CHAPTER III

INTERPLANETARY MAGNETIC MEASUREMENTS

LEVERETT DAVIS, JR.
California Institute of Technology, Pasadena, California

E. J. SMITH
Jet Propulsion Laboratory, Pasadena, California

P. J. COLEMAN, JR.
University of California, Los Angeles, California

C. P. SONETT
Ames Research Center, NASA, Moffett Field, California

(Presented by E. J. Smith)

The Mariner-2 Magnetometer Experiment

Among the instruments aboard *Mariner 2* was a triaxial fluxgate magnetometer with three orthogonal sensors (Ref. 1), one along each of three axes (X, Y, Z) fixed in the spacecraft. The readings of each of three magnetic-field components were separated by 1.9 sec, and a complete set of readings was relayed to Earth every 36.96 sec. Although the accuracy of each reading was about 0.5 γ ($1\ \gamma = 10^{-5}$ gauss), the observed field was really the vector sum of the interplanetary magnetic field and a nearly constant spacecraft magnetic field; so this accuracy applies only to changes in the interplanetary field. The spacecraft field must be subtracted from the combined field in order to give the true interplanetary field; but determination of the spacecraft field, or "bias," depends on certain assumptions, and the bias may therefore be known significantly less accurately than to within 0.5 γ. The data described in this paper were obtained in interplanetary space during late 1962 and far enough from the Earth to be unaffected by the Earth's presence. No magnetic measurements were obtained either inside the geomagnetic field or in the transition region.

The orientation of the spacecraft, and therefore of the magnetometer, was controlled so that the positive Z direction (roughly, the spacecraft axis-of-symmetry) pointed away from the Sun. The orientations of the other two axes, X and Y, depended upon the mode of operation of the spacecraft. From August 29 to September 3 the spacecraft was allowed to roll about the Z axis. On September 3 the spacecraft was stabilized with the Y axis in a plane defined by the Sun, the Earth, and the spacecraft; at that time the X axis was nearly parallel to the direction of the north ecliptic pole.

The variation in the X- and Y- component readings during the period preceding the stabilization can be attributed principally to the roll of the spacecraft. The contribution of any quiet transverse interplanetary field, when averaged over many complete revolutions, should be zero. Thus, the averages of the observed field values represent the X and Y components of the spacecraft field. Fortunately, the interplanetary field was relatively undisturbed during this period, permitting a precise evaluation of these components. The center-to-peak amplitude of the variations in the X and Y components during roll represents the transverse component of the interplanetary field.

Preliminary analysis of the *Mariner-2* data revealed a large-scale interplanetary field with characteristics similar to those expected on the basis of theory. Specifically, the field tended (on the average) to lie in the ecliptic and to make the expected spiral angle. However, one could not just look at the data and derive such conclusions immediately, the problem being that the measurements were not absolutely accurate. The accuracy of the measurements was affected by the substantial spacecraft magnetic field, which changed both during and after launch. Immediately after launch, the spacecraft field was found to be much larger than had been indicated by measurements made prior to launch. We believe that all components also changed slightly during the flight.

Consequently, in order to derive the characteristics of the interplanetary field, it has been necessary to try to construct a reasonable model that is consistent with the observations. A preliminary look at the data indicated that the usual model of the interplanetary field was valid; so we decided to use this model, together with our data, to infer the spacecraft-field components to a reasonable degree of accuracy. This procedure obviously has important implications, not only for studying the large-scale field and its characteristics, but also for studying the smaller-scale field fluctuations.

Preliminary Results

I will begin by reviewing some of the preliminary results (Ref. 1). This will refresh the memory of those who have seen them before, and will, I hope, indicate that the techniques used to determine the spacecraft field were not completely arbitrary. In discussing the data, we shall use alternately the magnetometer coordinate system (X, Y, Z) and one (R, T, N) based approximately on the ecliptic; in the latter system, R is radially outward from the Sun, T is in the azimuthal direction (positive in the direction of planetary motion), and N points close to the north ecliptic pole (see Fig. 2, Paper 9).

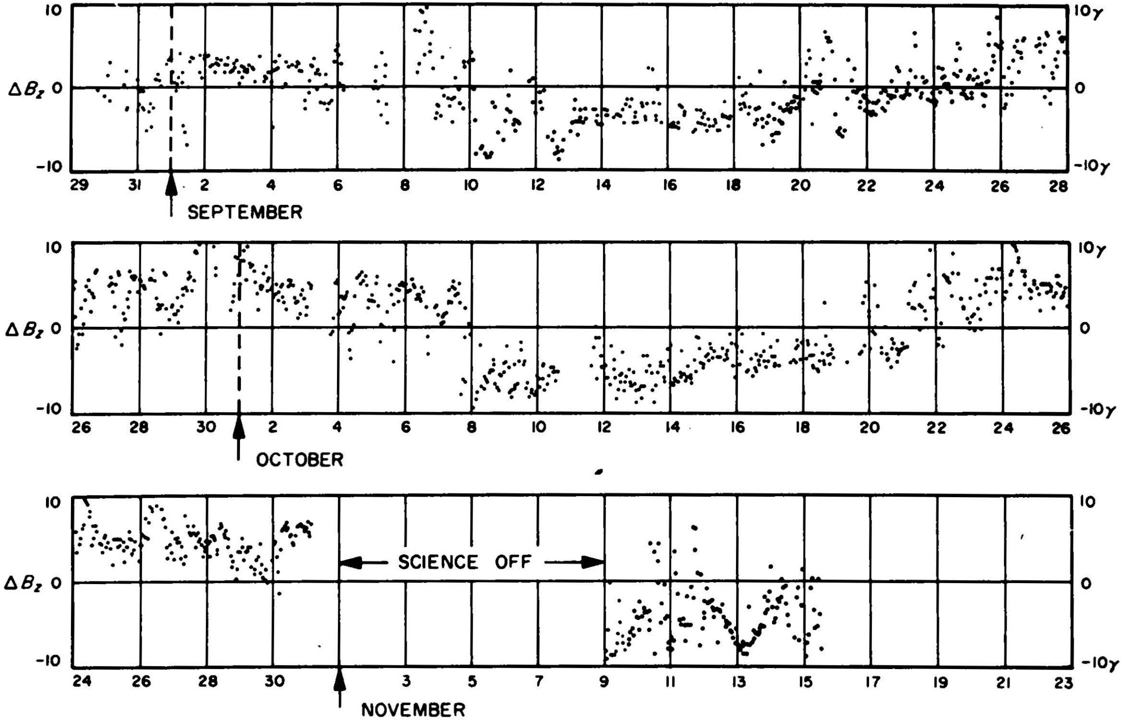

Fig. 1. Changes in the radial component of the magnetic field observed on *Mariner 2* (not corrected for spacecraft field)

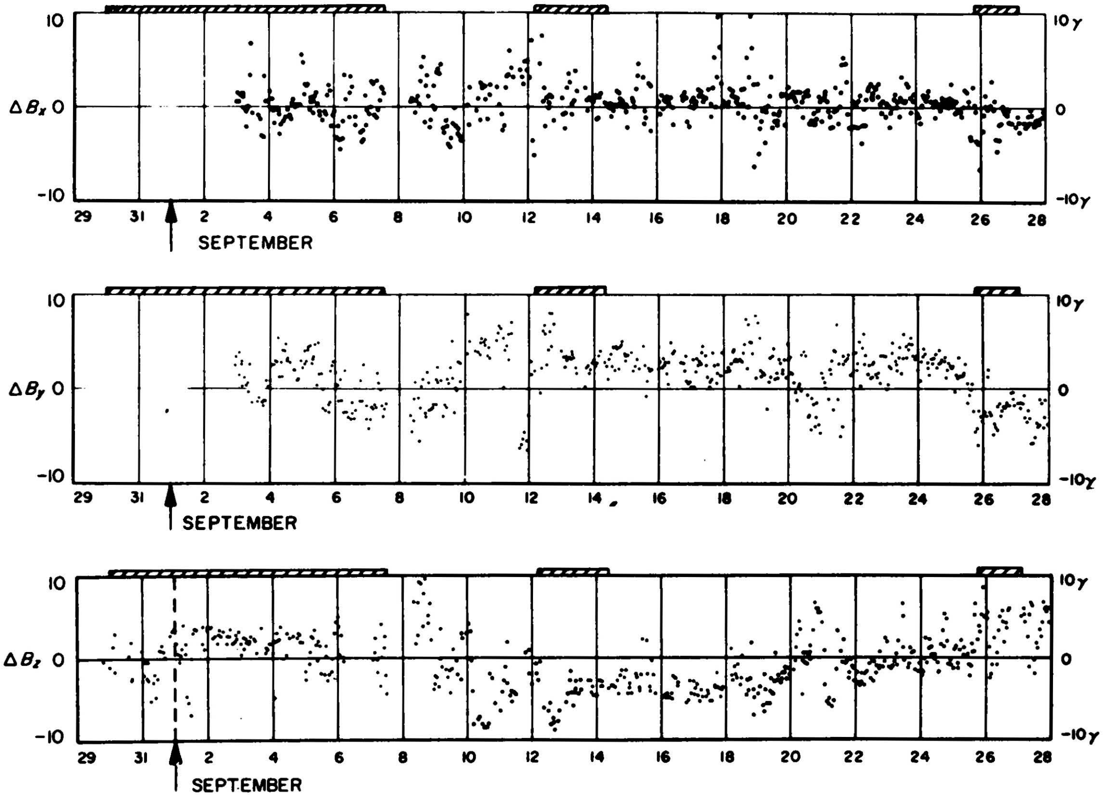

Fig. 2. Changes in the three components of the magnetic field (not corrected), given in spacecraft coordinates

Figure 1 shows the measured variation of the radial magnetic-field component ($\Delta B_R = \Delta B_Z$), not corrected for spacecraft field. Each point corresponds to an hourly average, and the data cover the period from the end of August to the middle of November. There are a couple of very interesting features in these data. The first is the extreme scatter in the data, which was due, it seems clear on further analysis, to the irregularities in the interplanetary field, that is, to the roughness of the field or to the disordering of the spiral structure. Another very marked feature is the periodic variation that coincided with the 27-day rotation of the Sun. This feature can be seen in two of the three components.

Figure 2 shows the data for only the first solar rotation (1767). The data for the period just prior to the start of Fig. 2 were obtained when the spacecraft was rolling. During this time it was possible, as described above, to determine the two spacecraft-field components that were perpendicular to the spacecraft–Sun direction; and averaging over the several days during which the spacecraft was rolling, we could obtain a fairly high degree of accuracy (±0.25γ).

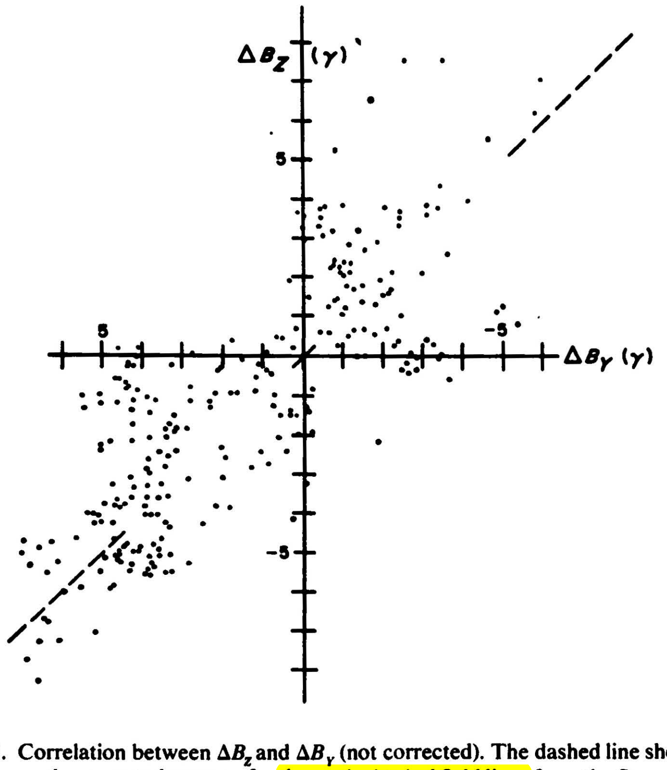

Fig. 3. Correlation between ΔB_z and ΔB_Y (not corrected). The dashed line shows the expected average for theoretical spiral field lines from the Sun

The structure following September 9 is interesting, because as the radial component ΔB_Z changed, the transverse component ΔB_Y tended to change simultaneously in the opposite direction. This is just what you would have expected on the basis of the spiral model. You can see this correlation a little better by plotting the two components against each other, as shown in Fig. 3 in which the plane of the paper represents the ecliptic.

Each of the points represents a "smoothed" hourly average—the average value of five successive hourly averages. Despite this averaging, one can't help being impressed by the disorder and irregularity in these measurements.

We have drawn the coordinate-system origin so that the dashed line, which represents approximately the expected spiral-field direction, appears to fit the data points. The value of the Y component of the spacecraft field, consistent with this selection of the origin, is reasonably close—say within 5γ or so—to its value as determined during the roll period. Thus the data points represent the endpoints of the interplanetary-field vector only. Wherever the true origin may be, this figure shows the way the end of the vector moved, and one can say at the very least that there was a tendency to cluster in the first and third quadrants. There does seem to have been a preferred direction that was at an angle of approximately 45 deg to the radial direction from the Sun. Thus the results look very much like the expected spiral angle.

Correction for Spacecraft Fields and Zero Offset

I shall now describe briefly what can be called a second-order approximation to the interplanetary magnetic field—an attempt to infer and subtract all components of the spacecraft field throughout the flight. Since preliminary indications are that the average solar field does lie in the ecliptic and does make the expected spiral angle, one can derive the spacecraft components at all times on the basis of three assumptions. The first assumption is that the spacecraft fields in the X and Y directions were known at the start of the data interval. These data were obtained from the roll period. The second assumption is that the components in the ecliptic, averaged over several days, took the streaming angle that was based on the solar-wind velocity as measured by the plasma experiment. The third assumption is that the Z component of the spacecraft field remained constant throughout the period prior to the first solar-panel failure (October 31). A preliminary look at the data indicated that this last assumption is valid, and the results are consistent with this assumption. The Z component seemed to be much less susceptible to change than either of the other two components.

If for each day we compute the values that the X and Y components of the spacecraft field would have to have if the average interplanetary field for that day were to fit the ideal spiral model, we get a rather irregular structure superimposed on some kind of slow drift. The irregular structure is presumably associated with the deviations of the interplanetary field from the spiral, but the slow changes, based on averages over several days, were taken to represent the spacecraft magnetic field itself.

Figure 4 shows the results of these calculations for the first 60 days of the flight. The solid curves represent the required corrections, that is, the negative of the inferred spacecraft fields. You can see not only that the spacecraft field was apparently changing, but that sometimes it changed very abruptly. It is important to note that these changes have little to do with, and are not responsible for, the correlation of the Y and Z (or T and R) components mentioned earlier. On the basis of our best evidence (although it is not completely conclusive) these changes seem to have been associated with some kind of currents flowing in the spacecraft—either ground-return currents associated with the spacecraft power system or some kind of thermoelectric current.

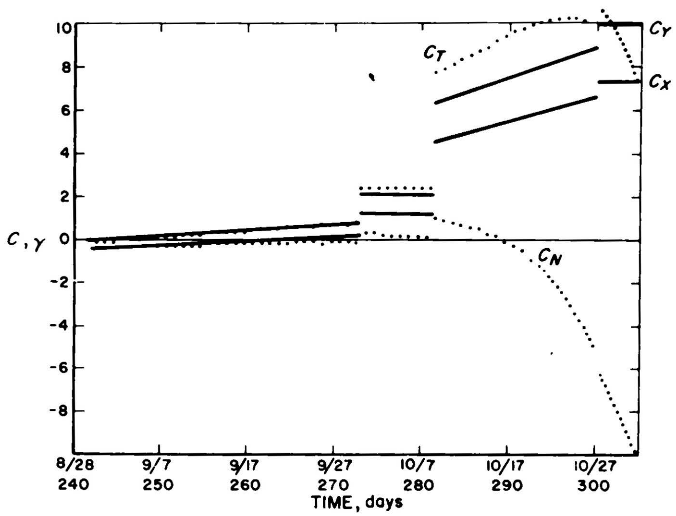

Fig. 4. Calculated corrections for *Mariner-2* spacecraft fields

The C_T and C_N curves (dotted) show the corrections in solar-ecliptic coordinates. Notice that the spacecraft rolled through nearly 90 deg between Day 280 and Day 300 as it overtook the Earth in solar longitude. This roll helped in determining the spacecraft fields.

The main thing that one notices from the figure is that the spacecraft field was very stable for the first 6 weeks or so. The changes along both axes were apparently less than 1 γ. Then there were both abrupt changes and periods of gradual change. The maximum corrections were about 10 γ.

It is difficult to know just how accurately one can do this sort of thing. If you consider the accuracy of the measurements and the accuracy associated with the digitalization of the data, and if you allow for the irregularities in the interplanetary field and so forth, then hopefully you can determine the spacecraft field to within perhaps 1γ—but this may be a little optimistic.

Corrected Data

The following figures show the corrected *Mariner-2* data over the same period of about 60 days. This period was prior to the time at which a rather catastrophic event occurred on the spacecraft: on October 31, one of the solar panels shorted. At the time the solar panel stopped providing power for the spacecraft, a very large but not-precisely-known change in the spacecraft field occurred. The spacecraft field was large enough that the magnetometer switched to the insensitive scale and gave less useful

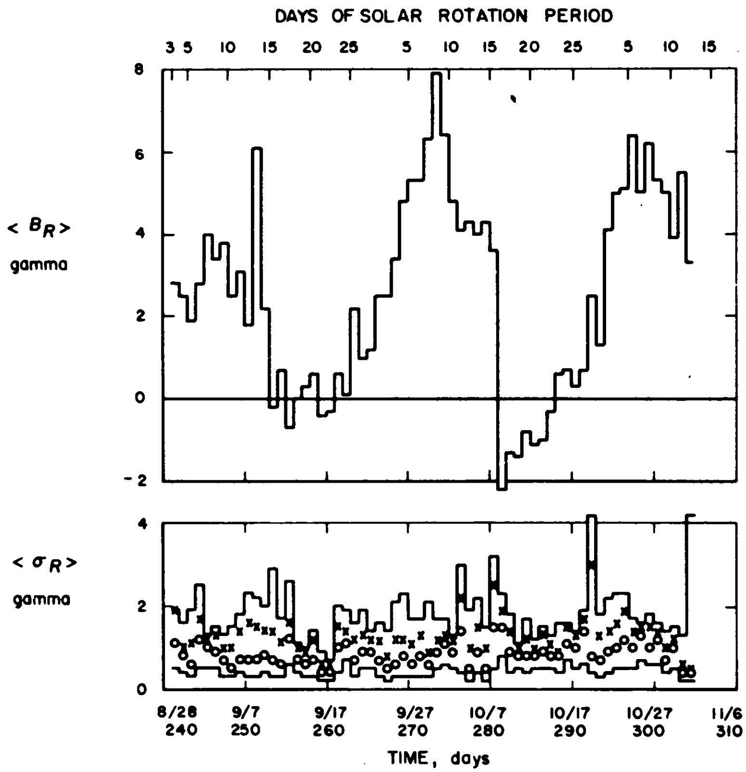

Fig. 5. Corrected interplanetary magnetic field, radial component, 1-day averages. The lower plot shows standard deviations for different time intervals: 3.7 min (bottom curve), 30 min (circles), 3 hr (crosses), 24 hr (top curve)

data. When the panel recovered, the field returned to normal and the magnetometer returned to its sensitive range—until a second failure occurred a week later.

The upper part of Fig. 5 shows the radial component of the interplanetary field. Each of the bars represents a daily average in the value of that field. The notable feature here is that the radial component did show a very strong periodic variation associated with the rotation of the Sun. (Solar rotation, in days, is shown at the top.)

One could conclude that the picture shown here suggests a solar magnetic-field configuration in which field lines come out of the Sun on one side, while the net outward flux is essentially zero on the other side. But since the values shown may well be uncertain to the extent of about 1 γ, any such conclusion must be made very carefully.

WILCOX: This base line is different from the base line in the earlier figure, is it not?
SMITH: That is correct.
WILCOX: Is this one more accurate?
SMITH: This one is more accurate: this picture is the result of a careful analysis of the data. In the earlier figure, the zero base line was more or less arbitrarily placed through the middle of the pattern, which made the field look as though it were pointing outward on one side of the Sun and inward on the other. When Fig. 1 was first shown, we tried to explain that the result shown here (Fig. 5) would also be essentially consistent with the data, since there were uncertainties in the spacecraft field.

The lower part of Fig. 5 shows the standard deviations in the field; the different symbols represent standard deviations taken over different time increments. The lowest curve corresponds to a period of 3.7 min, during which time six measurements of the field were made. The circles correspond to a period of a half-hour. The difference between the circles and the lower curve gives you some idea of those fluctuations having periods between 3.7 min and a half-hour. The crosses correspond to a period of 3 hr, while the upper curve corresponds to a period of a whole day. The data indicate that there was a fairly wide distribution of frequencies.

Comparing the amplitude of the fluctuations with the amplitude of the field provides a quantitative measure of the scatter seen in Fig. 3. The field was very typically about 4 γ; the rms value of the fluctuations over a period of a day was perhaps 2 γ or slightly more than 2 γ.

NESS: What was the noise level associated with the digitalization?
SMITH: It corresponded to about $\frac{1}{4}$ γ rms. That was the electrical noise level in the instrument, and was about the same as the uncertainty in the digitalization. The step size between the binary-coded integers was about $\frac{1}{3}$ γ. [The digitalization should not have significantly increased the mean of the standard deviations: it seems more likely to have reduced it.][1]

[1]Added in manuscript

NESS: Is the lower curve consistent with the noise level in the sense of a digitalization error?

SMITH: Very close to it: some of the values are $\frac{1}{2}\gamma$. Presumably some of the low values could have occurred at times when the fluctuations in the interplanetary fields could not be distinguished from the noise in the instrument. There were periods (though not very many) lasting as long as several hours during which there were no changes—in any of the components—larger than just one digital number; thus there were times when the field was extremely quiet. Such periods were used in estimating the noise in the instrument, and the estimated value agreed with expectations based on working with the instruments on the ground.

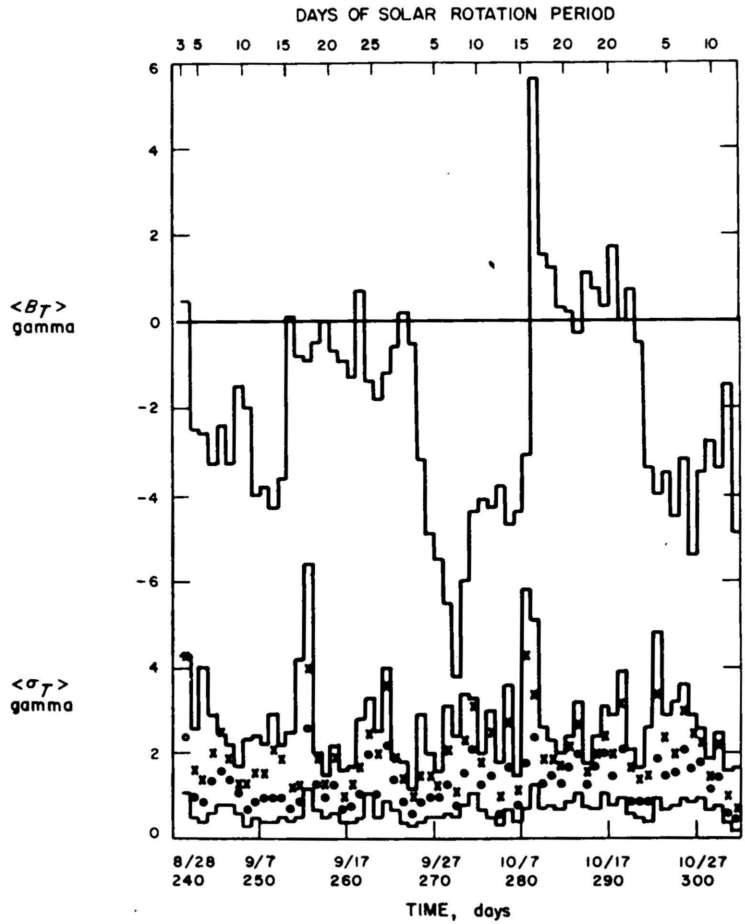

Fig. 6. Corrected interplanetary magnetic field, tangential component, 1-day averages. The lower plot shows standard deviations for different time intervals: 3.7 min (bottom curve), 30 min (circles), 3 hr (crosses), 24 hr (top curve)

Figure 6 shows the tangential component, which is positive in the direction of planetary motion. You can see again the presence of the 27-day pattern. The picture looks quite a bit different from that of ΔB_Y shown in Fig. 2, because not only has it been transformed to a different coordinate system, but significant spacecraft fields have been subtracted. In both this and the preceding figure, you can see that there was some kind of single, large source on the Sun that seemed to overshadow the other disturbed solar regions.

The lower half of the figure shows the standard deviations as before,

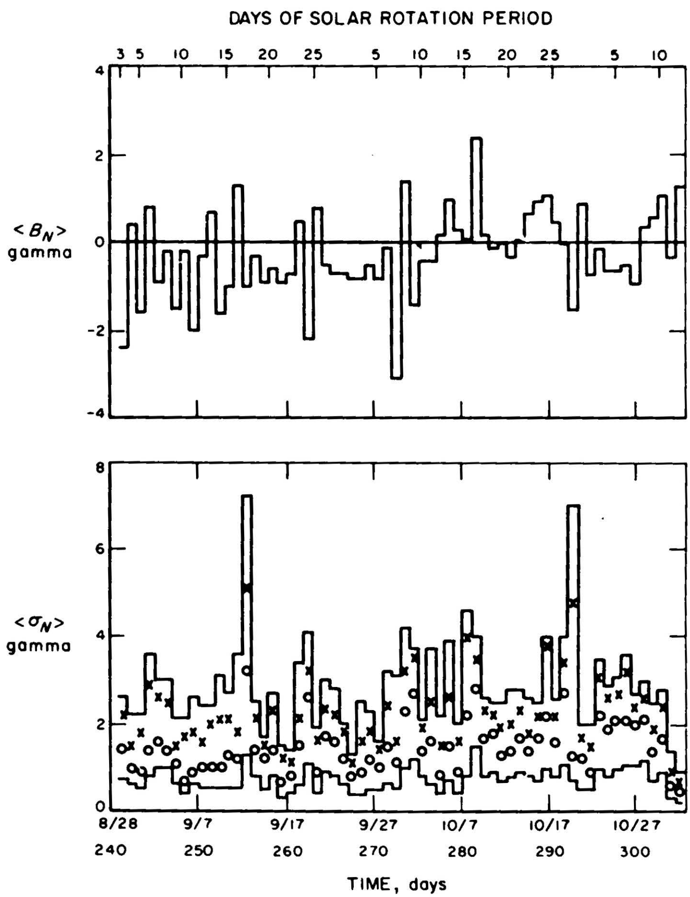

Fig. 7. Corrected interplanetary magnetic field, normal component, 1-day averages. The lower plot shows standard deviations for different time intervals: 3.7 min (bottom curve), 30 min (circles), 3 hr (crosses), 24 hr (top curve)

using the same symbols. Now, the interesting feature about these deviations is that they appear to be substantially larger. In Fig. 5, values of perhaps 2 γ were typical, and the standard deviations only twice exceeded 4 γ, even in the 1-day averages. The tangential component, as shown in Fig. 6, was apparently more disturbed than the radial component.

This aspect of the data is also seen in Fig. 7, which shows the normal component, B_N, perpendicular to the ecliptic. Here again you can see that the standard deviations were larger than those of the radial component by a factor of about 2. This figure has two other important features. First, this component shows no large effect associated with the rotation of the Sun. This fact tends to indicate that the calculated values of the spacecraft fields were reasonably accurate. At least, we would expect that there would be no effect associated with the solar rotation remaining after the corrections for spacecraft fields were made.

Another interesting and somewhat troublesome feature is that while $\mathbf{B}_N$ averaged near zero over this entire period of 60 days or so, there was a period, lasting just slightly over a month, in which there definitely appeared to be some average component that was out of the ecliptic—to the extent of about 1 γ. Now, this component was negative, that is, opposite to the north ecliptic pole. The zero level for this period, which immediately followed the time that the spacecraft had been rolling, is believed to have been very accurately determined. During later periods, this southward-pointing component gradually vanished.

WILCOX: Did your corrections tend to make $\mathbf{B}_N$ average to zero?
DAVIS: Yes, the corrections could easily account for $\mathbf{B}_N$ going to zero in the last half of the diagram.
COLBURN: Does the part of your analysis involving the spacecraft rotation depend on the assumption that the spiral angle was in the ecliptic during the spacecraft roll period?
DAVIS: All you have to assume is that, over a period of 4 days, the interplanetary field did not have a variation that correlated with the rotation of the spacecraft.
SMITH: It turned out that over this period of about 4 days, each of the half-day averages of the spacecraft field agreed to within $\frac{1}{2}\gamma$; the spacecraft field didn't change during this time.
GOLD: Can you tell us what the angle was between the spacecraft and the equatorial plane of the Sun during that period of time?
SNYDER: The solar latitude of the spacecraft was fairly constant during the first half of the mission, when the magnetometer data were most reliable. Starting at 7.1 deg north, it reached a maximum of 7.8 deg during the last half of September, and then decreased at an accelerating rate. It passed 6.0 deg on November 1 (Day 305), and 0.0 deg on December 7 (Day 341).
SMITH: Regardless of that, qualitatively, what you would expect at nonequatorial latitudes is inconsistent with the data. If the direction of the normal and radial components is determined by the general solar field, then there should be a positive normal component corresponding to a positive radial component. But the normal component was not positive, it was negative.

Figure 8 represents the interplanetary field in polar coordinates. In addition to the total magnitude B, the figure shows the angles β and Λ, defined by:

$$\langle B_N \rangle = \langle B \rangle \sin \beta$$

$$\langle B_R \rangle = \langle B \rangle \cos \beta \cos \Lambda$$

$$\langle B_T \rangle = \langle B \rangle \cos \beta \sin \Lambda$$

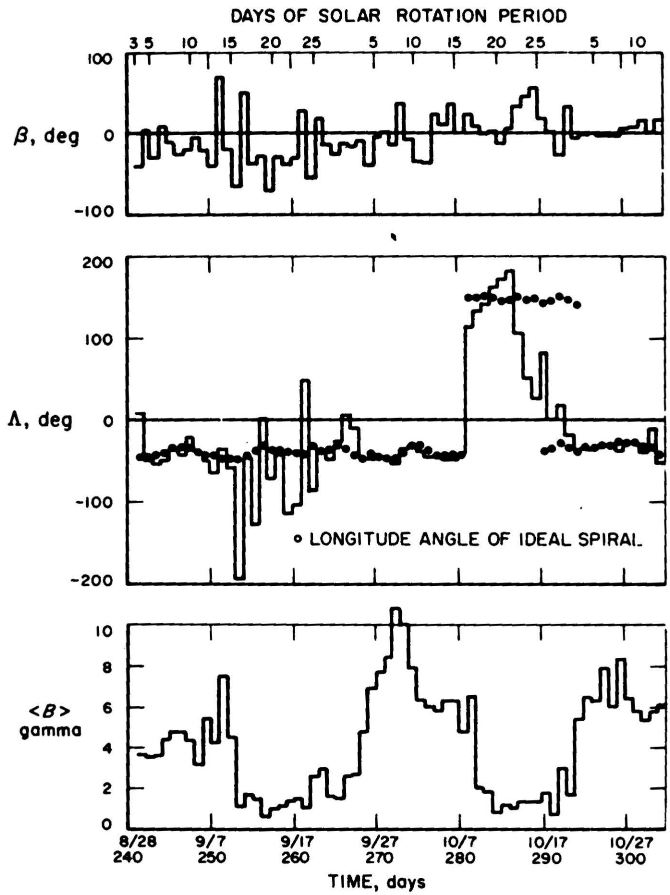

Fig. 8. Corrected interplanetary magnetic field, polar representation, 1-day averages. Λ is the azimuthal angle, measured from the radius vector; β is the polar angle, measured from the ecliptic: $\langle B \rangle$ is the total field strength

Thus Λ is the azimuthal angle of the projection of $\langle B \rangle$ in the ecliptic, and β is the ecliptic polar angle. The azimuthal angle Λ is compared with the theoretical streaming angle,

$$\Lambda_{\text{stream}} = -\tan^{-1}(r\Omega_s/v)$$

This ideal streaming angle is shown by the circles on the Λ plot. You must remember that the good agreement is one of the assumptions used in eliminating the spacecraft field. However, you can see that there were periods during which the angle Λ deviated substantially from the expected spiral angle, even after a fair amount of smoothing.

The bottom of Fig. 8 gives a fairly clear picture of how the magnitude of the field varied over this period. The average value, about 4γ, seems

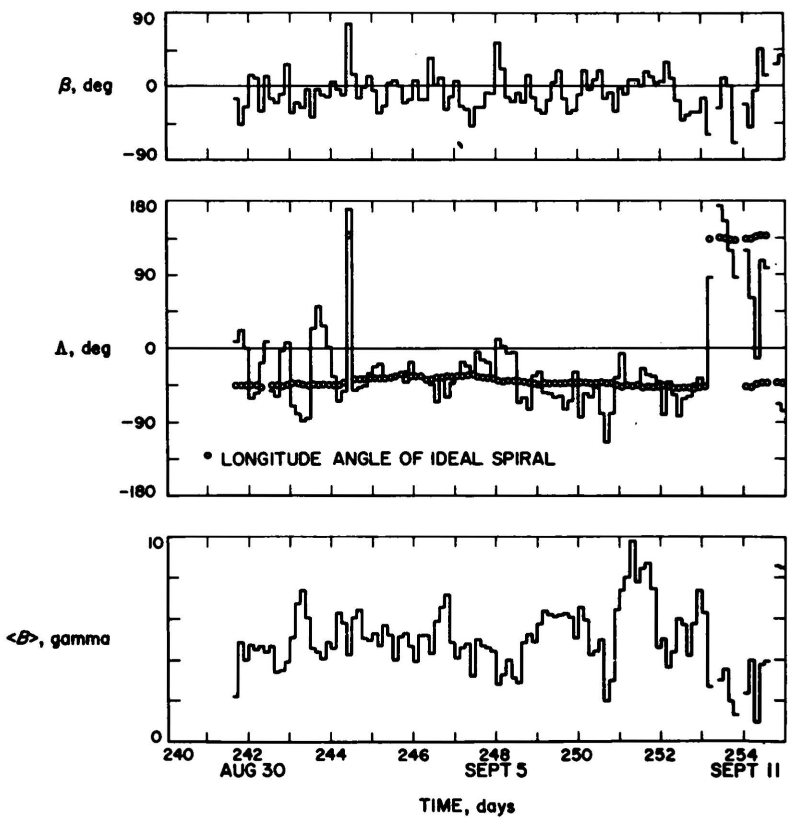

Fig. 9. Corrected interplanetary magnetic field, polar representation, 3-hr averages. Λ is the azimuthal angle, measured from the radius vector; β is the polar angle, measured from the ecliptic: Fig 8 $\langle B \rangle$ is the total field strength

quite reasonable, but variations extended all the way from about 1 to 10 γ. There are no obvious nulls in the data, although the averaging time is too long for this fact to be significant.

Figure 9 shows 3-hr averages, plotted over a period of about 2 weeks. Here the average field magnitude was about 5 γ. There is no indication that the field really went to zero for any period as long as 3 hr. Now, when you compare the data with the calculated value of the spiral angle, you can see quite a bit of roughness of the field. Also, the field was out of the ecliptic for periods lasting several hours.

Figure 10 is a comparison between the fluctuations in the total field,

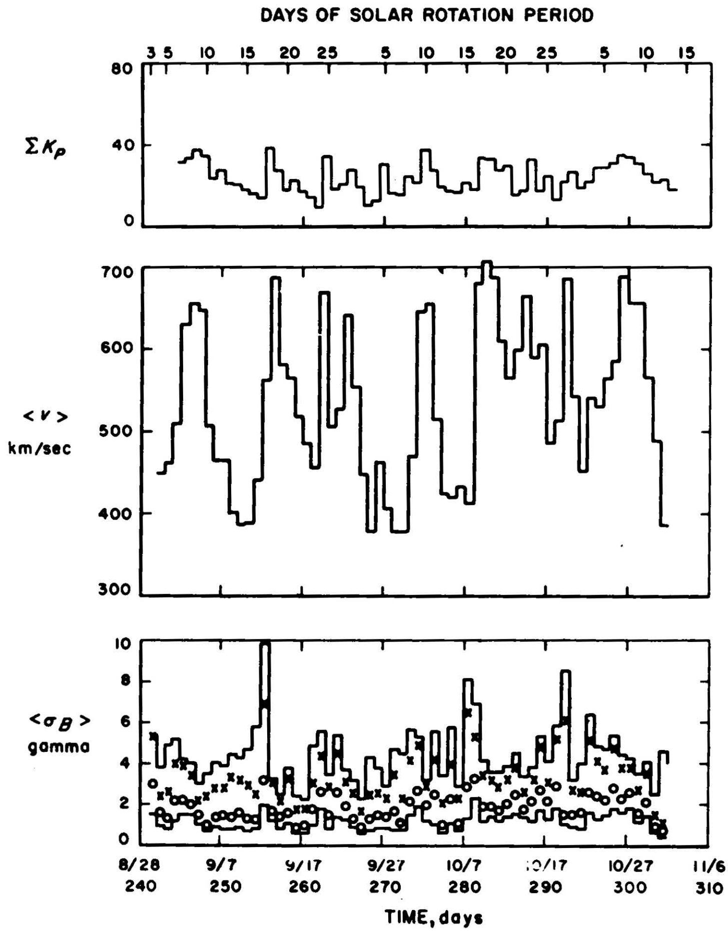

Fig. 10. Solar-wind and magnetic fluctuations. Top: the terrestrial magnetic-activity index ΣKp; center: the daily mean solar-wind velocity; bottom: standard deviations of the total interplanetary magnetic field for various time intervals