THE ORIGIN OF INTERPLANETARY SECTORS FROM RADIO OBSERVATIONS

M. MARTRES and M. PICK
Meudon Observatory, Meudon, France

and

G. K. PARKS
University of Toulouse, Toulouse, France

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Abstract. The interplanetary sectors have been correlated to observations of solar coronal active centers and condensations in the metric wavelengths. We have found that (1) a sector boundary is always located to the west of a coronal condensation, and (2) the effect of active centers is to displace systematically the boundary toward the east, thus enlarging the sector. A physical interpretation is discussed.

1. Introduction

Satellite and space probe measurements since 1961 have demonstrated the existence of an interplanetary magnetic field organized in broad and relatively stable sectors. Each sector corresponds, on the average, to a constant polarity. Although it is quite certain that the sectors' origin is solar, their precise cause remains obscure. At the present time it seems difficult to decide between two extreme hypotheses: does the interplanetary magnetic field arise from a mean photospheric field organized in 'photospheric' sectors of the same polarity (mapping hypothesis) or from a more limited region of the solar atmosphere (nozzle hypothesis)?

It is evident from the observations of Wilcox and Ness (1965) and Wilcox and Howard (1968) that there is good correlation between the direction of the magnetic field in the interplanetary space and the direction of the photospheric field. However, this correlation, while evident during the last solar minimum period, is not so evident during the growth period of the solar cycle.

The size of the interplanetary sectors, typically $\frac{1}{7}-\frac{2}{7}$ of the solar rotation during solar minimum, may become substantially larger, sometimes attaining about 180° during active periods, in spite of great magnetic complexities at the photospheric level. As an example one may cite the observations of Pioneer 6 indicated in Figure 2 of Wilcox and Ness (1965): broad sectors were observed in the course of rotation 1812 (January 2–14, 1966) and rotation 1814 (February 11–March 3, 1966). Fan *et al.* (1968) suggested that the longitudinal extension of the sectors could be directly influenced by the presence of a large number of active centers.

On the other hand the new active centers are capable of causing wide-ranging modifications of the photospheric magnetic field, and eventually of the organization of the

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interplanetary magnetic field itself. The time required for such transformation is estimated to be about one to two solar rotations (Schatten *et al.*, 1968).

To study further the origin of interplanetary sectors as well as the relationship these sectors have with certain solar features, radio observations of the solar corona made in the metric and centimetric wavelengths have been correlated to sector structures for the two well-studied periods in 1964 and 1966 (Wilcox and Ness, 1965; Ness and Wilcox, 1967). Evidence is presented in Section 2 of this paper that the boundaries of the interplanetary sectors are situated *systematically to the west of a stable coronal condensation*. The coronal condensations that are associated with eruptive active centers are *never* found at the sector boundaries, but are found to have a relationship with the size of the sectors. For the purpose of clarity in the discussion to follow, we review briefly some physical features of coronal condensations observed in radio frequencies.

The power spectra of thermal radiation from coronal condensations indicate existence of two components. The first, which is observable at centimeter and decimeter wavelengths, is very small (less than 1′ of arc) and is mainly associated with the presence of spots in the active centers. The temperatures may be as high as 4×10^6 K (Kundu, 1959; Pick and Steinberg, 1961; Kakinuma and Swarup, 1962) and are related to complex magnetic field structures. The second component, observed mainly at decimeter and meter wavelengths, is associated with the presence of faculae. Over sunspot regions, this component can be temporarily masked by transient radiations such as radio storms (Swarup and Parthasarathy, 1958; Moutot and Boischot, 1961; Leblanc, 1970). At meter wavelengths, the coronal condensations are relatively large ($\sim 10'$–$12'$ of arc) and the temperature is estimated to be around 1.5–2×10^6 K. The electron density is about three times that of the quiet corona (Leblanc, 1970).

When the coronal condensations are associated with old faculae during the declining phases of active centers, they do not exhibit any eruptive phenomena or rapid transformations. Here the coronal condensations may be stable and persist over several solar rotations with roughly constant density and temperature, and sometimes these coronal condensations are observable even after the disappearance of all faculae. In this paper, the term 'coronal memory' will be used to describe coronal condensations for which no visible phenomena are observed at the surface of the solar disc during the same solar rotation. These condensations associated with old faculae suggest the presence of a magnetic field that is probably *quite regular* and to some extent *radial* since it is known that during the declining phases of active centers, the leading and the following faculae very often separate from one another, becoming further and further separated as a result of their own independent movements. The two magnetic monopolar regions thus separated do not necessarily have the same lifetimes.

2. Radio Observations of Coronal Condensations and their Correlation to the Interplanetary Sector Patterns

The present study employs radio data obtained by Nançay interferometers operating at fixed frequencies of 169, 408 and 9300 MHz. The positions and the size of coronal condensations and storm centers can be obtained by these interferometers to an accuracy of better than one minute of arc. In addition, use is made of radio-spectroheliogram data at 10 cm wavelengths, published regularly in *Solar Geophysical Data* by the Stanford Group.

As mentioned earlier, the two periods we have chosen for correlation of radio observations with interplanetary sectors are (1) the interval December, 1963 and February, 1964 corresponding to the solar minimum period and already studied by Wilcox and Ness (1965), and (2) the first four months of 1966 corresponding to the rise of solar activity cycle and observed in the interplanetary space by Pioneer 6. In the following, the positions of the interplanetary sector boundaries will have an uncertainty of about one day owing to gaps present in the observations.

Tables I and II list all the coronal condensations observed in the meter wavelengths as well as some optical characteristics, radio flux data at 3 and 10 cm wavelengths, and associated flare data. Figures 1 and 2 show diagrammatically the interplanetary magnetic sectors and present a synoptic view of the positions of the solar active centers and the coronal condensations for the corresponding periods. Below are listed some of the important and significant correlation features that can be deduced from these figures, concerning the relationship between the positions of interplanetary sector boundaries and coronal condensations and the influence of active centers upon the longitudinal extent of the sectors. These observations do not take into account the highly localized polarity inversions that cover small regions of the larger sector patterns.

(1) The meridian passage of the sector boundaries always coincides to within one day with the crossing of a coronal condensation observable in the meter wavelengths. This striking association is observed practically without exception. Taking into account the four Sun-Earth transit days, one concludes that the boundary of the sector is always located to the *west* of a coronal condensation. Note that this conclusion holds true also for the 16 particularly well-established boundaries considered by Wilcox and Colburn (1969) for the period covering the end of 1966 and the beginning of 1968. These boundaries and the coronal condensation observations are shown in Table III.

(2) These coronal condensations correspond to recurrences of faculae or memories. They are not generally associated with any appreciable radio fluxes at 3 or 10 cm. This is particularly evident for the 1966 period (Figure 2, Table II). Of the seven boundaries observed during this period, four were associated with memories and the other three with faculae regions in which the activity had completely disappeared. The eight sector boundaries observed during the solar minimum (Figure 1) also correspond to recurrent faculae or memories.

(3) The strong eruptive active centers are never observed near the sector boundaries. However, their presence appears to influence the longitudinal extent of the interplanetary sectors. For example, if we consider the period 1966, we find that among the 23 coronal condensations observed, 16 were associated with centers that produced eruptions.

These active centers are characterized by high frequency emission and thus indicate presence of magnetic fields. It can be observed from Figure 2 that *a net effect of the*

TABLE I

Rotation number[1]	Year	Interplanetary boundaries (month – day)[2]	Coronal Condensation			Optical character[4]	Radio flux 3 cm–10 cm		Flares
			Ident. number[3]		C.M.P. (month – day)				
1784–1474	1963	12–02		1	12–01	–	no	no	0
1784–1474	1963	–	7053	2	12–06	AC	yes	yes	4
1784–1475	1963	12–12-13		3	12–12	Faculae return	no	no	0
1784–1475	1963	–	7065	4	12–15	AC	yes	yes	3
1784–1475	1963	12–20	7068	5	12–19	Faculae return	no	weak	0
						+AC − 4			2E[5]
1784–1475	1963	–	7080	6	12–22	Return	yes	yes	0
			7081	7	12–27	+AC + 5			0
						(perhaps associated to No.6)			
1785–1475	1964	1–1	7084	8	1–01	Facula return (2)	weak	weak	1
1785–1475	1964	–		9		(perhaps associated to No.8)			0
1785–1476	1964	1–08	7096	10	1–09	Facula + 3	yes	no	3[5]
			7097			+ AC + 4			
1785–1476	1964	–	7102	11	1–12	Facula return (4)	no	no	0
1785–1476	1964	1–16	7104	12	1–15	Facula return (5)			
						AC + 1 and + 4	weak	yes	3[5]
1785–1476	1964	–		13	1–18	– Memory (6)	no	no	0
1785–1476	1964	–		14	1–21	– Memory (6)	no	no	0
						(perhaps associated to No.13)			
1786–1476	1964	1–24	7108 }	15	1–24	AC	no	yes	5 }[5]
			7113 }			+ AC − 3			4 }
1786–1476	1964	1–29	–	16	1–29	– Memory (8)	no	no	0

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[1] Number of the Bartel's rotation and of the Carrington's rotation.

[2] Date of the passage of the observed boundary.

[3] The first number is the one indicated by the catalogues of plages of MacMath Observatory. The other an arbitrary reference number of the associated condensation.

[4] AC is an active center with spots. Facula or faculae are spotless. Memory indicates the position of an optical feature entirely disappeared.

[5] These centers are born at four days or less than four days to their central meridian passage.

TABLE II

Rotation number[1]	Year	Interplanetary boundaries (month – day)[2]	Coronal condensation			Optical character[4]	Radio flux 3 cm–10 cm		Flares
			Ident. number[3]		C.M.P. (month – day)				
1812–1502	1965		8110	1	12–31	AC + 4	yes	yes	6^5
	1966	01–02	8112 8113 8114	2	01–02	Faculae AC + 4	no	no	1
			8122	3	01–05	Facula	no	no	0
			8116	4	01–07	Facula	no	no	0
–1503			8117	5	01–12	Faculae	yes	yes	2
		01–14		6	01–14	Faculae	no	no	0
			8130 8131	7	01–19	AC	yes	yes	19
1813			8132 8133	8	01–21	AC	yes	yes	3
			8139	9	01–25	AC + 3	yes	yes	3^5
				10	01–31	Memory (2)	no	no	0
		02–02		11	02–02	Memory (3)	no	no	0
			8154	12	02–04	Facula	small	yes	3
–1504				13	02–07	AC	yes	yes	12
		02–10		14	02–10	Memory (6)	no	no	0
			8161	15	02–14	Facula } return (7)	no	no	0
			8163/64	16	02–16	Faculae } return (7)	yes	yes	0
			8166 8170	17	02–19	AC	yes	yes	3
			8171	18	02–21	AC + 2	yes	yes	3^5
			8174	19	02–23	AC + 5	yes	yes	26
	1966			20	03–01	Memory (11) AC	no	no	+5
		03–03		21	03–03	Memory (12)	no	no	0

Table II (continued)

Rotation number[1]	Year	Interplanetary boundaries (month – day)[2]	Coronal condensation			Optical character[4]	Radio flux 3 cm–10 cm		Flares
			Ident. number[3]		C.M.P. (month – day)				
–1505			8191 8184	22	03–05	Faculae return (13)	yes	yes	3
						AC + 5 AC + 2			
		03–08	8188 8190	23	03–08	Faculae return (13)	no	no	0[5]
				24	03–10	Memory (14)	no	no	0
			8201	25	03–13	Memory (15)	no	no	0
1815			8193 8204 8208	26	03–15	Faculae return (16) + AC – 4	no	10 cm	2[5]
			8206 8207	27	03–21	AC	yes	yes	115
			8225 8235	28	03–27	Faculae return + AC – 1	no	yes	1[5]
	*	03–31		noise storm					
			8238	29	04–03	AC	yes	yes	83
	*	04–08		noise storm		Emplacement of (23) + AC – 0	yes	yes	30[5]

[1] Number of the Bartel's rotation and of the Carrington's rotation.

[2] Date of the passage at the central meridian of the observed boundary.

[3] The first number is the one indicated by the catalogues of plages of MacMath Observatory. The other an arbitrary reference number of the associated condensation.

[4] AC is an active center with spots. Facula or faculae are spotless. Memory indicates the position of an optical feature entirely disappeared.

[5] These centers are born at four days or less than four days to their central meridian passage.

* When a noise storm enhancement is in progression, due to the existence of secondary lobes it is quite impossible to observe coronal condensations for the *whole sun* (example boundary: 1964 January 24 – The coronal condensation is in this case certainly situated at the same place as the new active center 7113 born 3 days after central meridian passage).

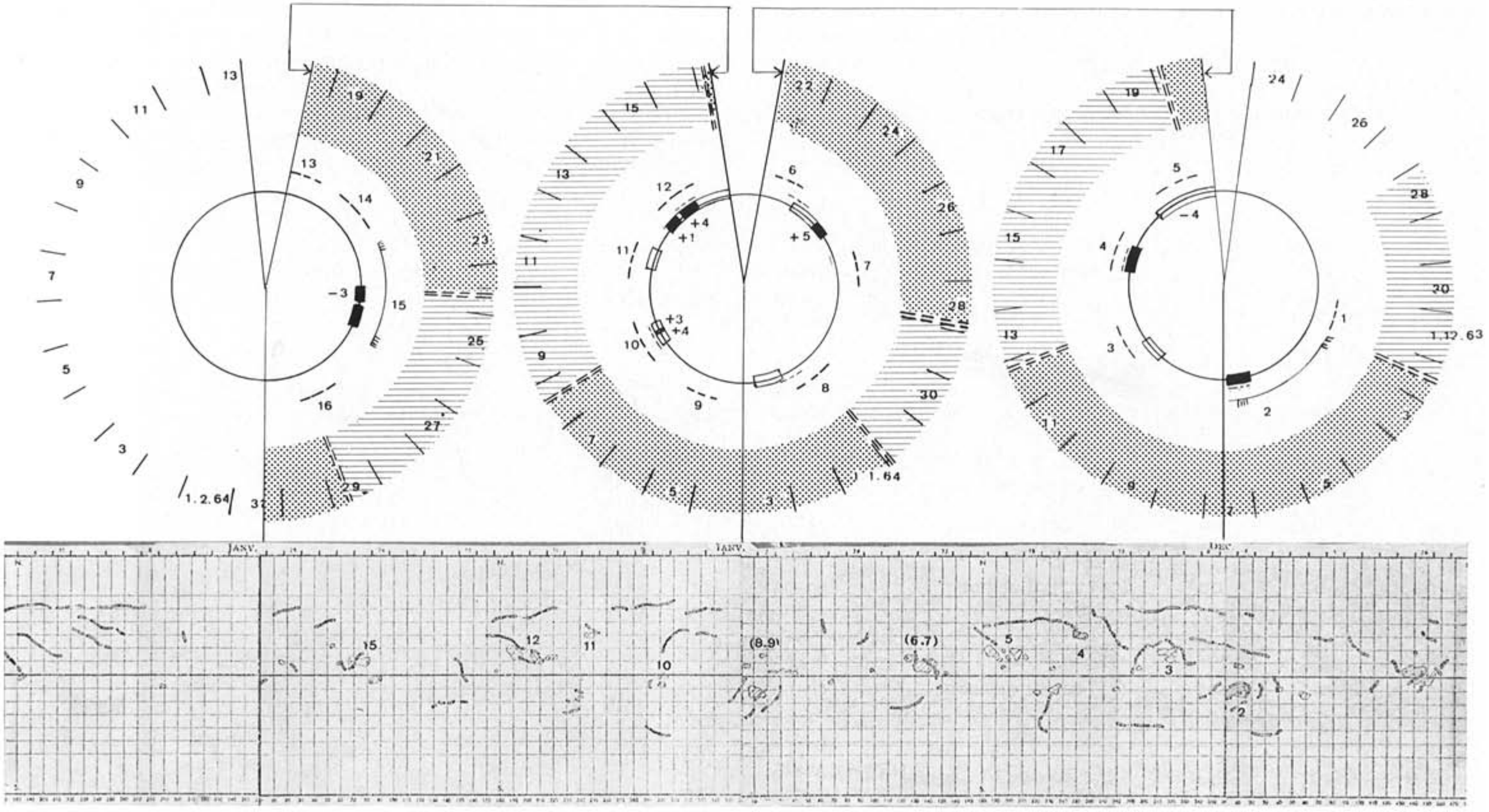


Fig. 1.

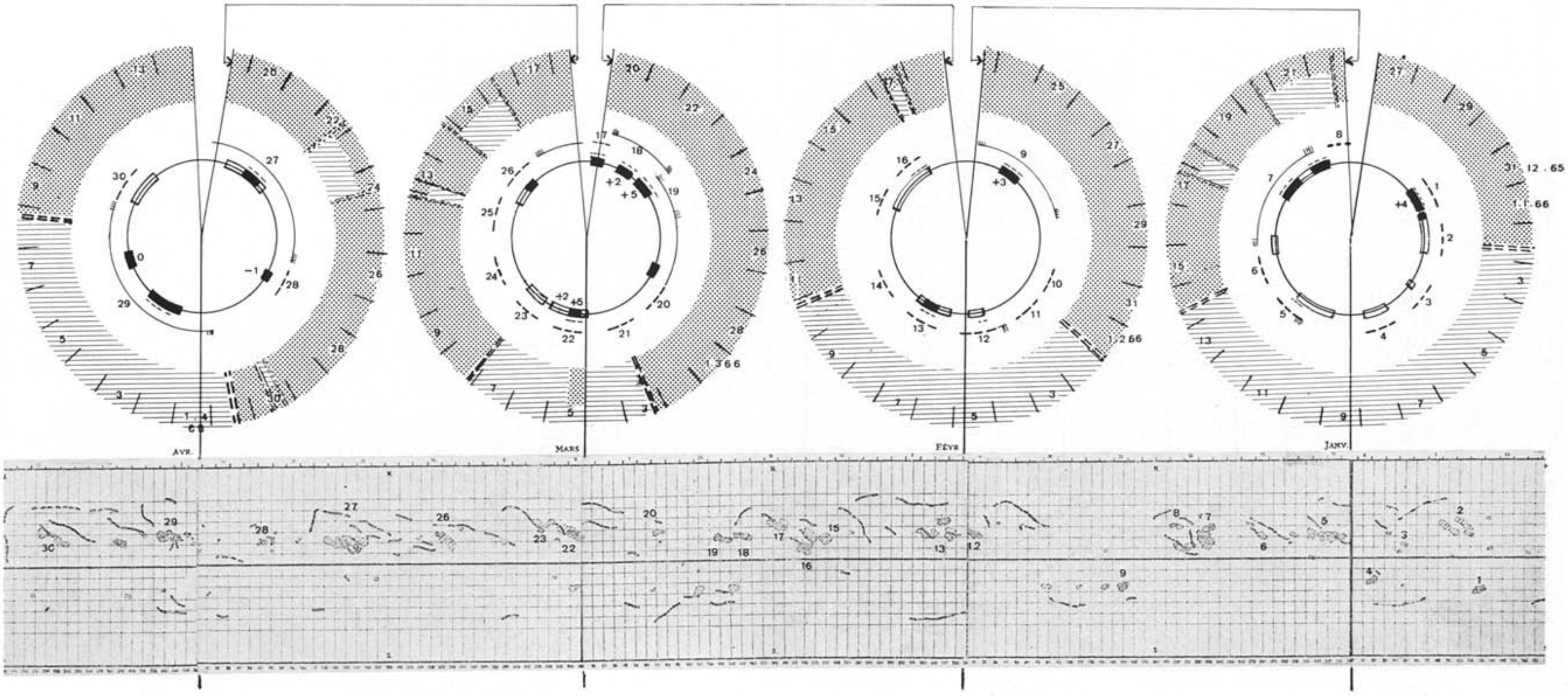
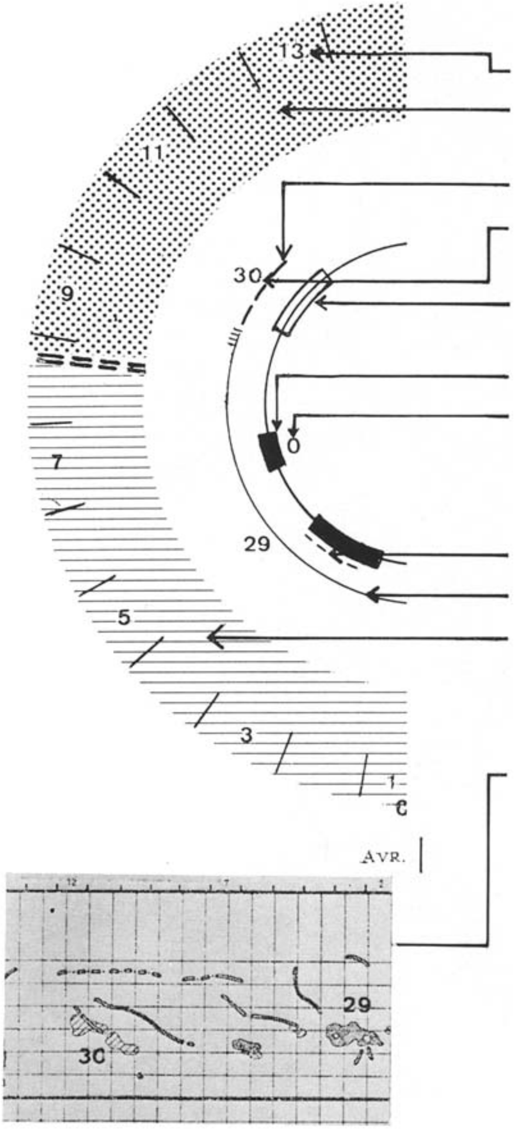


Fig. 2.

Figs. 1 and 2. Compared observations of the interplanetary sectors, radio and optical features for the two chosen periods. The first during the solar minimum. The second during the growing activity. The solar terrestrial transit time delay has not been included in these figures.



Dates

Polarity observed of the interplanetary magnetic sector (outward from the sun).

Metric coronal condensation

Arbitrary reference number of the coronal condensation indicated in the tables).

Active center spotless

Active center with spots

Birth (here at a central meridian passage). We have, for ex.: +2 when the birth is observed two days before the C.M.P. and −2 when the birth is observed two days after.

Centimetric condensation

Noise storm

Polarity observed in the interplanetary magnetic sector (toward the sun).

Synoptic chromospheric maps with reference numbers.

centers of activity is to displace the eastern boundary of a recurrent sector. In Table IV are listed the dates during which such effects were observed as well as estimates of the amount of shift of the eastern boundary. Note that the very active eruptive centers 7108, 8174, and 8238 were associated with exceptionally large sectors.

TABLE III

Sector boundaries		C.M.P. Coronal condensation
October 30,	1966	no data
December 4,	1966	* December 5
January 1,	1967	noise storm
January 13,	1967	noise storm
January 18,	1967	noise storm
February 7,	1967	noise storm
March 22,	1967	March 21
August 4,	1967	August 4
August 30,	1967	August 29
September 6,	1967	* September 6
September 27,	1967	* September 28
October 3,	1967	October 2
October 24,	1967	October 24
December 4,	1967	* December 3
January 2,	1968	January 1
January 28,	1968	noise storm

Sector boundaries from J. Wilcox and S. Colburn: 1969, *J. Geophys. Res.* **74**, 2388.

* No data at 169 MHz. Coronal condensations are observed at 408 MHz.

TABLE IV

Active center		C.M.P. of the Eastern boundary			Shift of the boundary toward the Eastern direction
Rotation	Number	Year	Month	Day	
1786	7108 7113	1964	01	29	20°
1813	8130–31? 8139 8132–33?	1966	02	02	40°
1814	8174	1966	03	03	25°
	8238	1966	04	08	55°

3. Discussion

The observations presented in this paper to a certain extent are consistent with the mapping hypothesis for small sectors from unipolar regions in the corona.

It is proposed that the stable coronal condensations observed after sector boundaries are the stable source regions from which regular radial magnetic fields emanate. Our analysis has shown presence of numerous coronal ‘memories’. The dimensions of these condensations at about $0.1\ R_\odot$ are typically $10'$ of arc and approach the dimensions of the interplanetary sectors at solar minimum, that is about $\frac{1}{7}$ of the solar rotation or about 50°, thus we see that the radial expansion of the magnetic field originating from coronal condensations can fill the $\frac{1}{7}$ sector of the interplanetary space, thus inducing the magnetic field polarity of these condensations and maintaining the flow of the coronal gas. Assuming that the corona is isothermal with a temperature of about 1.5–2.0×10^6 K, the wind velocity at one AU is about 650 km/sec, which is the typical velocity observed by Mariner 2 for small sectors and for regions near the leading edges of larger sectors (see Figure 4, Snyder and Neugebauer, 1965).

The increasing number of eruptive centers directly extends the size of the interplanetary sectors. We propose a simple model in Figure 3 to explain how the active centers can enlarge the sectors. Consider the magnetic field lines emanating from the active center as shown. Let us further assume that one of the loops extends beyond the Alfvén surface and that this line becomes annihilated in the manner described by Petschek (1966). The loop (numbered 2) that was originally behind the Alfvén surface can now be convected out easier because the reconnection of loop 1 effectively decreases the plasma pressure ahead of loop 2. A succession of field line reconnection between magnetic field lines originating from active centers and coronal condensation

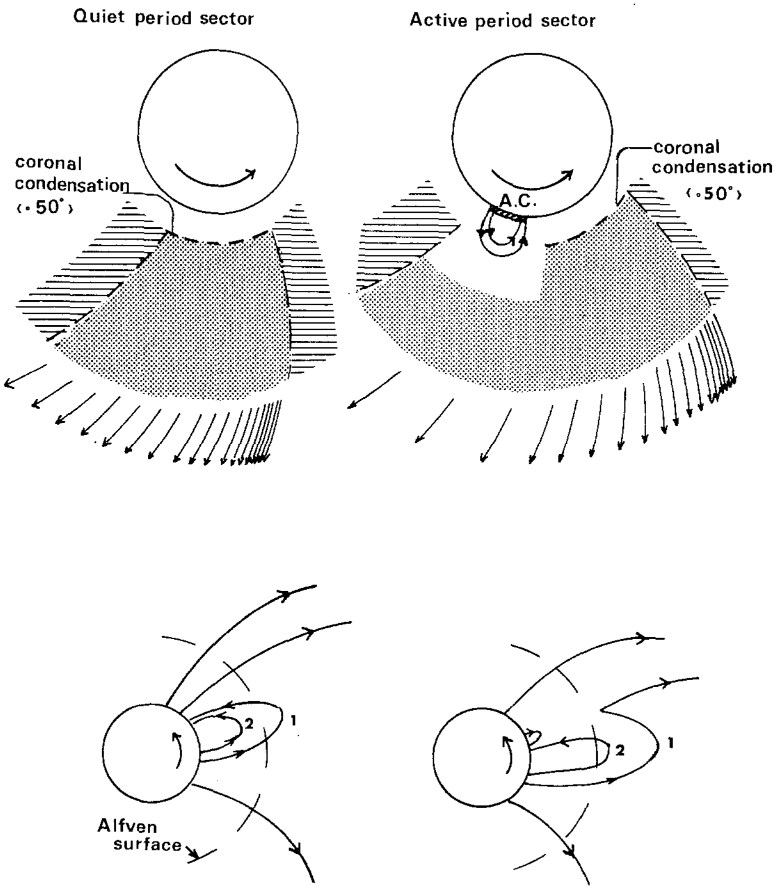


Fig. 3. Evolution of an interplanetary sector.

will eventually make possible to convect a large number of field lines into the interplanetary space. Thus the combination of field line reconnection and solar rotation can effective enlarge the original minimum sector.

This picture of the interplanetary sector, while simple and qualitative, is quite useful and explains other features observed in the interplanetary space. The model predicts that the strength of the interplanetary magnetic field will be greatest near the position of the coronal condensation where the field originates. The observation by Ness and Wilcox (1967) that larger magnetic field intensity is found within a day or two of the western sector boundary agrees with our observations. Our model further predicts that the magnetic field toward the eastern boundary will be increasingly non-uniform. The solar wind velocity within a large sector may be variable due to the presence of (for instance) active centers. The solar wind velocity should have in any case a maximum near the western boundary and such distributions have already been observed (Snyder and Neugebauer, 1966; Neugebauer and Snyder, 1966). Finally, one notes that the low energy protons that are confined in the sectors sometimes show a distribution with larger fluxes near the head of the sector (Kinsey, 1970; Mc Donald, private communication). This reinforcement of proton fluxes can result from the uniform and radial magnetic field characteristics at the western edge and can be interpreted in terms of 'privileged' propagation condition.

4. Conclusion

On the basis of observations reported in this article we have indicated that the coronal active centers and condensations are intimately associated with the interplanetary sectors.

We have seen that the smallest dimensions of an interplanetary sector during solar minimum are just related to the radial expansion of the magnetic field originating from one coronal condensation, which reasonably is related to the unipolar region identified by Bumba and Howard (1965), Schatten (1968). Evidence was also presented to show that the role played by the active centers is indirectly to evolve the longitudinal extent of the interplanetary sectors. These results can also be interpreted in terms of the original 'nozzle' model of Davis-Leverett (1966) with the nozzle size exceeding $\sim 50°$.

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