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II-5-7. Magnetic Field Measurements with the Explorer X Satellite

J. P. HEPPNER, N. F. NESS*, T. L. SKILLMAN
and C. S. SCEARCE

NASA, Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

The description to follow summarizes the results of a preliminary analysis of Explorer X magnetic field data. A more comprehensive and interpretative paper will be prepared in the near future for journal publication.

Explorer X (1961 Kappa), launched at 15:17 GMT, March 25 1961, was instrumented with a rubidium vapor magnetometer and two flux gate, saturable core magnetometers for field measurements, a plasma probe for measurement of the flux of low energy protons, and an optical aspect system for precise determination of the satellite's orientation relative to the sun.

Introduction

Fig. 1 illustrates the trajectory and satellite orientation in inertial coordinates. The satellite was intended to have an active battery life of about 55 hours which would provide operation approximately to apogee. In practice 53 hours of reliable operation was obtained and this was followed by several hours of uncalibrated operation (not presented here) in which only certain types of data could be obtained as battery power diminished.

Observatory magnetograms show that the magnetic field in low and middle latitudes was typically quiet for at least a week preceding the flight. In the auroral zone magnetic activity was confined to bays of weak to moderate intensity. These conditions prevailed until 15:03 GMT, March 27 at which time a sudden commencement occurred. Solar activity prior to the flight was comparatively low and confined largely to Class 1 and 1^- flares. This condition prevailed until 10:15 GMT, March 26 at which time a Class 3 flare occurred near the east limb of the sun. The sudden commencement is believed to be associated with this flare. The environment of the satellite prior to 15:03 GMT, March 27 is consequently thought to be typical of undisturbed conditions.

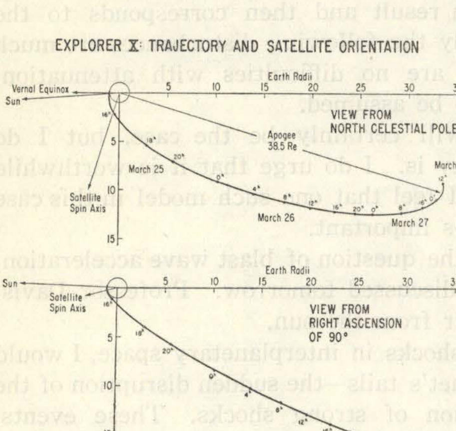

Fig. 1.

* NAS-NASA Post-doctoral Research Fellow.

1.8 to 6.6R_e (Fig. 2)

Fig. 2 shows the difference between the total scalar field measured by the Rb-vapor magnetometer and the total scalar field given by the Finch and Leaton[1)] representation of the geomagnetic field over the geocentric distance range of 11,100 to 42,000 km. (Note: a negative sign means the measured field is less intense than the computed, reference field). Field measurements are shown at one minute intervals. If the scale was enlarged to permit plotting in terms of seconds the deviations from a smooth curve would be only slightly increased. These fluctuations of several gammas are a minor feature compared to the large differences between the measured and computed fields.

In interpreting measurements relative to a reference field two sources of error have to be evaluated: (a) errors in the trajectory, or orbit, which cause the reference field to be calculated for a space location that is not identical with the satellite's location, and (b) the difference between the computed reference field and the true geomagnetic field which is unknown unless other absolute data is available. Considering (a) first, a number of orbit determinations have been made in which different weights have been given to the various types of tracking data (Minitrack, doppler, antenna pointing, etc.). The curve on Fig. 2 labeled "orbit analysis B" utilizes

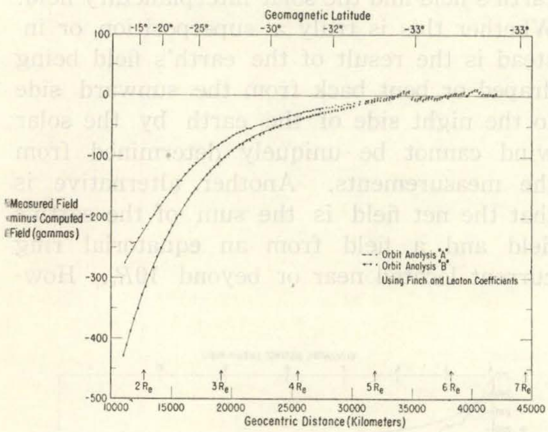

Fig. 2.

the orbit giving the best fit to the tracking data. The curve labeled "orbit analysis A" utilizes the orbit obtained which gives the smallest difference between the measured and computed fields. Thus, from orbit analyses it appears improbable that the large field difference can be attributed to errors in the orbit. Next, the accuracy of the Finch and Leaton ($m=6$, $n=6$) reference field in representing the true geomagnetic main field near $2R_e$ needs to be considered. The first measurement at 11,100 km was taken east of Ascension Island in the South Atlantic and as time progressed the satellite moved toward and then over South Africa. The closest region where the accuracy of the Finch and Leaton field is independently known from Vanguard III measurements[2] is over South Africa at geocentric distances up to 10,000 km. If it is assumed that the Finch and Leaton field has a comparable accuracy in the region toward Ascension Island from South Africa, up to 50 gammas of the difference curves, Fig. 2, below $2R_e$ can be attributed to lack of accuracy in the computed field. This assumption receives some support from the fact that this represents an error of about 1% in the Finch and Leaton field which is typical of other areas of the earth as well. (Note: a reference field based on Jensen and Whitaker coefficients is not used here as it gives greater differences from the measured field and is also known to be more incorrect over this region of the earth[2]. Above $3R_e$ the difference between reference fields is negligible.). To attribute the difference curves of Fig. 2 to errors in the computed field, the computed field near $2R_e$ would have to be in error by 5% (Curve A) to 8% (Curve B). Thus it appears that only a small fraction of the difference in fields can be attributed to errors in the computed field.

These arguments lead to the conclusion that a field source located in the "slot" between the inner and outer radiation belts near the equator is necessary to explain the measurements. The extent of the field source proceeding outward to the field shell coincident with the maximum of the outer radiation belt cannot be uniquely defined solely from measurements along this trajectory.

The possibility that the reference field is grossly in error between Brazil and South Africa is being investigated using Project Magnet data. If this is found to be the case, a smaller field source having its maximum strength at a somewhat greater altitude between 1.8 and $3R_e$ would still be required to explain the measurements. The fact that the per cent difference increases to a maximum of 6% (Curve A) and 9% (Curve B) at $2.4R_e$ and then decreases may also indicate that the source center is slightly above 1.8 R_e.

From 5 to $6.6R_e$, Fig. 2, there is excellent agreement between the measured and computed fields. The region 3 to $5R_e$ is transitional between the two conditions.

At $6.6R_e$ the Rb-vapor magnetometer became excessively hot as a result of contamination of thermal surfaces encountered during the launch phase. From 6.6 to $18R_e$ it operated intermittently on, a fast duty cycle. This data has been used to calibrate the flux-gate magnetometers in flight.

Coordinate System

The fact that the satellite was spin stable and the sun's position during each spin cycle was precisely given by the optical system made it convenient to define a coordinate system in terms of a plane containing the spin axis and the satellite-sun line as shown in Fig. 3. The same coordinate system is convenient to use in interplanetary regions when the field is primarily radial from the sun with a "stream" or "garden hose" angle

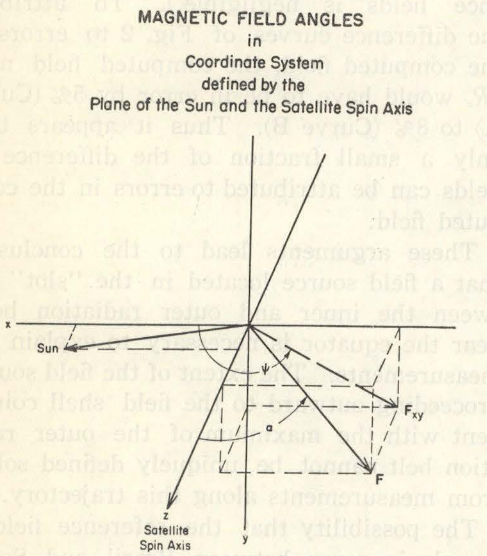

Fig. 3.

due to the sun's rotation as depicted in various solar wind and magnetic bottle pictures of the solar field. As shown later these angle conditions are frequently present; hence angle data is presented in this coordinate system in preference to ecliptic coordinates. In Fig. 3 the spin axis points below the celestial equator at a declination of 15 degrees. When the angle ψ is 180° and α equals 112° the field vector is directed away from the sun along the satellite-sun line. For $\psi=180°$ and $\alpha<112°$ the "stream" angle is given by $112°-\alpha$. (Note: the term "stream" angle is used here in the same context as the angle $\delta=\tan^{-1}\omega r/v$ for a particle stream ejected radially from the sun with velocity, v, where ω is the sun's angular velocity and r is the distance from the sun).

6.6 to 11R_e (Fig. 4)

As shown in Fig. 4, the agreement between the measured and computed field intensities observed between 5 and 6.6R_e continues out to 8R_e but an angular deviation between the measured and computed fields is evident as low as 6R_e. At 11R_e the angle ψ becomes relatively stable between 170° and 180°. The difference between the measured field and the Finch and Leaton "theoretical" field near 11R_e is approximately equal to the field intensity that is observed at much greater distances. The measured field thus has the character of a superposition of the earth's field and the solar-interplanetary field. Whether this is truly a superposition or instead is the result of the earth's field being draped or bent back from the sunward side to the night side of the earth by the solar wind cannot be uniquely determined from the measurements. Another alternative is that the net field is the sum of the earth's field and a field from an equatorial ring current located near or beyond 10R_e. How-

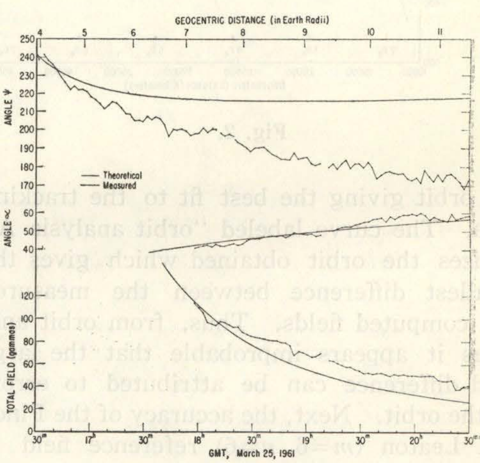

Fig. 4.

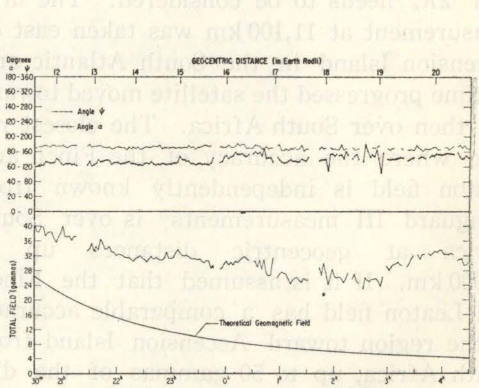

Fig. 5.

ever, with this explanation difficulty is encountered in explaining the measurements between 5 and $8R_e$.

11 to $20R_e$ (Fig. 5)

Between 11 and $19R_e$ the field continues to have the appearance of a superposition of the earth's field and the solar-interplanetary field. The influence of the earth's field appears to become negligible at $19R_e$. Between 20 and $21.5R_e$ (Fig. 6) the field is stable and approximately radial from the sun with a "stream" angle of 30° to 40°.

20 to $27R_e$ (Fig. 6)

At 05:30, March 26 the field changed character abruptly between flux-gate readings separated by 139 seconds. For the next 5 hours the field fluctuated greatly both in magnitude and direction. Multiple points occurring at the same time on Fig. 6 represent the degree of variation within one 3-second interval of continuous measurement from one of the two flux-gates (See Ref. 3 for a detailed example of a rapid fluctuation).

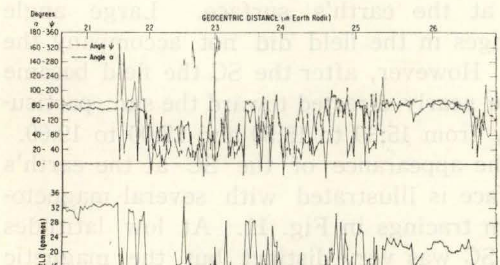

Fig. 6.

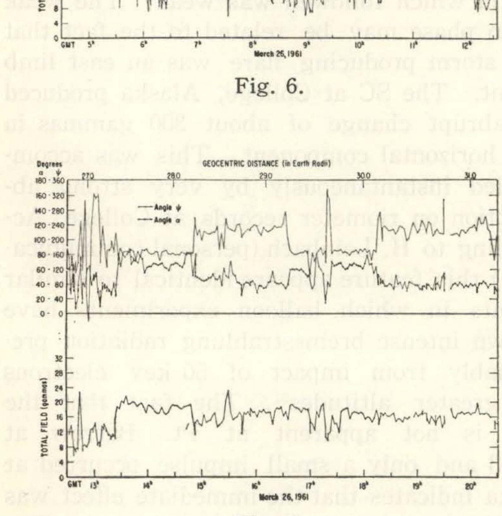

Fig. 7.

The sharp break at 05:30 is coincident with the first detection of solar plasma by the MIT plasma probe[4]. The field is directed into the eastern hemisphere of the celestial sphere with predominantly a south declination during the period of fluctuation. The field returned to a stable condition at 10:25 for a period of 1.5 hours.

27 to $31R_e$ (Fig. 7)

During this period the field direction changed character at intervals of 1.5 to 2 hours as shown. On alternate steps the field returned to the nearly radial condition with a "stream" angle of 35° to 55°. During the periods of $\psi > 180°$ the field is directed between 90° and 180° right ascension with predominantly a north declination. The field magnitude varies irregularly and does not show a pronounced change in character when the angles change.

31 to $34.5R_e$ (Fig. 8)

Throughout the 8 hours shown on Fig. 8 the field intensity fluctuates irregularly about mean values of 12 to 16 gammas. During the first 4 hours the field direction rotates slowly and irregularly about the spin axis of the satellite and is directed predominantly eastward in celestial coordinates.

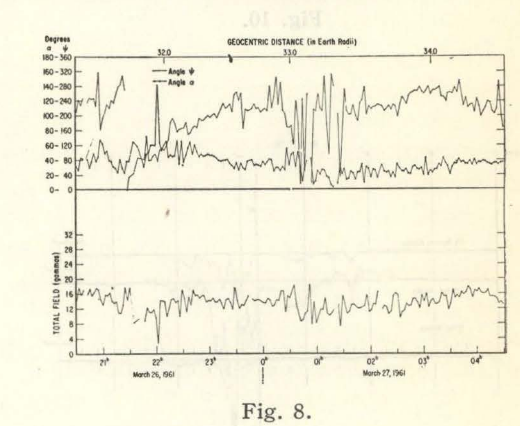

Fig. 8.

34.5 to $36.5R_e$ (Fig. 9)

The field during the 8 hours of Fig. 9 changed character at intervals of 1 to 2 hours in a manner somewhat similar to Figs. 6 and 7. The intervals when the field intensity is high coincide with a field direction which is nearly radial from the sun with a "stream" angle of 25° to 55°. The high intensity in-

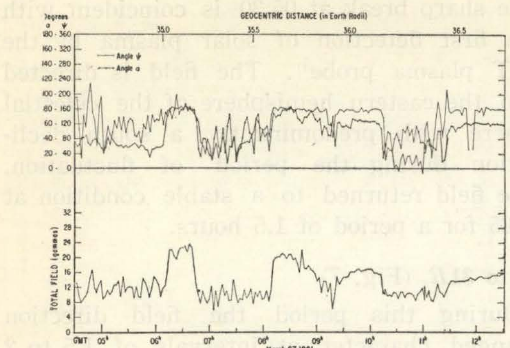

Fig. 9.

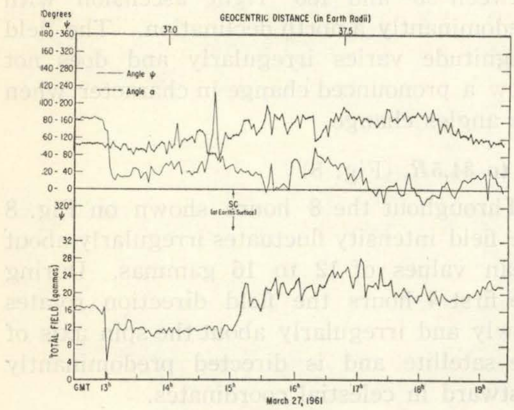

Fig. 10.

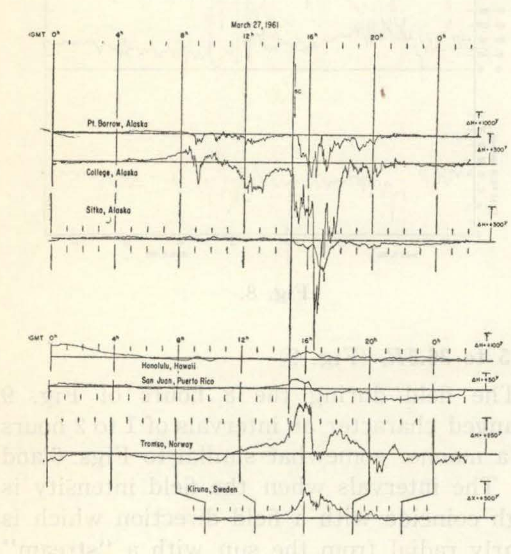

Fig. 11.

tervals also coincide with times when plasma is not detected by the plasma probe (Ref. 4 and Appendix). In general, short period fluctuations of the field are also reduced in amplitude when the field intensity increases.

37 to 38R_e (Figs. 10 and 11)

After 13:00 and prior to the sudden commencement at 15:03, March 27 the field vector pointed primarily toward a region east and south of the sun. The rotation of the vector at about 14:40 does not have a recognizable association with the SC. Using information on the plasma spectra[4] together with the increased field intensity after 15:03 it is believed that the increased field intensity at the satellite is associated with the sudden commencement at the earth's surface. The field at the satellite increases gradually from 15:03 to 15:10 and then makes a greater change both in intensity and the angle α between 15:10 and 15:12. Thus, depending on which time is chosen for the SC at the satellite it occurred 0 to 7 minutes later at the satellite than on earth with the largest change taking place 7 to 9 minutes after the SC at the earth's surface. Large angle changes in the field did not accompany the SC. However, after the SC the field became more nearly directed toward the sun: particularly from 15:30 to 15:50 and 17:00 to 19:00.

The appearance of the SC at the earth's surface is illustrated with several magnetogram tracings in Fig. 11. At low latitudes the SC was very distinct but the magnetic storm which followed was weak. The weak main phase may be related to the fact that the storm producing flare was an east limb event. The SC at College, Alaska produced an abrupt change of about 300 gammas in the horizontal component. This was accompanied instantaneously by very strong absorption on riometer records at College. According to H. Leinbach (personal communication) this feature appears identical to similar events in which balloon experiments have shown intense bremsstrahlung radiation presumably from impact of 50 kev electrons at greater altitudes[5]. The fact that the SC is not apparent at Pt. Barrow at 15:03 and only a small impulse occurred at Sitka indicates that the immediate effect was highly localized in the auroral zone. The satellite data indicates: (a) that there is little if any delay associated with the SC reaching the earth's surface from outside the earth's field, and (b) that other more pronounced field changes observed in space do not show visible effects on observatory magnetograms at low and middle latitudes. These features give support to the following concepts. One, bremsstrahlung associated with SC's are created by particles entering directly from outside the earth's field rather than by dumping of electrons from the outer radiation belt. Second, SC's may represent the response of the ionosphere to sudden impacts in the auroral zone rather than a uniform compression of the earth's field by a solar stream.

Correlations with Solar and Magnetic Activity

In addition to the SC event, correlations between the abrupt changes in the character of the solar-interplanetary field and plasma and other solar-terrestrial events can reasonably be anticipated. For this purpose R. T. Hansen of the High Altitude Observatory, Boulder, Colorado has complied a solar history for the dates of interest. In reviewing this information, the most notable feature is that minor flares, Class 1 and 1⁻, were observed at time intervals similar to the time intervals between major changes in the field at the satellite. However, attempts to make precise time correlations between particular flares and particular changes in the field character, assuming various time delays, have not yielded a positive result. Considering that a different velocity and path is probably associated with each source this is not unexpected. For this type of correlation a long observation period and an extremely quiet solar period is probably required.

From examination of standard observatory magnetograms it is apparent that at times other than the SC time the field changes in space were not accompanied by simultaneous field changes at the earth's surface in low and middle latitudes. This lack of correlation may not however apply to high latitude stations. From the magnetograms that have been available for examination there is some possibility that correlations with bay activity in the auroral zone may exist. As an example, using Fig. 11, prior to the time of the SC the usual bay activity was present in the auroral zone. The changes at College, Alaska near 09:00 and 13:00 GMT might be related to the changes in space shown in Figs. 9 and 10 at the same times. However, there are other changes which do not correlate and the coincidences can reasonably be attributed to chance until magnetograms distributed in longitude in the auroral zone are available for study.

Appendix: Explorer X Field and Plasma Correlations

The correlations between the plasma measurements (Bridge, Dilworth, Lazarus, Lyon, Rossi, and Scherb) and the magnetic field measurements (Heppner, Ness, Skillman, and Scearce) with Explorer X have been noted in each presentation. To illustrate these more effectively several examples are shown in

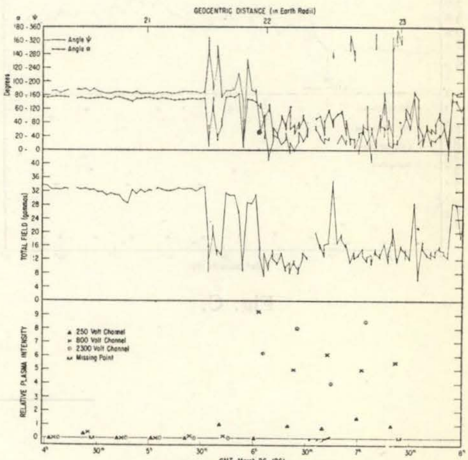

Fig. A.

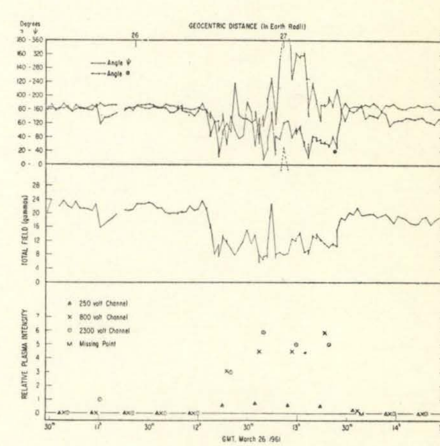

Fig. B.

Figs. A, B and C.

Figs. A and B are typical of the behavior prior to the sudden commencement. The presence of plasma coincides with periods when the field intensity is relatively weaker and the field direction is variable. This correlation exists even in fine detail. For example: (a) near 05:40 in Fig. A plasma was observed on the 250 volt channel when the field intensity dropped but on the next reading the plasma was not observed and the field intensity was again high, and (b) at 11:00 in Fig. B plasma appeared during an otherwise stable field period at a time when the field fluctuated.

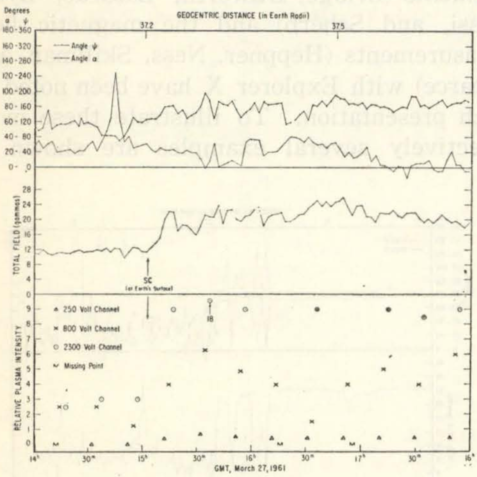

Fig. C.

After the SC, Fig. C, both the plasma and the field intensities are high. The field direction is however quite different from the previous period when the field intensity was high. Thus, whether or not the same correlation exists before and after the SC depends on knowing whether the field direction or the field magnitude is most important in the correlation. The probable answer is that the absence of plasma correlates with the condition when the field has both high intensity and directional stability.

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