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Solar-cycle variations of interaction regions: in-ecliptic observations from 1 to 5 AU

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RESUMEN

Analizamos diferentes características físicas de 98 regiones de interacción (RI) detectadas dentro del plano de la eclíptica entre 1 y 5 UA por diferentes naves espaciales para inferir sus variaciones con el ciclo solar. Este conjunto de RI lo obtuvimos combinando las mediciones de cinco naves que viajaron a Jupiter en diferentes fases del ciclo solar: los Pioneers 10 y 11 (fase descendente ciclo 20), los Voyagers 1 y 2 (fase ascendente ciclo 21) y el Ulysses (posterior al máximo ciclo 22). Encontramos que los patrones de corrientes de viento solar detectados varían continuamente durante todas las fases del ciclo. Estas variaciones ocurren en escalas temporales del orden de algunas rotaciones solares, lo cual hace muy difícil relacionar las cambios en la dinámica del medio interplanetario con los cambios en la configuración a gran escala de la corona. En general las corrientes de viento rápido asociadas con RI fueron más lentas en las observaciones de los Voyagers que en las observaciones de los Pioneers y del Ulysses. La comparación entre las orientaciones de las RI detectadas por los Voyagers y el Ulysses y la inclinación de la hoja de corrienta concuerda cualitativamente con las predicciones de los modelos numéricos. El ancho radial de las RI detectadas por los Pioneers tendieron a ser menores que los anchos en las observaciones de los Voyagers y el Ulysses. Esto sugiere un efecto asociado con el ciclo solar. En este trabajo se señalan algunos aspectos que necesitan ser estudiados en simulaciones numéricas para entender mejor como varía la dinámica a gran escala del medio interplanerio durante el ciclo solar.

PALABRAS CLAVE: Física del medio interplanetario, ondas de choque interplanetarias, regiones de interacción corrotantes, variaciones con el ciclo solar.

ABSTRACT

We study a combined set of 97 interaction regions detected by Pioneers 10 and 11, Voyagers 1 and 2, and Ulysses from 1 to 5 AU during their respective journeys to Jupiter at different phases of the solar cycle. The fast streams associated with the IRs detected by Voyager were slower than the fast streams detected by Pioneer and Ulysses. The comparison between the latitudinal tilts of the IRs detected by Voyager and Ulysses and the tilts of the current sheets show a qualitative agreement with the predictions of heliocentric evolution by numerical simulations of tilted interaction regions. The interaction regions detected by the Pioneers tend to be thinner than the interaction regions detected by Voyagers and Ulysses in the same heliocentric range.

KEY WORDS: Interplanetary physics, interplanetary shocks, corotating streams, solar cycle variations.

1. INTRODUCTION

Interaction regions play a fundamental role in the large-scale dynamics of the solar wind, and their variations may cause global changes in the heliosphere. We study a combined set of 97 interaction regions detected in the ecliptic plane between 1 and 5 AU by five spacecraft that traveled from Earth to Jupiter at different phases of the solar cycle. This set of IRs was identified by scanning solar wind and magnetic field data (González-Esparza and Smith, 1996, hereafter paper 1). It includes the Pioneer 10 and 11 obser-vations during the descending phase of solar cycle 20 (March, 1972-November, 1974); Voyager 1 and 2 observations during the ascending phase of solar cycle 21 (August, 1977-July, 1979); and Ulysses observations during the post-maximum phase of solar cycle 22 (October, 1990 - February, 1992). In this paper, we discuss three aspects of in-ecliptic observations of IRs from 1 to 5 AU with the solar cycle: (1) variations of the solar wind streams associated with IRs; (2) variations in IR geometry; and (3) variations in IR radial width.

Fast and slow solar wind streams are associated with different regions of the solar surface. Due to the solar rotation at low and mid heliolatitudes the interplanetary medium is filled with portions of different solar wind streams. When a fast solar wind stream overtakes a preceding slow stream a compression region develops surrounding the stream interface [Burlaga, 1974]. If the speed difference and the duration of the fast stream is sufficient, the compression region surrounding the stream interface grows and forms an interaction region bounded by two shock waves: a leading forward shock which accelerates the preceding slow solar wind, and a trailing reverse shock which decelerates the incoming fast solar wind (see, e.g., Burlaga, 1984 and references therein). Since the slow and fast wind sources corotate with the Sun, the IR projection on the ecliptic plane has an spiral shape. When the wind sources are stable for a few solar rotations, the IR appears recurrently at the same heliographic location every 27 days and is called a corotating interaction region (CIR) [Smith and Wolfe, 1977]. Since IRs are bounded by two shocks moving in opposite directions with respect to the solar wind reference frame, they expand as they propagate outwards. Thus, in the ecliptic plane, an IR at 1 AU has a radial width of about 0.2 AU, while at 5 AU its radial width is about 1.0 AU. The radial width expansion speed of an IR is about 100 km/s (paper 1).

One of the main results obtained by Ulysses after the Jupiter flyby during the descending phase of solar cycle 22 (1992-1993), was the absence, from about 28° to 38° south latitude, of interplanetary shocks leading to IRs and the continued presence of reverse shocks trailing these IRs [Gosling *et al.*, 1993]. On the basis of the 3-D model of corotating flows by Pizzo [1982, 1991, 1992], Gosling *et al.* [1993] suggested that these IRs were tilted with respect to the solar rotation axis. This tilted geometry would cause the front of the IR to evolve more strongly at low latitudes (towards the ecliptic plane), whereas the trailing edge would evolve more strongly at higher latitudes, thus causing strong latitudinal shear flows at the stream interface. Riley *et al.* [1996] reported that the normal orientations of the shock fronts were qualitatively consistent with the predictions by the 3-D model of corotating flows.

2. SOLAR CYCLE VARIATIONS OF SOLAR WIND STREAMS

Table 1 summarizes the slow temporal evolution of the coronal structure during the solar cycle. The size and location of coronal holes and the shape of the current sheet will change with the cycle. If the solar wind streams change the IRs should also change with the solar cycle. However, it is difficult to determine variations in the patterns of solar wind streams with the solar cycle when using in-ecliptic measurements from 1 to 5 AU. González-Esparza and Smith, (1997, hereafter paper 2) discussed the slow/fast solar wind streams just before/after the IRs detected by Pioneer 11, Voyagers 1 and 2, and Ulysses, taking averages of about four hours duration of the slow and fast solar wind streams adjacent to the IR. The last two columns in Table 1 show the average speeds of the fast and slow solar wind streams adjacent to the IRs for different phases of the cycle. In general, the fast solar wind streams detected by Voyager 1 and 2 were slower than those detected by Pioneer 11 and Ulysses. Besides, the speed differences between fast and slow solar wind streams associated with IRs were lower in Voyager 1 and 2 observations.

Table 1

Characteristics of the coronal magnetic structure through the solar cycle, and observations of solar wind streams associated with interaction regions by Voyager 1 and 2, Ulysses, and Pioneer 11 from 1 to 5 AU.

Solar Cycle	Coronal Holes[a]	Current Sheet[b]	Spacecraft[c]	IRs	Solar Wind Streams 1 to 5 AU[c]
Ascending phase	polar holes shrink and disappear, but the holes evolve in a very different way disappearing at different times	the latitudinal extent of the current sheet increases, disrupting the simple equatorial configuration of the previous minimum	Voyagers 1 and 2	25	mean value of the fast streams associated with IRs: 480 km/s mean value of the slow streams associated with IRs: 350 km/s
Post maximum	no polar holes, but small holes at mid-latitudes	very complex structure, the main current sheet extents almost from pole to pole, and at mid-latitudes small isolated current sheets appear	Ulysses	14	mean value of the fast streams associated with IRs: 575 km/s mean value of the slow streams associated with IRs: 412 km/s
Descending phase	after the reversal in polarity, polar holes reappear and grow in size with large equatorward extensions	the structure is simpler and the current sheet has a sinusoidal shape extended over a large range of latitudes	Pioneer 11	36	mean value of the fast streams associated with IRs: 592 km/s mean value of the slow streams associated with IRs: 386 km/s
Minimum	polar holes have maximum extensions and there are no equatorial	the current sheet is very stable, lying over the solar equator	no spacecraft observations		

[a] Based on the description by *Hundhausen et al.* [1981].
[b] Based on the description by *Hoeksema* [1986].
[c] Based on the study by *González-Esparza and Smith* [1997].

Of all five spacecraft to Jupiter, only the pattern of solar wind streams detected by Pioneer 11 was regular and stable. For the other spacecraft there were frequent intervals dominated by transient events and slow wind, alternating with intervals of fast wind streams and interaction regions. In general, the patterns of solar wind streams vary over a few solar rotations thus causing continual changes in solar wind dynamics. These fluctuations make it very difficult to characterize the large-scale solar wind dynamics at different phases of the solar cycle. Besides, the dynamics are more complex at low latitudes.

In paper 2 we studied the ratios of dynamic pressure (m_p N V_n^2) between fast and slow solar wind streams just before and after the IRs detected by Pioneer 11, Voyagers 1 and 2, and Ulysses. In about half of the IRs the slow wind dynamic pressure was higher. The variability in slow wind density produces significant changes in dynamic pressure; therefore, the slow wind often transfers momentum to the fast wind. This was found to be true in all three missions, suggesting that the variations are present at all phases of the solar cycle. These variations in the ratio of dynamic pressures have not been explored by numerical simulations of interaction regions. It seems likely that, when an IR is forming, the source of fast wind corotating with the Sun injects fast wind against ambient slow wind with different densities. Thus in some parts of the stream interface the fast wind may transfer momentum to the slow wind, and elsewhere the transfer would be in the opposite direction. These dynamic effects should produce deformations in the shape of the interaction region.

3. STREAM INTERFACES AND GEOMETRY OF INTERACTION REGIONS

The three-dimensional numerical simulations by Pizzo [1991, 1994] simplify conditions during the declining phase of the cycle, by assuming that the magnetic field in the corona can be approximated by a tilted dipole. This configuration may produce two oppositely tilted interaction regions in the interplanetary medium. We can use the magnetic source surface maps by the Wilcox observatory as a tool to infer the approximate configuration of solar wind streams in the interplanetary medium, where slow solar wind is associated with the current sheet and the fast solar wind is associated with coronal holes. In the descending phase, the slow wind can be thought as of emerging radially from a thick line around the sinusoidal shape of the current sheet (see Table 1). Thus, the shape of the current sheet would influence the pattern of solar wind streams and the geometry of IRs.

In paper 2 we used a minimum variance technique on the velocity shear flows at the stream interface to infer the orientation of the IRs detected by Pioneer 11, Voyagers 1 and 2, and Ulysses. We found that the stream interfaces in the IRs detected by Ulysses have their normals oriented nearly parallel to the ecliptic plane ($\Theta \approx 0°$), implying that these IRs were nearly normal to the ecliptic. On the other hand, the stream interfaces in the IRs detected by Voyager 1 and 2 and Pioneer 11 have significant tilts to the ecliptic plane ($\Theta \neq 0°$), implying that these IRs were tilted. According to Pizzo, the orientation of an IR is related to the coronal configuration, it changes with heliocentric distance. We traced the fast solar wind streams causing the interaction regions detected by the two Voyager spacecraft and by Ulysses, and we located their origin on the source surface maps from the Wilcox observatory. Source surface maps are not available for the Pioneer epoch. Following Smith [1990], we used the maximum latitudinal extension on the surface maps to estimate the tilt of each current sheet (α) associated with each fast stream.

Table 2 presents the results. The current sheet inclinations, α, were larger for Ulysses (post-maximum and declining phase) than for the two Voyager spacecraft (ascending phase), and the latitudinal inclinations of the interface normals, Θ, were very small for Ulysses and larger in the Voyager 1 and 2 observations. These results are in agreement with the Pizzo [1991] predictions. Specifically, when the inclination of the current sheet is small ($\alpha<20°$) the dynamic evolution of the interaction region causes the interface normal to point to high latitudes ($\Theta\neq0°$) at larger heliocentric distances, and if the inclination of the current sheet is large ($\alpha>30°$) the interface normal tends to point to the radial direction ($\Theta\approx0°$) at larger heliocentric distances. We found a qualitative agreement between the tilt of the IRs detected by the Voyager spacecraft and Ulysses and the tilts of their associated current sheets as predicted by the Pizzo model. The Voyager and Ulysses observations were made during phases of the solar cycle where the shape of the current sheet was not sinusoidal but more complex, and the coronal configuration did not satisfy the simple assumptions of the model. Thus, it is important to extend the simulations using fifferent configurations of the current sheet, which will lead to IRs with different shapes.

4. RADIAL WIDTH OF INTERACTION REGIONS

In paper 1 we estimated the radial width, Wr, of all IRs detected by the five spacecraft during their journey to Jupiter. Figure 1 shows the radial width of the 97 interaction regions against heliocentric distance. In the figure we applied the linear fit

$$Wr_{exp} = 0.02 + 0.2\times R \quad . \qquad (1)$$

The correlation coefficient is approximately 0.7. Similar coefficients were found when data from each spacecraft was

Table 2

Relationships between the latitudinal tilts of the stream interfases and the parent coronal configuration for the interaction regions detected by Voyager 1 and 2 and Ulysses.

spacecraft	CIR date	R	Vf	Δt	Sun	CR	Δt	angle	Vpol	α_p	Θ
Voyager 1	12-Nov-77	1.42	424	5.8	06-Nov-77	1661	5.8	-2	+	30	5
	29-Nov-77	1.58	408	6.7	22-Nov-77	1661	6.7	-5	+	10	7
	13-Dec-77	1.73	526	5.7	07-Dec-77	1662	5.7	-13	+	38	25
	25-Aug-78	4.0	491	14.1	10 -Aug-78	1671	14.1	-216	+	36	35
Voyager 2	13-Nov-77	1.45	477	5.3	07-Nov-77	1661	5.3	-3	+	30	6
	27-Jan-78	2.15	357	10.4	16-Jan-78	1663	10.4	-43	+	12	-12
	25-Aug-78	3.75	476	13.7	10-Aug-78	1671	13.7	146	+	36	14
	20-Sep-78	3.91	519	13.1	06-Sep-78	1672	13.1	237	+	33	15
	05-Oct-78	4.0	390	17.8	17-Sep-78	1672	17.8	110	--	45	-5
Ulysses	28-Apr-91	2.87	633	7.9	20-Apr-91	1841	7.9	-83	--	63	-35
	24-May-91	3.13	627	8.7	15-May-91	1842	8.7	-104	--	62	1
	07-Jun-91	3.26	646	8.8	29-May-91	1842	8.8	-116	+	26	-1
	20-Sep-91	4.27	453	16.4	03-Sep-91	1846	16.4	153	+	55	1
	19-Oct-91	4.48	470	16.5	02-Oct-91	1847	16.5	126	+	53	4
	14-Nov-91	4.7	591	13.8	01-Nov-91	1848	13.8	102	+	60	-3
	21-Nov-91	4.75	618	13.3	07-Nov-91	1848	13.3	95	--	55	2
	11-Dec-91	4.92	493	17.3	23-Nov-91	1849	17.3	76	+	52	-1
	20-Dec-91	5.0	493	17.6	02-Dec-91	1849	17.6	68	--	59	-1

The second column is the heliocentric distance of the interaction region. The third column is the latitudinal inclination of the stream interface normals obtained by González-Esparza and Smith [1997]. The fourth column is the Carrington's rotation associated with the fast stream causing the interaction region. The last column is the estimated inclination of the HCS associated with the fast stream as obtained from the source surface field maps (2.5 solar radii) from the Wilcox Solar Observatory.

analyzed individually. This trend, from 1 to 5 AU, was present in all three phases of the solar cycle. Note that we can use the linear fit (1) to define 'broad' and 'thin' IRs, depending on whether the points are above or below the line in Figure 1. We estimated the normalized variations of the radial width (Wr) of the 98 interaction regions with respect to the expected value Wr_{exp}, as follows:

$$\| \delta\, Wr \| \;=\; (Wr_{exp} - Wr) \,/\, (Wr_{exp})\,. \qquad (2)$$

Figure 2 shows histograms of the frequency of $\|\delta\, Wr\|$ for the interaction regions detected by the five spacecraft. Note that the interaction regions detected from 1 to 5 AU by Voyager 1 and 2 (ascending phase of solar cycle 21) and Ulysses (post-maximum phase cycle 22) tended to be thicker than the interaction regions detected by Pioneers 10 and 11 (descending phase cycle 20). These variations in the radial width may be related to the solar cycle.

5. DISCUSSION AND CONCLUSIONS

We studied IRs detected by five spacecraft that travelled out to Jupiter at different epochs to attemp to infer their variations with the solar cycle. The data set was restricted to in-ecliptic observations. Solar wind dynamics at low heliolatitudes are more complex at all phases of the solar cycle; and many latitudinal effects cannot be explored with this data. On the other hand, we have observations of different IRs at different heliocentric distances, sometimes including heliocentric effects. This unique data set enables us to

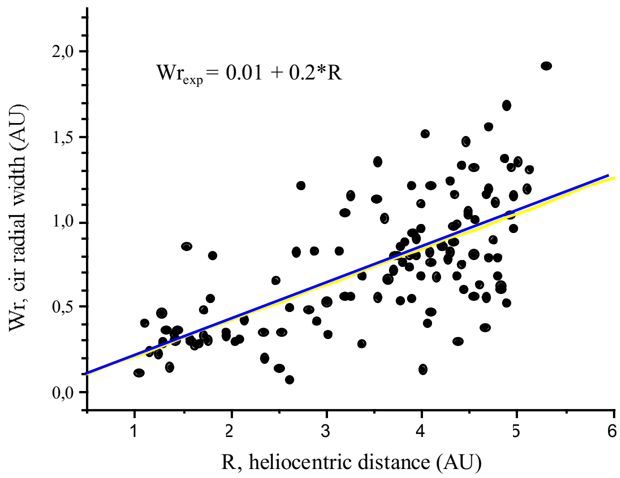

Fig. 1. Radial width, W_r, of all the interaction regions detected by Voyager 1 and 2, Pioneer 0 and 11, and Ulysses during their respective journeys to Jupiter against heliocentric distance. On the basis of the linear fit of the W_r points, from 1 to 5 AU, interaction regions expand by an approximated rate of about 0.2 UA per AU (adapted from González-Esparza and Smith (1996).

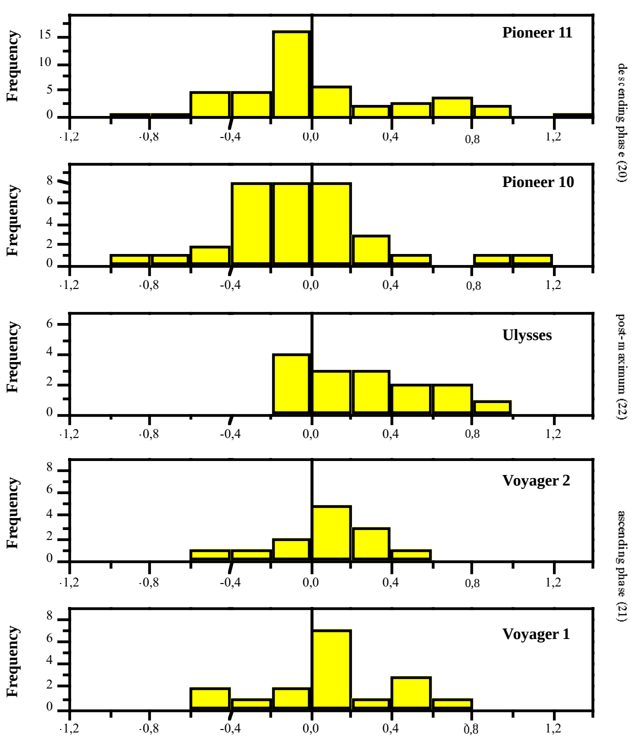

Fig. 2. Occurrence frequency histograms of the normalized variations of radial widths || δWr || of the interaction regions detected by a) Voyager 1 and 2, b) Ulysses, and c) Pioneer 10 and 11.

compare physical characteristics of IRs detected at different phases of the solar cycle, in a heliocentric range where distinct IRs dominate the large-scale dynamics and have not yet merged with each other.

Interaction regions between 1 and 5 AU are founded at low heliolatitudes at all phases of the solar cycle, however, during the descending phase they are more regular and frequent. There are continual variations in the patterns of solar wind streams changing the solar wind dynamics. These variations occur in temporal scales on the order of a few solar rotations, making it difficult to characterize the solar wind dynamics at different phases of the solar cycle. The inferred geometry of IRs agrees qualitatively with the predictions of the 3-D model by Pizzo. The IRs detected by the Pioneer spacecraft tended to be thinner than the IRs detected by the Voyager spacecraft and Ulysses.

Why do only about half the interaction regions contain a well-defined stream interface? How do the continual variations in the ratios of dynamic pressures between fast and slow streams affect the geometry and the heliocentric evolution of interaction regions? How do the changes in the coronal configuration affect the global properties of interaction regions throughout the solar cycle? Such questions should be explored by numerical modeling.

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