Interplanetary Scintillation Observations of Stream Interaction Regions in the Solar Wind

M.M. Bisi · R.A. Fallows · A.R. Breen · I.J. O'Neill

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Abstract We present a summary of results from ten years of interplanetary scintillation (IPS) observations of stream interaction regions (SIRs) in the solar wind. Previous studies had shown that SIRs were characterized by intermediate-velocity solar wind and – in the case of compressive interactions – higher levels of scintillation. In this study we considered all cases of intermediate velocities in IPS observations from the *European Incoherent SCATter* (EISCAT) radar facility made at low- and mid-heliographic latitudes between 1994 and 2003. After dismissing intermediate-velocity observations which were associated with solar-wind transients (such as coronal mass ejections) we found that the remaining cases of intermediate velocities lay above coronal structures where stream interaction would be expected. An improved ballistic mapping method (compared to that used in earlier EISCAT studies of interaction regions) was used to identify the regions of raypath in IPS observations which might be expected to include interaction regions and to project these regions out to the distances of *in-situ* observations. The early stages of developing compression regions, consistent with their development on the leading edges of compressive stream interaction

M.M. Bisi (✉)

Center for Astrophysics and Space Sciences, University of California, San Diego,
9500 Gilman Drive #0424, La Jolla, CA 92093-0424, USA
e-mail: mmbisi@ucsd.edu

M.M. Bisi

e-mail: Mario.Bisi@gmail.com

R.A. Fallows · A.R. Breen

Institute of Mathematical and Physical Sciences, Aberystwyth University, Penglais Campus,
Aberystwyth, Ceredigion, SY23 3BZ Wales, UK

R.A. Fallows

e-mail: raf@aber.ac.uk

A.R. Breen

e-mail: azb@aber.ac.uk

I.J. O'Neill

Woods-Fox Investments, Woodland Hills, CA 91364, USA
e-mail: ian.oneill@gmail.com

regions, were clearly detected as close to the Sun as $30 R_{\odot}$, and further ballistic projection out to the distances of *in-situ* observations clearly associated these developing structures with density and velocity features characteristic of developed interaction regions in *in-situ* data in the cases when such data were available. The same approach was applied to study non-compressive interaction regions (shear layers) between solar-wind streams of different velocities where the stream interface lay at near-constant latitude and the results compared with those from compressive interaction regions. The results confirm that intermediate velocities seen in IPS observations above stream boundaries may arise from either detection of intermediate-velocity flow in compression regions, or from non-compressive shear layers. The variation in velocity about the mean determined from IPS measurements (representing the spread in velocity across that part of the raypath associated with the interaction region in the analysis) was comparable in compressive and non-compressive regions – a potentially interesting result which may contain important information on the geometry of developing SIRs. It is clear from these results that compressive and non-compressive interaction regions belong to the same class of stream–stream interaction, with the dominant mode determined by the latitudinal gradient of the stream interface. Finally, we discuss the results from this survey in the light of new data from the *Heliospheric Imagers* (HI) on the *Solar TERrestrial Relations Observatory* (STEREO) spacecraft and other instruments, and suggest possible directions for further work.

Keywords Solar wind, SIRs · IPS, EISCAT · *Ulysses*, SWOOPS · *Wind*, SWE · SOHO, LASCO · MkIII, Mauna Loa

1. Introduction

Interplanetary scintillation (IPS) is the variation in the apparent intensity of radio waves from a distant, compact, radio source produced by variations in the density of the solar wind. This produces a drifting pattern of scintillation in the radio signal across the Earth and thus allows IPS to be used as a probe for investigating the inner heliosphere. The mainland antennas of the *European Incoherent SCATter radar* (EISCAT) have made such measurements of IPS since 1982 (*e.g.*, Bourgois *et al.*, 1985) and on a regular basis since 1990. Simultaneous observations of IPS from different combinations of the three antennas of the mainland EISCAT system can be combined in a cross-correlation analysis (*e.g.*, Coles, 1996; Fallows, Breen, and Dorrian, 2008) to yield more accurate estimates of solar-wind velocity (and other plasma parameters). This is only possible when the points of closest approach of the lines of sight from the radio source to each antenna lie close to the same Sun–Earth–source plane (*e.g.*, Breen *et al.*, 1996a; Coles, 1996). The point of closest approach of the line of sight (LOS) to the Sun is referred to as the P-Point (or sometimes as the “impact parameter”). Figure 1 gives a schematic example of IPS signals being received using two radio antennas from the EISCAT system (Tromsø and Kiruna) and an example cross-correlation analysis from 12 May 2004 with source J0319+415.

A principle advantage of the EISCAT facility is the long baselines (≈ 390 km) available separating the antennas. If the separation in the radial direction of the LOS (B_{Par} in Figure 2) to the two antennas in the Sun–Earth–source plane is increased, the difference in time lag between different solar-wind streams also increases (Grall, 1995; Rao *et al.*, 1995; Grall *et al.*, 1996; Moran, 1998; Moran *et al.*, 1998; Bisi *et al.*, 2005, 2007; Breen *et al.*, 2006) thus improving the ability to resolve these streams in the cross-correlation function (CCF). A schematic layout of the IPS observing baselines can be seen in Figure 2. Observations since 1994 have consistently demonstrated that both fast and slow solar-wind streams

(Bisi *et al.*, 2004)

Figure 1 The basic principles of multi-site (in this case two EISCAT antennas, Tromsø and Kiruna) interplanetary scintillation (IPS) through the simultaneous observation of a single radio source. The signal received from a distant, compact source has a variation in amplitude which is directly related to turbulence in the material crossing the line of sight (LOS), and can thus be related to variations in density. A cross correlation of the two signals received produces a cross-correlation function (CCF) which can be used as a first estimate of solar-wind velocity (or velocities) crossing the IPS LOS.

can appear as two distinct peaks in the CCF and streams closer in velocity make the CCF asymmetric when the baseline is not large enough to reveal both streams (*e.g.*, Klinglesmith, 1997; Bisi *et al.*, 2005).

This paper's basis builds on the preliminary work on interaction regions carried out in Canals (2002) and extended in Bisi (2006). We summarize the investigation of detections of compression regions/rarefaction regions, and shears, that can be seen in IPS data, and compare these with the *Wind/Solar Wind Experiment* (Wind/SWE) (Ogilvie and Desch, 1997; Ogilvie *et al.*, 1995) and the *Ulysses/Solar Wind Observations Over the Poles of the Sun* (Ulysses/SWOOPS) (Wenzel *et al.*, 1992; Bame *et al.*, 1992) hourly-averaged solar-wind velocity data.

The mapping method used for the IPS data is discussed in Section 2. We discuss the observations during the end of Solar Cycle 22 and the majority of Solar Cycle 23 (a 10-year period of the EISCAT IPS data between 1994 and 2003 inclusive) in Section 3, and describe the results in detail in Section 4. A discussion of these results is carried out in Section 5, and a summary is provided in Section 6. Recently, clearly developed co-rotating interaction regions (CIRs) have been reported in white-light images from the *Solar Terrestrial Relations Observatory* (STEREO)/*Heliospheric Imager* (HI) instruments by Rouillard *et al.* (2008), and some of the authors on this paper have combined IPS and HI data (to be discussed in a forthcoming paper) to study the interaction between a CIR and a small-scale solar-wind

(Breen *et al.*, 2002b)

Figure 2 The parallel and perpendicular components of a two-station IPS observation relative to the radial outflow of solar wind as if looking from the radio source (perpendicular to the page) towards the two IPS antennas labeled as Beam A and Beam B. Beam A and Beam B are representative of the raypath from each of the two IPS receivers. The raypaths are separated by a distance B_{par} in the direction radial to the Sun and B_{perp} tangential to this direction. Correlation of the signal received at each of the sites is greatest when the parallel baseline lies across the direction of flow of the solar wind – if the solar wind flows in a purely radial direction, then maximum correlation will be achieved when B_{par} lies parallel to the line R (which represents a purely radial outflow with zero B_{perp}).

transient. In Section 6 we also discuss how some of the uncertainties in interpreting IPS observations which were encountered in this survey can be reduced by combining IPS data with images from HI and *in-situ* measurements from STEREO, *Venus Express*, and *Messenger*.

2. IPS Line-of-Sight Mapping Methods

The scintillation pattern recorded in an IPS observation contains contributions from scattering events occurring along the whole of the LOS from source to antenna. The first attempts at IPS analysis treated the whole LOS as if it were immersed in a single stream of solar wind, obtaining estimates of solar-wind parameters which, at best, represented a weighted average of the real solar-wind properties. A substantial improvement in the analysis method was made by Coles (1996), who mapped the LOS ballistically back down to a “source surface” in the corona and overlaid it on a map of coronal brightness associating regions of the LOS above dark corona with fast flow and those above bright corona with slow flow, and fitting the two streams of solar wind-separately using a weak-scattering model. This model has subsequently been modified and developed (*e.g.*, Klinglesmith, 1997; Massey, 1998; Bisi *et al.*, 2007; Fallows, Breen, and Dorrian, 2008). This approach was used to study CIRs by Breen *et al.* (1998) and Breen *et al.* (2002a) with considerable success, but it was limited by the use of a single velocity for the ballistic projection. This led to significant uncertainty as to precisely where along the LOS the interaction region might be developing. An improved approach was adopted by Canals (2002) in which a single-velocity mapping was used to initially identify the main regions of fast and slow flow but these regions were then again projected back to the source surface separately with different speeds. The observation was then fitted using a two-mode weak-scattering model, with the scintillation from one of the

streams assumed to be dominated by the interaction region. The two regions were then projected down to the source surface again using the speeds derived from the model fitting, and the process repeated until a stable solution was achieved. This method was further developed in subsequent work by Canals (2002) and Bisi (2006) in line with a suggestion by J.T. Hoeksema (private communication, 2001; originally cited by Canals, 2002) by projecting the slow and fast wind parts of the LOS outwards at their respective speeds from the source surface into the heliosphere. By applying this approach to the different portions of the IPS LOS, potential locations of compressive interaction could be easily identified (by the development of an overlap between the two sections of the LOS), the likely sites of rarefaction regions were immediately apparent (divergence of the two LOS segments) and possible shear layers could be identified (overlap of the LOS segments but at slightly different latitudes). The broad umbrella classification, which these can be considered under, is that of stream-interaction regions (SIRs). Canals (2002) looked briefly at some preliminary case studies (which are also used in this paper).

3. Observations

This paper extends the approach of mapping the IPS observations outwards to a survey of all EISCAT IPS observations made between 1994 and 2003 when a SIR may have been present somewhere along the LOS. The approach has changed from a series of case studies to a study of the whole phenomenon of stream–stream interaction in the solar wind; although examples of a CIR and a shearing interaction are presented as the two limiting cases for interaction. Coronal Mass Ejections (CMEs), which can also cause intermediate velocities and compression/shock regions on much shorter-lived time scales (*e.g.*, Canals, 2002; Jones, 2007; Jones *et al.*, 2007), have been excluded from this investigation. Only relatively long-lived phenomena are studied. These data are summarized in tables after the example case study of each phenomenon investigated in this paper.

The importance of the improved mapping approach of the IPS raypaths to the *in-situ* distances is that it provides a much better indication of the region of interaction in the raypath; and thus the distance from the Sun where the interaction is taking place. It therefore provides a much more robust way of looking at how CIRs and other forms of long-lived interaction develop than those shown previously (*e.g.*, Breen *et al.* 1996a, 1996b, 1997a, 1998). Provided that interaction can be found in the raypath, high-frequency IPS measurements can be used to detect the early formation of compression regions or shear between fast and slow streams. Since IPS measurements are sensitive to the approximate electron density squared, the technique has a much greater sensitivity to density changes in the solar wind than, for example, white-light observations such as those by the *Solar Mass Ejection Imager* (SMEI) instrument (Eyles *et al.*, 2003; Jackson *et al.*, 2004) or the HIs (Harrison, Davis, and Eyles, 2005; Harrison *et al.*, 2008; Eyles *et al.*, 2009) onboard the twin STEREO spacecraft (Kaiser, 2005; Kaiser *et al.*, 2008): STEREO-A (Ahead) and STEREO-B (Behind). IPS measurements should therefore be able to detect compression regions closer to the Sun than other techniques.

Intermediate velocities have been detected in both *Ulysses* data (*e.g.*, while transiting through stream transitions) and in EISCAT IPS data for many years (*e.g.*, Breen *et al.*, 1997b; and Forsyth and Gosling, 2001). Interaction regions occur in the solar wind due to a fast wind being carried under the slow wind from the rotation of the Sun and this is mostly characterized by intermediate velocities and significantly enhanced (depleted) densities on the leading (trailing) edge of the structure. Compressive interaction regions – known generally as CIRs if they persist for more than one solar rotation – have long been known to arise

when coronal holes exist or extend to middle and equatorial latitudes, leading to the presence of streams of fast outflow flanked or bordered by slow wind (*e.g.*, Snyder and Neugebauer, 1965; and Neupert and Pizzo, 1974). The rotation of the Sun leads to the streamlines of the fast stream being carried under those of the slow wind above the leading edge of the coronal hole, while above the trailing edge the streams diverge. As the magnetic field carried out from the corona by the solar wind follows these streamlines, the different solar-wind streams cannot interpenetrate. This results in the build-up of regions of compression around the leading-stream interface and of density depletion around the trailing interface with intermediate velocities present in both the compression and rarefaction zones (*e.g.*, Gosling *et al.*, 1972, 1978). Shear layers between streams arise when the fast wind is “sliding” past the slow wind at an adjacent rotating latitude. This is not an interaction region *per se*, but interaction is probable along the shear boundary itself. Shear layers are not normally termed interaction regions, but changes of flow speed will occur across the interface. This can lead again to intermediate velocities being seen in the IPS data. This is particularly the case in IPS observations where there is a large proportion of the raypath passing through the boundary region between the shearing streams.

3.1. Data Refining

The initial filtering of the data, starting with well over 2000 individual IPS observations, was undertaken during the first stage of data analysis. This stage gives a view of the auto- and cross-correlation spectra (*e.g.*, Fallows, 2001; Canals, 2002; Bisi, 2006) for signs of intermediate velocities and/or more than one stream detected along the IPS raypath that is near to the velocity of the dominant stream crossing it. In other words, cases where there is no clear single slow or fast stream or clear non-interacting fast and slow streams. Cases that were thought to contain multiple streams, one of which being an intermediate-velocity stream, *i.e.*, having a projected IPS mid-value velocity into the scattering spheroid defined by the position of the P-Point and the IPS weighting function between 400 km s^{-1} and 600 km s^{-1} , were also selected as possible SIR cases from these data. In addition to these observations we considered measurements made using sources that lay close to them in the sky which did not show intermediate-velocity signatures, with the intention of trying to obtain information on solar-wind structure in the vicinity of the SIR candidate.

The next stage was to remove those observations that were possible CME candidates (Jones, 2007), and also those which showed signs of not remaining in the weak-scattering regime. A closer look at the shape of the CCFs was undertaken to check for observations that were showing signs of intermediate velocity, but not showing more than one stream, *i.e.*, not having any asymmetry in the shape of the CCF. These too were removed from the list of possible cases to be investigated; the reason for this being that an observation of a single intermediate-velocity stream will not be able to show compression/rarefaction or shear when mapped out to *in situ* distances using the method we use here, since there is only a single stream velocity detected in the entire IPS LOS. Observations that still displayed signs of noise after the noise filtering in the first stage of data analysis were also eliminated from the investigation. This then left around 300 observations of “clean” data that fulfilled the criteria. This is more than can be completely covered in a single paper. It should also be noted that, during this investigation, some of the fast-wind-dominated IPS observations around solar minimum were found to have structure within the fast wind (Bisi, 2006; Bisi *et al.*, 2007) itself.

The next stage of the investigation was to fit those cases deemed most-likely to show signs of compression/rarefaction/interaction, avoiding those that have had substantial investigation previously, and then ballistically map out (*e.g.*, Canals, 2002; Bisi, 2006) from the

IPS distance, the individual solar-wind streams in the IPS raypath at their fitted velocities to the *Ulysses* and *Wind* spacecraft distances. White-light maps were used to constrain the stream boundaries along the IPS raypath in the usual way (e.g., Breen *et al.*, 1999).

4. Results

The IPS observations investigated were dealt with as two separate phenomena of SIRs: CIRs and shear layers. This also included looking at some not-very-well-studied cases.

4.1. Co-rotating Interaction Regions (CIRs)

CIRs are familiar from spacecraft observations and are characterized in the main by a dense region of compression at the leading edge of the fast stream as it starts to interact and push into the trailing edge of the preceding slow stream (e.g., Forsyth and Gosling, 2001). This compression can cause enhanced scintillation in an IPS observation due to the density increases in a CIR-formation region. At the trailing edge of the fast stream, a low-density rarefaction region occurs where the flows diverge due to the following slow stream having a tighter spiral angle because of its lower velocity, and the fast stream seemingly “pulling away” from it out in front. The degree of compression steepens as the angle of the respective stream increases, *i.e.*, a greater difference in the velocities between the interacting streams. At large distances from the Sun, shocks can develop at the leading edge of the fast stream; as described in greater detail in Forsyth and Gosling (2001). At the EISCAT IPS observation distances however (typically inside 0.6 AU), the angle between the spirals is not as great as it is at the typical *in-situ* distances of spacecraft such as *Ulysses* (≈ 1.4 AU to ≈ 5.0 AU from the Sun). Therefore, the effects are not as dramatic seen in IPS data since IPS observations generally reveal the onset of the compression that can develop into a CIR near-to and outside-of 1 AU.

4.1.1. EISCAT IPS CIR Case Study

The CIR case study described here (Bisi, 2006) is taken from the dates 20 May 2000 to 25 May 2000 (inclusive), using the radio source J0318+164. This period is inclusive of the two preliminary sub-case studies from 2000 carried out by Canals (2002) on 21 May 2000 and 24 May 2000 with this radio source. These are roughly equatorial observations based in the southern hemisphere ranging from -6.2° latitude at a P-Point distance of $29.7 R_\odot$ on 20 May 2000 to -1.3° latitude at a P-Point distance of $47.1 R_\odot$ on 25 May 2000. All six observations are off the east limb of the Sun during Carrington rotation 1963 and were mapped onto the synoptic map from LASCO C2 data at $5 R_\odot$ to determine the stream boundaries in each case. An example can be seen with one of the middle observations, 22 May 2000, in the combined IPS – white-light map in Figure 3. This displays the IPS raypath ballistically mapped onto the white-light synoptic map (top panel), to the distance of the *Wind* spacecraft from the Sun (middle panel), and to the distance of the *Ulysses* spacecraft from the Sun (bottom panel). The small diamond-shaped IPS data points are separated at 5° intervals along the LOS relative to the Sun – P-Point line with negative angles towards the Earth end of the LOS and positive angles towards the source end. Also shown by the colored strips in the figure are the radial velocity components of solar wind outflow measured by the *Wind* spacecraft (around 0° latitude in the middle panel) and by the *Ulysses* spacecraft (around -57° latitude in the bottom panel) which coincide with the IPS data at their respective distances.

Figure 3 Observation of a CIR with radio source J0318+164 on 22 May 2000 mapped back at IPS detected stream velocities onto the LASCO C2 white-light synoptic map (top panel), and then mapped out from IPS distance out to the *Wind* (center panel) and *Ulysses* (bottom panel) distances respectively.

As can be seen in Figure 3, when the observation is mapped out to the distance of the *Wind* spacecraft, it provides excellent agreement with the velocities detected by *Wind* and their positioning in latitude and longitude (details of such figures can be found in Breen *et al.*, 2000, and Breen *et al.*, 2002c, and references therein). It can be seen from the maps, by the overlap of the fast- and slow-stream lines of sight, that the two streams will be starting to interact by the distance of the *Wind* spacecraft and will show strong interaction by the greater distance of *Ulysses*. It should be noted that the *Ulysses* data are only included here for illustration; the difference in latitude is too great for a meaningful comparison.

Figures 4 and 5 show the projected LOS for six observations of J0318+164 on 20–22 May 2000 (Figure 4) and 23–25 May 2000 (Figure 5), projected out ballistically to the distance of the *Wind* spacecraft. The trajectory of the *Wind* spacecraft during Carrington rotation 1963 is also plotted, and both the LOS and the *Wind* trajectory are color-coded for velocity (bulk solar-wind speed from IPS fitting for the LOS, measured solar-wind speed hourly-averaged for *Wind* data). Regions of the IPS LOS where the sections mapped outwards at fast and slow wind speeds overlap are marked as possible compression regions, while regions where they diverge are marked as potential rarefaction regions. In the observation made on 20 May 2000, both compression and rarefaction regions would be expected to be present in the LOS. In this case a significant contribution to the observed scintillation would be expected to come from the dense compression region – which straddles the P-Point for the observation – giving a clearly defined intermediate velocity when the IPS data are fitted with a weak-scattering model. The low-density rarefaction region lies well away from the P-Point and would not be expected to contribute significantly to the observed scintillation. In this case, an IPS observation with this geometry of LOS overlying the complex equatorial coronal structure (as shown in the top part of Figure 3) would be expected to show a normal slow wind and a slower-than-expected fast stream when fitted with a two-mode weak-scattering model with the compression region and fast stream grouped together. This is exactly what is seen in the IPS observation from 20 May 2000, suggesting that our interpretation of this structure is correct. Over 21–22 May 2000 the rotation of the Sun carries the observation LOS to higher longitudes, shifting the P-Point away from the expected compression region while the movement of the Earth carries the LOS from J0318+164 to successively lower latitudes. The result is that by 21 May 2000 the compression region expected to arise from the coronal-hole boundary near 15° longitude no longer lies along the LOS, and although the rarefaction region overlying the previous trailing coronal-hole boundary near 350° longitude now lies near the P-Point, the low densities expected in the interaction region would mean that we would not expect it to contribute enough to the scintillation pattern to be detected over the ambient fast and slow streams. We would therefore expect this observation to show normal fast- and slow-speed streams, as indeed was the case when the observed scintillation spectra were fitted (see Table 1). By 22 May 2000 a second coronal hole boundary had been carried under the LOS, placing a potential site for compressive interaction close to the P-Point. Fitting the IPS observation with the fast stream and compression region grouped together and the slow stream fitted separately suggested a fast stream only slightly slower than normal and a normal slow stream. This suggested that if the compression region lay on the LOS it was not sufficiently strongly developed to be resolved over the scintillation contributed by those parts of the LOS immersed in ambient fast wind (most of the LOS) or slow wind (the portion of the LOS flanking the P-Point). From 23 May 2000 the expected site of the compression region moves over the P-Point, and two-mode weak-scattering model fits to the IPS data show a steady decrease in solar-wind speed across the fast-wind/compression region section of the LOS (again, see Table 1), consistent with the compression region moving closer to the P-Point and increasingly dominating the observation. The increase in the strength of the compressive interaction suggested by the lower

Figure 4 The IPS raypath of J0318+164 mapped to the distance of the *Wind* spacecraft on dates (from top to bottom) 20 May 2000 to 22 May 2000 along with the *Wind* velocity data for Carrington rotation 1963. A full explanation of the figure can be found in the text.

Figure 5 The IPS raypath of J0318+164 mapped to the distance of the *Wind* spacecraft on dates (from top to bottom) 23 May 2000 to 25 May 2000 along with the *Wind* velocity data for Carrington rotation 1963. An explanation of the figure can be found in the text.

Table 1 Summary of the EISCAT IPS CIR results as estimated using the weak-scattering model where “vfast” is the estimated velocity of the faster of the two streams, “vslow” is the estimate of the velocity of the slower of the two streams, and “error vf” and “error vs” are the errors in velocities of each of the respective streams (see text for full explanation). The spacecraft comparison column indicates whether there was any comparison with either the *Wind* or *Ulysses* spacecraft, or both. Generally, where comparisons were possible, the IPS velocity results were approximately in agreement with the spacecraft data. The P-Point distance for each IPS observation is also given.

EISCAT IPS CIR results

Date (YYYYMMDD)	Source (J2000)	P-Point ($R_{\odot}$)	vfast (km s^{-1})	error vf (km s^{-1})	vslow (km s^{-1})	error vs (km s^{-1})	Spacecraft Comparison
19950704	0738+177	44.2	578.9	± 63.2	349.9	± 19.9	None
19950709	0738+177	28.2	680.1	± 133.8	297.3	± 28.0	None
19990502	0137+331	81.3	602.0	± 2.1	358.0	± 29.6	None
19990502	0318+164	37.7	448.0	± 0.0	378.0	± 0.0	<i>Wind</i>
19990503	0137+331	82.3	582.2	± 54.9	414.2	± 40.4	None
19990503	0318+164	34.1	676.0	± 2.8	312.0	± 19.9	<i>Wind</i>
19990504	0318+164	30.8	682.0	± 0.0	319.0	± 0.0	Both
19990505	0318+164	27.2	759.0	± 223.0	326.0	± 50.5	Both
19990506	0318+164	23.9	800.0	± 0.0	367.0	± 58.4	Both
19990507	0321+123	28.7	800.0	± 0.0	384.0	± 33.5	<i>Ulysses</i>
19990510	0336+323	60.2	447.8	± 15.9	317.8	± 49.0	None
19990515	0319+415	83.3	632.0	± 64.4	289.0	± 43.4	None
20000514	0319+415	83.1	403.0	± 62.6	295.0	± 29.6	None
20000518	0321+123	32.2	532.0	± 25.8	288.0	± 0.0	<i>Wind</i>
20000519	0403+260	27.4	506.0	± 0.0	399.0	± 86.6	<i>Wind</i>
20000520	0318+164	29.7	605.0	± 36.6	341.0	± 50.4	<i>Wind</i>
20000521	0318+164	33.2	716.0	± 175.0	363.0	± 57.0	<i>Wind</i>
20000521	0403+260	23.1	555.0	± 59.9	194.0	± 30.7	None
20000522	0318+164	36.5	668.0	± 23.8	356.0	± 47.2	<i>Wind</i>
20000523	0318+164	40.0	682.0	± 67.7	316.0	± 33.6	<i>Wind</i>
20000523	0431+206	25.1	556.0	± 52.2	283.0	± 24.0	<i>Wind</i>
20000524	0318+164	43.6	529.0	± 58.0	336.0	± 10.8	<i>Wind</i>
20000525	0318+164	47.1	528.0	± 0.0	349.0	± 0.0	<i>Wind</i>
20000527	0432+416	75.5	499.0	± 65.0	365.0	± 0.0	None
20000907	1042+120	30.4	750.0	± 0.0	365.0	± 46.9	<i>Wind</i>
20000908	1042+120	34.0	435.0	± 24.9	184.0	± 33.3	<i>Wind</i>
20000909	1042+120	37.8	697.0	± 82.0	290.0	± 30.0	<i>Wind</i>
20000910	1150-003	37.3	412.0	± 0.0	316.0	± 85.3	<i>Wind</i>
20000911	1150-003	33.7	423.0	± 27.3	163.0	± 9.9	<i>Wind</i>
20010523	0431+206	26.0	728.0	± 0.0	253.0	± 50.4	<i>Wind</i>
20030430	0318+164	44.8	624.0	± 95.3	244.0	± 0.0	<i>Wind</i>

fast/compression region speeds is also consistent with the increasing distances of the IPS observations from the Sun over this period; something which can be seen when the velocities determined from the IPS observations are compared with those from *Wind* at $\approx 215 R_{\odot}$. The distribution of velocities with longitude seen by *Wind* is consistent with those observed by

IPS, but the regions of intermediate velocity are broader and more marked – consistent with the development of interaction regions with increasing distance from the Sun. The overlap between the fast/compression region and slow wind regions of the IPS LOS when projected out to the distance of the *Wind* spacecraft from the Sun compares well with the extent of the intermediate-velocity regions observed by the *Wind* spacecraft instrumentation.

Figures 6 and 7 show successively the six observations of J0318+164 through the dates 20 May 2000 to 25 May 2000 at a mapped distance to the *Ulysses* spacecraft and marked in the same way as those for the *Wind* spacecraft. As the days progress, IPS observations start by detecting movement of the fast stream under the slow stream when mapped onto the *Ulysses* data at their respective velocities, which in reality, is likely to mean strong compression at *Ulysses* distance, or even shocks. No direct comparison of velocities of the *Ulysses* spacecraft can be made since the spacecraft does not achieve a latitude similar to that of the IPS observations. On 21 May 2000 however, movement of the fast stream under the slow stream is no longer detected, but a large rarefaction region is seen. This is comparable to what occurs when this observation is mapped to the *Wind* spacecraft distance. By 22 May 2000, the mapped rarefaction region disappears and compression is now detected (again as it was at the distance of *Wind*). By 23 May 2000, movement of the fast stream can be seen under the slow once more, with strong compression, and therefore in reality much more interaction on 24 May 2000 which is still present on 25 May 2000. The mapped IPS data at the *Ulysses* spacecraft distance continues to show good agreement with the features that are seen at the distance of *Wind* throughout this six-day period, suggesting that not only was this a spatially-extended event at *Wind*, but the same event continued out to *Ulysses* distance and probably beyond as would be expected from a CIR since they are largely long-lived structures (e.g., Gosling *et al.*, 1978; Forsyth and Gosling, 2001).

This case study of J0318+164 observations over the six days shows what has already been known for some time with respect to the scale and long length of a SIR, but also shows how strongly a developing SIR can be picked up at IPS distances (in this case $\approx 29 R_{\odot} - 47 R_{\odot}$) with intermediate/fast stream velocities ranging from 528 km s^{-1} to 716 km s^{-1} , and a more stable slow-stream velocity range of 316 km s^{-1} to 363 km s^{-1} . Clear signs of compression and rarefaction can be seen mapped at both *Wind* and *Ulysses* distances as well as having a good agreement with velocity measurements made by the *Wind* spacecraft and inferred to the *Ulysses* spacecraft. The fast stream being carried under the slow stream is noted from the mapping process at *Ulysses* distances in particular. However, it should be remembered that this may not be a completely true representation due to the ballistic mapping used here and the assumption of radial flow – the separate fast and slow streams seen in IPS will have ceased to exist well before the *Ulysses* distance and the resulting interaction is likely to result in non-radial flows.

4.1.2. EISCAT IPS CIR Observations Summary

The same method as for the case study was then applied to the other possible CIR cases and the results of the investigation are presented in Table 1. This includes all of the observations that were investigated in detail during this study. Also indicated in the table are those observations where comparison with *in-situ* data was possible in that they overlapped at a similar latitude and a similar time frame (a whole Carrington rotation was generally used as the time frame in line with the fact that coronagraph synoptic maps also cover a single Carrington rotation). In all, 31 separate observations of CIRs were detected in these IPS data that were mapped to *in-situ* distances. The IPS velocity errors are taken as the modeled values for the spread of velocities about the mean value for each stream

Figure 6 The IPS raypath of J0318+164 mapped to the distance of the *Ulysses* spacecraft on dates (from top to bottom) 20 May 2000 to 22 May 2000 along with the *Ulysses* velocity data for Carrington rotation 1963. An explanation of the figure can be found in the text.

Figure 7 The IPS raypath of J0318+164 mapped to the distance of the *Ulysses* spacecraft on dates (from top to bottom) 23 May 2000 to 25 May 2000 along with the *Ulysses* velocity data for Carrington rotation 1963. An explanation of the figure can be found in the text.

(Fallows, Breen, and Dorrian, 2008 and references therein); high values of this spread will often indicate the presence of an unmodeled farther solar-wind stream with a differing velocity.

4.2. Shear Layers

Shear layers are characterized in the main by a region of two streams lying at a very shallow angle (close to parallel latitude) with quite often some interaction detected along the stream – stream boundary. In IPS data, a velocity gradient is often detected but there is no significant increase in scintillation. Generally, this is because compression regions do not occur as they do in the case of CIRs and hence here there is no great increase in turbulence to detect. The flows merely “slide” pass each other instead of the compression and rarefaction that occurs in CIR formation.

4.2.1. EISCAT IPS Shear Layer Case Study

The shear-layer case study is taken from 23 May 1996 and 24 May 1996 using the source J0431+206. This is a southern hemisphere observation around -18° latitude at a P-Point distance around $25 R_\odot$ on 23 May 1996, and around -20° latitude at a P-Point distance around $21 R_\odot$ on 24 May 1996. Both observations were taken off the east limb of the Sun during Carrington rotation 1909 and were mapped onto the synoptic map from LASCO C2 data at $5 R_\odot$. This can be seen in the combined mapped Figures 8 and 9 displaying the IPS raypath ballistically mapped onto the white-light map, to the distance of the *Wind* spacecraft along with the *Wind* velocity data, and to the distance of the *Ulysses* spacecraft along with the *Ulysses* velocity data.

The first day of the two consecutive observations with this source (23 May 1996) has a much greater velocity difference between the streams compared with the second day. By the time the streams reach the distance of the *Ulysses* spacecraft, they show signs of compression as the mapped fast and slow stream lines of sight appear to “overlap”. This is probably because of the large difference in Parker spirals between the two different solar-wind streams. We can speculate that by *Ulysses* distance some sort of interaction would have occurred and the shear may have even started to build into a CIR, although the stream angle may be somewhat too shallow for this to have occurred. Without *in-situ* data at these specific latitudes and distances though, it is difficult to ascertain exactly what may happen since *Ulysses* was at a different location from the mapped IPS observation.

The second day of the observations of this source (24 May 1996) shows a faster fast stream with a slow-to-intermediate radial velocity second stream. The P-Point of the observation is a little closer to the Sun and a little further south in latitude. It has also moved along by a few degrees in longitude from that of the previous day making it lie less in the slowest regions of the streamer belt. Since the slower of the two streams is rather higher in velocity than on the previous day, the spiral angle is not so tightly wound and therefore by the distance of the *Ulysses* spacecraft it will not have formed compression as on the previous day’s observation, but shear is clearly seen in the mapping.

The small amounts of comparison achieved with the *Wind* velocity data reveal that velocities for the ends of the raypath are very similar, and where the raypath moves South and away from the *Wind* data where the shear is being detected, the *Wind* data show signs of a slow-to-intermediate radial velocity around equatorial regions. This is consistent with where the slow-to-intermediate radial-velocity stream is being detected in the IPS measurements on the second day of observing J0431+206 when mapped to the *Wind*-spacecraft distance.

Figure 8 Observation of a shear layer with source J0431+206 on 23 May 1996 mapped back at IPS detected stream velocities onto the LASCO C2 white-light synoptic map (top panel), and then mapped out from IPS distance to the *Wind* (center panel) and *Ulysses* (bottom panel) distances respectively.

Figure 9 Observation of a shear layer with source J0431+206 on 24 May 1996 mapped back at IPS detected stream velocities onto the LASCO C2 white-light synoptic map (top panel), and then mapped out from IPS distance to the *Wind* (center panel) and *Ulysses* (bottom panel) distances respectively.

Table 2 Summary of the EISCAT IPS Shear Layer results as estimated using the weak-scattering model where the columns are the same as those in Table 1. Generally, as with the CIR results, where there was a comparison with spacecraft data, the IPS velocity results were in agreement

EISCAT IPS shear layer results

Date (YYYYMMDD)	Source (J2000)	P-Point ($R_{\odot}$)	vfast (km s^{-1})	error vf (km s^{-1})	vslow (km s^{-1})	error vs (km s^{-1})	Spacecraft Comparison
19950709	0741+271	30.7	712.0	± 71.5	447.0	± 157.0	<i>Ulysses</i>
19950710	0735+331	43.4	696.0	± 73.6	232.0	± 53.4	Both
19950719	0735+331	47.5	786.0	± 137.4	325.0	± 0.0	<i>Wind</i>
19960523	0431+206	24.6	616.0	± 86.0	180.0	± 26.8	<i>Wind</i>
19960524	0431+206	21.0	729.0	± 49.0	429.0	± 7.9	<i>Wind</i>
19960525	0521+166	63.7	690.0	± 55.4	325.0	± 0.0	<i>Wind</i>
19960529	0403+260	25.7	661.0	± 119.6	165.0	± 12.1	Both
19990502	0242+110	17.0	742.0	± 156.4	311.0	± 86.8	<i>Ulysses</i>
19990502	0321+123	42.6	480.0	± 2.0	338.0	± 1.6	<i>Ulysses</i>
19990503	0242+110	17.2	748.6	± 158.2	352.9	± 20.9	Both
19990503	0321+123	39.5	638.0	± 59.8	344.0	± 21.3	<i>Ulysses</i>
19990508	0321+123	26.7	600.0	± 60.0	306.0	± 85.5	Both
19990509	0321+123	24.9	733.0	± 155.2	202.0	± 39.3	Both
19990514	0433+053	79.1	555.5	± 5.4	230.7	± 0.0	None
19990921	1008+075	96.8	620.0	± 57.3	259.0	± 16.2	<i>Wind</i>
20000517	0432+416	90.4	454.0	± 85.2	238.0	± 87.6	<i>Wind</i>
20000519	0321+123	34.9	619.0	± 0.0	393.0	± 0.0	None
20000520	0403+260	25.2	511.0	± 30.7	365.0	± 106.5	None
20000526	0319+415	84.9	424.0	± 72.9	234.0	± 24.5	None
20000911	1120+143	37.3	379.0	± 22.5	295.0	± 60.3	<i>Wind</i>
20000912	1120+143	38.7	397.0	± 38.0	287.0	± 83.9	<i>Wind</i>

Overall, with the shape of the streamer belt and the positioning of the IPS raypath (particularly that of the central fast stream), this case study over a two-day period displays good signs of shear between the streams of solar wind as they evolve out to *in-situ* distances. Unfortunately, due to the positioning of the source from one day to the next (as with all the cases of shear investigated here which were seen in more than one single observation), it is not possible to work out the latitudinal thickness of this shear as was carried out in Breen *et al.* (1999) where the sources observed moved through the shear in a latitudinal direction on a consecutive basis with each observation. However, this method does provide a solid way of finding cases of shear within the solar wind at IPS distances and in looking at how these cases of shear develop by *in-situ* observing distances.

4.2.2. EISCAT IPS Shear Layer Observations Summary

The same method as used for the case study was then applied to other possible shear-layer cases and the results of the investigation can be seen in Table 2. This includes all the observations that were looked at in detail during this investigation. Also indicated, are those where comparison with *in-situ* data were possible (as with the CIR detections). In all, 21 observations of shear in this investigation were detected in the IPS data when mapped to *in-situ*

distances. This combining of white-light, IPS, and *in situ* data with the method described in this paper provides a much-improved way at getting information from the EISCAT IPS data set, and discerning whether or not a particular observation is that of a shear layer. The columns in the table are as before with the CIR cases. Many of the observations displayed at least some agreement with spacecraft data, and in the most part, were consistent at similar latitudes as shown in the example case study.

5. Discussions

After looking at these data as a whole, they illustrate that CIRs and shear layers represent the two extremes of the same phenomenon caused by interaction along the boundary layers between fast and slow streams of the solar wind (Gosling *et al.*, 1978; Gosling, 1996; Gosling and Pizzo, 1999). In general, the closer the angle is between the two interacting streams to a longitudinal line, the more likely it is to form a CIR, and the closer the angle to a latitudinal line, the more likely it is to form a shear layer. It is difficult to discern between the two types in EISCAT IPS data without mapping outward since no discernible pattern of velocities or velocity variations comes from either of the two lists, which makes the mapping method a powerful technique when interpreting interaction detections in EISCAT IPS observations. This is a large enhancement of any previously-used technique with EISCAT IPS data.

In terms of the cases where comparison with spacecraft data were possible, good agreement was found between the mapped IPS raypaths and the hourly-averaged *in-situ* velocity measurements over a Carrington rotation. This can be seen especially in the CIR case study given here of successive observations with source J0318+164 over the six-day period from 20 May 2000 to 25 May 2000 inclusive.

The two summaries (CIR and shear layer) are a result of this far-improved method of looking at solar-wind interaction with IPS data and will be used with, and applied to, future EISCAT IPS observations of interaction regions to aid in their interpretation(s).

6. Conclusions and Future Prospects

The results of this investigation confirm that CIRs and shear layers represent the two extremes of the same phenomenon, which are caused by interaction along the boundary layers between fast and slow streams of solar wind (Gosling *et al.*, 1978). However, it is very difficult to distinguish between the two in EISCAT IPS data alone without mapping outward since no discernible pattern of velocities or velocity variations comes from either of the two lists compiled here in Tables 1 and 2. Some observations previously interpreted as CIRs have now been shown to be cases of shear between the streams (Bisi, 2006). In terms of the cases where comparison of the IPS observations with spacecraft data was possible, an overall good agreement was found between the mapped IPS raypath velocity portions, and the hourly-averaged *in-situ* velocity measurements over a period of one Carrington rotation of *in-situ* data.

The Sun is now at solar minimum and the structure of the corona and solar wind bear some resemblance to those solar conditions seen in 1996 during the first Whole Sun Month (WSM) campaign (Biesecker *et al.*, 1999), but with some additional complexities, overall lower densities, and a weaker magnetic dipole (S.W. McIntosh, private communication, 2008). The Whole Heliosphere Interval (WHI) has been the analog to the WSM of

the previous solar minimum. Now, with a well-established method, these conditions provide a perfect opportunity for it to be applied to new data when looking at interaction in the solar wind. Using this method with observations/measurements from other data sources, which are now more numerous than were available during the previous solar minimum, would also be advantageous where data exist; for example, CIR-type features detected with *Solar-Terrestrial Environment Laboratory* (STELab) IPS (Kojima and Kakinuma, 1987) observations when using a kinematic solar-wind model (Jackson and Hick, 2005) to tomographically reconstruct the inner heliosphere and give good comparison with *in-situ* measurements by STEREO-A, *Wind*, and STEREO-B instrumentation (Bisi *et al.*, 2009, 2010).

In addition to the two-stream method discussed here, added improvements have been made on the EISCAT data modeling to extract further multiple streams (extended from two streams to three) from an individual LOS (Bisi *et al.*, 2007; Breen *et al.*, 2008; Fallows, Breen, and Dorrian, 2008). This three-stream method has successfully been applied to fast solar-wind observations (Bisi *et al.*, 2007) and a CME (Breen *et al.*, 2008); a detailed summary of this extension can be found in Fallows, Breen, and Dorrian (2008). If this three-stream analysis can be applied to interaction-type IPS data, then a clearer picture of slow, interacting, and fast solar-wind streams inside of 1 AU should be relatively easy to achieve. Breen *et al.* (2008) also incorporated the tomography method of Jackson and Hick (2005) and used in Bisi *et al.* (2008) with STELab IPS observations to constrain the various solar-wind/CME portions crossing the EISCAT IPS LOS to enable more-accurate modeling of the CME observation. This should be applied globally to EISCAT IPS observations in the future to gain a greater understanding of how and where interaction takes place in the solar wind in the inner heliosphere.

With the three-point in-ecliptic (the Earth–Sun L_1 -point spacecraft, STEREO-A, and STEREO-B) and also the latest solar minimum polar pass out-of-the-ecliptic (*Ulysses*) measurements, supported by SMEI and STEREO heliospheric observations in Thomson-scattered white light, and a more-global coverage of IPS observations of the inner heliosphere with multiple IPS-capable systems, a better understanding of how interaction regions form and change throughout the inner heliosphere with the aid of the many models for heliospheric investigations should now be more easily achieved than ever before, and we can expect some exciting new discoveries as these data are analysed further throughout this solar minimum.

Imaging of CIRs by instruments such as HI adds considerably to the overall picture. The field of view of STEREO/HI overlaps with that of EISCAT IPS, meaning that the relationship between the structural variations revealed by IPS and the overall structure of the CIR can be determined with much greater accuracy. The greater sensitivity of IPS to small variations in electron density makes it the ideal complement to white-light imaging in investigating the range of stream–stream interactions discussed in this paper. The investigation of SIRs will be further assisted by using *in-situ* data from *Venus Express* and, in the near future, *Messenger* (orbiting the planets of Venus and Mercury, respectively). The closer proximity of these spacecraft to the Sun (and the overlap of their positions with IPS and HI fields of view) greatly reduces the uncertainty in relating stream interfaces observed *in-situ* to coronal and interplanetary structures.

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