

# Star-Exoplanet Interactions: A Growing Interdisciplinary Field in Heliophysics

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## 2 ABSTRACT

3 Traditionally, heliophysics is characterized as the study of the near-Earth space environment,  
4 where plasmas and neutral gases originating from the Earth, the Sun, and other solar system  
5 bodies interact in ways that are detectable only through in-situ or close-range (usually within  
6 ~10 AU) remote sensing. As a result, heliophysics has data from the space environment  
7 around a handful of solar system objects, in particular the Sun and Earth. Comparatively,  
8 astrophysics has data from an extensive array of objects, but is more limited in temporal, spatial,  
9 and wavelength information from any individual object. Thus, our understanding of planetary  
10 space environments as a complex, multi-dimensional network of specific interacting systems

11 may in the past have seemed to have little to do with the highly diverse space environments  
12 detected through astrophysical methods. Recent technological advances have begun to bridge  
13 this divide. Exoplanetary studies are opening up avenues to study planetary environments beyond  
14 our solar system, with missions like Kepler, TESS, and JWST, along with increasing capabilities  
15 of ground-based observations. At the same time, heliophysics studies are pushing beyond the  
16 boundaries of our heliosphere with Voyager, IBEX, and the future IMAP mission.

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

30 **Keywords:** heliophysics, exoplanets, space weather, multidisciplinary, stellar wind, magnetosphere, ionosphere, stellar activity

## 1 INTRODUCTION

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

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

49 The field of exoplanets is becoming a major area of interdisciplinary research that considers the full  
50 complexity of planets in the universe. It is essential that researchers from across the heliophysics community  
51 participate in exoplanet studies so that important insights gained from heliophysics are brought to the table

52 by experts in the field. Such interdisciplinary studies have been recognized as crucial in the decadal surveys  
53 and community white papers of other divisions and past heliophysics decadal surveys (e.g., National  
54 Research Council, 2003, 2013; National Academies of Sciences, Engineering, and Medicine, 2021;  
55 Koppurapu et al., 2021) as well as overview books on exoplanets and their stars (e.g., Basri, 2021; Linsky,  
56 2019; Deeg and Belmonte, 2018). This recognition provides an opportunity to expand the contribution  
57 of heliophysics, raising its profile to be acknowledged as a field with universal impact. It will also build  
58 intra-disciplinary collaborations that tie together heliophysics subfields, yielding scientific applications  
59 well beyond exoplanet studies.

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

## 2 RESEARCH AREAS

### 77 2.1 Stellar Activity/Sun as a Star

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

94 drivers such as coronal mass ejections (CMEs) and stellar energetic particles (SEPs). A more detailed  
95 understanding of stellar energetic output is needed to assess the influences that lead to both the Earth's  
96 present-day habitability, and the possible habitability of exoplanets through their lifetimes.

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

## 107 2.2 Astrospheres

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

123 From the heliophysics perspective, Parker Solar Probe is opening a new era of in situ observations  
124 of the very inner heliosphere, including the regime within about 20 solar radii where the solar wind is  
125 sub-Alfvénic, that is, having a bulk plasma velocity less than the local Alfvén speed,  $v_A = B/\sqrt{4\pi\rho}$ , where  
126  $\rho$  is the mass density and  $B$  is the magnetic field magnitude (e.g., He et al., 2021; Bandyopadhyay et al.,  
127 2022). This achievement in heliospheric observations is directly relevant to the exoplanet context, since  
128 many terrestrial exoplanets orbiting M stars are expected to fall within their host stars' Alfvén surfaces  
129 (the boundary between sub- and super-Alfvénic wind flow) for part or all of their orbital periods (e.g.,  
130 Garraffo et al., 2016; Farrish et al., 2019). Outside the Alfvén surface, upstream-directed interactions from  
131 the planets to the Sun cannot occur. The solar wind forms a bow shock ahead of any planetary obstacles.  
132 This bow shock slows and redirects the solar wind, influencing the interaction of the solar wind with the  
133 planet's magnetosphere, ionosphere, and atmosphere. Inside the Alfvén surface, by contrast, the flow of  
134 energy may occur in both directions, toward and away from the star, allowing direct interaction between  
135 the planet and its host star (e.g. (Cohen et al., 2014; Saur, J. et al., 2013)). Though some close-in planets on  
136 extremely short orbital periods may be moving fast enough to produce a bow shock ahead of the planet as

137 its Keplerian speed exceeds the local sound speed (for example, WASP-12b (Vidotto et al., 2011)), still  
138 other close-in planets are expected to experience sub-Alfvénic interaction with their host star winds for  
139 some or most of their orbits (for example, TRAPPIST-1e (Harbach et al., 2021) or AU Mic b Cohen et al.  
140 (2022)), even when the orbital speed of the planet is accounted for. It is therefore important to understand  
141 the interaction of planetary magnetospheres and atmospheres with their host star winds under a variety of  
142 conditions. In situ data of solar wind speeds and magnetic features such as switchbacks and shocks provide  
143 a better picture than ever before of the behavior of the Sun's very inner heliosphere. As a complement, the  
144 extension of solar wind and magnetospheric models to the sub-Alfvénic regime, and the transition between  
145 sub- and super-Alfvénic regimes, can provide more context for possible interactions between M stars and  
146 their extremely close-in planets. These cases of sub-Alfvénic interactions or transitions between sub- and  
147 super-Alfvénic conditions demonstrate an area where heliophysics observations are uniquely poised to  
148 help answer scientific questions in exoplanet systems, and where solar missions and heliophysics modelers  
149 can provide expertise to researchers in other exoplanet-related disciplines.

150 The 'superflare' extremes of stellar activity, and their potential planetary and exoplanetary consequences,  
151 have garnered considerable interest from heliophysics, planetary science, and astrophysics. By analogy with  
152 energetic solar flare events, stellar flares are expected to be associated with stellar CMEs, shocks, and stellar  
153 energetic particles (SEPs) whose properties are a critical factor of exoplanet habitability (Airapetian et al.,  
154 2020). The search for these astrospheric counterparts of stellar superflares along with stellar prominence  
155 and filament eruptions is a growing area of research and requires coordinated multi-observatory, multi-  
156 wavelength observations of active stars. Recent studies report several potential detections of stellar CMEs  
157 associated with (super-)flares on G, K and M-dwarfs. The observational signatures are based on detection  
158 of the Doppler shifted absorption/emission of optical/UV/X-ray emissions lines, coronal XUV/FUV  
159 dimming, radio bursts, and continuous absorption of X-rays due to eruptive filaments or passing CMEs  
160 (Veronig et al., 2021; Namekata et al., 2022). While past studies so far have relied on a single observational  
161 technique, coordinated studies to search for multiple signatures are required to constrain the properties  
162 of these ejections. Such coordinated observational campaigns are strongly encouraged, as they would  
163 provide critical constrains for modeling efforts of stellar CMEs in various coronal environments of active  
164 stars (see review by Lynch et al. 2022). Hu et al. (2022) modeled the extreme energetic particle events  
165 accelerated by superflare-associated CMEs from solar-like stars. Our knowledge so far depends on such  
166 data-constrained modeling capabilities, with the same tools used for our own space weather research as for  
167 exoplanetary space environments over a range of stellar activity assumptions. These modeling activities  
168 provide knowledge of not only astrospheric environments but also of our own solar system under a range of  
169 possible circumstances, and of the uniqueness of our situation among the broad populations of extrasolar  
170 systems.

## 171 **2.3 Exoplanet Magnetospheres**

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

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

191 Stellar XUV-driven atmospheric heating produces the significant expansion of of the upper atmospheres  
192 of rocky and giant exoplanets that in some cases can transition into hydrodynamic escape (Johnstone et al.,  
193 2018, 2019). The interaction between the expanding upper atmospheres of rotating hot Jupiters within  
194 their large-scale (dipole-like) magnetic fields drives the formation of a magnetodisk located outside the  
195 “Alfvénic surface” from the planet (Khodachenko et al., 2021). For close-in exoplanets, the tidal force and  
196 XUV driven heating are strong contributors to drive the expansion of planetary atmosphere beyond the  
197 Roche lobe and to accelerate its material in the form of a double stream planetary wind at the day- and  
198 night-sides of the planet (Shaikhislamov et al., 2019).

199 Knowledge about and accurate modeling of exoplanetary magnetic fields could constrain our  
200 understanding of planetary responses to their space environment and evolutionary path (Dong et al.,  
201 2019, 2020). In the Solar System, planetary magnetic fields can be probed via *in situ* measurements from  
202 spacecraft. For exoplanets, one of the few means of constraining the presence of exoplanetary magnetic  
203 fields is by their interactions with the host stars' stellar winds. Electron cyclotron masers operating in the  
204 polar regions of planets with planetary-scale magnetic fields and sourced by magnetic field-stellar wind  
205 interactions may be detectable over interstellar distances. Two potential observations of radio emission  
206 resulting from exoplanet magnetospheric processes have been found to date, from the hot Jupiter  $\tau$  Boo b  
207 (Turner, Jake D. et al., 2021) and an otherwise unconfirmed Earth-size planet (Vedantham et al., 2020).  
208 However, in dense plasmaspheres of close-in hot exoplanets around young G and K type stars, where  
209 plasma (Langmuir) frequency,  $f_L$ , gets close to the electron gyrofrequency,  $f_c$ , traditional ECMI generation  
210 mechanisms are likely not efficient (Weber et al., 2017). The account of plasmasphere cut-off (i.e., breaking  
211 of the ECMI condition  $f_L < 0.3f_c$ ) constitutes the specifics of exoplanetary radio emission problem, as  
212 compared to similar cases in the Solar System. In these cases, plasma maser mechanism of exoplanetary  
213 radio emission can be efficient in dense and weakly magnetized (or even non-magnetized) plasma (Zaitsev  
214 and Shaposhnikov, 2022). Similar mechanisms are known to play an important role in the generation of  
215 radio emission in solar corona, as well as in magnetospheres of the Solar System planets.

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

220 The importance of these questions is recognized on an interdisciplinary basis, and continued collaboration  
221 between heliophysics modelers and radio astronomers to predict the conditions necessary for detection  
222 and interpret any future detections is crucial. The report of the Panel on Exoplanets, Astrobiology, and

223 the Solar System, from the *Pathways to Discovery Astronomy & Astrophysics Decadal Survey*, stated,  
224 “For terrestrial planets, surface/atmosphere exchange mechanisms mediate atmospheric composition, and  
225 planetary magnetic fields can illuminate processes occurring deep in a planet’s interior, while providing  
226 critical insights into how the planet’s atmosphere interacts with the space environment.” In the *Origins,*  
227 *Worlds, and Life Planetary Science & Astrobiology Decadal Survey* report, two Priority Science Question  
228 Topics had elements involving the existence of planetary magnetic fields and their interactions with the  
229 solar wind, Question 6: “Solid body atmospheres, exospheres, magnetospheres, and climate evolution”  
230 and Question 12: “Exoplanets.” Further, the recommendation for the Uranus Orbiter & Probe as the next  
231 Planetary Science Flagship mission was based on the importance of studying its magnetosphere and its  
232 interaction with the solar wind as “ground truth” for ice giants in other planetary systems.

## 233 2.4 Exoplanet Ionospheres

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

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

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

## 257 2.5 Exoplanet Atmospheres

258 As explained in the previous section, a star’s activity has a major impact on the atmospheres of any  
259 planets orbiting it, and close-in exoplanets are subjected to more extreme conditions than any observable  
260 in our Solar System. This gives a unique opportunity to understand the impact of extreme events on the  
261 chemistry and climate of rocky exoplanets, the critical factors for their habitability. For example, stellar  
262 energetic particles (SEPs) - a source of ionizing radiation - from young solar-like stars during extreme space  
263 weather events could have modified planetary atmospheric compositions and may explain the formation of  
264 potent greenhouse gases and prebiotic molecules on early Earth and Mars (Airapetian et al., 2016; Jolitz

265 et al., 2017; Lingam et al., 2018). Analogously, stellar activity, including photons and particles emitted  
266 during CMEs and Stellar Proton Events (SPEs), and cosmic rays (both stellar and galactic) could affect  
267 the chemical composition of the atmosphere including biosignatures. The extent to which a particular  
268 biosignature might be detectable would depend upon the stellar activity level, the specific molecule under  
269 consideration, and the endogenous production rate of that molecule on the planet (e.g., Segura et al., 2005;  
270 Tabataba-Vakili et al., 2016; Griebmeier et al., 2016). Potential biosignature molecules can be directly  
271 destroyed by energetic particles or their downstream photochemical products, reducing their abundance  
272 and thus detectability at a given rate of planetary production (Tabataba-Vakili et al., 2016). Particles  
273 could have enough energy to split the nitrogen molecule,  $N_2$ , producing  $NO_x$  ( $NO$  and  $NO_2$ ), which can  
274 destroy the potential biosignature  $O_3$  (Segura et al., 2005, 2010; Tilley et al., 2019) or could contribute to  
275 create biosignature “false positives” by catalyzing the abiotic generation of biosignature molecules such  
276 as  $N_2O$  (Airapetian et al., 2016, 2020). Potential false positive scenarios could be predicted by extensive  
277 characterization of the host star or identified by searching for the spectrally active non-biosignature gases  
278 that are predicted to form in combination with the putative biosignatures (e.g., Tabataba-Vakili et al., 2016;  
279 Schwieterman et al., 2022). For example, abiotic production of  $N_2O$  would be accompanied by more  
280 robust production of  $NO_2$ ,  $HNO_3$ , and/or  $HCN$  (Ibid.). The abiotic production or destruction of greenhouse  
281 gas molecules such as nitrous oxide via stellar activity could impact planetary climate, depending on  
282 the abundances of the produced or destroyed gases and their endogenous production rates (e.g., Tian  
283 et al., 2020; Airapetian et al., 2016, 2020). For hot Jupiters, photons and particles can influence detectable  
284 chemical species (e.g.  $NH_3$ ,  $HCN$ ). In general, the photochemistry driven by all phenomena associated  
285 with stellar activity should be considered when predicting or analyzing the spectra of exoplanets (Venot  
286 et al., 2016; Barth et al., 2021).

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

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

### 3 OBSERVATIONAL OPPORTUNITIES AND CHALLENGES

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

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

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

346 Astronomical observations are increasingly expected to make measurements that are highly relevant  
347 to the stellar and exoplanetary space environments, providing the crucial measurements needed to test  
348 understanding of basic heliophysics processes. Studies of the radio emission generated by CMEs from  
349 other stars or the magnetospheric emissions from exoplanets or both would be enabled by space-based

350 observations at a few Megahertz and below, e.g., as a successor to the Sun Radio Interferometer Space  
351 Experiment (SunRISE, Kasper et al. (2021)). The TESS mission provides extensive data from nearby  
352 star systems, including observations of stellar flares (Günther et al., 2020). JWST has already reported  
353 a detection of a CO<sub>2</sub> atmosphere (Team, 2022) and can be expected to vastly extend our knowledge of  
354 exoplanet atmospheric compositions.

#### 4 MODELING OPPORTUNITIES AND CHALLENGES

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

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

375 While the above examples detail a few of the many cases where exoplanetary systems with extreme  
376 conditions may require extensive new physics to model, the considerable expertise in sophisticated and  
377 validated models that have been developed or are becoming available within the heliophysics community  
378 serves as an excellent starting point for development of exoplanetary models even in extreme conditions.  
379 These models not only include the important magnetic coupling of planetary magnetic fields to a dynamic  
380 stellar wind, but also include the equally important effects of the ionosphere and atmospheric outflow (e.g.  
381 Brambles et al., 2011; Garcia-Sage et al., 2015; Glocer, 2016; Garcia-Sage et al., 2015; Airapetian et al.,  
382 2017; Dong et al., 2017a, 2018a; Airapetian et al., 2020). In addition, there is a considerable amount to  
383 be learned from applying heliophysics models to less extreme situations, which are likely to be of more  
384 interest in addressing the question of habitability.

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

## 5 COLLABORATION OPPORTUNITIES, CHALLENGES, AND RECOMMENDATIONS

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

### CONFLICT OF INTEREST STATEMENT

410 The authors declare that the research was conducted in the absence of any commercial or financial  
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### AUTHOR CONTRIBUTIONS

412 KG-S organized and led the discussions that gave rise to this paper and that developed the recommendations  
413 therein. KG-S and AF organized the writing of the paper, wrote major portions of the paper, and revised  
414 the entirety of the paper for scientific content and scope. VSA, DA, OC, SD-G, CD, GG, AH, JLa, JLu, ES,  
415 ASc, ASe, FT, and JV contributed to the conception of the paper and generated crucial content, references,  
416 and revisions to the scientific content and scope. MRA, KB, TC, and GR contributed text and revisions of  
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