Predictive Capabilities and Limitations of Stream Interaction Region Observations at Different Solar Longitudes

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Abstract Advanced warning of a stream interaction region (SIR) or corotating interaction region (CIR) impinging upon the magnetosphere of Earth is important for space weather forecasting, due to the ability of SIRs/CIRs to trigger geomagnetic storms and affect ionospheric composition and winds. However, a focused investigation of the likelihood that either an L5 monitor or Earth-trailing “string-of-pearl” constellation of satellites would be able to serve as an effective warning buoy for SIRs/CIRs that will affect the near-Earth space environment has yet to be extensively performed. Through comparing 10 years of SIRs/CIRs observed at L1 and at STEREO, we have investigated the probability of sequentially detecting SIRs/CIRs at two locations as a function of the difference in heliospheric longitude and latitudinal separation between the two spacecraft. By examining the probability of repeat detection of SIRs/CIRs using variable separation distances between two observing points, we explore the utility of an Earth-trailing monitor for SIR/CIR predictability (i.e., 74.6% of SIRs observed at L5 reach L1 within ±3 days of rigid corotation). While the probability of predicting the occurrence of SIRs/CIRs at another spacecraft decreases with longitudinal separation, there is no significant dependence on latitude. The primary source of error in reliably predicting the arrival time of an SIR/CIR is uncertainty in the rotational speed of the structure. While an L5 monitor would be an advancement in our operational warning ability, an Earth-trailing “string-of-pearls” constellation utilizing multiple point of measurements would engender much more certainty in predicting the arrival time of SIRs/CIRs.

Key Points:
• Probability of repeated SIR/CIR observations was tested against spacecraft longitudinal separation
• The peak angular speed between repeat SIR/CIR observations is 14.375° per day, corresponding to a solar latitude of ~20°
• Latitudinal separation between the spacecraft did not significantly affect the probability of recurrent SIR/CIR detection

Plain Language Summary Stream interaction regions (SIRs) form when fast solar wind overtakes slow solar wind. These structures are long-lasting and can corotate (i.e., a corotating interaction region) with the Sun, allowing for these structures to be observed by a warning buoy prior to encountering the Earth. When SIRs hit the magnetic field surrounding the Earth, they can trigger geomagnetic storms, which can negatively affect spacecraft and astronaut health, communications, and the electric grid. For this reason, predicting when an SIR may hit the Earth is an important problem in space weather. This paper investigates the utility of deploying spacecraft to different locations around the Sun to act as a warning buoy system for these solar wind structures. For example, we find a 74.6% (46.1%) chance of predicting the arrival of an SIR at Earth within ±3 (±1) days after being observed at the Earth-trailing Sun-Earth Lagrange point, L5.

1. Introduction

Stream interaction regions (SIRs) are known to trigger geomagnetic storms (e.g., B.T. Tsurutani & Gonzalez, 1997; I.G. Richardson, 2018; I.G. Richardson et al., 2006; N.E. Turner et al., 2006), affect the ionosphere/thermosphere at Earth (e.g., Chen et al., 2014; McGranaghan et al., 2014), serve as a major source of energetic particles in the interplanetary medium (e.g., B.T. Tsurutani et al., 1982; I.G. Richardson, 2018; Van Hollebeke et al., 1981), and pose a serious threat to the health of humans in space and on high-altitude aircraft (Cannon et al., 2013). SIRs arise where high-speed solar wind streams overtake slow speed streams and are associated with a density “pile-up” of compressed plasma just upstream of the SIR, with the faster speed stream comprised of lower density plasma (e.g., Belcher & Davis, 1971; I.G. Richardson, 2018; Pizzo, 1978). The stream interface is often associated with a peak in both the magnitude of the magnetic field and total pressure at the transition from the slow to fast streams (e.g., L.K. Jian et al., 2006). The solar wind temperature and specific entropy argument also increase from the slow to fast...
SIR/CIR related storms are also similar to ICMEs (e.g., Chi et al., 2018). As such, accurately predicting the arrival of an SIR/CIR is important for understanding and mitigating the effects of space weather.

Two of the main geoeffective heliospheric structures are SIRs/CIRs and interplanetary coronal mass ejections (ICMEs). While both ICMEs and SIRs/CIRs are geoeffective, important differences and similarities in the effects upon the near-Earth space environment have been observed. For example, SIR/CIR-triggered geomagnetic storms lead to elevated levels of spacecraft charging at geosynchronous orbit for longer durations than storms driven by ICMEs (e.g., Denton et al., 2006). Additionally, SIRs/CIRs heat the nightside plasma sheet to a greater extent and for longer durations than ICMEs (e.g., Denton et al., 2006). However, ICME-driven storms have been found to be responsible for the majority of major ($D_{st} < -100$ nT) storms (e.g., Zhang et al., 2003) and to induce higher levels of radiation belt electron flux (e.g., Shen et al., 2017). SIR/CIR related storms are also similar to ICME-associated storms in their ability to generate electromagnetic ion cyclotron waves in the inner magnetosphere (Bingham, 2019), which are an important loss mechanism for radiation belt electrons. More generally, magnetopause compressions caused by increases in the solar wind dynamic pressure, which often occur during SIRs/CIRs, can broadly trigger electromagnetic ion cyclotron waves in the outer magnetosphere (e.g., Engebretson et al., 2018; McCollough et al., 2010; R.C. Allen et al., 2015, 2016; Vines et al., 2019). Additionally, in some cases, SIRs/CIRs and ICMEs have been found to interact and be significantly more geoeffective than either of an isolated SIR/CIR or ICME (e.g., Chi et al., 2018). As such, accurately predicting the arrival of an SIR/CIR is important for understanding and mitigating the effects of space weather.

Many studies have attempted to better understand and predict qualities of SIRs/CIRs at 1 au, such as by studying solar cycle variations (e.g., L.K. Jian et al., 2011; L.K. Jian et al., 2019; Lario et al., 2003; Mason et al., 2012; R.C. Allen et al., 2019; R.J. Filwet et al., 2017), investigating the evolution of SIRs/CIRs from close proximity to the Sun out to 1 au (e.g., L.K. Jian et al., 2008b; 2008c; L.K. Jian, Russell, Luhmann, Skoug, 2008a; R.C. Allen et al., 2020; Richter & Luttrell, 1986), and delving into the various SIR/CIR-associated particle acceleration mechanisms (e.g., Ebert et al., 2012; Fisk & Lee, 1980; Mewaldt et al., 1978; R.J. Filwet et al., 2019; Schwadron et al., 1996). However, few studies have tried to better understand the utility of spacecraft at different solar longitudes, such as a L5 monitor (i.e., a satellite stationed at the Earth-trailing Sun-Earth Lagrange point), to act as a warning buoy for SIRs/CIRs that affect the near-Earth space environment. These prior studies were limited to only a few months of data comparing observations from the two Solar Terrestrial Relations Observatory (STEREO) spacecraft, as well as STEREO and Earth/L1-orbiting spacecraft, when separated by ~60° (e.g., D.L. Turner & Li, 2011; Simunac et al., 2009; Thomas et al., 2018).

The persistence of SIRs/CIRs may allow either a L5 monitor or an Earth-trailing “string-of-pearls” concept (i.e., multiple spacecraft released trailing the Earth) to act as an effective warning prior to a geoeffective SIR/CIR encountering the magnetosphere of Earth. However, results from recent MHD simulations have suggested caution since L5 and Earth are often at different heliographic latitudes (M.J. Owens et al., 2019). Differences in the ecliptic and solar rotational planes would lead a L5 monitor to sample a slightly different latitude than Earth during different times of year, and as such, the solar wind observed at L5 may not have the same interplanetary magnetic field direction and solar wind velocity as the solar wind that will eventually reach Earth. This effect is expected to be greater during solar minimum than during solar maximum due to coronal and solar wind structures during solar minimum being more latitudinally ordered than during solar maximum (see M.J. Owens et al., 2019). Thomas et al. (2018) also found that SIR/CIR properties are less well predicted when STEREO moved to near L5 and was at large latitudinal separations from the Advanced Composition Explorer (ACE). However, these studies focused on the simple ability of L5 in situ observations to be identical to those at L1, rather than studying the ability for L5 to warn of SIRs/CIRs or how L5 observations may be able to correct for errors in models. While latitudinal variations have been observed for SIRs/CIRs (e.g., R. Gómez-Herrero et al., 2009, 2011), it is not clear how this may affect the ability of a L5 monitor to effectively predict the SIR/CIR arrival time at Earth. An additional complication with
predicting SIRs/CIRs is that the low-latitude coronal hole structures from which the high-speed streams originate are themselves variable. Heinemann et al. (2018) studied long-lived low-latitude coronal holes over 10 solar rotations with extreme ultraviolet observations from STEREO. Coronal holes were found to consist of three development phases: (1) a growth phase, when the coronal hole increases in size over the duration of months with solar wind speeds being 460–600 km/s; (2) a maximum phase, when the coronal hole size is steady for roughly a month with solar wind speeds between 600 and 720 km/s; and (3) a decaying phase, when the coronal hole reduces in area over about 3 months with solar wind speeds ranging from 350 to 550 km/s (Heinemann et al., 2018). Additionally, the coronal hole boundaries are continually changing due to photospheric convection, field diffusion, and differential rotation (e.g., J.G. Luhmann et al., 2002; Wang & Sheeley, 1990). It is unclear how the variations in coronal hole size, boundaries, and high-speed steam speeds may affect the predictability of SIRs/CIRs at Earth. Current modeling capabilities can produce predictions of SIRs/CIRs arriving days early, or miss them entirely, which reduces the operational usefulness of a model-only approach (e.g., R.C. Allen et al., 2020). As such, it is typical for models to be adjusted in time to match observed features (e.g., M.J. Owens et al., 2005). The ability for an L5 monitor or Earth-trailing “string-of-pearls” to estimate the timing and quantitative error in simulations may help in predicting the solar wind at L1.

Currently, concepts for a L5 mission (e.g., Akioka et al., 2005; Gopalswamy et al., 2011; Happgood, 2017; Lavraud et al., 2016; Vourlidas, 2015; Winkler et al., 2003) or an Earth-trailing “string-of-pearls” constellation (e.g., Moldwin et al., 2003) are being discussed within the solar and heliospheric communities. Such a mission would engender great advances, both scientifically and for space weather forecasting. The European Space Agency has also been considering an L5 mission using an operational framework (e.g., Luntama et al., 2019). As such, investigations on the best implementation and limitations of both L5 and “string-of-pearls” concepts are currently timely and needed for future mission planning.

In this study, we utilize previously published lists of SIRs/CIRs observed by Wind and ACE, when Wind data were unavailable (Chi et al., 2018; L.K. Jian et al., 2011), and STEREO (L.K. Jian et al., 2013, 2019) to address the predictive capability of spacecraft at varying longitudinal separations to warn against an approaching SIR/CIR. The data sets and lists used in this study are discussed in section 2. The results of this analysis are given in section 3, while a discussion of the findings and a summary of the conclusions are given in sections 4 and 5, respectively.

2. Methodology

The ACE spacecraft (Stone et al., 1998) was launched on 25 August 1997 and has since been orbiting around the sunward Sun-Earth Lagrange point (L1). Meanwhile the Wind spacecraft (Acuña et al., 1995), which was launched on 1 November 1994, orbited the Earth until being stationed around L1 in 2004. Using both of these spacecraft, L.K. Jian et al. (2006, 2011) created an online SIR catalog spanning from 1995 to 2009 based on 93-s data from the Solar Wind Experiment (Ogilvie et al., 1995) and Magnetic Field Investigation (Lepping et al., 1995) instruments on Wind and 64-s data from the Solar Wind Electron Proton Alpha Monitor (McComas et al., 1998) and magnetic field experiment (Smith et al., 1998) instruments on ACE. This catalog identified SIRs by requiring simultaneous observations of an increase in solar wind speed and proton temperature, a compression immediately followed by a decline of solar wind density, and a peaked enhancement of the magnetic field and total pressure. More information on the selection criteria can be found in L.K. Jian et al. (2006, 2019). Using the same criteria as L.K. Jian et al. (2006), Chi et al. (2018) extended this list to span until the end of 2016 to further study the geoeffectiveness of the SIRs.

Since both ACE and Wind are very close in heliographic longitude at all times, this study also utilizes a list of SIRs observed by the STEREO mission (Kaiser et al., 2008), which was compiled using the same selection criteria as used for ACE and Wind (L.K. Jian et al., 2013; L.K. Jian et al., 2019). This catalog of SIRs observed by STEREO utilized 1-min magnetic field and plasma measurements obtained by the In situ Measurements of Particle and CME Transients (IMPACT; J.G. Luhmann et al., 2008) and Plasma and Suprathermal Ion Composition (PLASTIC; Galvin et al., 2008) instruments, respectively. The STEREO mission was launched on 25 October 2006 and comprised of two identical spacecraft orbiting around the Sun close to the ecliptic plane. STEREO-Ahead (STEREO-A) was put into an orbit slightly
closer to the Sun and the spacecraft orbital velocity was faster than Earth’s, while STEREO-Behind (STEREO-B) orbits more slowly than the Earth. Overtime, STEREO-A and STEREO-B increased in longitudinal separation until 2011, when they were separated by 180°, before decreasing their longitudinal separation and reuniting on the far side of the Sun from Earth, which occurred in 2015. Since then, they have been approaching Earth in declining longitudinal separation at about 22° per year. Contact with STEREO-B was lost in October 2014. For this reason, the SIR list for the STEREO spacecraft spans from 2007 through October 2014 for STEREO-B and from 2007 through the end of 2016 for STEREO-A. This allows for 10 years of overlap between L1 (ACE/Wind) and STEREO-A and for ~8 years of overlap between STEREO-B and both L1 (ACE/Wind) and STEREO-A.

For all SIR/CIR events identified and used in this study, the instantaneous longitudinal separation of the spacecraft is known; however, the spacecraft are not all moving at the same speed around the Sun. Figure 1 illustrates the relative motion of the spacecraft in a Sun-Earth-fixed frame. Due to the motion of the spacecraft, the longitudinal separation at the moment when a single SIR/CIR was first observed is not necessarily the same as the separation when the SIR/CIR is observed at the next spacecraft. As such, when computing the expected time lag of a SIR/CIR to corotate from one spacecraft to the next, this motion needs to be considered.

As an example, the colored arcs denote the distance a SIR/CIR would move from a single SIR/CIR was first observed to another spacecraft if observed within a given time window of a predicted corotation time to another spacecraft? To this effect, while the subsequently observed SIRs/CIRs during these windows are treated as if they are the same structure, they are not required to be since this would not be known a priori and in an operational sense, this would be irrelevant. However, the consequence to this is that the probability of repeat detection,
especially for large longitudinal separations, would likely be slightly higher than if we required the subsequent observation to be the same structure.

3. Results

3.1. Angular Speed of SIR/CIR Corotation

Figure 2a shows the normalized occurrence of subsequent SIRs/CIRs versus the computed SIR/CIR angular rotation speed. The overplotted red vertical dashed line denotes the equatorial rotation speed of the Sun (14.7° per day), while the green dash-dot line denotes the peak occurrence speed (14.375° per day) and the blue dotted line denotes the slowest speed before the occurrence quickly drops off (13.4° per day). Solar rotation is known to have a latitudinal dependence (e.g., Beck, 2000), and the differential rotation rate can be expressed as

$$\omega = A + B \sin^2 \phi + C \sin^4 \phi,$$

where $A = 14.713$, $B = -2.396$, and $C = -1.787$ in units of degrees per day (Snodgrass & Ulrich, 1990). Using this expression, the profile of rotation speed vs. latitude is shown in Figure 2b with vertical and horizontal lines marking the latitude corresponding to the three reference speeds in Figure 2a. This suggests that most of the SIRs/CIRs observed along the ecliptic plane arose from coronal holes below ~40°, with the peak occurrence originating from ~20°, if assuming strict corotation. Beyond not knowing the precise latitude of origin, one source of uncertainty in estimating the rotation speed is that SIRs/CIRs are not necessarily rigid structures rotating with a fixed speed. Instead, the speed of the fast stream can vary, which could lead to the SIR/CIR reaching a subsequent spacecraft before/after rigid corotation would predict. Likely, the events associated with a faster-than-equatorial rotation speed (i.e., those to the right of the red dashed line in Figure 2a) are instances where the fast streams appear to speed up during corotation. Another reason for an apparent faster-than-equatorial rotation speed is if the SIR/CIR has any latitudinal structure, since the spacecraft are sometimes at different latitudinal separations. Lastly, temporal evolution of the coronal hole structure, from which the fast stream emanates, may also lead to variations in the arrival time of subsequent SIRs/CIRs.

3.2. Probability of Repeated Observations vs. Longitudinal Separation

For an SIR/CIR warning buoy to be useful for operational space weather applications, it needs to be able to predict the arrival of an SIR/CIR with a reasonable error in time (i.e., hours). This is currently one limitation of model-only approaches, in which the expected time of arrival can be off by orders of days. To investigate if
an in situ L5 buoy would be able to reliably perform better, the peak SIR/CIR rotation rate from Figure 2 (14.375° per day) is used to estimate the time of arrival within various time windows. It should be noted that while a strict fixed corotation speed is still being assumed, this approach is more rigorous than assuming the high-speed streams are all simply originating at the equator as done in other solar recurrence studies (e.g., Kohutova et al., 2016; M.J. Owens et al., 2013; Thomas et al., 2018). However, the error associated with picking a fixed corotation speed and the assumption that the high-speed stream velocity does not change in time is significant, as seen in Figure 2, and will lower the outcome probability. Since this study is seeking to quantify the performance of an Earth-trailing warning buoy, this unknown is likely a constraint for such a mission.

Figure 3 displays the probability of repeated observations (i.e., the ratio of SIRs/CIRs observed by a subsequent spacecraft to the total number of possible subsequent observations) as a function of longitudinal separation of spacecraft for various allowed time windows (shown in different colors). Vertical dashed lines are overplotted to show the longitudinal separation of a monitor at L5 (60°), L3 (180°), and L4 (300°) with respect to Earth following the corotational motion. As expected, a longer allowable time window increases the likelihood of repeated observation; however, the space weather utility decreases rapidly. The probabilities for different temporal windows are given with their Poisson errors ($\text{err} = 1/\sqrt{n}$, where $n$ is the total number of potential matches) in Table 1. Unsurprisingly, binning the events by whether or not the first observation of the pair was observed in the previous solar rotation (i.e., a CIR) does not significantly affect the probability of repeat observation within statistical error (not shown). This is due to the fact that the previous lifetime of the SIR is not a good indicator of how long the SIR will persist. For example, either the SIR could persist for the entire upcoming solar rotation and become a CIR, or the high-speed stream could cease prior to then.

**Table 1**

| Longitudinal separation (°) | Window size (±-days) |
|-----------------------------|-----------------------|
|                             | 0.25                  | 0.5                  | 0.75                  | 1                    | 2                    | 3                    |
| 10                          | 16.3 ± 10%            | 46.5 ± 10%           | 59.3 ± 10%            | 68.6 ± 10%           | 80.2 ± 10%           | 82.6 ± 10%           |
| 30                          | 15.5 ± 12%            | 32.4 ± 12%           | 47.9 ± 12%            | 57.7 ± 12%           | 81.7 ± 12%           | 83.1 ± 12%           |
| 60 (L5)                     | 8.3 ± 10%             | 22.4 ± 10%           | 35.9 ± 10%            | 46.1 ± 10%           | 65.4 ± 10%           | 74.6 ± 10%           |
| 180 (L3)                    | 7.8 ± 9.8%            | 12.5 ± 9.8%          | 21.7 ± 9.8%           | 25.9 ± 9.8%          | 44.5 ± 9.8%          | 56.4 ± 9.8%          |
| 300 (L4)                    | 3.5 ± 10%             | 9.1 ± 10%            | 13.1 ± 10%            | 19.2 ± 10%           | 40.9 ± 10%           | 57.1 ± 10%           |
3.3. Latitudinal Effects on Predictive Capabilities

MHD simulations estimated that the latitudinal structure of the solar wind would be fine enough that an in situ L5 monitor would not always be able to act as a reliable warning buoy, since a satellite at L5 would sometimes be at a different heliographic latitude than the Earth (M.J. Owens et al., 2019). To test how this may affect the ability of an L5 monitor to predict SIRs/CIRs, given possible latitudinal variations, the SIR/CIR events were binned into low latitudinal separations (less than 7.5°) and high latitudinal separations (greater than 7.5°). The probability of repeat observations versus latitudinal separation for these two bins is shown in Figure 4. For most of the allowed time windows, there is virtually no difference in the probability of repeated observations, within Poisson error, for different latitudinal separations. The singular exception is when allowing for a very large time window (±3 days), and even in this case, the probability of repeated observations for the low latitudinal separation events is only slightly higher than for high latitudinal separation events. It should be noted, however, that while the probability of repeat detection does not seem to have a

**Figure 4.** The probability of repeated SIR/CIR observations as a function of longitudinal separation for low (<7.5°, blue) and high (>7.5°, orange) latitudinal separation using a time window of (a) ±0.25, (b) 0.5, (c) 0.75, (d) 1, (e) 2, and (f) 3 days. The profile including all latitudes is shown in gray.
strong latitudinal dependence, the properties of SIRs/CIRs are in fact known to strongly depend on latitudinal separations (e.g., L.K. Jian et al., 2019; Thomas et al., 2018).

4. Discussion

This study investigated the predictive capabilities and limitations of in situ SIR/CIR observations at various longitudinal and latitudinal separations. Using 10 years (2007 through the end of 2016) of SIRs/CIRs observed at STEREO (L.K. Jian et al., 2013) and ACE/Wind (Chi et al., 2018; L.K. Jian et al., 2006; L.K. Jian et al., 2011), the probability of SIR/CIR repeated observation (i.e., observed by another spacecraft) has been studied as a function of longitudinal and latitudinal separation. Additionally, the occurrence frequency of various SIR/CIR corotation speeds has been investigated. This study does not investigate variations in the properties of the SIRs/CIRs, which has been the focus of other studies (e.g., L.K. Jian et al., 2019; Thomas et al., 2018). They found that SIR/CIR parameters (i.e., minimum velocity and maximum velocity, density, magnetic field, dynamic pressure, and thermal pressure) vary widely with longitudinal and latitudinal separation between observers (e.g., L.K. Jian et al., 2019).

The largest source of error in predicting SIRs/CIRs from L5, or any other single point measurement trailing the Earth, is uncertainty in the corotation speed of the structure. While some of the ambiguity comes from how dynamic the solar wind velocity can be (i.e., it is not necessarily a fixed value in time; e.g., Heinemann et al., 2018) and the temporal evolution of coronal hole structures, another large source of error is the differential rotation of the Sun (e.g., J.G. Luhmann et al., 2002; Wang & Sheeley, 1990). SIRs/CIRs formed from high-speed streams emanating from different latitudes will corotate at a different speed, which can lead to a predicted arrival time that is too early or too late. Additionally, the boundaries of coronal holes are constantly evolving through the growth, maximum, and declining phases of their existence (Heinemann et al., 2018). Remote observations of the solar surface from L5 can aid in resolving this ambiguity by providing information about the location and evolution of coronal hole structures, but these observations are not able to constrain temporal variations in the velocity of high-speed streams. Instead, an Earth-trailing “string-of-pearls” concept would be able to constrain the static corotation velocity, and the limitations associated with time-varying velocity fluctuations would be proportional to the longitudinal separation of the spacecraft.

Binning the SIR/CIR observations by relative latitudinal variations found no significant dependence on latitudinal separation between observations of the ability to predict an SIR/CIR. However, the properties of SIRs/CIRs are known to have a strong latitudinal dependence (e.g., L.K. Jian et al., 2019; Thomas et al., 2018). Since previous studies utilizing MHD simulations to look at the predictive ability of a L5 monitor to predict solar wind at L1 found a significant latitudinal dependence, suggesting that the bulk properties of the solar wind are finely structured in latitude in MHD models (see M.J. Owens et al., 2019), this type of latitudinal structuring does not seem to be as significant for the repeated observations of SIRs/CIRs. It is unclear if this is due to SIR/CIR structures being broader in latitude than typical solar wind, or if the simulations produce solar wind with finer structure than observed. While previous studies have explored smaller latitudinal variations of SIRs from a case study standpoint (e.g., R. Gómez-Herrero et al., 2009, 2011), future comparisons between Solar Orbiter and Parker Solar Probe at different latitudes may be able to help provide insight into the larger latitudinal scale variations of the fast versus slow solar wind streams and SIRs/CIRs by providing simultaneous multipoint, latitudinally separated observations.

5. Conclusions

This study investigated the predictive capabilities and limitations of in situ SIR/CIR observations at various longitudinal and latitudinal separations. The conclusions of this study are summarized as follows:

1. The vast majority of SIRs/CIRs observed by STEREO and ACE/Wind have a rotational speed corresponding to a solar latitude less than ~40°, and the peak occurrence was near a rotational speed of ~14.375° per day (corresponding to ~20° solar latitude). However, large variations in the rotational speed are observed, illustrating a limitation of the predictive ability of a single in situ warning buoy. Operationally, multiple longitudinally spaced spacecraft would be able to better determine the rotational speed of an SIR/CIR prior to it reaching Earth by overcoming the intrinsic limitation of localized measurements.
2. A nonnegligible number of SIRs/CIRs were found to have a rotational speed faster than the equatorial rotational speed. This suggests either nonfixed stream speeds, latitudinal structure, or the temporal evolution of the coronal hole sources of the high-speed streams.

3. The probability of recurrence of SIRs/CIRs (i.e., seen by multiple spacecraft) was investigated as a function of longitudinal separation and of different allowed time windows for subsequently observing the SIR/CIR. At L5, we find a 74.6% ± 10% probability of predicting an SIR/CIR arrival at Earth within a 3-day window. The probability decreases with increasing longitudinal separation. The primary limitation of forecasting the time of arrival is related to the difficulty in predicting the rotational speed of a SIR/CIR, likely due to the evolution of coronal holes and the variations in coronal hole boundaries and solar wind velocities.

4. Contrary to previous MHD simulation results of steady solar wind (M.J. Owens et al., 2019), the probability of repeat SIR/CIR occurrence is not significantly affected by the latitudinal separation of the spacecraft. This may indicate that the SIR/CIR structures are broader in latitude than the properties of steady solar wind streams. Future comparisons between Solar Orbiter and Parker Solar Probe at different latitudes when those spacecraft are at similar longitudes may be able to help provide insight into the larger-scale latitudinal scale variations of the fast versus slow solar wind streams and SIRs/CIRs.

The mutual benefits and limitations of both an in situ or modeling-only approach demonstrate the need for improvements to both. While adding magnetograms at L5 would improve the arrival time predictions of current simulations, being able to compare multipoint in situ observations with the simulations in real time is likely to be the most accurate approach to predicting SIR/CIR arrival times.

References

Acuña, M. H., Ogilvie, K. W., Baker, D. N., Curtis, S. A., Fairfield, D. H., & Mish, W. H. (1995). The global geospace science program and its investigations. Space Science Reviews, 71, 5–21. https://doi.org/10.1007/BF00751323

Akioka, M., Nagatsuma, T., Miyake, W., Ohtaka, K., & Maruhashi, K. (2005). The L5 mission for space weather forecasting. Advances in Space Research, 35(1), 65–69. https://doi.org/10.1016/j.asr.2004.09.014

Allen, R. C., Ho, G. C., & Mason, G. M. (2019). Suprathermal ion abundance variations in corotating interaction regions over two solar cycles. The Astrophysical Journal Letters, 883, L10. https://doi.org/10.3847/2041-8213/ab3f2f

Allen, R. C., Lario, D., Odstrcil, D., Ho, G. C., Jian, L. K., Cohen, C. M. S., et al. (2020). Solar wind streams and stream interaction regions observed by Parker solar probe with corresponding observations at one au. The Astrophysical Journal Supplement Series, 246(2), 36. https://doi.org/10.3847/1538-4365/ab576f

Allen, R. C., Zhang, J.-C., Kistler, L. M., Spence, H. E., Lin, R.-L., Klecker, B., et al. (2015). A statistical study of EMIC waves observed by cluster: 1. Wave properties. Journal of Geophysical Research: Space Physics, 120, 5574–5592. https://doi.org/10.1002/2015JA021333

Allen, R. C., Zhang, J.-C., Kistler, L. M., Spence, H. E., Lin, R.-L., Klecker, B., et al. (2016). A statistical study of EMIC waves observed by cluster: 2. Associated plasma conditions. Journal of Geophysical Research: Space Physics, 121, 6458–6479. https://doi.org/10.1002/2016JA025241

Binga, S. T. (2019). The storm time response of the inner magnetosphere during coronal mass ejection and corotating interaction region driven storms, University of New Hampshire PhD Thesis, ProQuest Dissertations Publishing, 13881671.

Borovsky, J. E., & Lockwood, M. (2000). A comparison of differential rotation measurements. Solar Physics, 191, 47–70. https://doi.org/10.1023/A:1005226402796

Bridge, J., & Davis, L. (1971). Large-amplitude Alfvén waves in the interplanetary medium. 2. Journal of Geophysical Research, 76, 3534–3563. https://doi.org/10.1029/JA076i016p03534

Chen, G.-M., Xu, J., Wang, W., & Burns, A. G. (2014). A comparison of the effects of CIR- and CME-induced geomagnetic activity on thermospheric densities and spacecraft orbits: Statistical studies. Journal of Geophysical Research: Space Physics, 119, 7926–7939. https://doi.org/10.1002/2014JA019831

Chi, Y., Shen, C., Luo, B., Wang, Y., & Xu, M. (2018). Geoeffectiveness of stream interaction regions from 1995 to 2016. Space Weather, 16, 1960–1971. https://doi.org/10.1029/2018SW001894

Denton, M. H., Borovsky, J. E., Skoug, R. M., Thomsen, M. F., Lavraud, B., Henderson, M. G., et al. (2006). Geomagnetic storms driven by ICME- and CIR-dominated solar wind. Journal of Geophysical Research, 111, A07S07. https://doi.org/10.1029/2005JA011436

Ebert, R. W., Desai, M. I., Dayeh, M. A., & Mason, G. M. (2012). Helium ion anisotropies in corotating interaction regions at 1 au. The Astrophysical Journal Letters, 754, L30. https://doi.org/10.1088/2041-8205/754/2/L30

Engebretson, M. J., Posch, J. L., Capman, N. S. S., Campuzano, N. G., Belik, P., Allen, R. C., et al. (2018). MMS, Van Allen Probes, GOES 13, and ground-based magnetometer observations of EMIC wave events before, during, and after a modest interplanetary shock. Journal of Geophysical Research: Space Physics, 123, 8331–8357. https://doi.org/10.1002/2018JA025984

Filwet, R. J., Desai, M. I., Dayeh, M. A., & Broiles, T. W. (2017). Source population and acceleration location of suprathermal heavy ions in corotating interaction regions. The Astrophysical Journal, 858, 23. https://doi.org/10.3847/1538-4357/aa5ca9

Filwet, R. J., Desai, M. I., Ebert, R. W., & Dayeh, M. A. (2019). Spectral properties and abundances of suprathermal heavy ions in compression regions near 1 au. The Astrophysical Journal, 876, 88. https://doi.org/10.3847/1538-4357/ab12cf

Fisk, L. A., & Lee, M. A. (1980). Shock acceleration of energetic particles in corotating interactions regions in the solar wind. The Astrophysical Journal, 237, 620–626. https://doi.org/10.1086/157907

Galvin, A. B., Kisler, L. M., Popecki, M. A., Farrugia, C. J., Simunac, K. D. C., Ellis, L., et al. (2008). The Plasma and Suprathermal Ion Composition (PLASTIC) investigation on the STEREO observatories. Space Science Reviews, 136(1-4), 437–486. https://doi.org/10.1007/s11214-007-9296-x
