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Radial Variation of the Interplanetary Magnetic Field between 0.3 AU and 1.0 AU

Observations by the Helios-1 Spacecraft

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Abstract. We have investigated the radial dependence of the radial and azimuthal components and the magnitude of the interplanetary magnetic field obtained by the Technical University of Braunschweig magnetometer experiment on-board of Helios-1 from December 10, 1974 to first perihelion on March 15, 1975. Absolute values of daily averages of each quantity have been employed. The regression analysis based on power laws leads to $2.55\,\gamma \times r^{-2.0}$, $2.26\,\gamma \times r^{-1.0}$ and $F = 5.53\,\gamma \times r^{-1.6}$ with standard deviations of $2.5\,\gamma$, $2.0\,\gamma$ and $3.2\,\gamma$ for the radial and azimuthal components and magnitude, respectively.

Here r is the radial distance from the sun in astronomical units. The results are compared with results obtained for Mariners 4, 5 and 10 and Pioneers 6 and 10. The differences are probably due to different epochs in the solar cycle and the different statistical techniques used.

Key words: Interplanetary magnetic field – Helios-1 results.

Introduction

The study of the variation of the components and magnitude of the interplanetary magnetic field with heliocentric distance is very intersting at the present time.

The mission of Mariner 10 to the inner solar system to a heliocentric distance of 0.46 AU and the missions of Pioneer 10 and Pioneer 11 to the outer solar system to heliocentric distances beyond 5 AU have provided new data over a wide range of heliocentric distance. For a recent review see Behannon (1975).

In the mean-time the two Helios-1 and -2 missions are under way with perihelion distances of 0.31 AU and 0.29 AU, respectively, closer to the sun than any spacecraft in the past and in the foreseeable future.

The first perihelion of Helios-1 was reached on March 15, 1975 with a heliocentric distance of 0.31 AU while Helios-2 first reached the closest distance to the sun of 0.29 AU on April 17, 1976.

Due to the high degree of magnetic cleanliness of the two Helios spacecrafts and the proper operation of the spacecrafts and the magnetometer experiments the two Helios-1 and -2 missions will expand our information on the radial variation of the interplanetary magnetic field appreciably. It is the purpose of this paper to present first results on gradients of components and magnitude of the interplanetary magnetic field.

Instrumentation

The Institute for Geophysics and Meteorology of the Technical University of Braunschweig magnetometer is a three component flux-gate magnetometer (Förstersonde) with 4 automatically switchable measurement ranges of $\pm 100\,\gamma$ and $\pm 400\,\gamma$. The highest resolution is $\pm 0.2\,\gamma$ with a maximum sampling rate of 8 vectors/s. The experiment sensors are located at a distance of approximately 2.75 m from the center of the spacecraft. Included in the experiment is a mechanical flipper device which makes it possible to flip by command the sensor parallel to the spin axis into the spinning plane of the spacecraft to help determine the zero-offset of the Z-component parallel to the spin axis. The overall offsets of the components in the spin plane composed of sensor offsets and spacecraft field are removed by properly averaging over the spin variation. The experiment also includes a so called Shock Identification Computer (SIC) for triggering a memory-mode to observe discontinuities and shocks characterised by positive increases of field magnitude. Results using this capability will be presented in the future.

A detailed description of the experiment is given by Musmann et al. (1975).

Radial Variation of the Interplanetary Magnetic Field with Heliocentric Distance

The interplanetary magnetic field is due to solar magnetic fields dragged out from the sun by the solar wind. By the solar rotation this field is twisted into an Archimedean spiral structure. Assuming axial symmetry Parker (1963) has derived the field variation with distance from the sun in the solar equatorial plane. According to this simple model the magnetic field components B_r, B_ϕ, B_θ in a polar coordinate system based on the rotational axis of the sun are given by

$$B_r = B_0 \left(\frac{r_0}{r}\right)^2$$

$$B_\phi = B_0 \frac{r_0}{r} \frac{r_0\,\Omega}{V_s}$$

$$B_\theta = 0,$$

where Ω is the angular speed of the sun – more precisely of the source regions of the interplanetary magnetoplasma – and V_s is the solar wind speed assumed to be constant. B_0 is the radial component at distance r_0. Because of the inclination

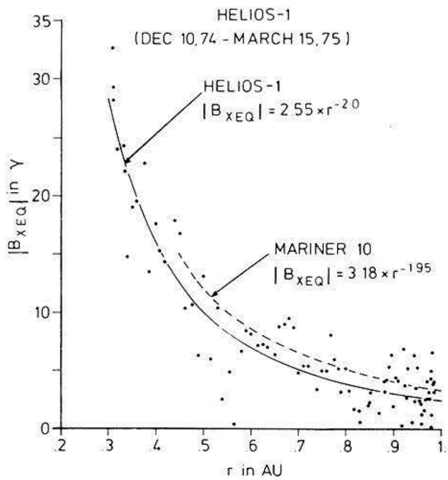

Fig. 1. Magnitude of daily average radial magnetic field component $|B_{XEQ}|$ versus heliocentric distance according to measurements by the Helios-1 TU Braunschweig magnetometer during the time interval from launch on December 10, 1974 to first perihelion on March 15, 1975. Least-mean-squares best fit curves for Mariner 10 (dashed) and Helios-1 (solid) are also shown

of the solar equator of only 7° 15′ a spacecraft like Helios moving in the ecliptic plane does not deviate more than 7° 15′ from the equatorial plane.

During the primary mission of Helios-1 defined as the time interval between launch and the first black-out by sun occultation the first perihelion was reached on March 15, 1975. The following analysis is based on this interval from launch to first perihelion. We shall use the daily average solar equatorial components $B_{XEQ} = -B_r$, $B_{YEQ} = -B_\phi$ and $B_{ZEQ} = -B_\theta$ and the magnitude $|\underline{B}| = F$. With a few exceptions the data available for the days used was more than 75%.

In Figure 1 absolute values of the daily averages radial component B_{XEQ} are shown. A best fit curve was calculated from the data in a least mean squares regression-analysis. The result is shown in Figure 1 as a solid curve. An inverse power law dependence with an exponent of -2.0 was found (standard dev. $= 2.5\,\gamma$). This exponent is in exellent agreement with the theoretical model. As can be seen from Figure 1 there is a large variability of even the daily averages around the best fit curve. This large variability of the daily average components $|B_{XEQ}|$ is probably mostly due to variations in heliographic longitude and to a lesser extent to variations in latitude and time. The figure also includes the best fit curve calculated for the 24-h averages of the magnitude of the radial component observed by Mariner 10 (Behannon, 1976) as a dashed curve. Note that we are always using absolute values of daily averages and not daily averages of absolute values.

So far the distance range between 0.29 AU and more than 5.0 AU has been covered by different spacecrafts. Mariner 5 covered the region between earth and the orbit of Venus at 0.71 AU (Rosenberg and Coleman, 1973). Solar rotation averages of $|B_{XEQ}|$ from Mariner 4 and 5 and Pioneer 6 are shown in Figure 2.

A dependence on heliocentric distance with an exponent -1.78 for the power law was found from Mariner 5 data. For Mariner 4 Coleman et al. (1969) calculated an exponent of -1.46. Villante and Mariani (1975) have confirmed the r^{-2} dependence of the radial field component using Pioneer 6 data.

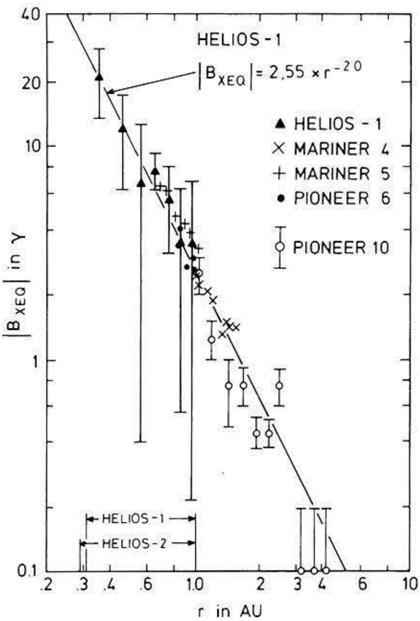

Fig. 2. Range and central value (black triangle) of $|B_{XEQ}|$ for heliocentric distance bins of 0.1 AU versus distance from the sun. The regression curve for Helios-1 is shown together with the results from the spacecrafts (see text for further explanation)

Pioneer 10 has observed the magnetic vield out to beyond the orbit of Jupiter. For observations out to 4.3 AU Smith (1974) calculated the most probable value for each solar rotation while the vertical lines in Figure 2 represent the maximum and minimum values of the distribution from which the most probable value was selected. Helios-1 covered essentially three solar rotations during the time interval considered. For the Helios data Figure 2 shows the maximum and minimum values for distance bins of 0.1 AU by vertical bars with the central values represented by black triangles. The straight solid line through all the measured values is the inverse power law calculated for Helios-1 according to Figure 1 with an exponent of -2.0.

From Figure 2 one may then conclude, that for the magnitude of the radial component $|B_{XEQ}|$ the observed radial dependence between 0.3 and 4.3 AU is in excellent agreement with the inverse square power law predicted by the Parker model. The differences between the various results are probably due to the different times during the solar cycle and of Pioneer 10 due to the different definitions of the displayed value of $|B_{XEQ}|$.

The radial dependence of the daily average azimuthal component $|B_{YEQ}|$ for the same time interval of Helios-1 is shown in Figure 3.

The best fit curve calculated from the 24-h averages shows a dependence of $r^{-1.0}$ very close to the Parker model. It is shown as the solid curve. The Mariner 10 data evaluation of the transverse component $B_t = \sqrt{B_{XEQ}^2 + B_{YEQ}^2}$ gives an exponent for the inverse power law of -1.4. It is presented by the dashed curve in the figure.

The observations of the radial dependence of the azimuthal component for the total range between 0.3 AU and 4.3 AU covered by Helios-1, Mariner 4, Mariner 5, Pioneer 6 and Pioneer 10 are shown in Figure 4. The Helios-1 data

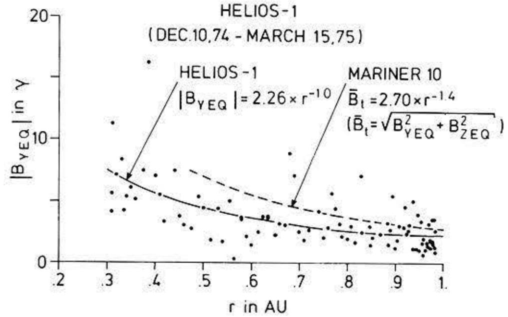

Fig. 3. Magnitude of daily average solar equatorial azimuthal component $|B_{YEQ}|$ versus heliocentric distance. The least-mean-squares best fit curve for $|B_{YEQ}|$ from Helios-1 (solid) is compared with the least-mean-squares best fit curve for $\sqrt{B_{XEQ}^2+B_{YEQ}^2}$ from Mariner 10

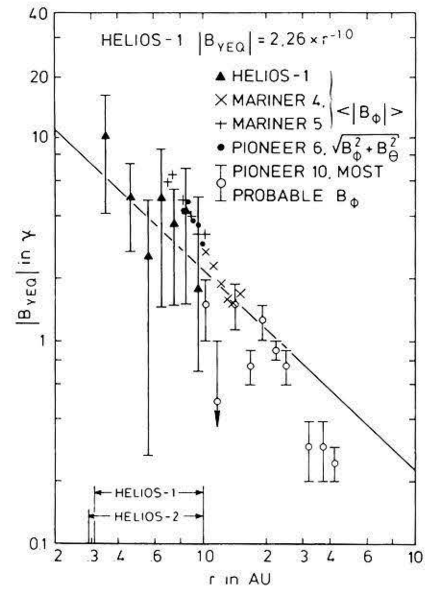

Fig. 4. Range and central value (black triangle) of $|B_{YEQ}|$ for distance bins of 0.1 AU versus heliocentric distance. Also shown are data from other spacecrafts in comparison with the least-mean-squares best fit power law for Helios-1. (For further explanation see text)

in this figure give again the minimum and maximum values for distance bins of 0.1 AU by a vertical bar and the central value by a black triangle. The Helios-1 power law shows the best agreement with the prediction of the simple Parker model i.e. a r^{-1} dependence whereas all other spacecrafts yield a much steeper dependence e.g. Mariner 4 shows an average power law of $r^{-1.29}$ and for Mariner 5 a best fit curve of $r^{-1.85}$ was computed. Villante and Mariani (1975) deduced a $r^{-2.5}$ dependence from the Pioneer 6 data.

Apart from the small distance variation of Pioneer 6 and to a decreasing extent of Mariner 5 and Mariner 4 leading to appreciable uncertainties the differences in the results for a power law dependence can firstly be due to the different statistical techniques and magnetic field components used. Note that in the case of Helios-1, Mariner 4 and Mariner 5 the azimuthal components B_{YEQ} were used, in the case of Pioneer 6 and Mariner 10 $\sqrt{B_{XEQ}^2+B_{YEQ}^2}$ and in the case of Pioneer 10 the most probable value of $|B_{YEQ}|$ during a solar rotation. In addition latitude variations and time variations have to be considered. Also

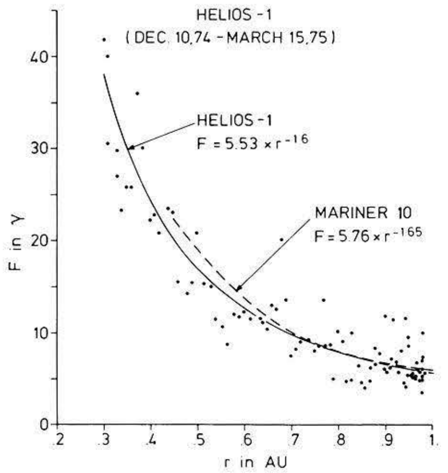

Fig. 5. Daily averages of magnetic field magnitudes versus distance from the sun. The least-mean-squares best fit power law curve from Helios-1 (solid) is compared with the corresponding curve for Mariner 10

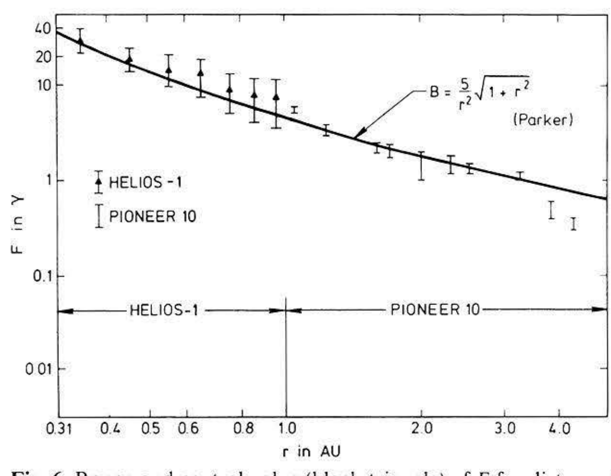

Fig. 6. Range and central value (black triangle) of F for distance bins of 0.1 AU versus distance from the sun. Also shown are Pioneer 10 results beyond 1 AU and a simple interpolation curve based on theory

Jokipii (1975) studied the role of fluctuations on the radial variation of the azimuthal component. Parker and Jokipii (1976) explain the Pioneer 10 results on the radial variation of the transverse component in terms of the systematic increase in velocity during the corresponding part of the missions.

For the same time period as for the components (Dec. 10, 1974 – March 15, 1975) the 24-h averages of the field magnitude F calculated from the components are shown in Figure 5.

The solid best fit curve gives an inverse power law dependence of $r^{-1.6}$ (standard dev. $=3.7\gamma$). The dashed line in Figure 5 represents the Mariner 10 best fit curve with an exponent of -1.65 calculated by Behannon (1975).

The relation $F=5\gamma\cdot\sqrt{1+r^2}/r^2$ with r in AU is shown in Figure 6 together with the Helios-1 data and the Pioneer 10 data. For Pioneer 10 the vertical lines are again the most probable values of the field magnitude for each solar rotation.

It can be seen from Figure 6 that the Parker model is in good agreement with Pioneer 10 data except for heliocentric distances beyond 3 AU. The Helios data shown in Figure 6 are presented in the same way as in Figures 2 and 4. The agreement with the theoretical formula is good again.

Conclusions

As a first step to understand the macrostructure of the interplanetary magnetic field between 0.3 AU and 1 AU we have used the data from the TU Braunschweig fluxgate magnetometer experiment on-board Helios-1 from launch on December 10, 1974 to first perihelion on March 15, 1975 to investigate the radial variation of the solar variation of the solar equatorial radial component, azimuthal component and the magnitude of the magnetic field. Daily averages covering more than three solar rotations have led to the following results:

1. The radial component $|B_{XEQ}|$ varies as $2.55\,\gamma \cdot r^{-2.0}$ with a standard dev. of $2.5\,\gamma$, where r is the distance from the sun in AU.

2. The azimuthal component $|B_{YEQ}|$ varies like $2.26\,\gamma \cdot r^{-1.0}$ with a standard dev. of $2.0\,\gamma$.

These results are in very good agreement with the simple Parker theory of the interplanetary magnetic field. They differ somewhat from results of previous spacecrafts covering fractions of the distance range of Helios i.e. Mariner 5, Mariner 10 and Pioneer 6. The distance range covered by Mariner 5 and Pioneer 6 is too small to make strong statements on the radial variation. In addition the regression analysis in each case implies a different weighting due to the differing orbital characteristics. The difference between Helios-1 and Mariner 10 may be due to the different latitude profile, the time difference of about one year between both missions and to the different way of computing $|B_{XEQ}|$ and $|B_{YEQ}|$.

Extrapolation of the Helios regression results to distance beyond 1 AU are in reasonable agreement with Mariner 4 data out to Mars (1.5 AU) and with Pioneer 10 data out to about 3 AU where appreciable deviations start to occur.

The magnetitude F can be described by $5.5\,\gamma \cdot r^{-1.6}$ with a rms deviation of $3.2\,\gamma$ between 0.3 and 1.0 AU. In the range from 0.3 AU to 3 AU the law $5\,\gamma\sqrt{1+r^2}/r^2$ based on simple Parker theory provides a good representation.

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References

Behannon, K.: Observations of the interplanetary magnetic field between 0.46 and 1 AU by the Mariner 10 spacecraft, NASA-X-692-76-2, January 1976

Behannon, K.W.: Variation of the interplanetary magnetic field with heliocentric distance, GSFC Rep. X-692-75-143, June 1975

Coleman, P.J., Smith, E., Jr., Davis, L., Jones, E.D.: The radial dependence of the interplanetary magnetic field: 1.0–1,5 AU. J. Geophys. Res. **74**, 2826–2850, 1969

Jokipii, J.R.: Fluctuations and the radial variation of the interplanetary magnetic field. Geophys. Res. Lett. **2**, 473–475, 1975

Musmann, G., Neubauer, F.M., Maier, A., Lammers, E.: Das Förstensonden-Magnetfeldexperiment (E2). Raumfahrtforschung **19**, 232–237, 1975

Neugebauer, M.: Large scale and solar-cycle variations of the solar wind. Space Sci. Rev. **17**, 221–254, 1975

Parker, E.N.: Interplanetary dynamical processes. New York: Interscience 1963

Parker, G.D., Jokipii, J.R.: The spiral structure of the interplanetary magnetic field. Geophys. Res. Lett. **3**, 561–564, 1976

Rosenberg, R.L., Coleman, P.J., Jr.: The radial dependence of the interplanetary magnetic field: 1.0–0.7 AU, Institute of Geophysical and Planetary Physics No. 1196–26, Univ. of California, Los Angeles, 1973

Smith, E.J.: Radial gradients in the interplanetary magnetic field between 1.0 and 4.3 AU: Pioneer 10, Jet Propulsion Lab., California, Institute of Techn., Pasadena, California 91103, 1974

Villante, U., Mariani, F.: On the radial variation of the interplanetary magnetic field: Pioneer 6, Geophys. Res. Lett. **2**, 73–74, 1975

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