





# The Importance of Local Interstellar Conditions on the Galactic Cosmic-Ray Spectrum at Exoplanets

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## Abstract

Galactic cosmic rays (GCRs) are highly energetic particles that can have significant effects on the atmospheres and potentially also surfaces of (exo)planets and moons. Their propagation through the Sun’s heliosphere and their interaction with planetary bodies have been widely studied in the solar system (e.g., Earth, Mars, Venus, and Europa). There is currently much interest in exoplanetary science, particularly in terms of characterizing the potential habitability of exoplanetary environments. As a consequence of this, models have been developed to quantify the effect of GCRs on exoplanet systems. However, many such studies assume Earth-like (1 au) GCR fluxes. Here we will demonstrate why this is not a reasonable assumption. We briefly discuss the journey that GCRs make from their birth to the arrival at an exoplanet, and discuss the various implications this will have on GCR fluxes. We demonstrate the importance of understanding the specific local interstellar medium (ISM) that an exoplanetary system resides within, as this determines the size of the astrosphere of the host star. This has strong implications for the modulation of GCR fluxes throughout an astrosphere. We estimate how GCR proton fluxes at 1 au (from the Sun) would be different from current values if the solar system was embedded in a different ISM environment. Furthermore, we provide estimates of the wide range of possible GCR proton fluxes at the exoplanets Kepler-20f and Kepler-88c using previously published estimates for the local ISM parameters at these bodies.

*Unified Astronomy Thesaurus concepts:* [Habitable planets \(695\)](#); [Exoplanets \(498\)](#); [Astrospheres \(107\)](#); [Galactic cosmic rays \(567\)](#)

## 1. Introduction

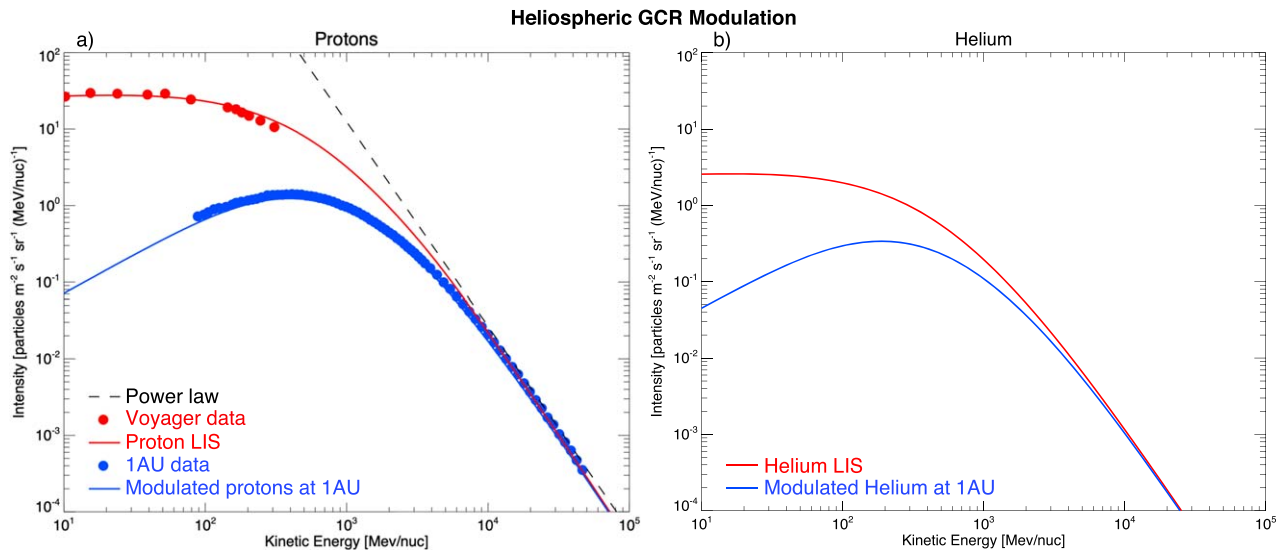
Galactic cosmic rays (GCRs) are highly energetic charged particles with energies of  $10^6$  to  $>10^{13}$  eV (Bazilevskaya et al. 2008). GCRs originate from outside the solar system and precipitate onto planetary atmospheres and surfaces. The Earth’s magnetic field deflects GCRs as a function of their kinetic energy, reducing the flux that impacts the atmosphere, while at Venus, the entire GCR spectrum interacts directly with the atmosphere because the planet is unmagnetized. For planets with dense atmospheres (such as, e.g., Earth, Venus, the giant planets), most low-energy GCRs are absorbed in the upper atmosphere, while GCRs with energies  $>10^3$  MeV produce widespread secondary particle cascades (or “showers”) and can thus affect the deep atmosphere and potentially even the surface of planetary bodies (e.g., Nordheim et al. 2015). GCRs therefore represent a driver of atmospheric ionization and chemistry, and may also be an important factor controlling atmospheric electricity at planetary and exoplanetary bodies (e.g., Helling et al. 2016). At Mars, which lacks a dense atmosphere, GCRs are able to pass through the atmosphere relatively unimpeded and the surface has therefore been heavily processed by GCR radiation. Thus, the GCRs’ secondary particle cascades occur in the top  $\sim 1$  m of the Martian soil (e.g., Hassler et al. 2014). Similarly, GCRs can precipitate onto the surface of the Jovian moon Europa, which also lacks a substantial atmosphere. However, since Europa orbits deep inside Jupiter’s magnetosphere, it is therefore shielded from the majority of the GCR flux (Nordheim et al. 2019).

GCR precipitation is a topic that also requires careful understanding in the context of exoplanets. Unlike the solar system, where the GCR flux spectrum has been measured and is relatively well understood, we do not know how the GCR flux spectrum will vary at any particular exoplanet. Therefore, several assumptions must be made in studies trying to quantify GCR effects at exoplanets. In this Letter we discuss the origins of GCRs, their propagation through the interstellar medium (ISM) of the Milky Way, and their propagation through a stellar astrosphere. This allows us to understand how the various local conditions at an exoplanetary system will change the resulting GCR flux spectrum, and how this knowledge could be applied to future exoplanet GCR studies. We also show how some of these underlying conditions can change the GCR spectrum for the exoplanetary systems Kepler-20 and Kepler-88.

## 2. Origin of GCRs and Their Propagation in the ISM

GCRs are primarily produced by diffusive shock acceleration (a form of first-order Fermi acceleration) at supernova remnants (e.g., Malkov & Drury 2001; Ackermann et al. 2013). The theoretical flux spectrum  $f(E)$ , where  $E$  is the energy of the GCR particle, derived from diffusive shock acceleration mechanism follows a power law,  $f(E) \propto E^{-q}$ . This matches the detected GCR proton flux spectrum at Earth for energies greater than  $>10^4$  MeV where the exponent,  $q$ , is observed to be  $\sim 2.7$  (below this energy, the GCRs have been heavily attenuated by the heliosphere by the time they are detected at 1 au).

It is believed that the spectrum of GCRs in the local interstellar spectrum (LIS—i.e., the GCR spectrum in the ISM that the solar system resides within) is similar throughout the galactic disk (e.g., Strong et al. 2007), and that there is a “sea” of GCRs that pervade throughout the Milky Way, and provide a homogeneous GCR background. However, as the GCRs propagate away from their



**Figure 1.** GCR spectra for (a) protons and (b) helium. The red line is the local interstellar spectrum (LIS) function as described by Bischoff et al. (2019). The overlaid red dots are proton data from Voyager 1 (Cummings et al. 2016). The blue line is the modulated LIS at 1 au estimated using our modulation code, while the overlaid blue dots show GCR protons at 1 au measured by PAMELA from 2008 November 19–December 15 (Adriani et al. 2013).

source region, the GCR spectrum may exhibit variations on small scales. For example, close proximity to acceleration regions will likely cause variation, especially at lower energies of  $<10^4$  MeV.  $\gamma$ -ray observations have been considered a unique way to probe GCR intensities in other locations in the Milky Way (e.g., Bloemen et al. 1986; Casanova et al. 2010). As GCRs propagate throughout the Milky Way, they interact with matter and through inelastic collisions produce  $\gamma$ -rays.  $\gamma$ -ray observations from eight nearby giant molecular clouds (located at distances  $<500$  pc) found variations in the spectra for energies  $<10^4$  MeV, showing that there are local variations in the GCR spectrum throughout the galaxy (Yang et al. 2014). Abdo et al. (2007) found that in the Cygnus Region (coincidentally, where the Kepler field of view is located), the GCR spectrum is harder ( $q \sim 2.3$ ) compared to that experienced by our solar system. Recently, however, it has been shown that the GCR spectrum is uniform within the local ( $\sim 200$  pc) galactic environment (Prokhorov & Colafrancesco 2018). Aharonian et al. (2020) argued that observed variations of the GCR spectrum are a localized effect due to the presence of giant molecular clouds, and that the GCR environment is in fact a largely uniform “sea” for galactocentric distances  $>4$  kpc (the solar system is located at  $\sim 8$  kpc).

Based on recently published studies, it may therefore be incorrect to assume that the GCR LIS that is used for the solar system is also applicable for every exoplanetary local interstellar spectrum (*exoLIS*). A more robust characterization of the *exoLIS* would be to model the propagation of GCRs throughout the Galaxy. One such model is the GALPROP transport code (Moskalenko & Strong 1998), which is widely used to interpret remote  $\gamma$ -ray observations and GCR measurements made locally within our solar system. Such a study will be the focus of a future paper. In this Letter, we focus on how the propagation of GCRs described by an *exoLIS* can vary within an astrosphere and how this propagation is dependent on the local interstellar environment. For the purposes of the present study, we therefore assume that the GCR “sea” is uniform for locations outside the galactic center. Kepler-20 and Kepler-88 both lie at similar radial distances from the galactic center as the Sun, so we assume here that their *exoLISes* will be similar to the LIS of the solar system.

### 3. GCR Propagation through the Heliosphere and an Astrosphere

The propagation and subsequent modulation of the GCR flux spectrum throughout the heliosphere (or for exoplanetary systems, their astrospheres) start with the LIS. Until recently, the correct shape of the solar system LIS was only theorized and inferred using propagation models based on measurements made near Earth (at 1 au). However, with the recent crossing of Voyager 1 through the heliopause (e.g., Gurnett et al. 2013; Stone et al. 2013), we can now define a LIS based on actual in situ measurements. Voyager 1 and Voyager 2 crossed the heliopause at 122 and 119 au from the Sun, respectively (Richardson et al. 2019). Here, in Figure 1 we show the functional forms of the LIS proton and He spectra as described by Bischoff et al. (2019) based on Voyager 1 GCR measurements made after the spacecraft crossed the heliopause. The resulting LIS proton spectrum, calculated using Equation (14) of Bischoff et al. (2019), is shown in Figure 1(a) (red line) alongside GCR proton measurements from the Cosmic-Ray Subsystem (CRS) instrument on board Voyager 1 (red dots; Cummings et al. 2016). Also shown are observations of GCRs at 1 au made by the Earth-orbiting PAMELA spacecraft (blue dots; Adriani et al. 2013). Similarly, Figure 1(b) shows the LIS for He calculated using Equation (15) of Bischoff et al. (2019). These observations show how the GCR spectrum is reduced by its passage through the heliosphere to the orbit of Earth at 1 au. In this Letter we focus on GCR protons to illustrate and explore how this modulation may vary at other stars and their exoplanets. We note that GCR He accounts for  $\sim 12\%$  of the total GCR number flux (e.g., Simpson 1983), and therefore should be considered in simulation studies seeking to carry out detailed GCR modeling.

In Figure 1 we also show the results of the GCR modulation model we use throughout the Letter. The modulation of cosmic rays through the Sun’s heliosphere has been studied extensively, and the first approximation of cosmic-ray transport using the Fokker–Planck equation was proposed by Parker (1965). The full solution is rarely used due to its complexity. Here we use the spherically symmetric or one-dimensional

solution (i.e., Fisk 1971 Equation 20 from Caballero-Lopez & Moraal 2004):

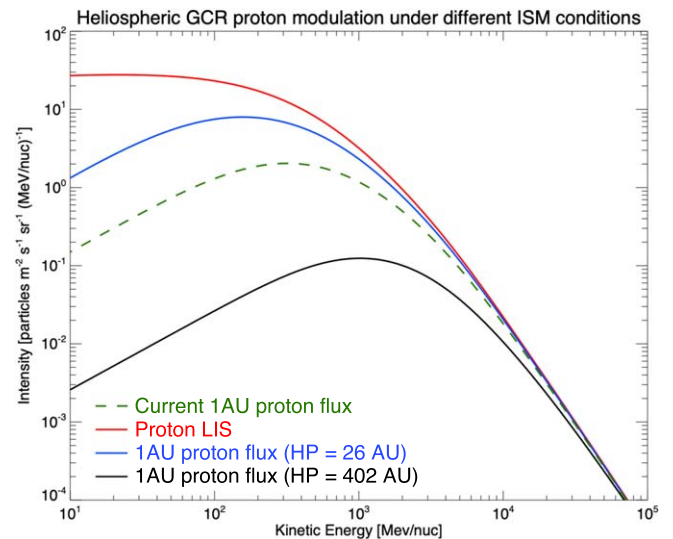
$$V \frac{\partial f}{\partial r} - \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \kappa \frac{\partial f}{\partial r} \right) - \frac{1}{3r^2} \frac{\partial}{\partial r} (r^2 V) \frac{\partial f}{\partial \ln p} = 0, \quad (1)$$

where  $f$  is the cosmic-ray distribution function,  $V$  is the solar wind velocity,  $p$  is momentum of the particle,  $r$  is distance from the Sun, and  $\kappa$  is the interplanetary diffusion coefficient. The reader is referred to Caballero-Lopez & Moraal (2004) for a more thorough description of the modulation model that we use here (and the comparison to other approximations), as well as to Moraal (2011) for an overview of GCR modulation.

To calculate the modulated GCR flux at Earth’s orbital location at 1 au, we have used the solution of Equation (1) using  $r_b = 125$  au (where  $b$  is the outer boundary of modulation) and a solar wind velocity  $V$  of  $400 \text{ km s}^{-1}$ . We use the diffusion coefficient ( $\kappa$ ) from Caballero-Lopez & Moraal (2004) of  $4.38 \times 10^{22} \beta P \text{ (GV) cm}^2 \text{ s}^{-1}$ .  $P$ , given in units of gigavolts, is the rigidity of the particle and is a measure of the particles momentum and its inability to be deflected by magnetic fields (i.e., higher rigidity particles are deflected less by magnetic fields).  $\beta$  is the dimensionless speed of a GCR ion and can be calculated in terms of rigidity  $P$  from  $\beta = P / \sqrt{P^2 + (A/Z)^2 E_0^2}$  (see Moraal 2011 for more details), where  $A$  is the mass number,  $Z$  is the atomic number, and  $E_0$  is the proton rest mass and equal to  $938 \text{ MeV}$ . From Figure 1, we can see that the GCR proton intensity at  $10^2 \text{ MeV nuc}^{-1}$  has been modulated during its propagation from the heliopause to 1 au; at 1 au it is an order of magnitude lower than that of the LIS. This demonstrates the strong modulation that GCRs experience as they propagate through the heliosphere and other astrospheres.

#### 4. Variations due to the Interstellar Medium

We have demonstrated how the GCR flux spectrum is modulated from the ISM to 1 au within the heliosphere. However, this modulation is also dependent on the local ISM that the heliosphere is embedded within (Indriolo & McCall 2012). Table 1 illustrates the range of different ISM environments that the Sun, or another star, may reside in during their galactic orbit. For the last  $\sim 100$  kyr, the solar system has been traversing through a “cloudlet” of low-density warm gas (the Local Interstellar Cloud). Within the Local Interstellar Cloud, the gas has a density of  $n_{\text{H,H}^+} \sim 10^5 \text{ m}^{-3}$  and a temperature  $T \sim 7000 \text{ K}$  (e.g., Frisch & Slavin 2006; Crawford et al. 2010). This cloud lies within the larger Local Bubble, which has a much lower density ( $\sim 10^3 \text{ m}^{-3}$ ) and is  $\sim 200$  pc in diameter. The heliosphere is dynamic and responds to the changing ISM conditions, and therefore the location of the heliopause will be dependent on a pressure balance between the outflowing solar wind and the ram pressure of the ISM. Neutral hydrogen from the ISM will also affect the heliospheric morphology due to charge exchange with the solar wind plasma (Opher et al. 2020). The complexity of the heliospheric interaction cannot be fully explained in a short Letter, so we refer the reader to a more detailed review (e.g., Zank 1999) or a model of the heliospheric interaction with the ISM (Müller & Zank 2004). However, a simple dependency of the substellar heliopause distance,  $R_{\text{helio}}$ , can be estimated as (from



**Figure 2.** Heliospheric estimates of GCR proton modulation at 1 au, as the heliosphere passed through different ISM conditions, and therefore the heliopause (HP) had different locations from the Sun.

Shaviv 2006)

$$R_{\text{helio}} \sim \sqrt{\frac{VM}{4P_{\text{ISM}}}}, \quad (2)$$

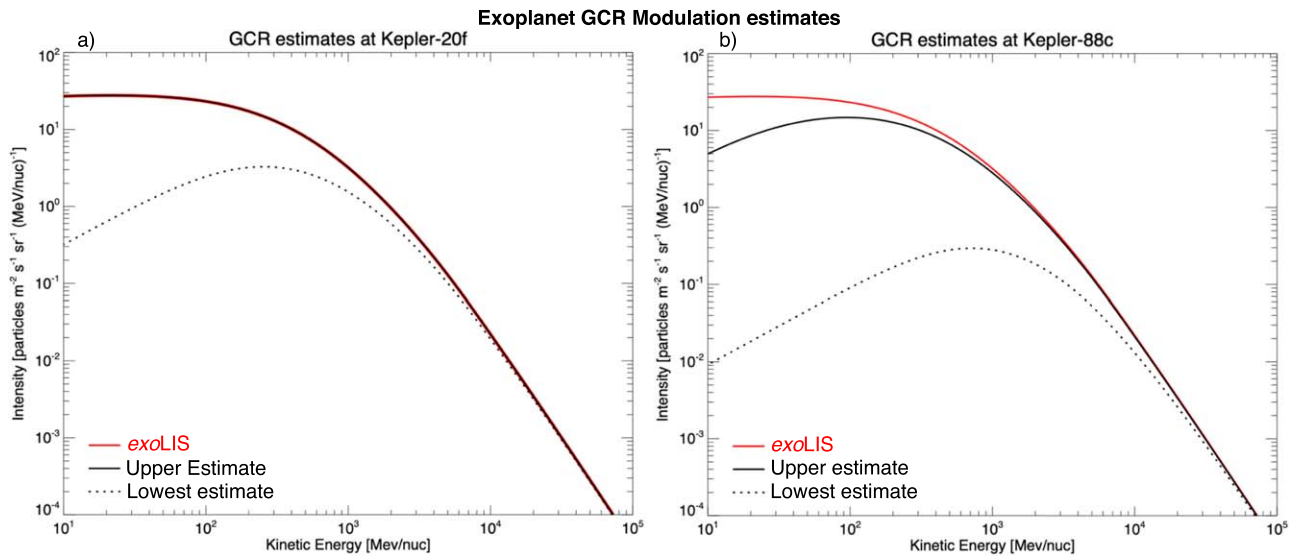
where  $\dot{M}$  is the mass-loss rate of the Sun,  $V$  is the solar wind velocity, and  $P_{\text{ISM}}$  is the ISM ram pressure. Therefore, we can see that the size of the heliosphere (or an astrosphere) is dependent on both the solar wind conditions and the upstream ISM environment.

Zank & Frisch (1999) modeled how changes in the ISM affect the heliopause location by modeling ISM densities up to  $50\times$  greater than current values. They found that, for such ISM density increases, the heliopause standoff distance is reduced to 10–14 au. Müller et al. (2006) modeled 15 different ISM conditions to explore the consequences of changing ISM on the size and structure of the heliosphere and found a wide range of possible heliopause locations (12–400 au). The GCR flux spectrum at Earth is known to be sensitive to such variations in the heliosphere size, and it is expected that changes in the size and shape of the heliosphere may result in an order of magnitude variation in the GCR flux at 1 au (e.g., Scherer et al. 2002; Florinski et al. 2003; Müller et al. 2006).

To demonstrate this effect, we plot the expected modulated GCR flux spectrum at 1 au (using the one-dimensional transport code described earlier) for two extreme heliopause locations (at 402 and 26 au from the Sun) assuming current solar wind conditions. These heliopause locations are from models 2 and 15, respectively, in Müller et al. (2006). Their Model 2 is for subsonic conditions for a partially ionized warm ISM, which the authors suggest could be representative of a warm cloud that the Sun encountered within the Local Interstellar Cloud  $\sim 40,000$  yr ago. Their Model 15 is for a denser gas, based on the ISM that 23 Ori resides in (Welty et al. 1999). The results are shown in Figure 2, where the GCR proton flux can be seen to vary significantly for different ISM conditions and thus different heliopause distances.

Throughout the Sun’s history, solar activity and the solar wind have varied significantly (Güdel 2007). It is thought that the solar wind was substantially more intense when the Sun





**Figure 3.** Different estimates of possible GCR proton fluxes at (a) Kepler-20f and (b) Kepler-88c.

**Table 1**  
Types of ISM Environment in the Milky Way (MW) Galaxy, Taken from Biswas (2000)

Regions	Density ( $\text{m}^{-3}$ )	Temperature (K)	Composition	Mass of MW (%)	Volume of MW (%)
Hot “Coronal” Gas	$\sim 10^3$	$\sim 10^6$	H+, e-	<1	50
“Warm” Medium	$10^5$ – $10^6$	8000	H, H+, e-	20	40
Diffuse H I Clouds	$10^6$ – $10^8$	80	H, C, O	40	5
Molecular Clouds	$\geq 10^9$	10–30	H <sub>2</sub> , CO, etc.	40	<1

was younger (Güdel 2007). Such variations would also significantly affect GCR modulation through the heliosphere. In this Letter, however, we focus on the relationship between local ISM conditions and GCR flux.

### 5. Kepler-20f and Kepler-88c

Given the discussion and results in the preceding sections, it should be clear that estimating the GCR flux spectrum at a given exoplanet is not trivial. To demonstrate this further we will *attempt* to estimate a set of GCR flux environments that *may* be considered somewhat realistic for the exoplanets Kepler-20f and Kepler-88c. The aim of this Letter is not to produce accurate GCR estimates at these specific exoplanets, but rather to demonstrate that, even with some knowledge of the environment at these astrospheres, estimating the exact GCR environment is very challenging. The selection of these two exoplanets is not arbitrary; they are a subset of a few exoplanetary systems whose ISM conditions have been estimated by observations. Kepler-20f is an Earth-sized planet, with a radius and mass equal to that of Earth’s (Fressin et al. 2012) and Kepler-88c has a mass equal to 0.6 of Jupiter’s mass (Nesvorný et al. 2013). Both planets have a similar orbital semimajor axis, with 0.15 and 0.14 au, respectively. Kepler-20 and Kepler-88 are Sun-like stars, with effective surface temperatures of  $5455 \pm 100$  K and  $5471 \pm 50$  K (5780 K for the Sun) and stellar masses of 0.91 and 0.96 solar masses, respectively (Nesvorný et al. 2013; Swift et al. 2013).

In order to constrain the ISM conditions for stars in the Kepler field of view, Johnson et al. (2015) made observations of interstellar Na I and K I absorptions from interstellar clouds.

From these observations they estimated the velocities of the interstellar clouds relative to the stars as well as the gas density within the clouds. Based on these estimates, they calculated the upper limit of the astrosphere size for 11 stars. Among these was Kepler-20 and Kepler-88, results for which we use here. Their upper limit constraints for the astrosphere size were calculated using the lower estimate from their density range and velocity of the local ISM cloud, and were estimated to be <63 au for Kepler-20 and <270 au for Kepler-88 (for ISM density ranges of 0.21–690 and 0.21–170  $\text{cm}^{-3}$ , respectively). Using the upper value for the density we scale their astrosphere sizes to estimate the lower boundary for these systems, using the relation shown in Equation (2). This results in possible astrosphere sizes of 2–63 au for Kepler-20 and 10–270 for Kepler-88. Using these astrosphere sizes, we use our GCR modulation model described above to model estimates of the GCR flux spectrum for protons at these two exoplanets, Kepler-20f and Kepler-88c. The results are shown in Figure 3.

To be clear, the method of our scaling for astrosphere size is very simplistic and, in reality, the physics of the astrosphere boundary location is vastly more complex (e.g., as demonstrated by the ISM model results at the heliosphere by Müller et al. 2006). As a test, we scale the heliopause location from model 5 of Müller et al. (2006) using the simple scaling method to that of the ISM conditions of model 15 from the same study. Using this simple method, we estimate a heliopause location of  $\sim 22$  au, compared to 26 au predicted by the detailed model of Müller et al. (2006). In other words, in this case, the simple scaling relation reproduces the heliopause distance to within  $\sim 15\%$ . Furthermore, we also use solar wind parameters for our

stellar convection model (for Kepler-20 and Kepler-88), so we assume that the stellar winds (e.g., density, speed) at these stars are identical to that of the solar wind, which undoubtedly is not the case. However, both of these Kepler stars have solar-level activity, either from activity indicators or solar rotation periods. Kepler-20 has a rotational period of  $\sim 25$  days (Gautier et al. 2012) and has an identical CA II HK chromospheric activity level—a good indicator for solar-type star activity levels—to the Sun (Buchhave et al. 2016), while Kepler-88 has a  $\sim 31$  day solar rotation period (McQuillan et al. 2013), which again is comparable to that of the Sun ( $\sim 27$  days). As a first approximation, using the solar wind is therefore acceptable and we believe this to be adequate in demonstrating how even with (1) a measure of the local ISM and (2) with estimates of some stellar wind parameters, the expected range of GCR fluxes at these exoplanets covers a very large parameter space.

## 6. Discussion

The variation in the possible GCR proton fluxes (due to astrosphere modulation) at the orbital locations of Kepler-20f and Kepler-88c are displayed in Figure 3. As shown, there is a  $\geq 2$  order of magnitude difference between the upper and lower estimates for GCRs with energies in the  $10^1$ – $10^2$  MeV  $\text{nuc}^{-1}$  range, and an order of magnitude difference for energies of  $10^3$  MeV  $\text{nuc}^{-1}$ . At exoplanetary bodies with dense atmospheres, GCRs in this energy range will interact primarily with the upper atmosphere. For exoplanets with thin or negligible atmospheres, these low-energy GCRs may interact directly with surface and subsurface.

At Kepler-20f, there is no modulation by the astrosphere for the upper estimate (the red and black lines overlap), and so the exoplanet would be exposed to the full GCR spectrum described by the exoLIS. The integrated energy flux and integrated number flux range for Kepler-20f are  $(0.9\text{--}1.4) \times 10^7$  MeV  $\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$  and  $(0.4\text{--}1.3) \times 10^4$   $\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$ , respectively, and for Kepler-88c these are  $(0.5\text{--}1.3) \times 10^7$  MeV  $\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$  and  $(0.1\text{--}1) \times 10^4$   $\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$ , respectively. GCR effects on the atmospheres and/or surfaces of the exoplanets would likely be strongly different depending on whether the actual GCR spectrum at these bodies is closer to the upper or lower bounds.

Such large ranges would be expected for most exoplanetary systems, and therefore should be taken into consideration when investigating GCR effects. For instance, Grießmeier et al. (2009) explore how a magnetosphere at an exoplanetary system with an M-star will experience higher GCR fluxes due to the compression of a magnetosphere (which will act to modulate the GCRs) by more dense stellar winds. However, they do not explore how a denser stellar wind will cause greater modulation throughout the astrosphere, thereby lowering the GCR fluxes. The magnitude of this affect will also vary for different ISM conditions (which this study also did not explore). The effects of GCRs at an exoplanet with varying degrees of magnetization have been investigated (e.g., Atri et al. 2013; Grießmeier et al. 2016). By using the GCR spectrum observed at Earth's orbit to model the GCRs at an exoplanet, the authors miss a wide parameter space where the GCR flux could be significantly higher or lower due to a compressed or enlarged astrosphere. Similarly, Tabataba-Vakili et al. (2016) use sophisticated atmospheric interaction models to investigate the atmospheric interaction with stellar cosmic-rays and GCRs at M-dwarf stars but prescribe an Earth-like GCR flux, which is not likely to be representative of the actual GCR spectrum at an exoplanet.

Struminsky et al. (2018) found that, for the TRAPPIST-1 system, the GCR modulation is so strong that at a distance of 1 au from the TRAPPIST-1 star, the GCR fluxes would be negligible. However, those authors assumed that the ISM conditions are the same as at the Sun's heliosphere, which may not necessarily be appropriate for the TRAPPIST-1 system.

## 7. Conclusions

There is considerable interest in characterizing potential habitability of exoplanets (e.g., Kopparapu et al. 2020). The effects of GCRs at planetary bodies are important to understand in the context of habitability, and therefore GCRs have been modeled at exoplanets recently (e.g., Grießmeier et al. 2009, 2016; Atri et al. 2013). In this Letter, we have briefly discussed the journey of GCRs from their origins to their arrival at the Earth or an exoplanet. We have shown that there are many parameters that will change the resulting flux at a planetary body (before any modulation by a planetary magnetosphere takes place). Significant modulation of the GCR flux will occur during passage through the heliosphere or an exoplanetary astrosphere, and this modulation is dependent on the stellar wind, the size of the astrosphere, and the local ISM conditions. Therefore, even with estimates of the local ISM for a given exoplanetary system, there is a large range of possible GCR flux spectra. By extension, there would therefore be a large uncertainty on any GCR-related magnetospheric, atmospheric, or surface processes present at a given exoplanet. We therefore advise caution when attempting to model GCR effects at exoplanets, and emphasize that the local interstellar environment of the host star must be explicitly considered.

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## Appendix Data Availability Statement

PAMELA and Voyager data were obtained from references Adriani et al. (2013) and Cummings et al. (2016).

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