X-616-69-449

REVISED DECEMBER 1969

NASA TM X- 63812

SEARCH FOR MAGNETIC MONOPOLES IN THE MOON

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OCTOBER 1969

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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(Received 17 October 1969)

Revised
December 1969

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The effects of a possible magnetic charge of the moon upon the magnetic field in the lunar vicinity have been analyzed. Magnetic field observations obtained by the GSFC magnetometer aboard Explorer 35 have been studied to search for these effects. Using these observations it is possible to obtain a measure of the net difference between the number of northern and southern monopoles within the moon which are of opposite sign. The search has resulted in negative findings and places an approximate upper limit on the average difference in the number of monopoles within the moon at 1.6×10^{-7} cm^{-3} or 7×10^{-32} per nucleon.

Introduction

The existence of a magnetic monopole with a charge g, quantized such that $g = \frac{1}{2}\hbar c/e$, was first proposed by Dirac (1). The Dirac monopole was permitted by quantum theory and also provided a basic symmetry if incorporated into Maxwell's equations. Tamm (2), Jordon (3), Banderet (4), Dirac (5), and Ramsey (6). furthered the incorporation of monopoles into the known physical laws. Schwinger (7) later showed that the monopole charge should be quantized in integral multiples of $\hbar c/e$. This yields a value of g given by the equation:

$$g = (\hbar c/e^2)\ e = \alpha^{-1}\ e = 137\ e \simeq 6.6 \times 10^{-8}\ \text{esu.} \tag{1}$$

Malkus (8) first searched for the elusive magnetic particle using a current carrying solenoid to attract them in the cosmic ray flux. A flux of monopoles more than $10^{-10}/\text{cm}^2$ sec would have been detected or the particles would have to have had a collisional cross-section less than $3 \times 10^{-35}/\text{cm}^2$ to explain their not being detected.

Later experiments concerning monopoles and the study of their interaction with matter further reduced the upper limits of the monopole flux (see Bauer (9), Cole (10), Ford and Wheeler (11), Bradner and Isbell (12), Purcell et al. (13), Goto et al. (14), and Katz and Butts (15). Goto et al. (14) reported a flux less than $10^{-13}/\text{cm}^2$ sec or a mass greater than 10 Gev to escape detection. The high field of a pulsed magnet was used to extract magnetic monopoles should they exist in a magnetic outcrop on the earth's surface and from fragments of a stony iron meteorite.

Schwinger (16) has suggested a new model of matter where the basic units of electric and magnetic charge are one third of the electronic charge and one third of the related magnetic charge. The fundamental particles in this model would be symmetrically charged, possessing both magnetic and electric charges. Schwinger has proposed the name dyon for such a particle. A combination of dyons could eliminate either the magnetic charge or the electric charge resulting in a pure electric or magnetic particle.

McCusker (17) has recently searched for quarks, particles with charge of one or two thirds the electron charge. Using delayed action Wilson cloud chambers in cores of extensive air showers McCusker has found five lightly ionizing tracks. Such light tracks are the signature of a particle with less then the electron charge. McCusker's observations favor a particle with a charge of two thirds the electron charge. A particle possessing just a pure electrical charge of one or two-thirds the electron charge would appear to be inconsistent with Schwinger's model as a Schwinger Dynon would produce more ionization than McCusker's quarks did.

Kolm (18) has been looking for magnetic monopoles in ocean slurry using an extracting field with four scintillators in coincidence and an emulsion to further identify the particle. Kolm found two cases of high scintillator coincidence counts with more than twice the alpha ionization rate. The very thick uniform track left in the emulsion suggests a highly charged particle. The amount of ionization seemed too large for an electrically charged particle and too small for a Dirac or a Schwinger monopole which would produce about 19,000 times the ionization per unit path length. It seems conceivable that Kolm has found either a Schwinger dyon or a magnetic quark, which would produce ionization intermediate of that for the previous two particles.

Schwinger dyons, or magnetic quarks, would produce less ionization than pure magnetic particles as they only possess one or two-thirds the magnetic charge of a pure magnetic monopole. The magnetic charge of these particles is primarily responsible for their ionization since their electric charge is small compared to their magnetic charge.

The observed low monopole flux in cosmic rays allows the possibility that heavenly bodies still possess a net magnetic charge possibly arising during the formation of these bodies. Our portion of the universe is asymmetrical with respect to matter and anti-matter, therefore it is not unreasonable to suggest an asymmetry with respect to magnetic charge. The earth is not a suitable body to observe any net charge as it possesses a strong inherent magnetic field with a complicated structure. Chapman and Bartels (19) give a detailed account of the classical complexities known about the geomagnetic field and Ness (20) reports the modern day complexities due to a magnetospheric tail formed by the solar wind-earth interaction.

The moon appears to be a more suitable object to investigate any small remnant magnetic charge as it appears to have no large inherent magnetic field (Behannon, 21). This report will discuss the theoretical effects of a net magnetic monopole charge associated with the moon on the field configuration in the lunar vicinity. Observations of the field structure that represent a search for these particles in the moon will then be presented.

Magnetic Field Structure in the Vicinity of the Moon

The structure of the magnetic field in the vicinity of a monopole rich moon would appear as a radially diverging field if the moon were imbedded in a vacuum. When not passing through the extension of the earth's magnetic field, the moon, however, is imbedded within the solar wind. This hot, tenuous plasma flows approximately radially away from the sun at the orbit of the earth and carries with it the extended solar magnetic field (Ness and Wilcox, (22). This interplanetary magnetic field is "frozen" into the highly conducting plasma and is swept past the moon at super-Alfvénic velocities. The interplanetary magnetic field is spatially uniform on the scale of lunar dimensions. The observed interaction of the interplanetary magnetic field with moon is entirely due to the absorption of solar wind plasma on the lunar surface. As yet, no inherent lunar field has been detected and few electrical conductivity effects of the moon have been observed by spacecraft observations in the lunar vicinity (Behannon, 21; Ness, 20).

A theory for the plasma and field structure behind the moon that is supported by observations of the magnetic field in the lunar vicinity has been proposed by Whang (23). Figure 1 illustrates the distortions of the magnetic field in the solar wind plasma umbral and penumbral regions behind the moon. These field line distortions results in an increase in the field strength in the umbral region and often a decrease in field strength in the penumbral regions when compared with the strength of the undisturbed interplanetary field.

The dashed lines indicate the undisturbed interplanetary field direction.

Let us temporarily neglect the interplanetary magnetic field and the field distortions caused by the plasma flow around the moon and consider only the effect of a net charge of monopoles in the moon. The field from these monopoles imbedded in the highly conductive plasma environment will obey the equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) \qquad (2)$$

from Maxwell's equations with infinite conductivity. A steady state situation would require $\frac{\partial \vec{B}}{\partial t}$ to equal zero, in which case a magnetic field parallel to the velocity field would be a solution to equation 2. The velocity field and the magnetic field parallel to the flow pattern around the moon are shown in Figure 2. The condition that the influence of magnetic monopoles be restricted to the wake region is obeyed. This condition arises from the super Alfvénic flow of the solar wind around the moon. Near the earth Alfvén waves travel at about 50 km/sec with respect to the interplanetary medium and the plasma velocity is about 400 km/sec.

The solution to the general problem may be obtained by considering the superposition of the undisturbed (or the solar wind plasma-moon interaction) solution with the monopole solution. This is not strictly valid as equation 2 is not linear. The field, however, distorts the plasma flow to only a very small extent and hence a linear superposition is a reasonable approximation.

Figure 3 (top panel) shows the undisturbed field lines as solid lines, superposed with the monopole solution shown as dashed lines. A potential solution may be employed within the moon in the absence of any conductive or intrinsic lunar magnetic field effects. Ness (20) observes the effects of sudden discontinuities in the magnetic field convected past the moon and thus concludes an electrical conductivity less than 10^{-4} mhos/meter in the lunar interior. Behannon (21) looks at observations of the magnetic field in the vicinity of the moon when the moon is located in the tail of the earth's magnetosphere and sets an upper limit of 10^{20} gauss cm^3 on the lunar magnetic moment. The superposition of these fields is shown in the bottom panel of Figure 3. The distortions of the magnetic field are confined to the wake in accordance with the super Alfvénic flow. In addition, the distortions are such that a net flux into or out of the moon occurs on any closed surface surrounding the moon as Gauss' theorm would require if applied to the magnetic divergence equation.

This solution is shown again in Figure 4, (solid lines) along with the undisturbed solution (dashed line) and the solution of the field pattern considering plasma effects (heavy dashed line). The main feature of the monopole distortion that distinguishes it from the plasma distortion is a net shift in position of the field line in the X_{SSE} direction as the lunar wake is traversed. This field line shift arises from a net flux into (or out of) the moon in accordance with Gauss' theorem applied in the magnetic case.

Experimental Observations of the Magnetic Field in the Vicinity of the Moon

The search for monopoles in the moon may then be carried out by tracking field lines across the lunar wake and seeing if there is a net shift of these field lines in the X_{SSE} direction or equivalently by integrating flux in the X_{SSE} direction. Since the field in the solar wind is variable over the time it takes the satellite to cross the lunar wake, a method for comparing the field in the wake with the field in interplanetary space must be employed. This is done utilizing simultaneous observations of the magnetic field by the earth orbiting Explorer 33 and Explorer 35. While Explorer 35 is sampling the magnetic field in the lunar wake, Explorer 33 is observing the undisturbed interplanetary field pattern. The method of comparison is shown with reference to Figure 5. A portion of the orbit of Explorer 35 on April 29, 1968 is shown. The spacecraft is in the lunar wake between 1345 UT and 1430 UT (positions 2 and 3 on the orbit). The field line behind the moon, line AD, is traced by laying the observed field vectors end to end. They are placed such that their orientation is in the direction of the magnetic field and their length is such that the field line component along the spacecraft orbit is the same as the distance the spacecraft has moved between successive field observations. This assumes the field is carried without much distortion between the spacecraft and the position the vector is placed. The field line then stops at a certain point. The process is then repeated utilizing

Explorer 33 observations of the interplanetary field for a similar time interval displaced slightly in time to account for the spatial displacement of the two spacecraft in the solar wind. Line AC results from the Explorer 33 observations. An "average" field is obtained by averaging the Explorer 35 field a half hour before and after the wake region is encountered by the spacecraft resulting in line AB. The field configuration in this case is close to being perpendicular to the sun-moon line and thus plasma distortions to the field are small. If the field line traced through the wake shows a consistent displacement in the X_{SSE} direction over a wide range of conditions, compared with the "average" field line and the Explorer 33 field line this would be evidence of a field pattern in the lunar wake similar to that which would be expected should the moon possess a net magnetic charge.

Of the 37 orbits examined, the number suggesting a positive or negative monopole are shown in Table I. The expected value and uncertainty for zero magnetic charge is 18.5 ± 6.1. Thus the first and second columns essentially show zero findings. The third column, just using interplanetary data as a check, also has equal distributions within the statistical uncertainties.

A more quantitative estimate may be obtained by integrating the flux in the X_{SSE} direction. Histograms of the distribution of the average field in the X_{SSE} direction are shown in Figure 6 for each lunar wake pass. The distributions have also been subdivided into whether B_y was positive or negative to check that plasma effects are not disturbing the distributions. Means and their standard deviations are shown by circles with error bars in the Figure. A lunar associated field source would result in a displacement of the first and second distributions but no displacement of the third. Although a slight displacement of the first two distributions is noted, it is within the associated error bars and thus no significance is attributed to it. A value of .6 $\pm$ 0.6 gamma (1 gamma is 10^{-5} Gauss) is obtained for the average B_x difference between Explorer 35 in the lunar wake and Explorer 33 in interplanetary space. Thus no statistically significant result is obtained. An upper limit on the net magnetic charge in the moon may be set, however. This limit applies to the average difference between the number of northern and southern magnetic monopoles within the moon. The total difference in the number of oppositely signed magnetic monopoles in the moon is given by $N = 4\pi n R^3/3$ where n is the average number density difference and R is the lunar radius. The amount of flux is $4\pi gN$. Hence the field strength enhancement in the X_{SSE} direction would be approximately $4gN/R^2$ or $16\pi ngR/3$. A conservative limit of 3 gamma uncertainty placed on the field throughout the lunar wake results in an upper limit of $1.6x10^{-7}cm^{-3}$ for the average net monopole density. With an average lunar density of 3.34 $gm(cm)^{-3}$, the upper limit on the difference in the number of northern and southern magnetic monopoles per nucleon is placed at $7x10^{-32}$. This analysis provides a smaller upper limit for the net magnetic charge of matter than known previously.

Acknowledgements

I am appreciative of the discussions, support, and the use of satellite observations of Dr. Norman F. Ness of the Goddard Space Flight Center. Helpful ideas and suggestions were also contributed by numerous other colleagues at Goddard Space Flight Center.

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	Explorer 35-33 Wake vs. Interplanetary Space	Explorer 35 Wake vs. Interplanetary Space	Explorer 35-33 Interplanetary Space
+ Monopole	15	13	22
- Monopole	22	24	15

Number of Lunar Wake Orbital Passes Suggesting Either a Net Positive or Negative Magnetic Charge in the Moon

TABLE I

FIGURE CAPTIONS

Figure 1 The distortions to the solar wind magnetic field and plasma in the vicinity of the moon, as viewed in the ecliptic plane. The dashed lines shown the unperturbed field and the solid lines indicate the changes that occur.

Figure 2 The solar wind plasma velocity field in the vicinity of the moon (top panel). The magnetic configuration resulting from a magnetic monopole rich moon in the absence of any interplanetary field (bottom panel).

Figure 3 The top panel shows the solutions of the pure magnetic monopole case (dashed lines) and the interplanetary magnetic field case (solid lines). The bottom panel shows the superposition of these solutions.

Figure 4 A comparison of the magnetic monopole solution (solid lines) with the plasma solution (heavy dashed lines) and the undistorted interplanetary field line (dashed line).

Figure 5 Magnetic field line traced in the lunar wake on April 29, 1969. Line AD represents the field in the wake of the moon; line AC, the unperturbed interplanetary field, and line AB, the "average" field a half hour on either side of the wake. A consistent displacement of line AD in the X_{SSE} direction with respect to lines AC and AB would be indicative of a lunar associated magnetic field source.

Figure 6 Histograms of the average Bx difference between Explorer 35 in the lunar wake and Explorer 33 in interplanetary space (top panel), Explorer 35 in the lunar wake and in interplanetary space (middle panel), and Explorers 35 and 33 in interplanetary space (bottom panel). A lunar associated field source would be indicated by constant displacement of the first and second distributions but no displacement of the third. The mean and standard deviations of the distributions are shown by circles with error bars.

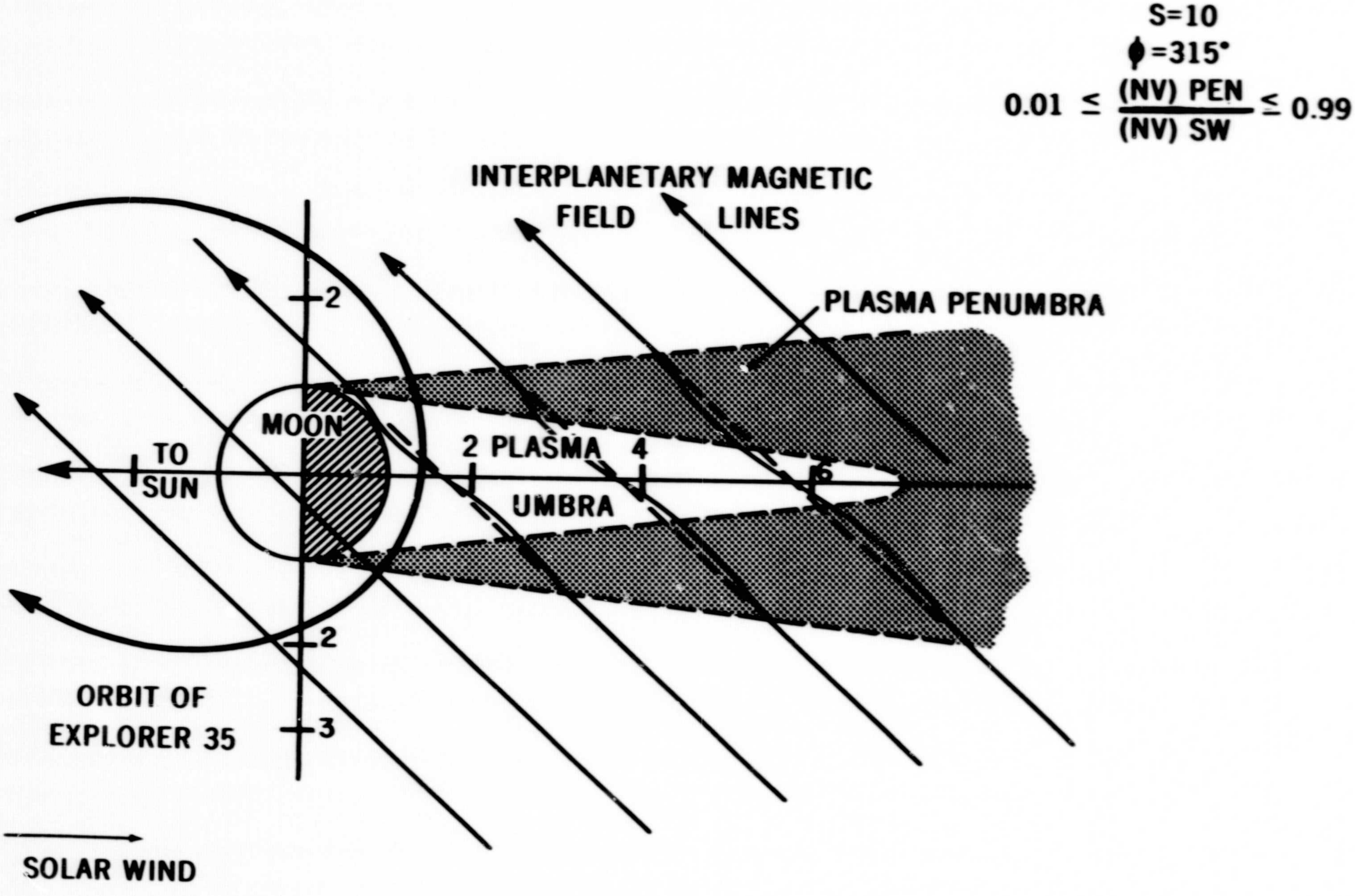

S=10
ϕ=315°
$0.01 \leq \frac{(NV)\ PEN}{(NV)\ SW} \leq 0.99$
INTERPLANETARY MAGNETIC FIELD LINES
PLASMA PENUMBRA
MOON
TO SUN
2 PLASMA
4
UMBRA
6
2
2
3
ORBIT OF EXPLORER 35
SOLAR WIND

FIGURE 1

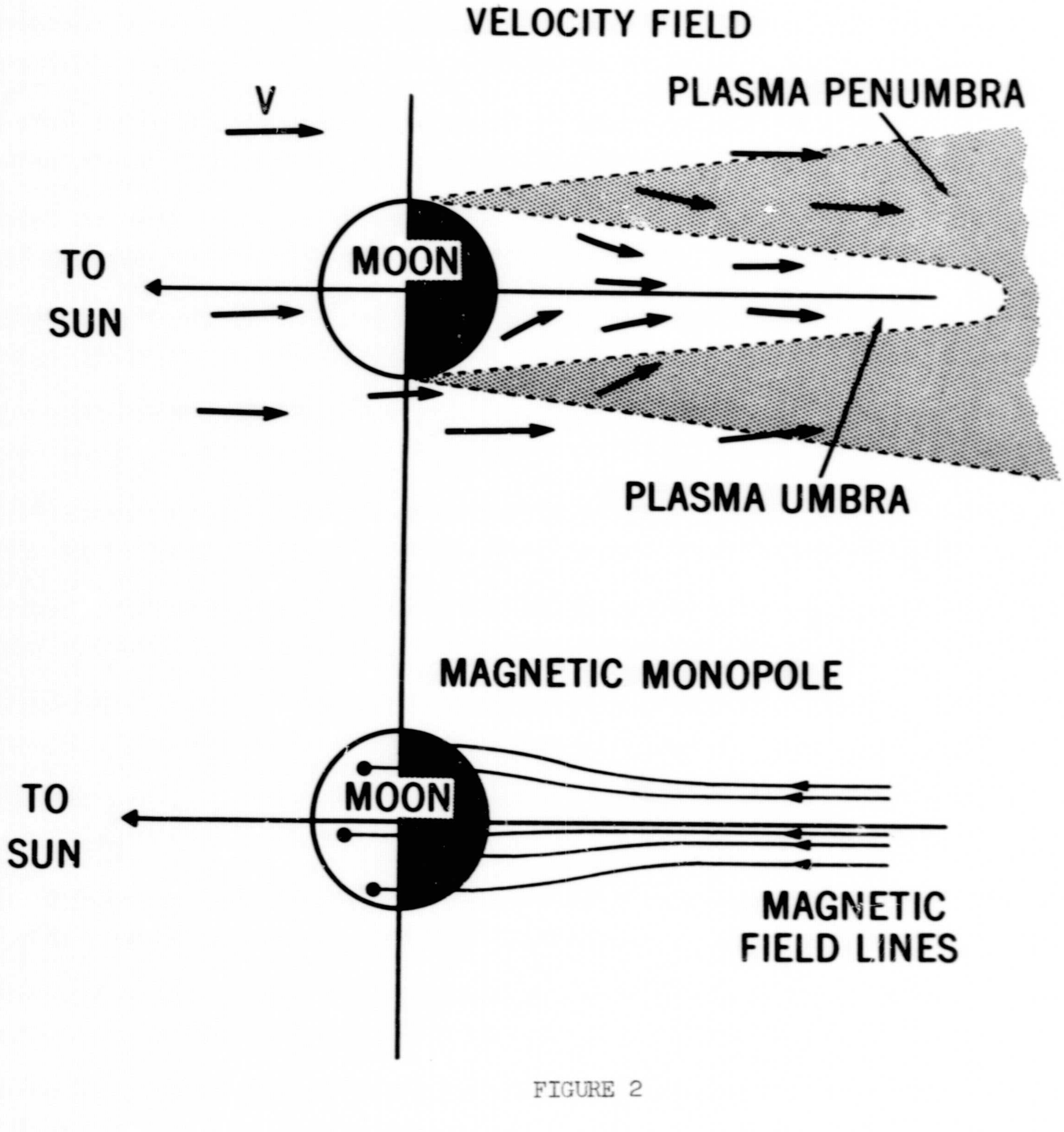

VELOCITY FIELD
V
PLASMA PENUMBRA
TO
SUN
MOON
PLASMA UMBRA
MAGNETIC MONOPOLE
TO
SUN
MOON
MAGNETIC
FIELD LINES

FIGURE 2

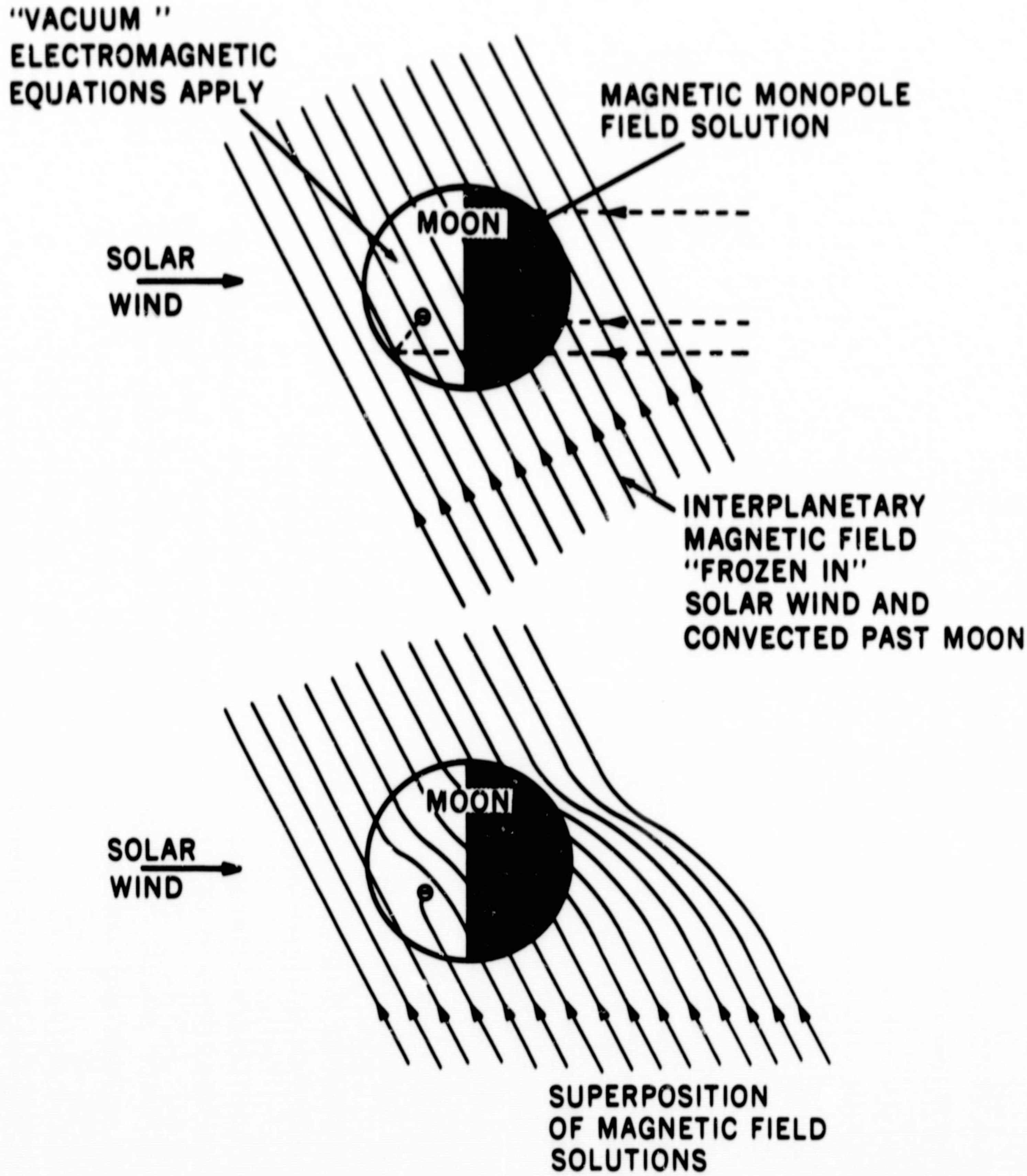

"VACUUM "
ELECTROMAGNETIC
EQUATIONS APPLY
MAGNETIC MONOPOLE
FIELD SOLUTION
MOON
SOLAR
WIND
INTERPLANETARY
MAGNETIC FIELD
"FROZEN IN"
SOLAR WIND AND
CONVECTED PAST MOON
MOON
SOLAR
WIND
SUPERPOSITION
OF MAGNETIC FIELD
SOLUTIONS

FIGURE 3

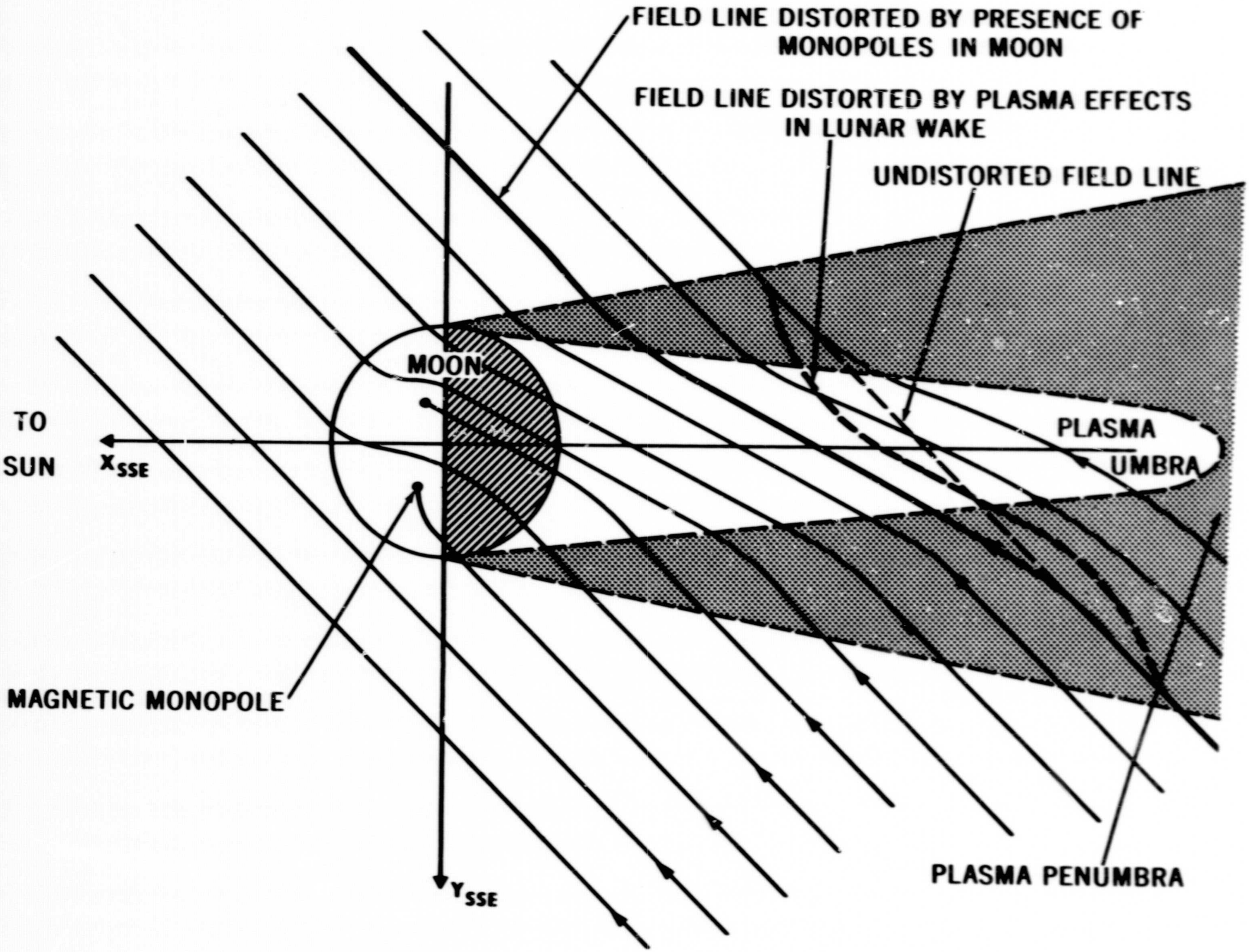
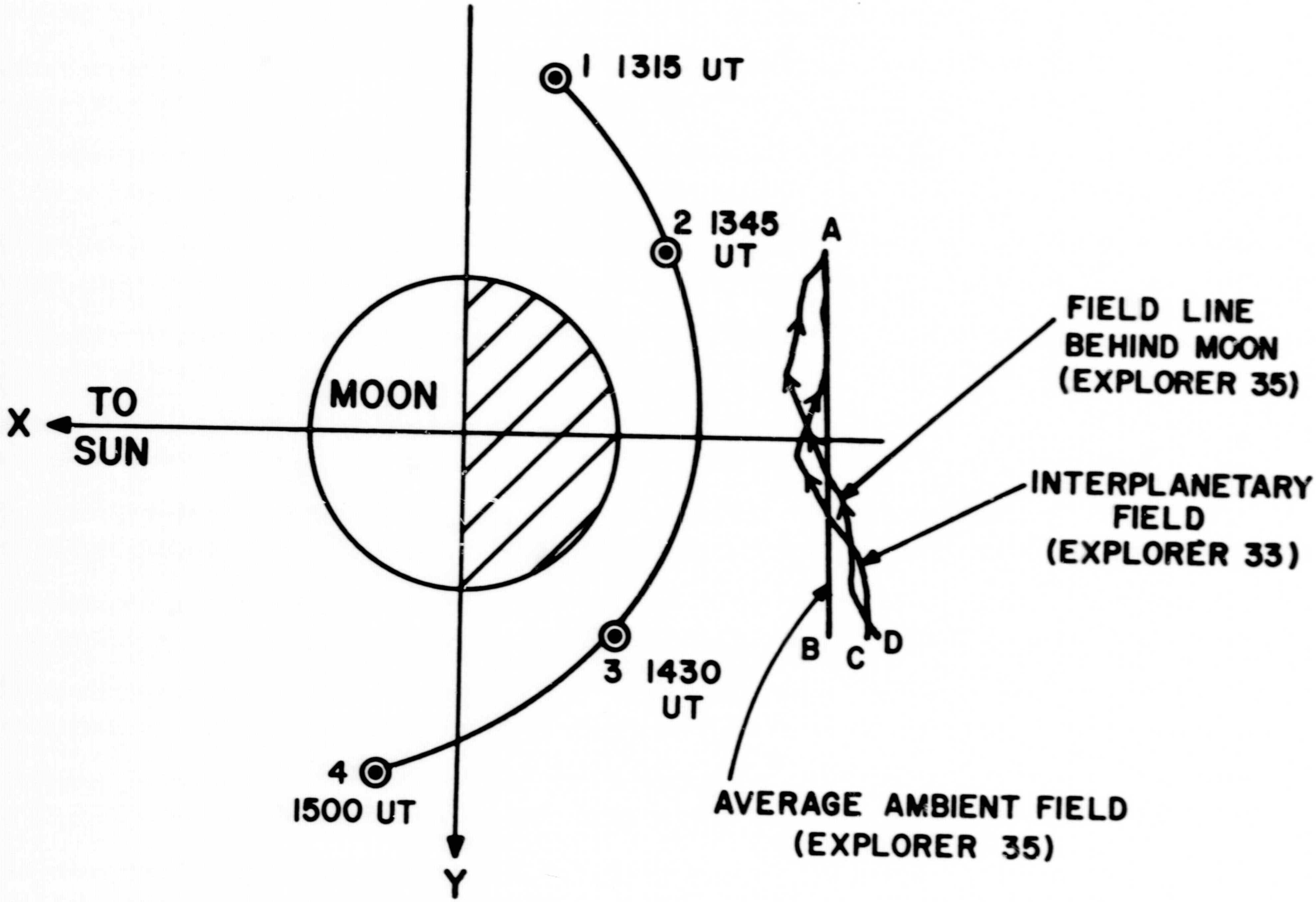

FIELD LINE DISTORTED BY PRESENCE OF MONOPOLES IN MOON
FIELD LINE DISTORTED BY PLASMA EFFECTS IN LUNAR WAKE
UNDISTORTED FIELD LINE
MOON
TO SUN
X_{SSE}
PLASMA UMBRA
MAGNETIC MONOPOLE
PLASMA PENUMBRA
Y_{SSE}

FIGURE 4

APRIL 29, 1968



FIELD LINE TRACE IN LUNAR WAKE

FIGURE 5

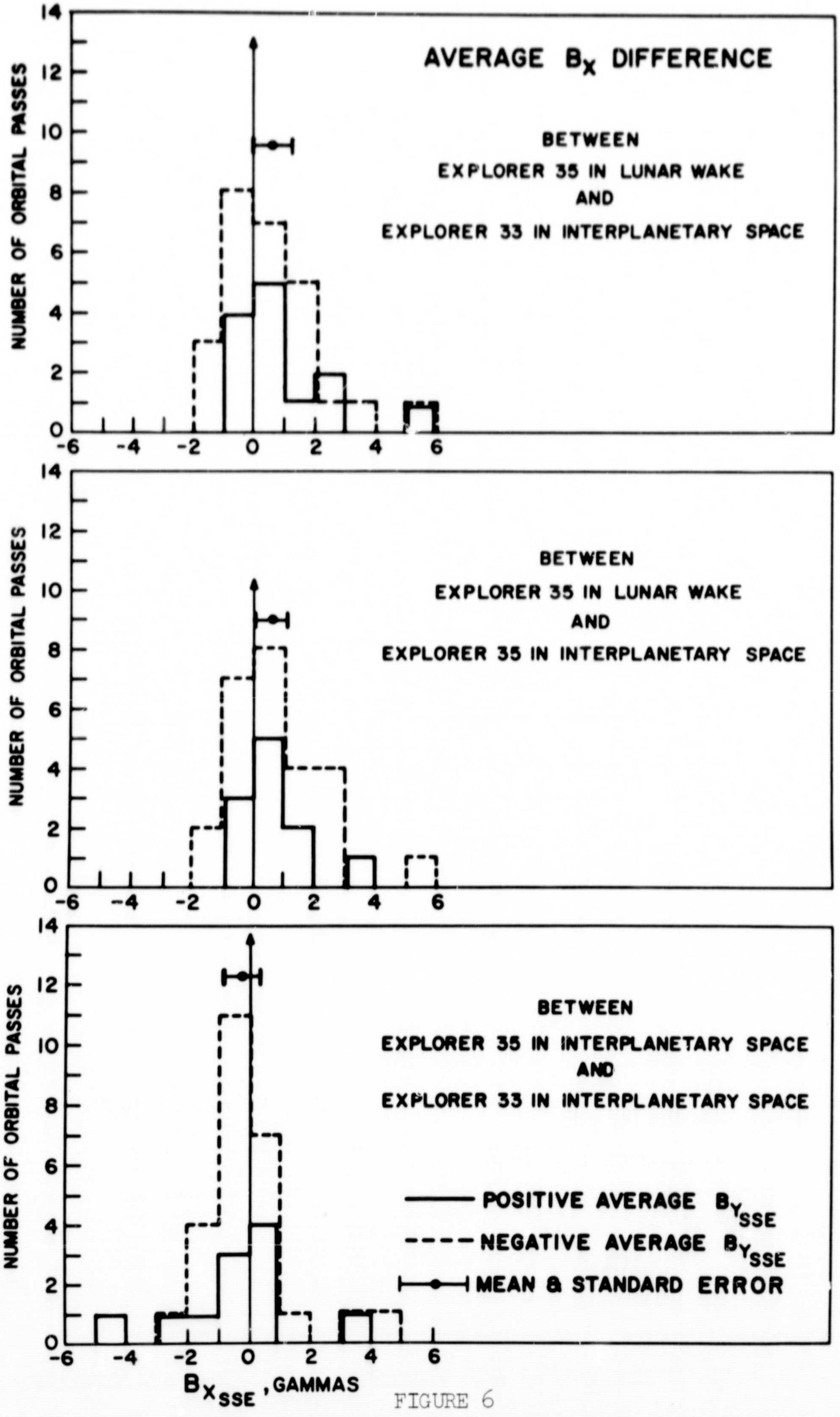

AVERAGE B_X DIFFERENCE
BETWEEN
EXPLORER 35 IN LUNAR WAKE
AND
EXPLORER 33 IN INTERPLANETARY SPACE
BETWEEN
EXPLORER 35 IN LUNAR WAKE
AND
EXPLORER 35 IN INTERPLANETARY SPACE
BETWEEN
EXPLORER 35 IN INTERPLANETARY SPACE
AND
EXPLORER 33 IN INTERPLANETARY SPACE
POSITIVE AVERAGE $B_{Y_{SSE}}$
NEGATIVE AVERAGE $B_{Y_{SSE}}$
MEAN & STANDARD ERROR
NUMBER OF ORBITAL PASSES
$B_{X_{SSE}}$, GAMMAS
0
2
4
6
8
10
12
14
-6
-4
-2
0
2
4
6

FIGURE 6