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SOLAR ORIGIN OF THE INTERPLANETARY MAGNETIC FIELD

Norman F. Ness
National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland

and

John M. Wilcox
Space Sciences Laboratory, University of California, Berkeley, California

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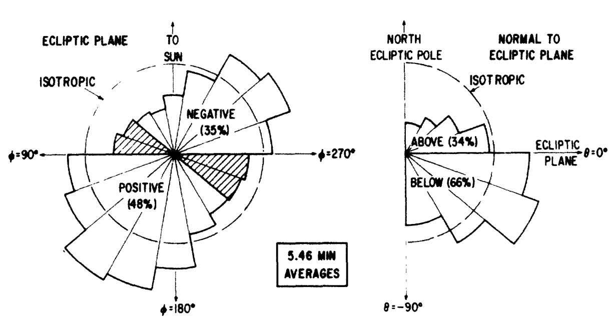
Direct measurements of the interplanetary magnetic field at 1 A.U. have recently been made by an experiment[1] conducted on the Interplanetary Monitoring Platform (IMP-1). The 63-kg spin-stabilized satellite was launched on 17 November 1963 into a highly eccentric orbit with a geocentric apogee of 197 616 km and an orbital period of 93.5 hours. The sun-earth-apogee angle was initially 25° west of the sun and increased approximately 1°/day due to the earth's heliocentric motion. Successful transmission of scientific data continued for 180 days until 30 May 1964 when the sun-earth-apogee angle had increased to 201°. The interplanetary data are based on the average magnetic field computed every 5.46 minutes using 12 successive data transmissions at 20.5-second intervals. The absolute uncertainty of the data is less than 0.25 γ ($1\ \gamma = 10^{-5}$ gauss). This Letter presents the initial results of a detailed comparison of these interplanetary magnetic field measurements with solar magnetograph observations of the photospheric magnetic fields as measured at the Mt. Wilson Observatory.

Previous space probe measurements[2] of the interplanetary magnetic field by Pioneer V in 1960 were interpreted as evidence of a 2.5-γ field normal to the ecliptic plane. A recent reanalysis[3] of these data has yielded the result that the direction of the interplanetary field was nearly parallel to the plane of the ecliptic and that the magnitude was between 5 and 10 γ. The measurements[4] of the solar plasma efflux in 1962 by the Mariner II Venus probe have confirmed the initial restricted results[5] of the Explorer X satellite obtained in 1961 and the Lunik II moon probe[6] in 1960. The Mariner II results showed that a continual flow of plasma, the solar wind,[7] existed with an average streaming velocity of 504 km/sec.

The interaction of the solar wind with the geomagnetic field disturbs the interplanetary medium in the immediate vicinity of the earth and spatially confines the Earth's field. Thus measurements of the relatively undisturbed interplanetary medium by IMP-1 are restricted to times centered about the satellite apogee and outside the interaction region. This region is limited to about 85 000 km at the subsolar point, but is not spherically symmetrical[1] and instead broadens out away from the stagnation point and eventually trails out behind the earth. Hence as the orbit of IMP-1 precessed in the solar-ecliptic coordinate system,[1] the maximum length of time possible for measurements of the interplanetary medium decreased from about three days during Orbit 1 to one day on Orbit 22. The interplanetary magnetic field data obtained during this portion of the IMP-1 lifetime were distributed over the time interval 27 November 1963 to 17 February 1964 covering the three solar rotations 1784 to 1786.

The initial results of these measurements are consistent with the general model[8] of an interplanetary field of solar origin in which the effects of a radial solar wind velocity and the solar rotation combine to produce magnetic lines of force which are twisted in the plane of the ecliptic in the form of an Archimedes spiral. Figure 1 summarizes the orientation histograms for the interplanetary magnetic field data. The angular distribution of the field component in the ecliptic plane is shown on the left-hand side with an angular increment of 20° selected on the basis of an uncertainty of direction of less than 5° for each 5.46-minute average. A total of 12 510 data points was obtained during the 83-day interval covered by these data. The decided tendency of the field to be oriented parallel or antiparallel to the theoretical angle (~135°) proposed by Parker[8] is clearly indicated. The asymmetry between the oppositely directed fields is presently being investigated. Figure 1 also identifies those sectors in which the direction of the field is predominantly away from the sun ($\theta = 90°$ to 230°, "positive" direction) and those in which the field is predominantly towards the sun ($\theta = 270°$ to 50°, "negative" direction). Also shown in Fig. 1 is the angular distribution of the field component perpendicular to the ecliptic plane. This illustrates the tendency of the nearby interplanetary field to be directed nearly parallel to the ecliptic plane, although a slight but distinct southward directed component is apparent. These facts suggest that magnetic-field filaments exist in the interplanetary medium. The average field magnitude is close to 5 γ and ranges principally between 3 and 6 γ.



DISTRIBUTION OF INTERPLANETARY MAGNETIC FIELD DIRECTION

FIG. 1. Distribution of the interplanetary magnetic field direction in the plane of the ecliptic and normal to the ecliptic. Both histograms show the field angular distribution per unit solid angle; the dashed circles would correspond to an isotropic distribution of the same number of vectors.

For direct comparison with the solar magnetograph data, the IMP-1 data have been averaged over a 12-hour interval. Each such interval was divided into four subintervals which were assigned a polarity on the basis of the direction of the most frequent occurrence of the initial 5.46-minute averages. If three or four of the subintervals were of the same polarity the 12-hour interval was assigned that polarity. Other possible results including incomplete data coverage were considered too ambiguous and were not assigned any polarity. The purpose of this procedure was to obtain the large-scale polarity distribution of the interplanetary magnetic field. These IMP-1 data were first examined for evidence of a 27-day recurrence period, on the assumption that this would be a measure of the solar influence on the measured interplanetary field. A prominent peak with an amplitude of 0.55 ± 0.05 in the autocorrelation[9] curve was observed at a lag of about 27 days. It was observed that if the first eight days of IMP observations (including the magnetic storm of 2 December 1963) were omitted, the remaining data yielded a 27-day autocorrelation peak with an amplitude of about 0.85 ± 0.10. Therefore, this 75-day interval of data was selected for further analysis on the assumption that this represented a period of time in which the large-scale features of the interplanetary magnetic field were quasistatic.

Dr. Robert Howard of the Mt. Wilson Observatory kindly made available the daily solar magnetograms that were obtained with the solar magnetograph.[10] With this instrument the photospheric magnetic field is measured utilizing the longitudinal Zeeman effect. The minimum detectable field was 2 gauss (averaged over an area on the sun of 4×10^8 km^2) in the observations used in this note. Each magnetic region occupied an appreciable portion of the visible disk (i.e., this note is not directly concerned with the much stronger but much more localized fields associated with sunspots; discrete events such as flares also do not enter into this analysis). The direction (out of or into the sun) of the photospheric field at the center of the visible disk was assigned a polarity (plus or minus) during the three solar rotations of interest. An increment of 6.7° in longitude (corresponding to the solar rotation in 12 hours) and of 10° in latitude was chosen. Occasionally the field direction in an increment of area was ambiguous and such an area was omitted in the analysis. There are also gaps in the photospheric data for about 25 days caused by weather conditions at Mt. Wilson. A cross correlation between the IMP-1 field direction and the solar field direction was then computed. The computation was repeated at 5° intervals for latitudes from 25°N to 25°S of the center of the visible disk.

Three such cross correlations are shown in Fig. 2 as a function of the time lag from central meridian passage of the photospheric field area to the time the field was measured by IMP-1. The prominent positive peak at a lag of approximately $4\frac{1}{2}$ days is common to all of the latitudes examined. Because several of the photospheric field regions have a considerable extent in latitude, the limited data sample available does not permit a statistically significant determination of the solar latitude at which the best correlation with IMP is obtained. The peak in the correlation at a lag of $4\frac{1}{2} \pm \frac{1}{2}$ days would correspond to an average radial solar wind velocity of 385 ± 45 km/sec. The average radial solar wind velocity over the first seven IMP orbits measured by the MIT plasma detector experiment[11] was 398 km/sec.

The latitude of the photospheric source of the interplanetary magnetic field has been investigated by means of the differential rotation of the photospheric magnetic field. Figure 3 shows the rotation period as a function of latitude as determined from autocorrelations of the photospheric field data previously described.[12] Also shown is the recurrence period determined from autocorrelation of the IMP data. This comparison suggests that the latitude of the photospheric source of the interplanetary field was within 10 or 15° of the center of the visible disk (or of the equator; the present analysis cannot make a distinction between the two).

These results indicate that during three solar rotations near the minimum of the solar cycle, some of the magnetic field lines passing through the photosphere near the center of the visible

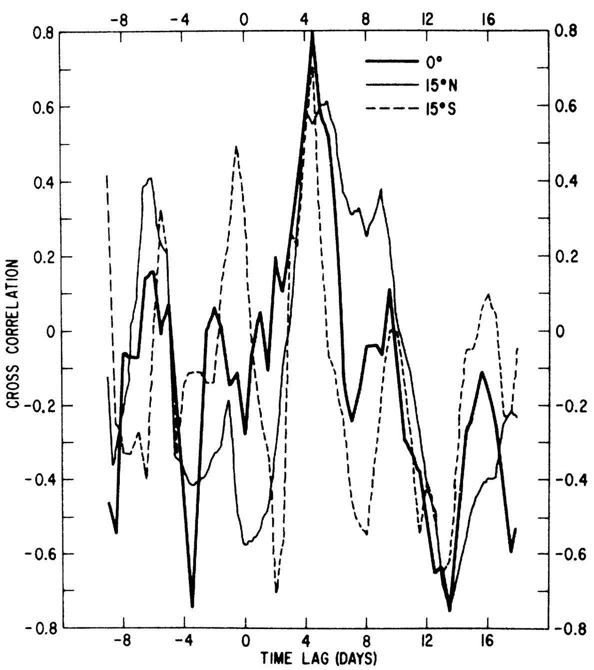


FIG. 2. Cross correlation between IMP magnetic field direction (toward or away from the sun) and the photospheric field direction (into or out of the sun) for three latitudes on the sun. The positive peak at about $4\frac{1}{2}$ days would correspond to a uniform radial solar wind velocity of about 385 km/sec. The negative peaks at $-3\frac{1}{2}$ days and +13 days can be understood in terms of a quasiperiodicity in the data. The latitudes are measured from the center of the visible disk.

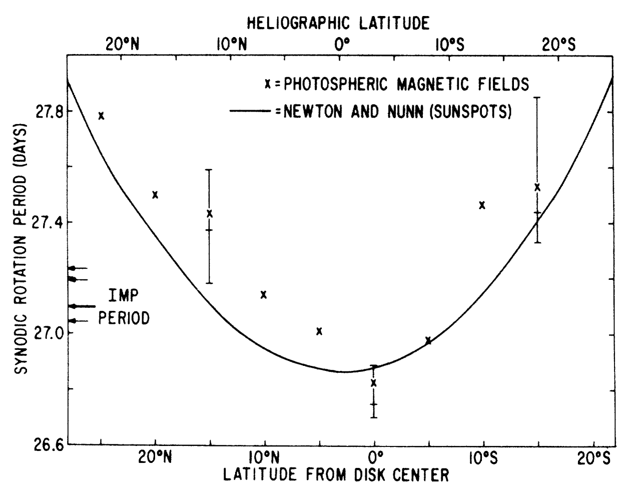


FIG. 3. Differential rotation periods of the photospheric magnetic field. The latitude of the photospheric observations is measured from the center of the visible disk, whose average heliographic latitude was 3°S during the time considered here. The error bars were estimated by dividing the data into three parts and analyzing each separately. The solid line is from the sunspot observations of H. W. Newton and M. L. Nunn, Monthly Notices Roy. Astron. Soc. 111, 413 (1951). The arrows at the left indicate the IMP recurrence period; the position of the heavy arrow was computed using all the data, and the light arrows represent a division of the data into three parts.

disk tended to be dragged out by the solar wind plasma to become part of the nearby interplanetary magnetic field. The best correlation was obtained when the photospheric field was in the same direction throughout an area corresponding to at least two or three days rotation. These conclusions are consistent with the model suggested by Ahluwalia and Dessler[13] in which the sense of the interplanetary magnetic field filaments is related to the sense of photospheric magnetic field regions.

We thank Dr. Robert Howard for making the solar magnetograms available, and Dr. Howard and Dr. V. Bumba for several valuable discussions. One of us (J.M.W.) thanks the director of the Mt. Wilson Observatory for guest investigator privileges at the observatory.

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[9]In computing the "correlations" described in this note, a weight of +1 was assigned to a field directed out of or away from the Sun, and vice versa for −1. Each individual set of data did not add up exactly to zero. If the data sample was enough that each set of data would sum to zero, then this computation would yield a formal correlation. The error is estimated by dividing the data sample into three parts and repeating the computation on each.

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SUPPRESSION OF CONVECTIVE LOSSES FROM A STEADY-STATE PLASMA BY A POSITIVE-GRADIENT FIELD*

C. C. Damm, J. H. Foote, A. H. Futch, A. L. Gardner, and R. F. Post
Lawrence Radiation Laboratory, University of California, Livermore, California
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The experiments of Baiborodov *et al.*[1] and of Perkins and Barr[2] have demonstrated stabilization of transient plasmas against convective "flute" instability losses by means of positive-gradient magnetic fields. In such fields the plasma is located in a region of nonzero field minimum, and is theoretically predicted to be hydromagnetically stable.[3,4] Both experiments cited above utilized a hexapole set of longitudinal line cusps superimposed on a simple magnetic mirror field to form the positive-gradient field. We here report the suppression of convective plasma losses by a dodecapole array of longitudinal line cusps in combination with a mirror field. In addition to the difference in the number of poles, our experiment contrasts with the previously reported experiments in the method of plasma formation (neutral-atom injection), in the higher plasma ion energy (20 keV), and in the fact that it is essentially a steady-state rather than a transient experiment. In a steady-state experiment the effect of convective losses is to limit the plasma density. We have found that with the convective losses suppressed, evidence appears for a lower order density limitation, by another instability mechanism. Preliminary observations show an apparent relation between this new limitation and the detection of coherent oscillations at the ion gyrofrequency.

The qualitative effect of adding the multipole line-cusp field to the mirror field is shown in Fig. 1. With a steady mirror field only and with a constant beam injection, the ion density is limited to a low value [first 0.2 sec of Fig. 1(b)] by the convective instability losses. Low-frequency oscillations characteristic of this instability[5] are evident on a capacitive probe [Fig. 1(a)]. At 0.2 sec the cusp field is turned on, the oscillation amplitude decreases (by a factor of at least 50, from other data), and the ion density increases markedly. At 0.49 sec the injected beam is switched off and the plasma decays with a char-