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STUDIES OF THE INTERPLANETARY MAGNETIC FIELD: IMP'S TO VOYAGER

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1. INTRODUCTION

It is my very great pleasure to participate in this special symposium honoring Dr. Frank McDonald and his significant contributions to space sciences. It was my good fortune in 1961 to become associated with Jim Heppner (Project Scientist and principal investigator) on the Explorer 10 project while at the NASA-Goddard Space Flight Center on an NAS-NRC postdoctoral Resident Research Associateship on a leave of absence from UCLA. At its termination in October 1961, I readily accepted an offer of permanent employment with NASA-GSFC, encouraged by both Frank McDonald and Les Meredith.

Following the 1961 successes of both the Explorer 10 and Frank's Explorer 12 spacecraft, Frank McDonald and colleagues proposed the first three spacecraft in a series to be called Interplanetary Monitoring Platforms or Probes. These were to be small, spin-stabilized, long-lived spacecraft placed in highly elliptical earth orbits to study the radiation environment in extraterrestrial space. It was proposed that I be the principal investigator for the Magnetic Field Studies on these IMP's and I was joined by Clell Scearce and Joseph Seek from the Explorer 10 team to round out the magnetic field instrument team.

The outstanding scientific successes of the 10 spacecraft which formed the IMP series is well known to almost all of you. It is not my intent to overview all of those results here but only to highlight some of the main contributions related to the study of the Interplanetary Magnetic Field.

2. EARLY IMP PERIOD: 1963-1967

Earlier studies of the Interplanetary Magnetic Field by United States' spacecraft were of limited value due to spacecraft magnetic field contamination, incomplete vector measurements, limited data coverage, and limited spacecraft lifetime. With the full support of Frank McDonald, the technical staff at NASA-GSFC responded affirmatively to our request to double the length of the magnetometer booms on the IMP spacecraft from that originally planned. In addition, the other experiments and subsystem engineers cooperated fully in producing minimally magnetic electronic and detector modules so that the IMP spacecraft were the most magnetically clean spacecraft yet launched.

A brief summary of the IMP spacecraft program is presented in Figure 1 with launch date and Explorer designator indicated. The very significant increase in weight, for both spacecraft and experiments, for the last three in the series was due to the incorporation of solid strap-on rockets to create the thrust-augmented Delta (TAD) launch vehicle.

As the early IMP spacecraft were being constructed, tested, and integrated, Frank encouraged me to follow up on an idea of mine to place an IMP type spacecraft in close lunar orbit in order to study its magnetic field and radiation environment. Working with study manager Paul Marcotte and other staff at GSFC, we developed a proposal in late 1963 which subsequently led to the approval of the Anchored IMP series of two spacecraft for lunar studies. The chronology of that project is shown in Figure 2, illustrating the speed and vitality of the space program at that epoch: "The Swinging '60's".

One unique feature of the many spacecraft projects then being built at NASA-GSFC was the high esprit de corps which project staff and associated personnel maintained. This is illustrated in the cartoon shown in Figure 3, contrasting between the "cleanliness" of the Anchored IMP spacecraft procedures (due

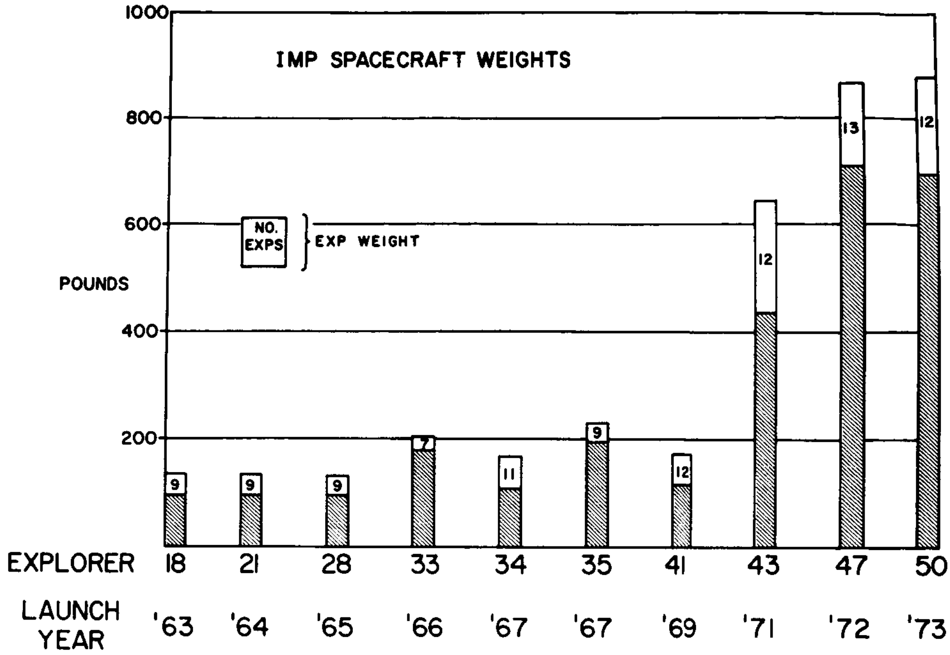

Figure 1. Summary of the Interplanetary Monitoring Platform spacecraft: launch date, Explorer numerical designation, spacecraft and experiment weight, and number of experiments.

to the Planetary Quarantine Requirements) and those of the regular IMP series. No one who participated in this period of space science shall ever forget the tremendous enthusiasm, dedication, and accomplishments which small, hard-working teams of scientists and engineers achieved in what appear now to be incredibly short periods of time.

The reputation and principal contributions of the Goddard Space Flight Center to the national space program have been in the area of customized spacecraft for scientific studies, and the IMP series under the tutelage of Frank McDonald best typifies that spirit.

EXPLORERS 33 & 35

AKA: LUNAR ANCHORED IMP/IMPs D & E

EVENT	DATE	APPROVAL
FINAL FEASIBILITY STUDY	NOVEMBER 27, 1963	H. GOETT
REVISED AO	DECEMBER 26, 1963	H. NEWELL
PROJECT APPROVED	JANUARY 20, 1964	H. NEWELL
PROPOSALS SUBMITTED	MARCH 1, 1964	---
EXPERIMENTS SELECTED	AUGUST , 1964	H. NEWELL
EXPLORER 33/IMP D LAUNCHED	JULY 1, 1966	TAD #39
EXPLORER 35/IMP E LAUNCHED	JULY 19, 1967	TAD #50

Figure 2. Chronology of the Anchored IMP mission, from proposal to launch. Approval by cognizant officials indicated. Dr. Harry Goett, then Director of the Goddard Space Flight Center and Dr. Homer Newell, Associate Administrator for Space Sciences of NASA.

3. SECTOR STRUCTURE OF INTERPLANETARY MAGNETIC FIELD

The data obtained by the IMP's 1, 2, 3, and 4 provided the first definitive measurements of the Interplanetary Magnetic Field structure and its variations. Figure 4 presents the distribution function of the magnitude of the Interplanetary Magnetic Field, as measured initially by the IMP-1 spacecraft

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Figure 3. Cartoon typifying the friendly but competitive spirit between the regular IMP and anchored IMP projects. Due to planetary quarantine restrictions, the AIMP spacecraft were constructed and integrated under substantially more restrictive conditions than the regular IMP series.

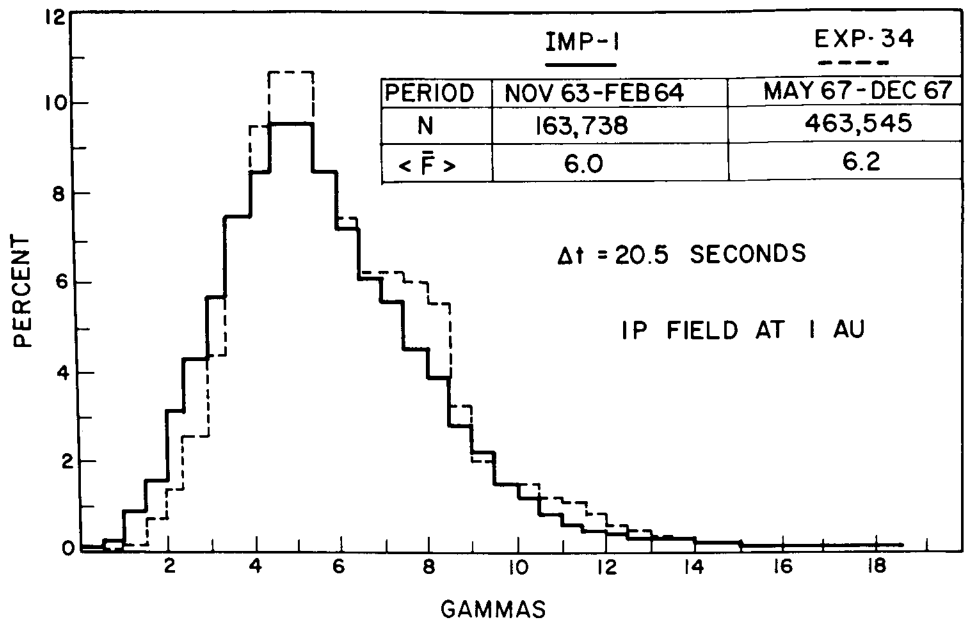

Figure 4. Histogram of the instantaneous magnitude of the interplanetary magnetic field as measured by the IMP-1 and IMP-4 spacecraft during the time those spacecraft were in the interplanetary medium outside the Earth's bow shock. Note that there is no substantial difference in the distribution, although the average field intensity is slightly larger for the later time interval.

in 1963-1964 and the IMP-4 spacecraft in 1967. In addition to confirming the average Archimedian spiral structure of the Interplanetary Magnetic Field, these early results showed an ordering of the polarity of the magnetic field which my colleague John Wilcox and I termed the interplanetary sector structure. (See Figure 5.) We were able to correlate these observations with the solar magnetic field and thereby establish conclusively its solar origin.

Nearly continuous observations of the Interplanetary Magnetic Field and sector structure was possible during the 1960's and 1970's as a result, primarily, of the data from the IMP series of spacecraft. More recent results in 1970 are shown in Figure 6, with an overlay on the planetary magnetic activity index

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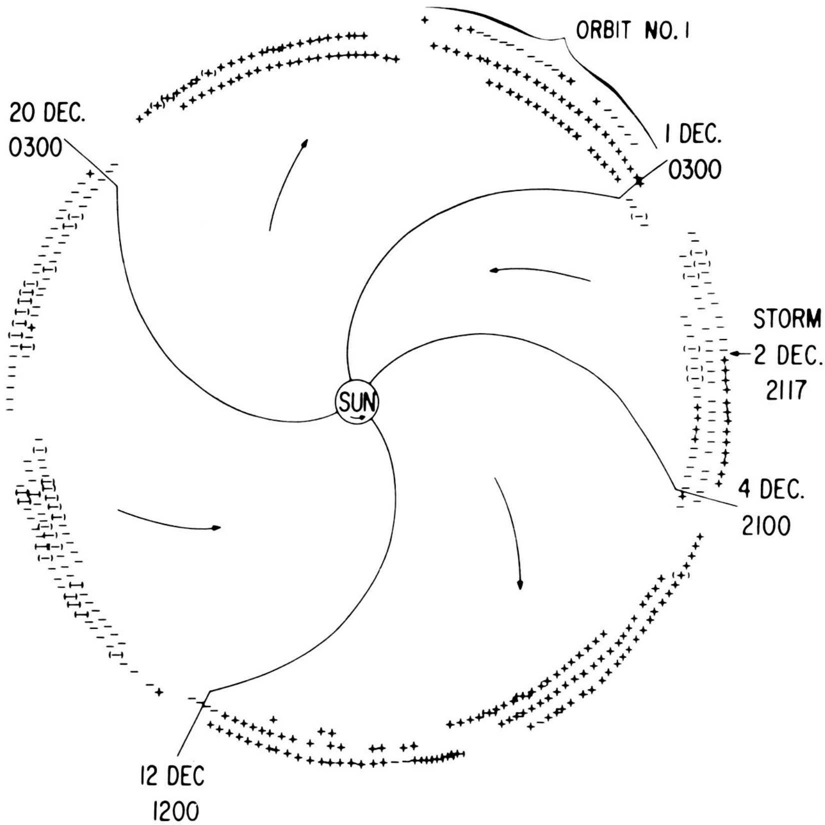

Figure 5. A well-known figure illustrating the sector structure of the interplanetary medium discovered by the IMP-1 spacecraft and measured over three solar rotations. [Ness and Wilcox, 1965]

(K_p) plots. Note here that only two sectors are shown in contrast to the earlier observations of four sectors. Also note that the location of the sector boundaries in heliographic longitude is time variable throughout this interval.

In addition to observations of the interplanetary sector structure at 1 AU, spacecraft enroute to encounters with the planets showed that the sector structure extended throughout interplanetary space. Observations by the Mariner

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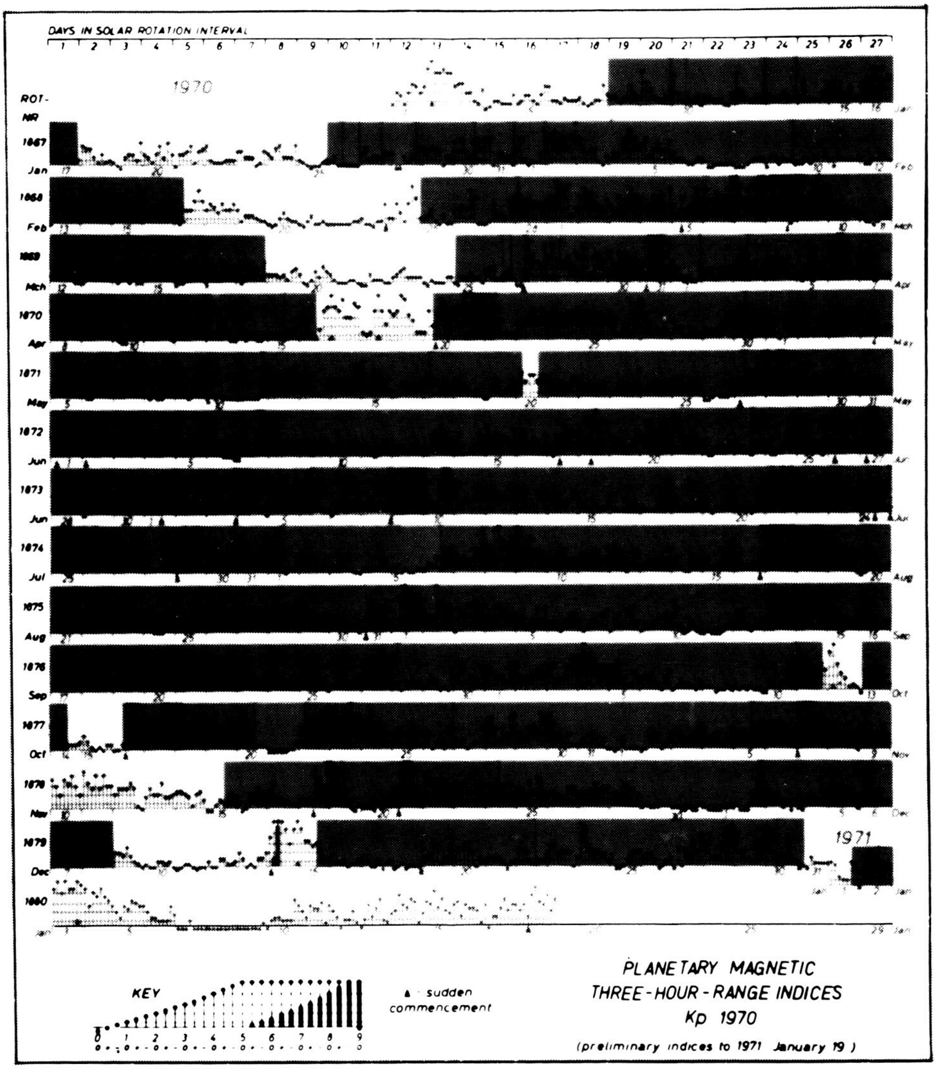

Figure 6. Overlay of the interplanetary sector structure during 1970 on the planetary magnetic activity index K_p. Note that only two sectors are shown and that the structure is not stationary during this time interval.

10 spacecraft (studied by Ken Behannon in his Ph.D. thesis) are shown in Figure 7. Again, a two-sector structure is observed throughout the several solar rotations covered by this data.

The understanding of the change from two to four sectors and the evolution of the sector structure boundaries with time initially eluded a clear explanation. That is until the concept of the heliospheric current sheet, analogous to that in Earth's magnetic tail separating regions of opposite magnetic polarity, was developed theoretically and empirically by a number of authors [Schulz, 1973; Rosenberg et al., 1973].

The inclination of the solar dipolar magnetic field axis to the rotation axis of the Sun will, together with a radial solar wind flow, transport the solar field into interplanetary space and lead to a two sector structure as illustrated in Figure 8. More complicated, i.e., a curved surface rather than a plane, configurations of the interplanetary neutral sheet arise since the solar magnetic field is not often well represented by a pure dipole. This is shown in Figure 9 where a change of sector structure from two to four sectors observed in the ecliptic at one AU occurs during three successive solar rotations.

The origin and location of the interplanetary neutral sheet on the Sun has been closely studied for sometime with observations obtained by the K coronameter brightness data. Figure 10 presents a plot of the contours of this parameter on the solar disk, with a superposition of the polarity of the magnetic field observed by the Voyager 1 and 2 spacecraft. It is seen that the correlation with the minimum brightness is excellent.Thus, the continuing observation of the interplanetary medium by the IMP and Voyager spacecraft has provided a substantial data set, not only for the study of the interplanetary medium, but for elaborate investigations of the response of the terrestrial magnetosphere to variations in the interplanetary medium structure.

4. COSMIC RAY MODULATION

One of the fundamental problems of cosmic ray studies has been to identify the mechanism responsible for both short- and long-term modulation of the

IMF SECTOR STRUCTURE DECEMBER '73 - APRIL '74

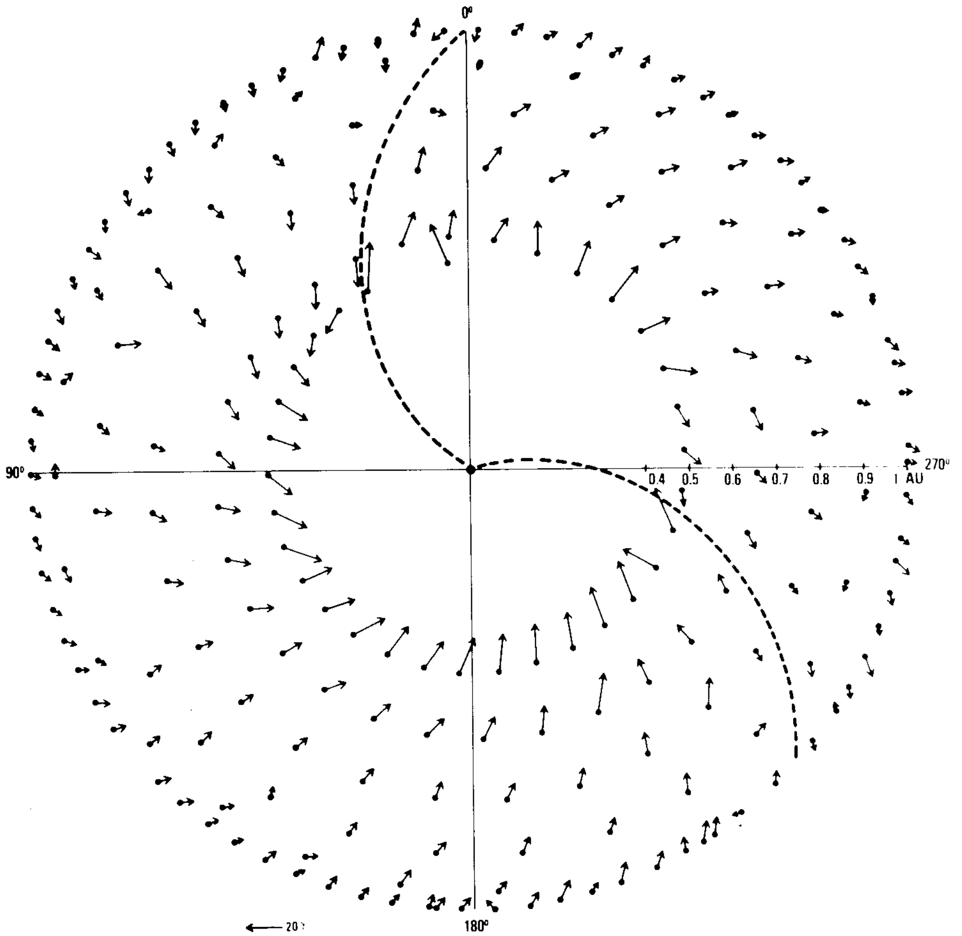

Figure 7. Interplanetary Magnetic Field sector observations obtained by the Mariner-10 spacecraft as it passed from 1 AU to encounter with Mercury in March 1974. The direction and intensity of the interplanetary field over one day intervals are shown by their vector projection. [Behannon, 1976]

Figure 8. Sketch of the orientation of the heliospheric neutral sheet and the extended solar dipolar magnetic field, leading to a two-sector structure in the interplanetary medium. The polarity in the ecliptic depends upon whether the observations are made above or below the equatorial plane.

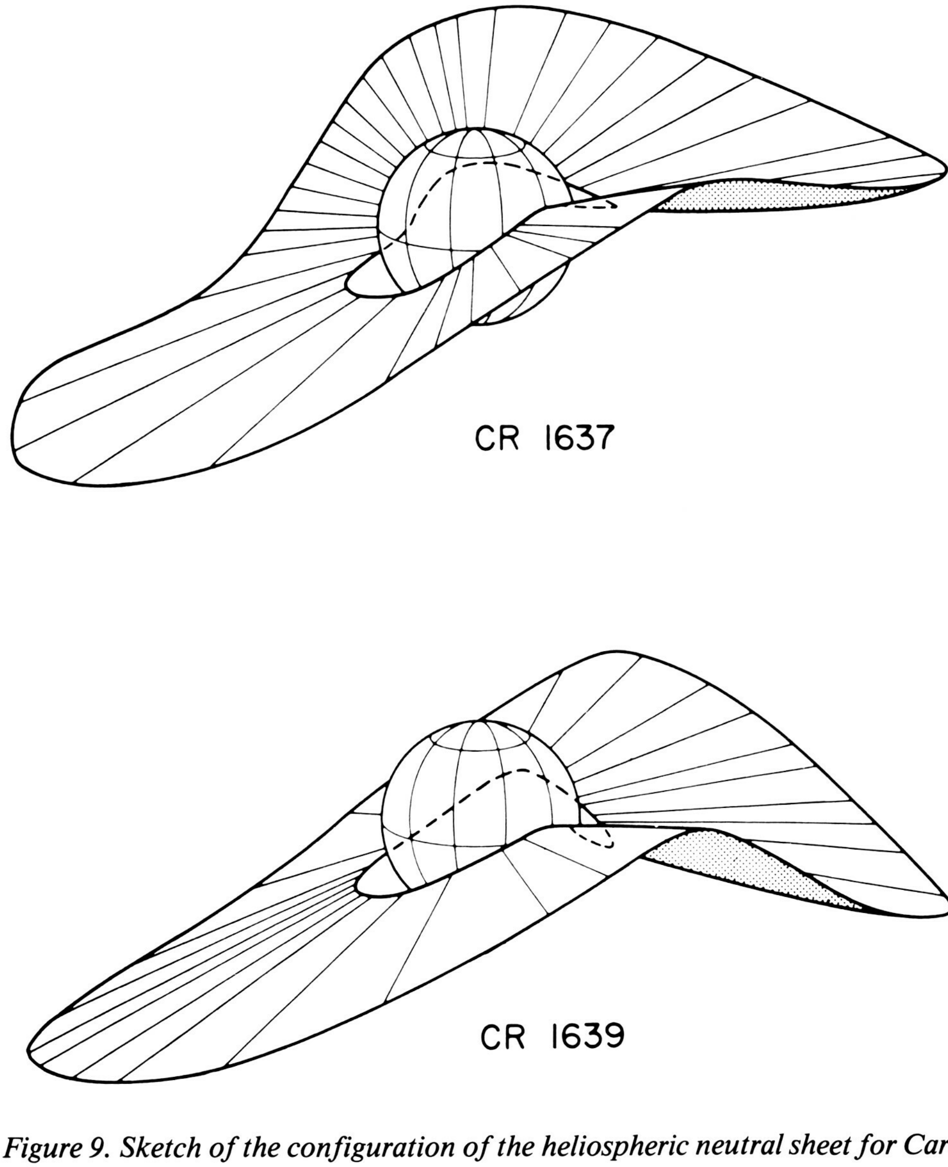

Figure 9. Sketch of the configuration of the heliospheric neutral sheet for Carrington solar rotations 1637 and 1639. During this time interval the sector structure changed from 2 to 4 sectors, as observed at 1 AU in the ecliptic. [Burlaga, Hundhausen, and Zhao, 1981]

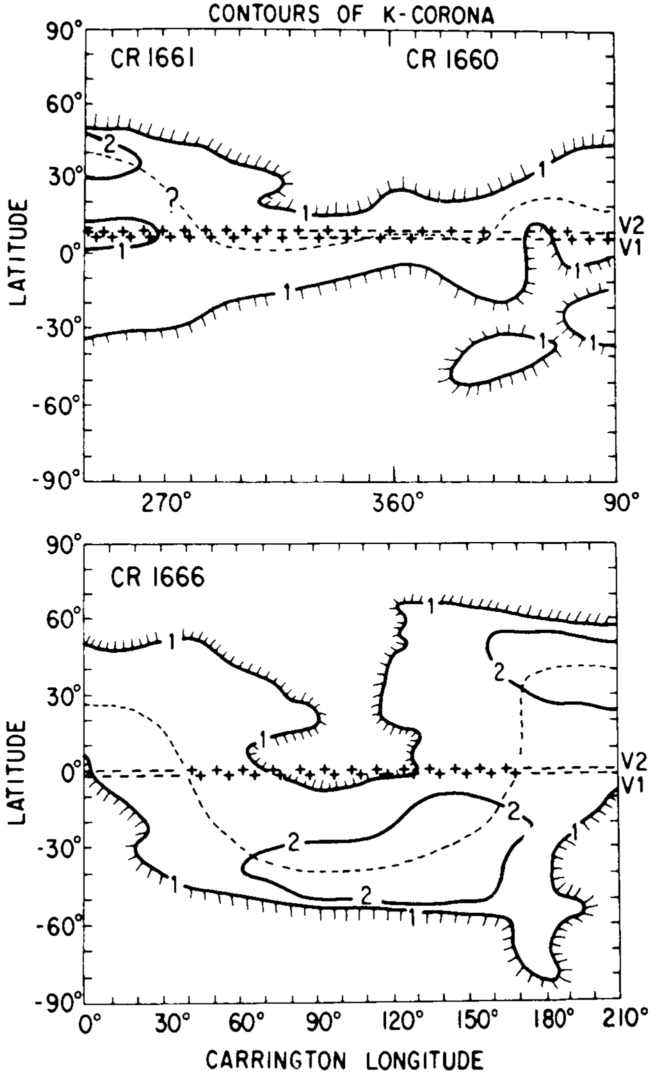

Figure 10. Plots of the K corona-meter brightness contours, used to investigate the configuration of the interplanetary neutral sheet at its source location on the Sun. Superimposed are the traces of the footprint of the polarities observed by the Voyager 1 and 2 spacecraft shortly after launch in 1977. [Behannon, Burlaga, and Hundhausen, 1983]

observed cosmic ray flux. The IMP series of spacecraft and other experiments of Frank McDonald on other spacecraft such as HELIOS, Pioneer and Voyager have contributed significantly to a resolution of some of the major issues related to this problem.

Different concepts of the magnetic structure of interplanetary space and the magnetic field configuration responsible for cosmic ray modulation are illustrated in Figure 11. Most of these were proposed prior to the recognition that interplanetary space is filled continually with the solar wind flux transporting solar magnetic fields into interplanetary space. With the knowledge of a continual solar wind flux, the question arose as to how variable-velocity solar plasma streams (or jets) would evolve in interplanetary space.

Figure 12 illustrates qualitatively the result of a high-speed plasma stream overtaking one of lower velocity. These "co-rotating" stream-stream interactions are a characteristic feature of the large-scale structure of the interplanetary medium, and a study of their radial evolution has been made possible with observations on solar and planetary probes.

Simultaneous observations of the interplanetary medium by the IMP-7 spacecraft at 1 AU and the Pioneer 10 spacecraft at 5 AU, just prior to encounter with Jupiter in 1973, demonstrate the changes which occur as a high-speed stream moves to 5 AU (see Figure 13). The concept of "filtering" of isolated streams and short wavelength speed fluctuations with streams is an important one. It has only recently been proposed as a result of data obtained and analyzed from the constellation of Pioneer, IMP, HELIOS, and Voyager spacecraft distributed throughout the heliosphere.

On a very large scale, Figure 14 shows how two co-rotating solar wind streams on opposite sides of the Sun with lifetimes of many solar rotations would modify the structure of the heliosphere. It is the compression region with enhanced magnetic fields which are found to be responsible for modulation of the cosmic ray flux observed both terrestrially and on deep space probes.

Correlation of the solar wind speed, Interplanetary Magnetic Field, and cosmic ray proton flux observed in the inner solar system is shown in Figure 15. Here

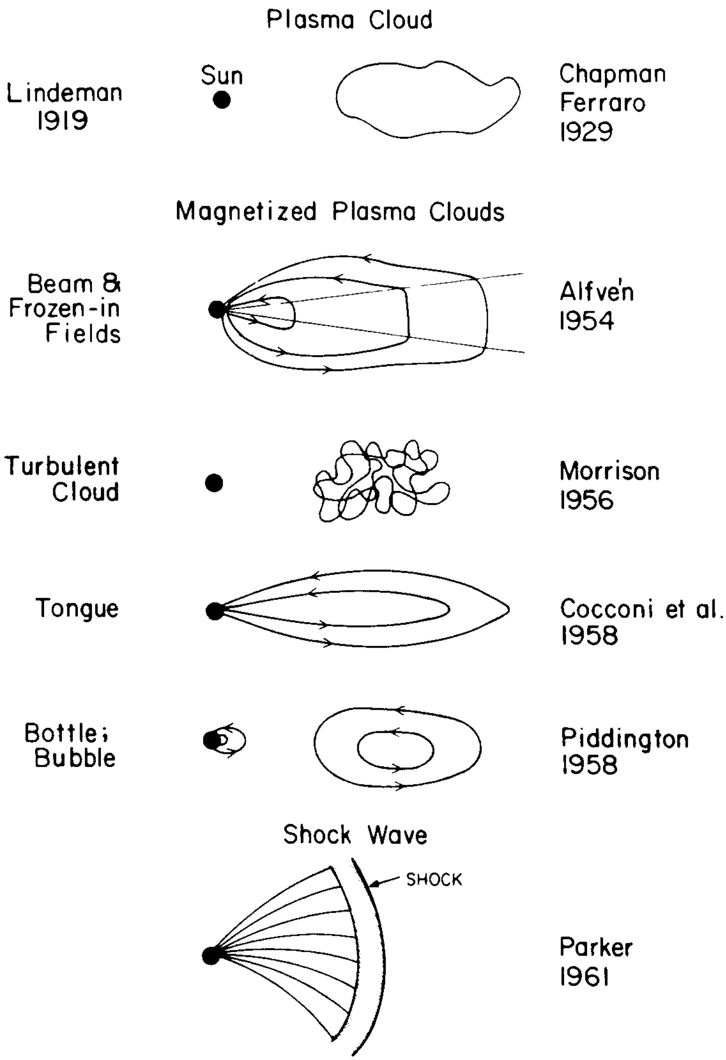

Figure 11. A summary of different concepts of the magnetic structure of interplanetary space considered responsible for cosmic ray modulation. [Burlaga, 1983]

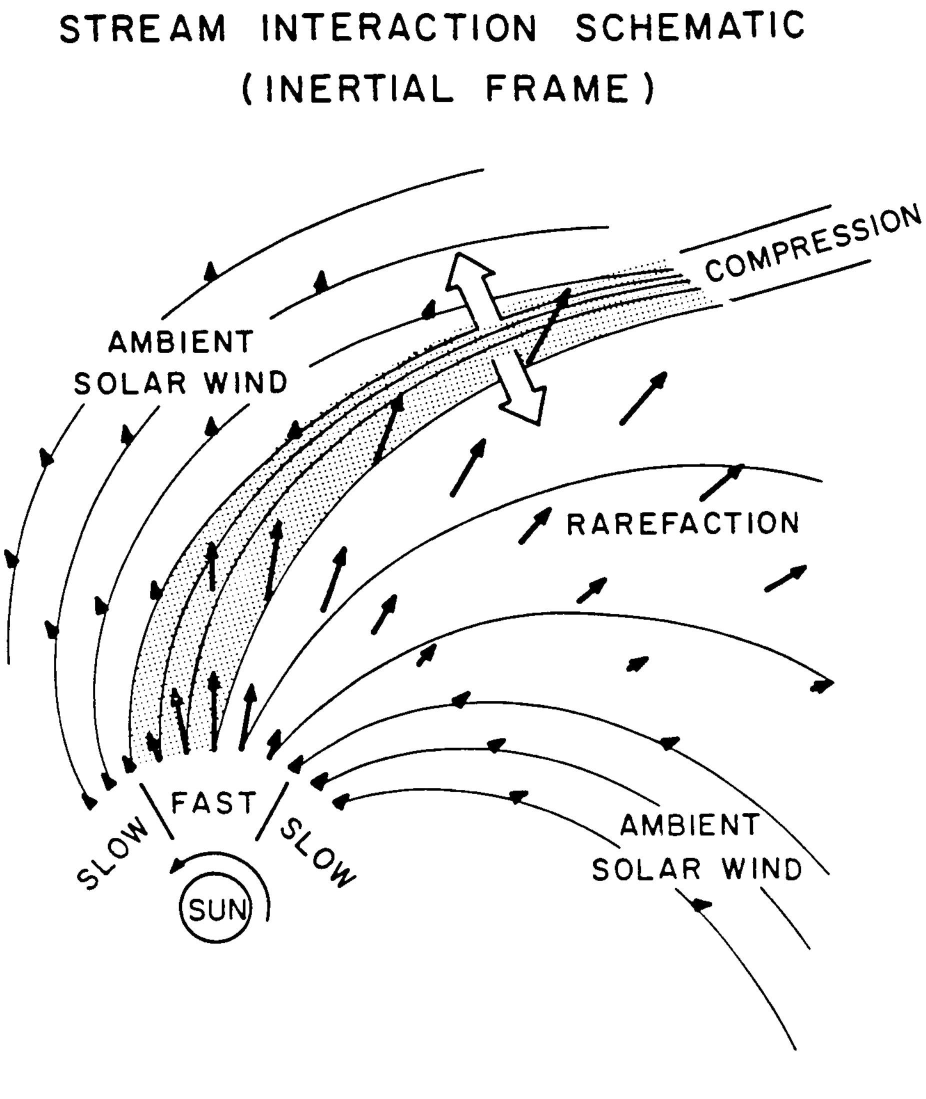

Figure 12. Diagram of the evolution, in interplanetary space, of the evolution of a co-rotating stream and interaction region. [Pizzo, 1978]

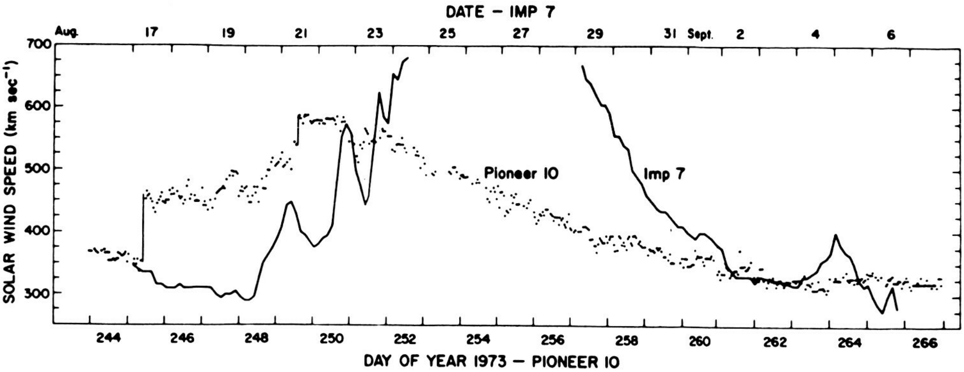

Figure 13. Comparison of solar wind speed profiles observed by IMP-7 at 1 AU and Pioneer-10 at 4.65 AU, illustrating the filtering or damping of large amplitude, short wavelength speed fluctuations at larger radial distances. [Gosling et al., 1976]

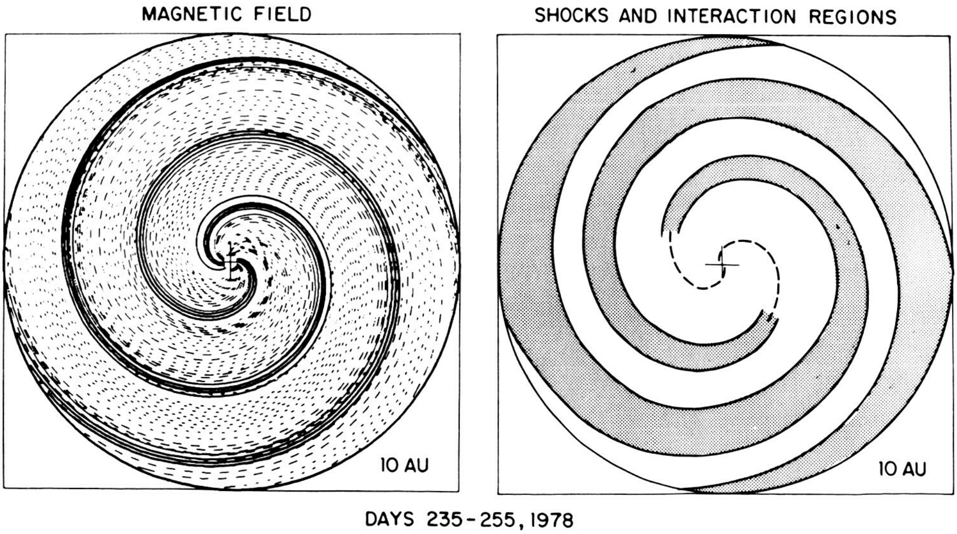

Figure 14. Diagram illustrating the evolution of the magnetic field geometry and compression regions as well as shocks and interaction regions associated with two co-rotating, high-speed solar wind streams on opposite sides of the Sun. [Burlaga, 1984]

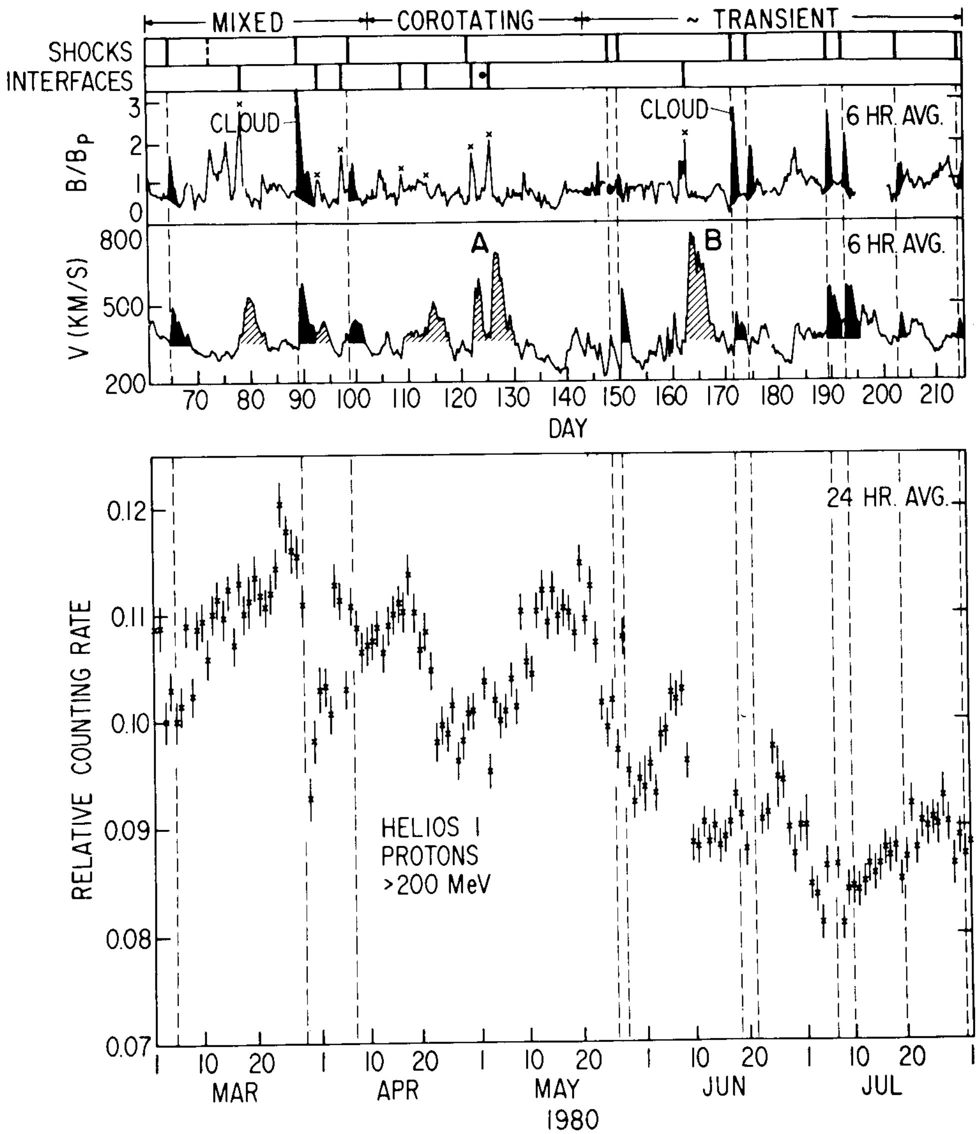

Figure 15. Observations of the flux of protons in interplanetary space as observed by HELIOS-1 compared with the solar wind and Interplanetary Magnetic Field parameters, emphasizing the modulation by co-rotating and transient features in the heliospheric structure. [Burlaga et al., 1984]

the important features are the modulation of the cosmic ray flux by the co-rotating, as well as transient, features in the interplanetary medium. Similar correlations have been observed at much greater heliocentric distances, and these are illustrated in Figure 16. Again, it is the compression region of significantly enhanced magnetic fields that are seen to be associated with the sudden decrease in the cosmic ray flux. It is known that the level of turbulence in the Interplanetary Magnetic Field is higher in the compression regions than in the rarefaction regions.

Frank McDonald, working in close collaboration with Len Burlaga, has conducted a systematic study of the time variations of cosmic ray flux, and solar wind structure, both in the inner and outer regions of the solar system. These

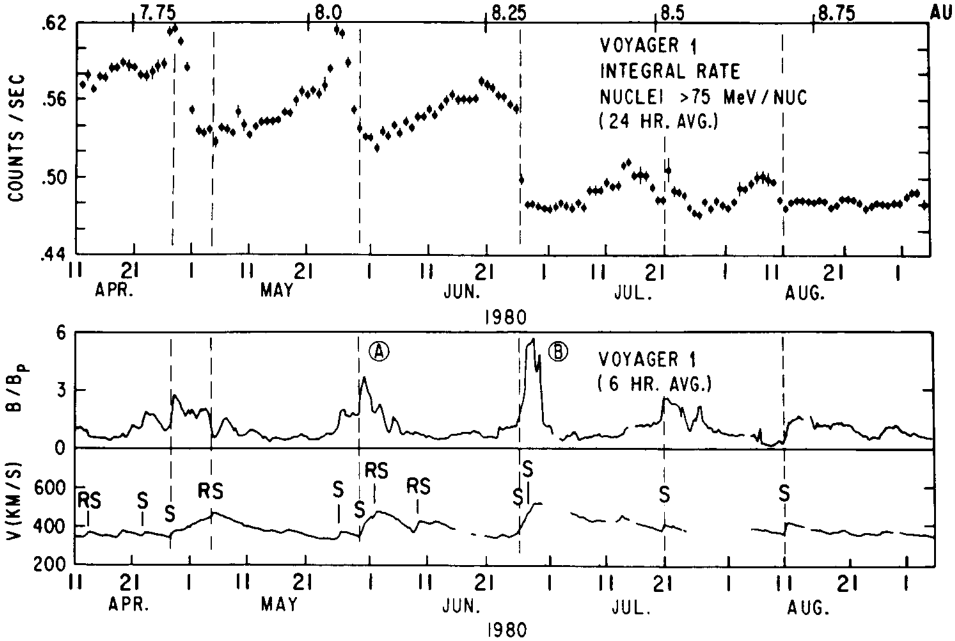

Figure 16. Comparison of cosmic ray observations by Voyager 1 with the magnetic field and solar wind velocity at a distance of approximately 10 AU. Compression regions at A and B are correlated with sudden decreases in the integral flux. [Burlaga et al., 1984]

studies have led to the current view that the transient high speed flows and disturbances originating at the surface of the Sun coalesce at large distances from the Sun to form essentially concentric shells of disturbed regions. These are the regions responsible for the modulation of the cosmic ray flux. This feature of the structure of the interplanetary medium on the large scale is illustrated in Figure 17.

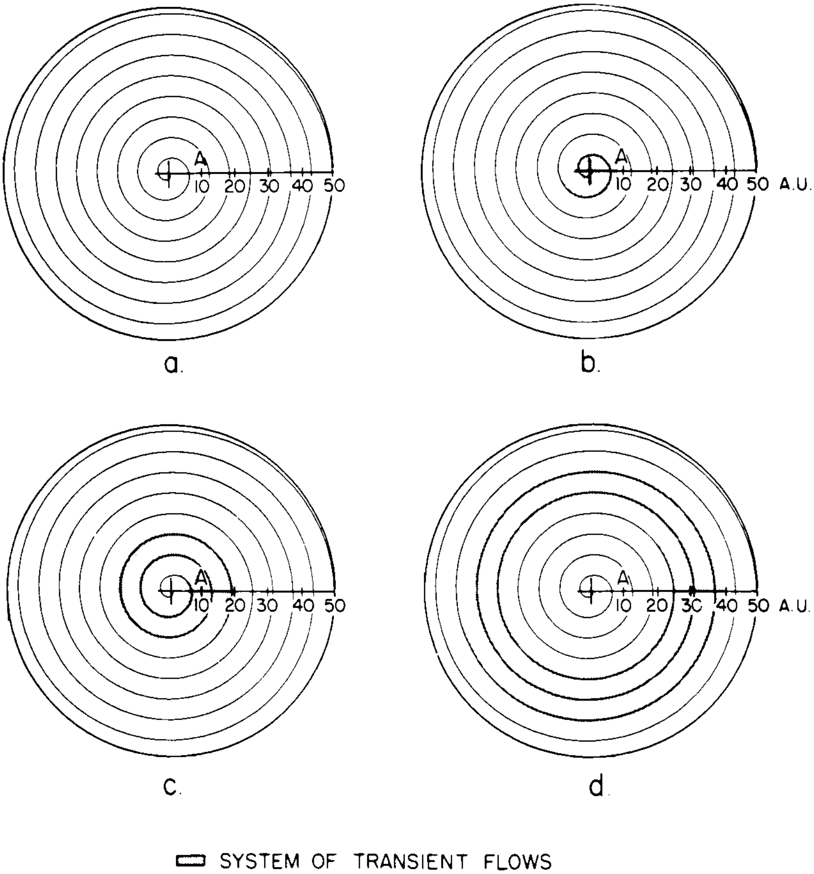

Figure 17. Very large-scale view of heliospheric structure in which systems of transient flows coalesce at large distances to form concentric shells of disturbed regions responsible for modulating the cosmic ray flux. [Burlaga et al., 1984]

5. SUMMARY

During the last two decades, spacecraft projects and individual experiments for which Frank McDonald has been a leader have contributed very significantly to our current understanding of the structure of interplanetary space and the correlation between solar and interplanetary disturbances. He had the foresight and ability to anticipate the unique value of small, simple, spin-stabilized spacecraft early in the NASA program.

For in situ observations of the interplanetary medium, this has proved critical. Studies on the IMP, HELIOS, and Pioneer spin-stabilized spacecraft and the larger attitude-stabilized Voyager spacecraft have provided unique data sets from which the modern view of the heliosphere has evolved. That concept is illustrated in Figure 18, in which the inner solar system is shown to be dominated by individual streams associated with specific source regions on the Sun. As these high-speed streams overtake the preexisting solar plasma, they coalesce and modify the characteristics so that at larger heliocentric distances, these disturbances appear as radially propagating concentric shells of compressed magnetic fields and enhanced fluctuations.

Frank McDonald has worked with a number of collaborators in his scientific investigations, both directly and indirectly. He has stimulated quality scientific investigations that have set a standard to which future investigations should aspire. These contributions will certainly stand the test of time as a remembrance of the efforts of FBM.

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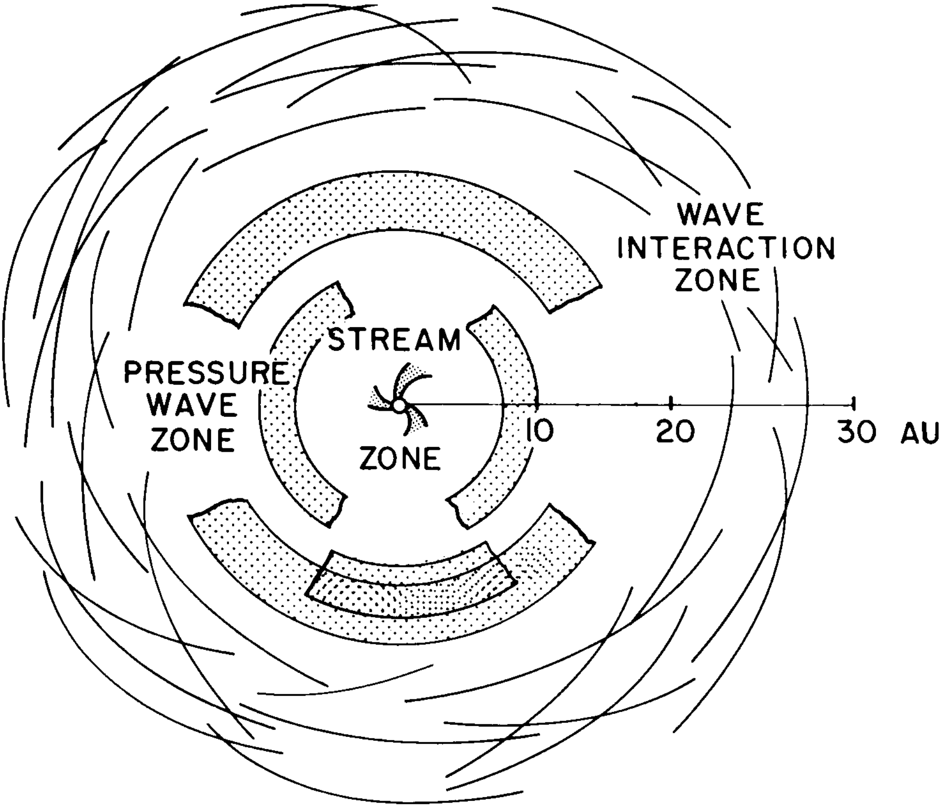

Figure 18. Diagram emphasizing the transition from an individual stream dominated zone within a few AU close to the Sun to a region of concentric shells where pressure waves dominate the structure, and, finally, the postulate that a wave interaction region exists beyond. [Burlaga, Schwenn, and Rosenbauer, 1983]

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