. W., Isaacson, H., Marcy, G. W., Cargile, P. A., et al. (2017). The California-kepler survey. iii. a gap in the radius distribution of small planets. *Astronomical J.* 154, 109. doi:10.3847/1538-3881/aa80eb

Galarza, J. Y., Meléndez, J., and Cohen, J. G. (2016). Serendipitous discovery of the faint solar twin Inti 1. *A&A* 589, A65. doi:10.1051/0004-6361/201527477

Garcia-Sage, K., Glocer, A., Drake, J. J., Gronoff, G., and Cohen, O. (2017). On the magnetic protection of the atmosphere of proxima centauri b. *Astrophysical J. Lett.* 844, L13. doi:10.3847/2041-8213/aa7eca

Garcia-Sage, K., Moore, T., Pembroke, A., Merkin, V., and Hughes, W. (2015). Modeling the effects of ionospheric oxygen outflow on bursty magnetotail flows. *J. Geophys. Res. A Space Phys.* 120, 8723–8737. doi:10.1002/2015JA021228

Garraffo, C., Drake, J. J., Cohen, O., Alvarado-Gómez, J. D., and Moschou, S. P. (2017). The threatening magnetic and plasma environment of the TRAPPIST-1 planets. *Astrophysical J. Lett.* 843, L33. doi:10.3847/2041-8213/aa79ed

Garraffo, C., Drake, J. J., and Cohen, O. (2016). The space weather of proxima centauri b. *Astrophysical J. Lett.* 833, L4. doi:10.3847/2041-8205/833/1/L4

Glocer, A. (2016). *Coupling ionospheric outflow into magnetospheric models*. Hoboken, New Jersey: John Wiley & Sons, Inc. doi:10.1002/9781119066880.ch15

Grießmeier, J. M., Tabataba-Vakili, F., Stadelmann, A., Grenfell, J. L., and Atri, D. (2016). Galactic cosmic rays on extrasolar Earth-like planets. II. Atmospheric implications. *A&A* 587, A159. doi:10.1051/0004-6361/201425452

Gronoff, G., Arras, P., Baraka, S., Bell, J. M., Cessateur, G., Cohen, O., et al. (2020). Atmospheric escape processes and planetary atmospheric evolution. *J. Geophys. Res. (Space Phys.* 125, e27639. doi:10.1029/2019JA027639

Günther, M. N., Zhan, Z., Seager, S., Rimmer, P. B., Ranjan, S., Stassun, K. G., et al. (2020). Stellar flares from the first TESS data release: Exploring a new sample of M dwarfs. *Astronomical J.* 159, 60. doi:10.3847/1538-3881/ab5d3a

Harbach, L. M., Moschou, S. P., Garraffo, C., Drake, J. J., Alvarado-Gómez, J. D., Cohen, O., et al. (2021). Stellar winds drive strong variations in exoplanet evaporative outflow patterns and transit absorption signatures. *Astrophysical J.* 913, 130. doi:10.3847/1538-4357/abf63a

He, J., Cui, B., Yang, L., Hou, C., Zhang, L., Ip, W. H., et al. (2021). The encounter of the parker solar probe and a comet-like object near the Sun: Model predictions and measurements. *Astrophysical J.* 910, 7. doi:10.3847/1538-4357/abdf4a

Hu, J., Airapetian, V. S., Li, G., Zank, G., and Jin, M. (2022). Extreme energetic particle events by superflare-asssociated CMEs from solar-like stars. *Sci. Adv.* 8, eabi9743. doi:10.1126/sciadv.abi9743

Hussain, G. A. J., Alvarado-Gómez, J. D., Grunhut, J., Donati, J. F., Alecian, E., Oksala, M., et al. (2016). A spectro-polarimetric study of the planet-hosting G dwarf, HD 147513. *A&A* 585, A77. doi:10.1051/0004-6361/201526595

Jakosky, B., Brain, D., Chaffin, M., Curry, S., Deighan, J., Grebowsky, J., et al. (2018). Loss of the martian atmosphere to space: Present-day loss rates determined from maven observations and integrated loss through time. *Icarus* 315, 146–157. doi:10.1016/j.icarus.2018.05.030

Johnstone, C., Khodachenko, M., Lüftinger, T., Kislyakova, K., Lammer, H., and Güdel, M. (2019). Extreme hydrodynamic losses of Earth-like atmospheres in the habitable zones of very active stars. *Astronomy Astrophysics* 624, L10. doi:10.1051/0004-6361/201935279

Johnstone, C. P., Güdel, M., Lammer, H., and Kislyakova, K. G. (2018). Upper atmospheres of terrestrial planets: Carbon dioxide cooling and the Earth's thermospheric evolution. *Astronomy Astrophysics* 617, A107. doi:10.1051/0004-6361/201832776

Jolitz, R. D., Dong, C. F., Lee, C. O., Lillis, R. J., Brain, D. A., Curry, S. M., et al. (2017). A Monte Carlo model of crustal field influences on solar energetic particle precipitation into the Martian atmosphere. *J. Geophys. Res. (Space Phys.* 122, 5653–5669. doi:10.1002/2016JA023781

JWST Transiting Exoplanet Community Early Release Science Team (2022). Identification of carbon dioxide in an exoplanet atmosphere. *Nature*. doi:10.1038/s41586-022-05269-w

Kasper, J., Lazio, J., Romero-Wolf, A., Lux, J., and Neilsen, T. (2021). "The Sun radio interferometer space experiment (SunRISE) mission," in 2021 IEEE Aerospace Conference, Big Sky, MT, USA, 06-13 March 2021 (IEEE). doi:10.1109/AERO50100.2021.9438184

Ketzer, L., and Poppenhaeger, K. (2022). The influence of host star activity evolution on the population of super-earths and mini-neptunes. *Mon. Notices R. Astronomical Soc.* 518, 1683–1706. doi:10.1093/mnras/stac2643

Khodachenko, M. L., Shaikhislamov, I. F., Lammer, H., Miroshnichenko, I. B., Rumenskikh, M. S., Berezutsky, A. G., et al. (2021). The impact of intrinsic magnetic field on the absorption signatures of elements probing the upper atmosphere of HD209458b. *Mon. Notices R. Astronomical Soc.* 507, 3626–3637. doi:10.1093/mnras/stab2366

Kopparapu, R., Arney, G., Domagal-Goldman, S., Schwieterman, E., Hartnett, H., Kiang, N., et al. (2021). Strange new Worlds: Comparative planetology of exoplanets and the solar system. *Bull. AAS* 53, 106. doi:10.3847/25c2cfeb.479f6cc8

Laneuville, M., Dong, C., O'Rourke, J. G., and Schneider, A. C. (2020). "Magnetic fields on rocky planets," in *Planetary diversity* (Bristol, United Kingdom: IOP Publishing), 2514–3433. doi:10.1088/2514-3433/abb4d9ch3

Lazio, J., Hallinan, G., Airapetian, A., Brain, D. A., Clarke, T. E., Dolch, T., et al. (2019). Magnetic fields of extrasolar planets: Planetary interiors and habitability. *Bull. Am. Astronomical Soc.* 51, 135.

Lecavelier Des Etangs, A., Ehrenreich, D., Vidal-Madjar, A., Ballester, G. E., Désert, J. M., Ferlet, R., et al. (2010). Evaporation of the planet HD 189733b observed in H I Lyman-α. *A&A* 514, A72. doi:10.1051/0004-6361/200913347

Lee, Y., Dong, C., and Tenishev, V. (2021). Exosphere modeling of proxima b: A case study of photochemical escape with a venus-like atmosphere. *Astrophysical J.* 923, 190. doi:10.3847/1538-4357/ac26bb

Lingam, M., Dong, C., Fang, X., Jakosky, B. M., and Loeb, A. (2018). The propitious role of solar energetic particles in the origin of life. *Astrophysical J.* 853, 10. doi:10.3847/1538-4357/aa9fef

Linsky, J. (2019). *Lecture notes in physics*. Cham: Springer International Publishing.Host stars and their effects on exoplanet atmospheres an introductory overview

Lynch, B., Wood, B., Jin, M., Török, T., Sun, X., Palmerio, E., et al. (2022). *Connecting solar and stellar flares/cmes: Expanding heliophysics to encompass exoplanetary space weather*. arXiv preprint arXiv:2210. doi:10.48550/arXiv.2210.06476

Moore, T. E., Brenneman, K. S., Chappell, C. R., Clemmons, J. H., Collinson, G. A., Cully, C., et al. (2016). *Future atmosphere-ionosphere-magnetosphere coupling study requirements*. Hoboken, New Jersey: John Wiley & Sons, Inc. doi:10.1002/9781119066880.ch28

Namekata, K., Maehara, H., Honda, S., Notsu, Y., Okamoto, S., Takahashi, J., et al. (2022). Probable detection of an eruptive filament from a superflare on a solar-type star. *Nat. Astron.* 6, 241–248. doi:10.1038/s41550-021-01532-8

National Academies of Sciences (2021). *Pathways to Discovery in Astronomy and astrophysics for the 2020s*. Washington, DC: The National Academies Press. doi:10.17226/26141 Engineering, and medicine

National Research Council (2013). *Solar and space physics*. Washington, DC: A Science for a Technological SocietyThe National Academies Press. doi:10.17226/13060

National Research Council (2003). *The Sun to the Earth – and beyond: A decadal research strategy in solar and space physics*. Washington, DC: The National Academies Press. doi:10.17226/10477

Parsay, K., Yienger, K., Rowland, D., Moore, T., Glocer, A., and Garcia-Sage, K. (2021). On formation flying in low Earth mirrored orbits — a case study. *Acta Astronaut.* 184, 142–149. doi:10.1016/j.actaastro.2021.04.005

Porto de Mello, G. F., da Silva, R., da Silva, L., and de Nader, R. V. (2014). A photometric and spectroscopic survey of solar twin stars within 50 parsecs of the Sun. *A&A* 563, A52. doi:10.1051/0004-6361/201322277

Ribas, I., Guinan, E. F., Gudel, M., and Audard, M. (2005). Evolution of the solar activity over time and effects on planetary atmospheres. i. high-energy irradiances (1–1700 a). *Astrophysical J.* 622, 680–694. doi:10.1086/427977

Saur, J., Grambusch, T., Duling, S., Neubauer, F. M., and Simon, S. (2013). Magnetic energy fluxes in sub-alfvénic planet star and moon planet interactions. *A&A* 552, A119. doi:10.1051/0004-6361/201118179

Schwieterman, E. W., Olson, S. L., Pidhorodetska, D., Reinhard, C. T., Ganti, A., Fauchez, T. J., et al. (2022). Evaluating the plausible range of N2O biosignatures on exo-earths: An integrated biogeochemical, photochemical, and spectral modeling approach. *Astrophysical J.* 937, 109. doi:10.3847/1538-4357/ac8cfb

Sciola, A., Toffoletto, F., Alexander, D., Sorathia, K., Merkin, V., and Farrish, A. (2021). Incorporating inner magnetosphere current-driven electron acceleration in numerical simulations of exoplanet radio emission. *Astrophysical J.* 914, 60. doi:10.3847/1538-4357/abefd9

Segura, A., Kasting, J. F., Meadows, V., Cohen, M., Scalo, J., Crisp, D., et al. (2005). Biosignatures from earth-like planets around M dwarfs. *Astrobiology* 5, 706–725. doi:10.1089/ast.2005.5.706

Segura, A., Walkowicz, L. M., Meadows, V., Kasting, J., and Hawley, S. (2010). The effect of a strong stellar flare on the atmospheric chemistry of an earth-like planet orbiting an M dwarf. *Astrobiology* 10, 751–771. doi:10.1089/ast.2009.0376

Shaikhislamov, I. F., Khodachenko, M. L., Lammer, H., Berezutsky, A. G., Miroshnichenko, I. B., and Rumenskikh, M. S. (2019). 3D Modeling of absorption by various species for hot jupiter HD209458b. *Mon. Notices R. Astronomical Soc.* 491, 3435–3447. doi:10.1093/mnras/stz3211

Slavin, J. A., Middleton, H. R., Raines, J. M., Jia, X., Zhong, J., Sun, W. J., et al. (2019). Messenger observations of disappearing dayside magnetosphere events at mercury. *J. Geophys. Res. Space Phys.* 124, 6613–6635. doi:10.1029/2019JA026892

Tabataba-Vakili, F., Grenfell, J. L., Grießmeier, J. M., and Rauer, H. (2016). Atmospheric effects of stellar cosmic rays on Earth-like exoplanets orbiting M-dwarfs. *A&A* 585, A96. doi:10.1051/0004-6361/201425602

Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., et al. (2020). A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* 586, 248–256. doi:10.1038/s41586-020-2780-0

Tilley, M. A., Segura, A., Meadows, V., Hawley, S., and Davenport, J. (2019). Modeling repeated M dwarf flaring at an earth-like planet in the habitable zone: Atmospheric effects for an unmagnetized planet. *Astrobiology* 19, 64–86. doi:10.1089/ast.2017.1794

Toriumi, S., Airapetian, V. S., Namekata, K., and Notsu, Y. (2022). Universal scaling laws for solar and stellar atmospheric heating: Catalog of power-law index between solar activity proxies and various spectral irradiances. *Astrophysical J. Suppl. Ser.* 262, 46. doi:10.3847/1538-4365/ac8b15

Toriumi, S., and Airapetian, V. S. (2022). Universal scaling laws for solar and stellar atmospheric heating. *Astrophysical J.* 927, 179. doi:10.3847/1538-4357/ac5179

Turner, J. D., Zarka, P., Grießmeier, J-M., Lazio, J., Cecconi, B., Emilio Enriquez, J., et al. (2021). The search for radio emission from the exoplanetary systems 55 Cancri, υ Andromedae, and τ Boötis using LOFAR beam-formed observations. *A&A* 645, A59. doi:10.1051/0004-6361/201937201

Vedantham, H. K., Callingham, J. R., Shimwell, T. W., Tasse, C., Pope, B. J. S., Bedell, M., et al. (2020). Coherent radio emission from a quiescent red dwarf indicative of star–planet interaction. *Nat. Astron.* 4, 577–583. doi:10.1038/s41550-020-1011-9

Venot, O., Rocchetto, M., Carl, S., Hashim, A. R., and Decin, L. (2016). Influence of stellar flares on the chemical composition of exoplanets and spectra. *Astrophysical J.* 830, 77. doi:10.3847/0004-637x/830/2/77

Veronig, A. M., Odert, P., Leitzinger, M., Dissauer, K., Fleck, N. C., and Hudson, H. S. (2021). Indications of stellar coronal mass ejections through coronal dimmings. *Nat. Astron.* 5, 697–706. doi:10.1038/s41550-021-01345-9

Vidotto, A. A., Llama, J., Jardine, M., Helling, C., and Wood, K. (2011). Shock formation around planets orbiting M-dwarf stars. *Astron. Nachrichten* 332, 1055–1061. doi:10.1002/asna.201111622

Weber, C., Lammer, H., Shaikhislamov, I. F., Chadney, J., Khodachenko, M., Grießmeier, J. M., et al. (2017). How expanded ionospheres of hot jupiters can prevent escape of radio emission generated by the cyclotron maser instability. *Mon. Notices R. Astronomical Soc.* 469, 3505–3517. doi:10.1093/mnras/stx1099

Wood, B. E., Müller, H. R., Redfield, S., Konow, F., Vannier, H., Linsky, J. L., et al. (2021). New observational constraints on the winds of m dwarf stars. *Astrophysical J.* 915, 37. doi:10.3847/1538-4357/abfda5

Wood, B. E., Redfield, S., Linsky, J. L., Muller, H. R., and Zank, G. P. (2005). Stellar lyα emission lines in the *Hubble Space Telescope* archive: Intrinsic line fluxes and absorption from the heliosphere and astrospheres. *Astrophysical J. Suppl. Ser.* 159, 118–140. doi:10.1086/430523

Zaitsev, V., and Shaposhnikov, V. (2022). Plasma maser in the plasmasphere of hd 189733b. *Mon. Notices R. Astronomical Soc.* 513, 4082–4089. doi:10.1093/mnras/stac1140