1 up

X-693-73-90

NASA TM X- 66226

PROPAGATION PATTERN OF INTERPLANETARY SHOCK WAVES ASSOCIATED WITH SOLAR PROTON FLARES

KUNITOMO SAKURAI

APRIL 1973

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

(NASA-TM-X-66226) PROPAGATION PATTERN OF INTERPLANETARY SHOCK WAVES ASSOCIATED WITH SOLAR PROTON FLARES (NASA) 24 p HC $3.25 CSCL 03B

N73-21704

Unclas
G3/29 69012

23

PROPAGATION PATTERN OF INTERPLANETARY SHOCK WAVES ASSOCIATED WITH SOLAR PROTON FLARES

Kunitomo Sakurai*
Radio Astronomy Branch
Laboratory for Extraterrestrial Physics
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

ABSTRACT

The two dimensional pattern of interplanetary shock waves are deduced by taking into account the solar longitude dependence of the time intervals between SSC geomagnetic storms and responsible flares. This pattern near the earth's orbit is not symmetric with respect to the meridian plane which crosses the position of the flare, and the highest speed of this wave propagation is observed in the direction about 30 degrees east of this meridian plane. The magnitude of the Forbush decreases of galactic cosmic rays also varies with the longitude positions of those flares. This is used to estimate the distribution of magnetic fields behind the shock waves.

The propagation pattern deduced above coincides with the expanding pattern of magnetic bottles which are the sources of moving type IV radio bursts. Discussion is given on the relationship between the interplanetary shock waves and these magnetic bottles.

*NASA Associate with University of Maryland, Astronomy Program

1. Introduction

Wide-band type IV radio bursts are usually associated with solar proton flares (e.g., Obayashi, 1964; Sakurai, 1973a). These flares are also accompanied by type II radio bursts which precede moving type IV bursts in metric frequencies. These type II bursts are, moreover, usually followed by SSC geomagnetic storms. The relationships between type II bursts and these storms have been statistically investigated (e.g., Maeda et al., 1962; Akasofu and Yoshida, 1967). Hirshberg (1968) has studied the propagation pattern of interplanetary shock waves. Recently, the shape of these waves has been estimated by using satellite data (e.g., Taylor, 1969; Landt and Croft, 1970; Chao and Lepping, 1972). Furthermore, this shape has been theoretically investigated by de Young and Hundhausen (1971) and Hundhausen (1972). In this case, however, they assumed that there is no magnetic field in interplanetary space, and neglected the solar rotation.

In this paper, to estimate a shape of interplanetary shock wave, we shall first analyze the time delays from solar flares to SSC geomagnetic storms and the Forbush decrease of galactic cosmic rays as a function of the longitude positions of the flares on the solar disk, and then estimate the shape of the shock wave near the earth's orbit. Relationship between this shape and the expanding magnetic bottles associated with moving type IV bursts near the sun will be investigated by taking into account the influence of the interplanetary magnetic field.

2. Solar Longitude Dependence of Some Characteristics of Interplanetary Shock Waves Associated with Proton Flares

The time intervals between solar flares and SSC geomagnetic storms have been examined as a function of the longitude positions of the flares on the solar disk. In this analysis, we have used the observed data for 125 proton flares during 1956 - 1967 (see, Maeda et al., 1962; Jonah et al., 1965; Obayashi et al., 1967; Hakura, 1968). These time intervals seem to give an information for the propagation speed of interplanetary shock waves dependent on the flare positions over the solar disk*. These time intervals are shown in

*It is known that the magnitude of the geomagnetic horizontal component increase during the sudden commencement is useful to study the relationship between flare positions and the propagation speed of shock waves (Hirshberg, 1968). However, these magnetic data have not been considered in this paper, because enough data were not available.

Fig. 1 with respect to the longitude positions of associated flares. In this figure, an envelope for the shortest time intervals is indicated by a chain line. The minimum interval is seen about 30 degrees west of the central meridian of the solar disk. Using the result shown in Fig. 1, we have estimated the mean time intervals for the propagation of interplanetary shock waves as a function of the solar longitude (Fig. 2). These mean time intervals will be used to estimate the mean speed of the interplanetary shock waves during their propagation between the sun and the earth.

During 23 October to 4 November, 1968, the active region McMath No. 9740 passed over the solar disk. This region was quite active for the production of type IV radio bursts and solar cosmic rays (e.g., Lincoln, 1970; Sakurai, 1973b). As reported by Barallio (1970), solar flares, which occurred in this active region during the above period, produced ten times SSC geomagnetic storms. The time intervals between associated flares and these storms have been examined as a function of the longitude positions of these flares (Fig. 3). This figure also shows that the minimum time interval was observed while this active region was about 40 degrees west of the central meridian. It may be said, therefore, that the result shown in Fig. 3 is consistent with the statistical results shown in Figs. 1 and 2.

Using the mean time intervals shown in Fig. 2, we have estimated the angular distribution of the mean speed of the shock waves with respect to the position of a typical flare (Fig. 4). This indicates that these shock waves do not propagate isotropically in interplanetary space and that the highest speed ($\simeq$ 1200 Km sec^{-1}) is observed in the direction about 30 degrees east of the meridian plane which crosses the flare region. We do not know, however, what mechanism produces a propagation pattern of the shock waves, as shown in Fig. 4. This mechanism may be related to some characteristics of an associated flare or to the distribution of the interplanetary magnetic field along the propagation path.

To examine the influence of the interplanetary magnetic field on the propagation of these waves, we have analyzed the relationship between the Forbush decrease of galactic cosmic rays and associated flares. Fig. 5 shows that the magnitude of the Forbush decreases becomes larger as the flare position moves eastwards from the west limb over the solar disk. As discussed by Sinno (1962) and Sakurai (1965), this dependence of the Forbush decrease may be explained by taking into account the deformation of the interplanetary magnetic field by the shock waves. The result shown in Fig. 5 suggests that the west side of the shock waves is higher in the intensity of magnetic field than that for the east side. This may be a result of the formation of the wave pattern, as shown in Fig. 4, because the increase of magnetic intensity must have been produced as a result of the compression of the interplanetary magnetic field by the shock waves. Therefore, the original shape of interplanetary shock waves just after emission by flares may not necessarily be equal to that shown in Fig. 4.

3. Shape of Interplanetary Shock Waves near the Earth's Orbit

The shape of interplanetary shock waves near the earth's orbit has been investigated by Hirshberg (1968), Taylor (1969) and Chao and Lepping (1972). Their results show that the shape of these shock waves is not spherical, but symmetric with respect to the meridian plane which crosses the position of an associated flare. In our analysis, however, this shape is deformed from a spherical form (Fig. 4).

In the case of the 8 July 1966 storm event, the data obtained by the Pioneer 6 and IMP-3 spacecrafts for magnetic and cosmic ray measurements are useful for estimating the shape of the shock waves associated with a flare on 7 July (Ness and Taylor, 1969; Rao et al., 1969; Lazarus and Binsack, 1969). When this event occurred, the Pioneer 6 spacecraft was at a distance of approximately 0.8 A.U. from the sun and the spacecraft-sun-earth angle was about 45 degrees as shown in Fig. 6. Taylor (1969) has determined the direction of the shock front at the earth's position in this event. Based on the magnetic field measurement by the two spacecrafts, Ness and Taylor (1969) have shown that the shape of this shock front was not spherical with respect to the position of the responsible flare (see Fig. 6). The observation by Landt et al. (1970) supports this conclusion by Ness et al. (1969). The cosmic ray observations also suggest a non-spherical expansion of the shock wave in this event (Fig. 6) (Rao et al., 1969). Although the onset time of the Forbush decrease was not equal to that of the passage of the shock front, the deduced patterns of the expanding shock waves are similar between them, as shown in Fig. 6. The propagation pattern of the shock waves associated with this event is, therefore, consistent with the results obtained statistically in the last section.

A non-spherical expansion of the shock waves may be related to the action of the interplanetary magnetic field. As shown by Dulk et al. (1971), these shock waves tend to propagate along the magnetic lines of force near and above the regions where responsible flares occur. This suggests that, on average, these waves also tend to propagate along the magnetic lines of force in interplanetary space. If this is the case, it is said that the observed shape of the shock waves forms partly because of an anisotropic propagation of these waves into interplanetary space.

The dependence of the Forbush decreases on the longitude positions of associated flares may be explained by taking into account the propagation pattern of the shock waves near the earth. Shock waves crossing magnetic field lines tend to strengthen the field intensity behind these waves (e.g., Ferraro and Plumpton, 1966). When a flare occurs on the eastern hemisphere of the sun, say 45 degrees east, an associatedshock wave to be observed at the earth must propagate across the magnetic field ambient in interplanetary space. This type of propagation may be effective for intensification of the magnetic field behind the shock wave. This explanation may be applied to the result shown in Fig. 5.

4. Relation to Solar Radio Events Associated with Proton Flares

Radio bursts of spectral type II and IV are generally associated with proton flares. In order to obtain information for the movement of radio sources for these bursts, we have analyzed the onset time differences between the microwave and metric components of type IV radio bursts associated with flares which produced SSC geomagnetic storms. These differences are shown in Fig. 7 as a function of the longitude positions of associated flares (Sakurai, 1973c). In this figure, the mean time differences are indicated by a thick solid line.

Since these two component of the bursts are emitted by gyro-synchrotron mechanism from mildly relativistic electrons due to their interaction with sunspot magnetic fields ambient in the flare regions, the result shown in

Fig. 7 is useful to estimate the movement of radio sources for these bursts (Sakurai, 1970, 1973c). Because these electrons seem to be trapped by sunspot magnetic field lines near and above the flare regions, the shape of the radio sources may be identified as magnetic bottles. Taking into account the time differences shown in Fig. 7, Sakurai (1973c) has suggested that the magnetic bottle tends to expand a few ten degrees east of the meridian plane which crosses the flare region. From this consideration, an expanding pattern of the magnetic bottle has been deduced as shown in Fig. 8. This type of bottles would be sometimes ejected into interplanetary space, as suggested by Gold (1959).

As shown by Dulk et al. (1971) and Smerd et al. (1971), this expanding pattern is slightly different from the propagation pattern of the shock waves exciting type II bursts. It, however, seems likely that this expanding pattern forms under the influence of the magnetic fields ambient in and around the flare region. The difference of the patterns between the magnetic bottle expansion and the shock propagation may be explained by taking into account the path of the propagation of shock waves, near the flare region, which excite type II bursts: that is, these shock waves mainly tend to propagate along the magnetic field lines extending into interplanetary space (e.g., Dulk et al., 1971). Taking into account this propagation characteristic, we here propose a model that interplanetary shock waves propagate mainly along the magnetic field lines in interplanetary space. This can explain the results shown in Figs. 2 and 4. It seems, however, that the magnetic bottles do not follow behind the shock waves in interplanetary space (Sakurai and Chao, 1973) because the expanding pattern of the former is different from that of the latter (see Figs. 4 and 8).

5. Conclusion

Using the dependence on the solar longitude of the time intervals between SSC geomagnetic storms and responsible flares, the shape and the propagation pattern of interplanetary shock waves near the earth's orbit have been deduced. The shape of these waves is not spherically symmetric with respect to the position of an associated flare, although a deduction of this shape is limited in the two dimensional plane in which both the sun and the earth are located. Associated Forbush decreases of cosmic rays also depend on the longitude positions of responsible flares on the solar disk. This may give a clue to estimate the distribution of magnetic field behind the shock fronts in interplanetary space.

These shock waves are usually emitted by solar flares which are accompanied by radio bursts of spectral type II and IV. Initial stage of the development of a moving type IV burst in metric frequency is dependent on the longitudinal position of an associated flare (Fig. 7). This suggests that the expansion of magnetic bottles which trap mildly relativistic electrons responsible for these bursts is not isotropic. An expanding pattern thus estimated qualitatively coincides with the propagation pattern of interplanetary shock waves.

Acknowledgement

I wish to thank Drs. R.P. Lepping and J.K. Chao for their helpful suggestions on this work.

References

Akasofu, S.-I. and Yoshida, S.: 1967, Planet. Space Sci. 15, 39.

Ballario, M.C.: 1970, WDC A, UAG-8, Part II, 231.

Chao, J.K. and Lepping, R.P.: 1972, A correlative study of SSC's, interplanetary shocks, and solar activity, presented to the Conference on Interplanetary Shock Waves, August 1972, Boulder, Colorado.

De Young, D.S. and Hundhausen, A.J.: 1971, J. Geophys. Res. 76, 2245.

Dulk, G.A., Altschuler, M.D. and Smerd, S.F.: 1971, Astrophys. Letters 8, 235.

Ferraro, V.C.A. and Plumpton, C.: 1966, Introduction to Magnetofluid Dynamics, Oxford, Oxford.

Gold, T.: 1959, J. Geophys. Res. 64, 1665.

Hakura, Y.: 1968, NASA, Goddard Space Flight Center, Rep. X-641-68-62.

Hirshberg, J.: 1968, Planet. Space Sci. 16, 309.

Hundhausen, A.J.: 1972, in: C.P. Sonett et al. (eds), Solar Wind, NASA SP-308, p. 393.

Jonah, F.C., Dodson-Prince, H. and Hedeman, E.R.: 1965, NASA, Manned Spacecraft Center, Rep. No. 00538.

Landt, J.A. and Croft, T.A.: 1970, J. Geophys. Res. 75, 4623.

Lazarus, A.J. and Binsack, J.H.: 1969, Ann. of IQSY 3, 378.

Lincoln, V.: 1970, W.D.C. A Rep. UAG-8, p.2.

Maeda, H., Sakurai, K., Ondoh, T. and Yamamoto, M.: 1962, Ann. d'Geophys. 18, 305.

Ness, N.F. and Taylor, H.E.: 1969, Ann. of IQSY 3, 366.

Obayashi, T.: 1964, Planet. Space Sci. 12, 463.

Obayashi, T., Sakurai, K., Hakura, Y., Nishida, A., Kai, K., Yoshida, S., Wada, M. and Yamamoto, M.: 1967, Table of Solar Geophysical Events, Jan. 1957 - Dec. 1963, Kyoto Univ., Kyoto.

Rao, U.R., McCracken, K.G. and Bukata, R.P.: 1969, Ann. of IQSY 3, 329.

Sakurai, K.: 1965, Planet. Space Sci. 13, 745.

Sakurai, K.: 1970, Planet. Space Sci. 18, 33.

Sakurai, K.: 1973a, Physics of Solar Cosmic Rays (In press).

Sakurai, K.: 1973b, Planet. Space Sci. 21, 23.

Sakurai, K.: 1973c, to be submitted to Nature.

Sakurai, K. and Chao, J.K.: 1973, to be published.

Sinno, K.: 1962, J. Phys. Soc. Japan, 17, Suppl. A-II, 395.

Smerd, S.F. and Dulk, G.A.: 1971, in: R. Howard (ed), Solar Magnetic Fields, D. Reidel, Dordrecht, p. 616.

Taylor, H.E.: 1969, Solar Phys. 6, 320.

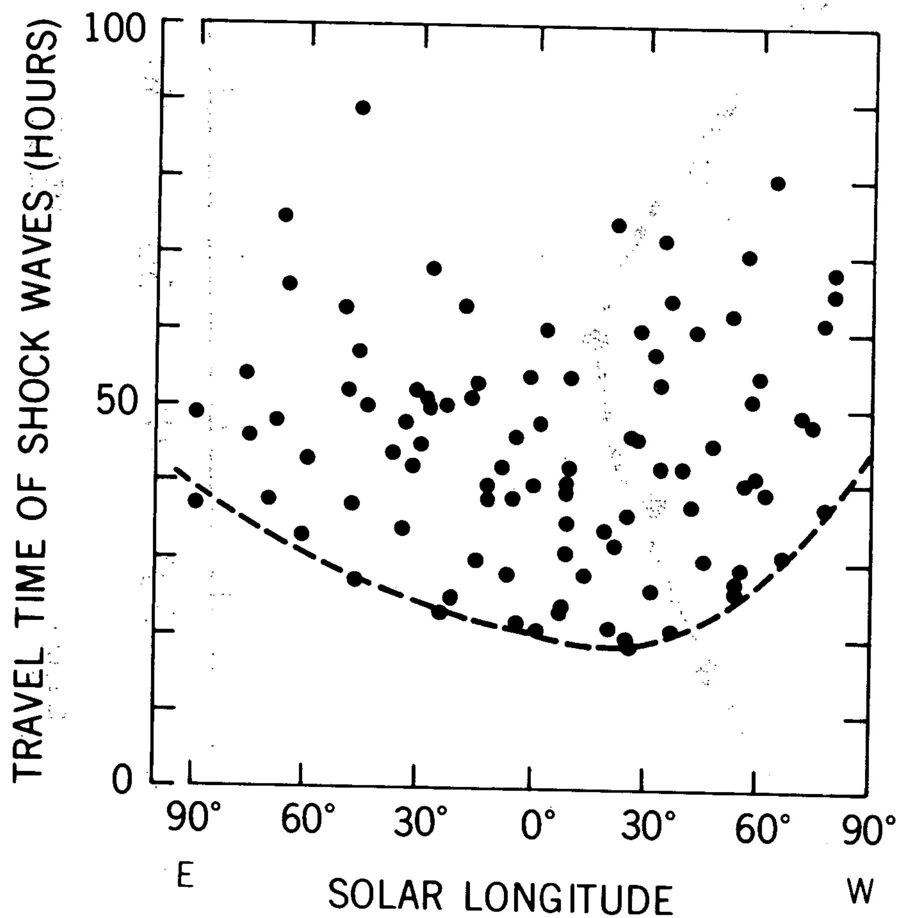

Fig. 1. - Distribution of the time delays from solar flares to SSC geomagnetic storms with respect to the longitude positions of flares. A chain line indicates the envelope for the shortest time delays.

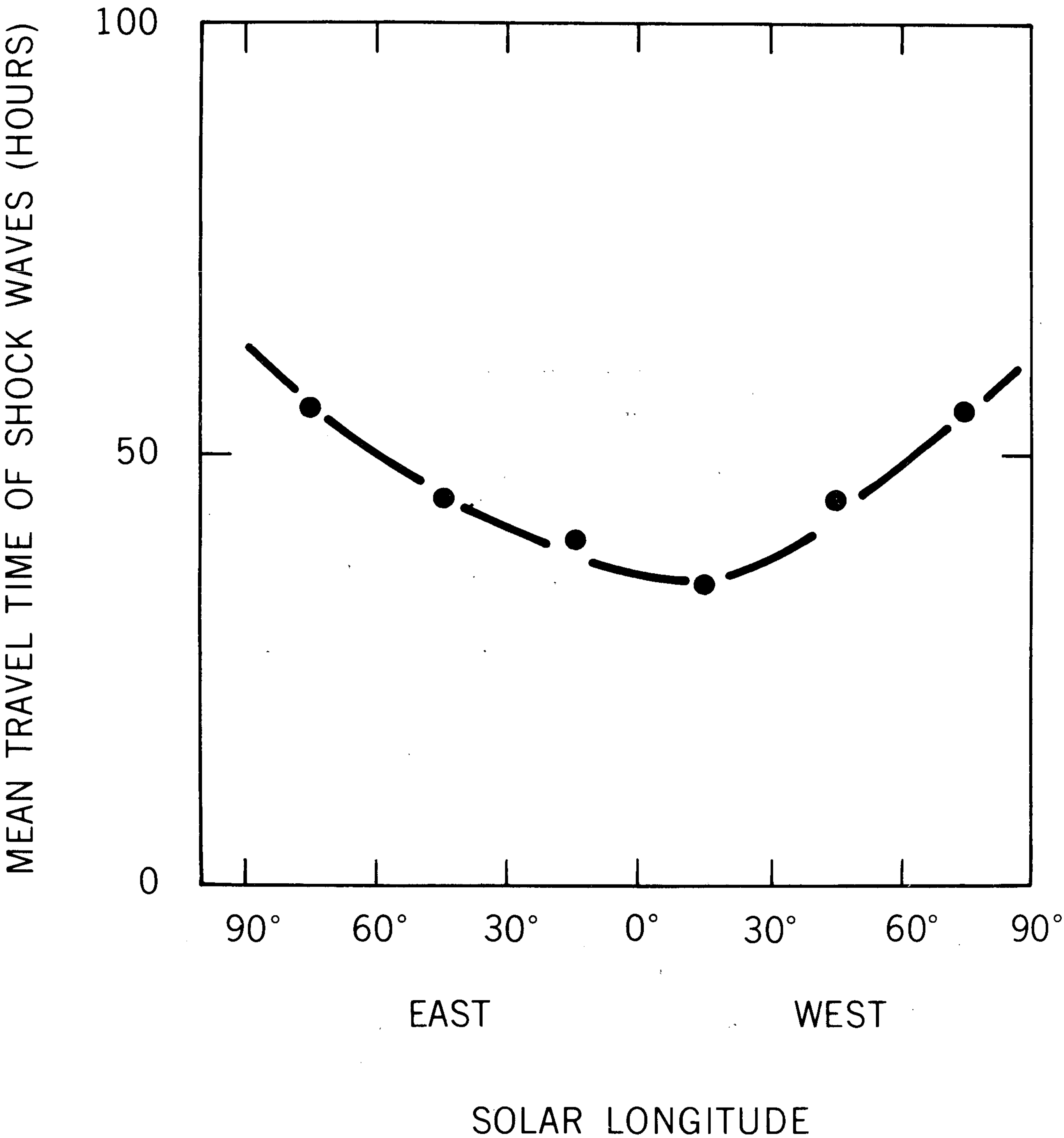

Fig. 2. - The mean time delays as a function of the longitude positions of responsible flares.

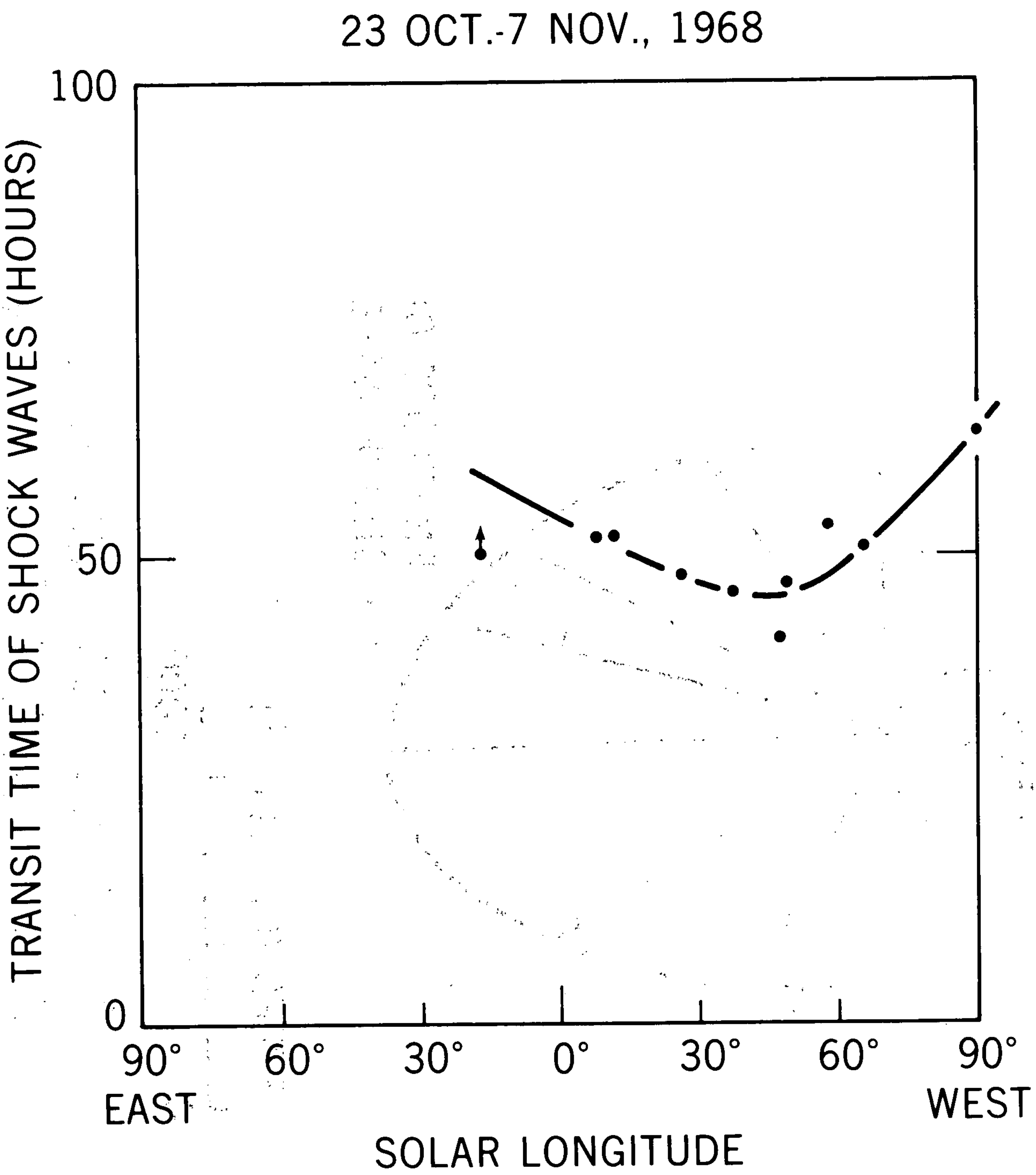

Fig. 3. - The time delays observed during the passage of the active region McMath No. 9740 between 29 October and 4 November, 1968.

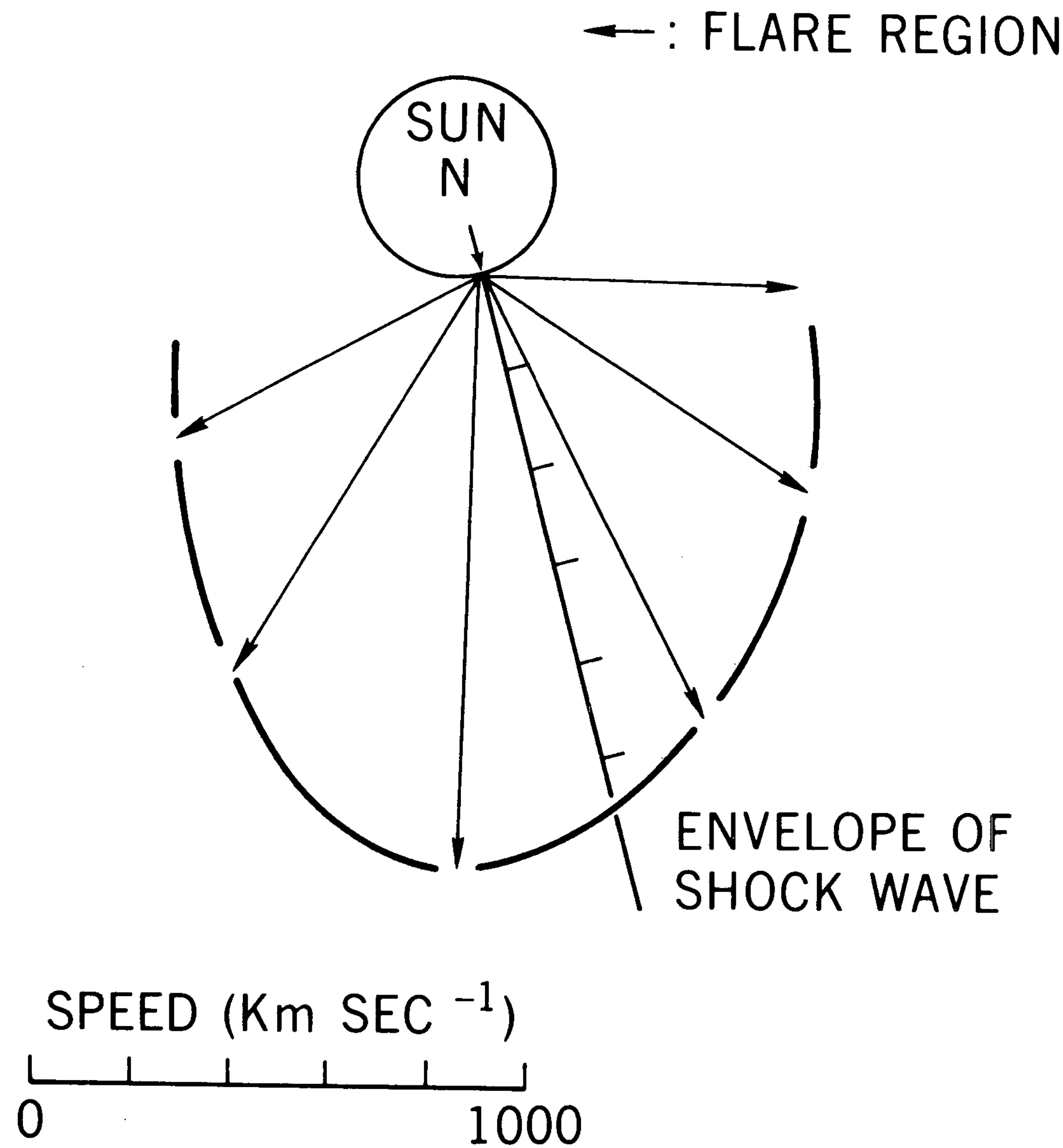

Fig. 4. - Mean expansion speeds of interplanetary shock waves which are dependent on the observing direction to the flare region from the earth. These speeds have been derived using the result shown in Fig. 2.

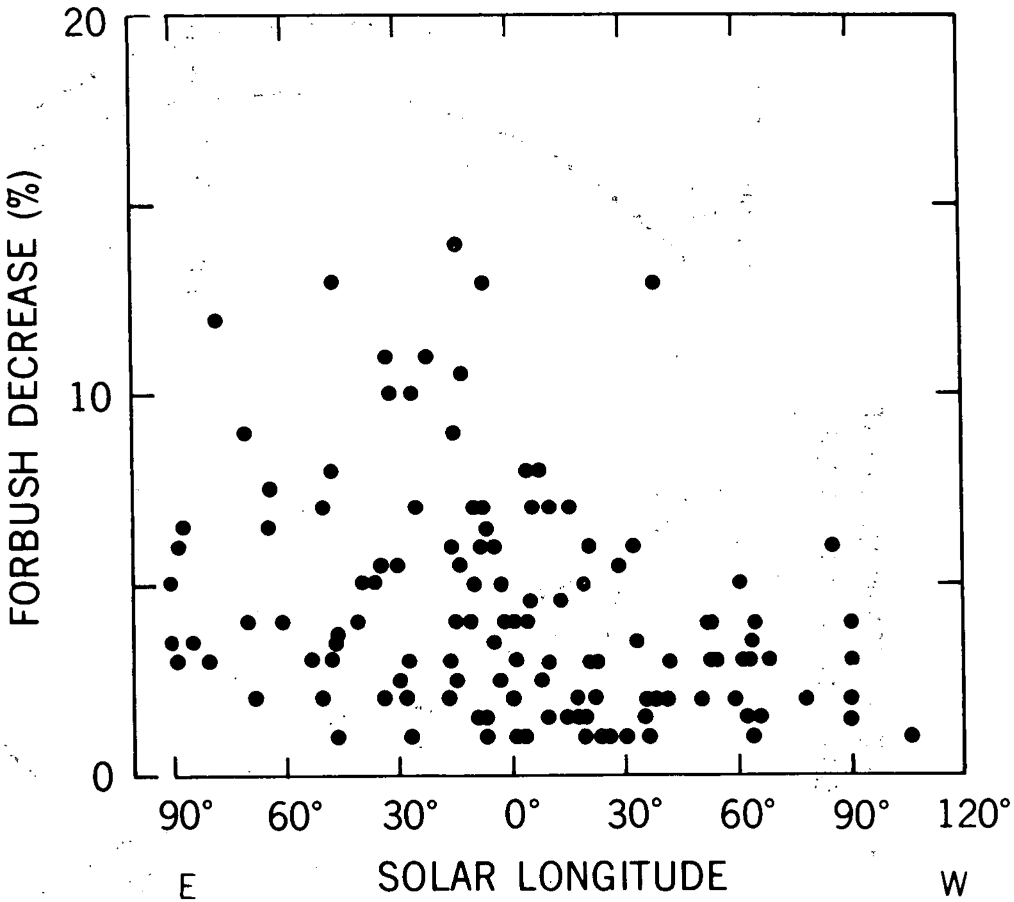

Fig. 5. - Distribution of the Forbush decrease of galactic cosmic ray intensity with respect to the longitude positions of responsible flares.

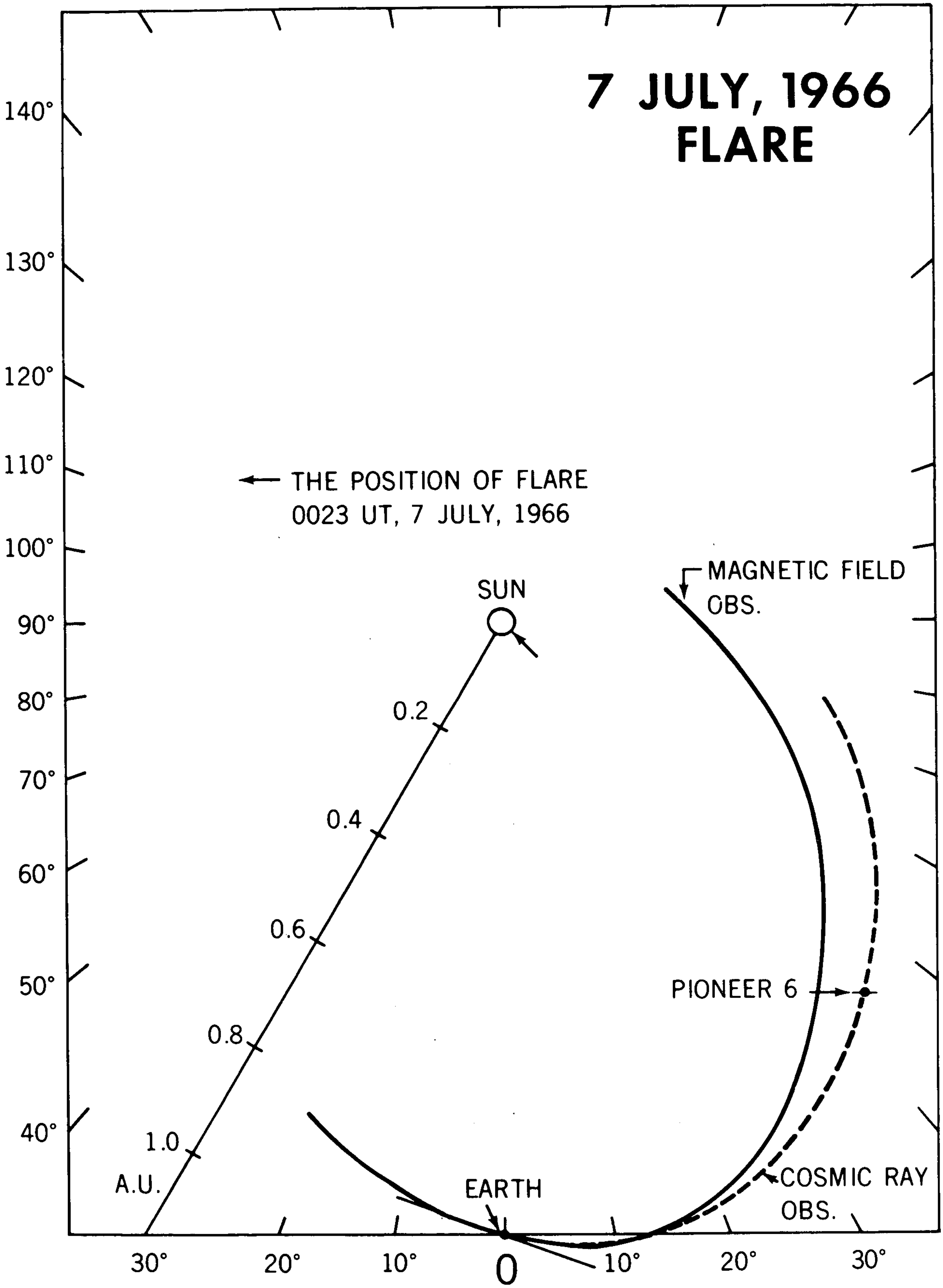

Fig. 6. - Estimated shapes of the interplanetary shock wave associated with a flare on 7 July 1966. Solid line: magnetic field observation. Chain line: cosmic ray observation.

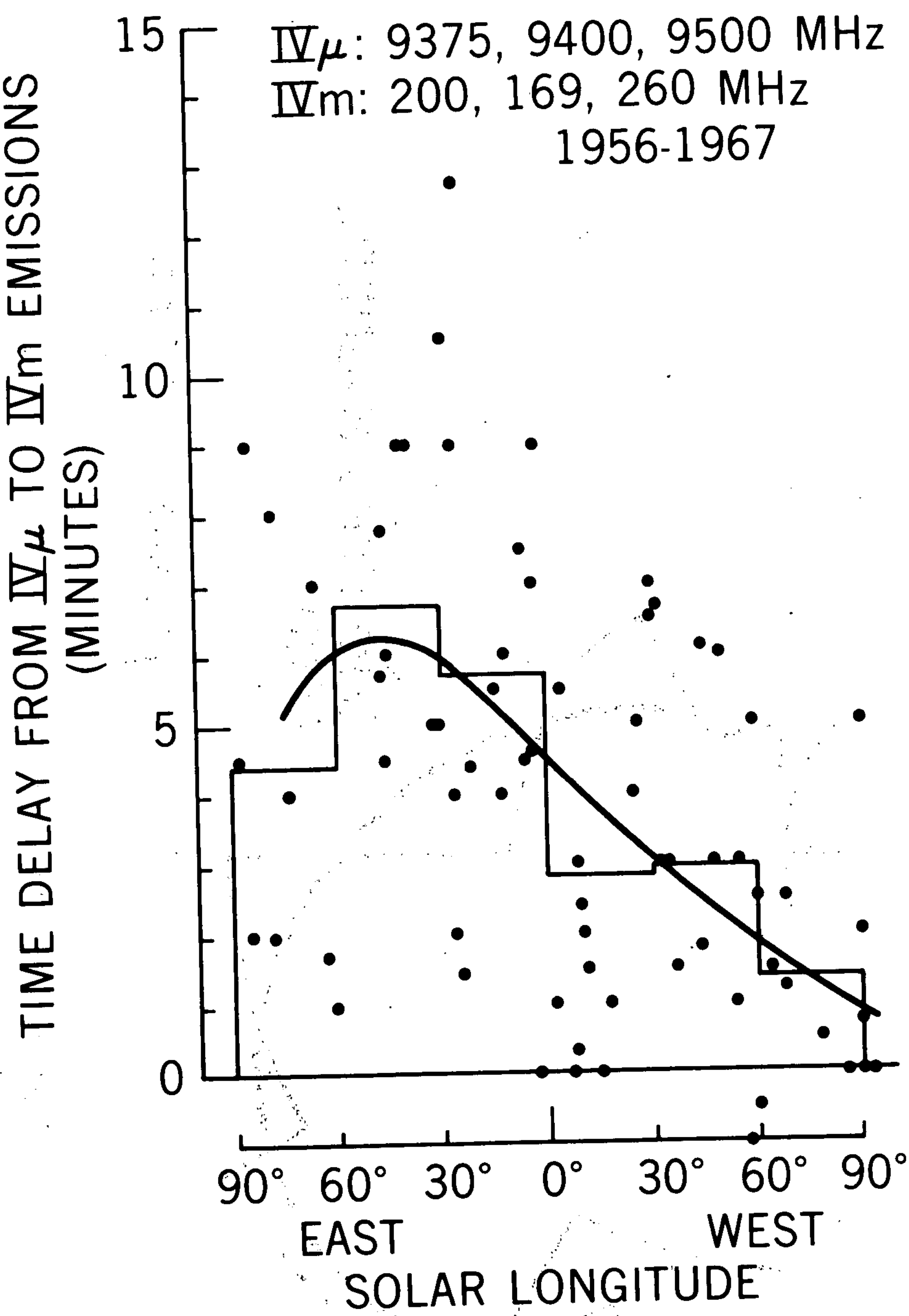

Fig. 7. - Onset time intervals between the microwave and the metric emissions of type IV radio bursts with respect to the longitude positions of responsible flares. Solid lines indicate the mean time intervals.

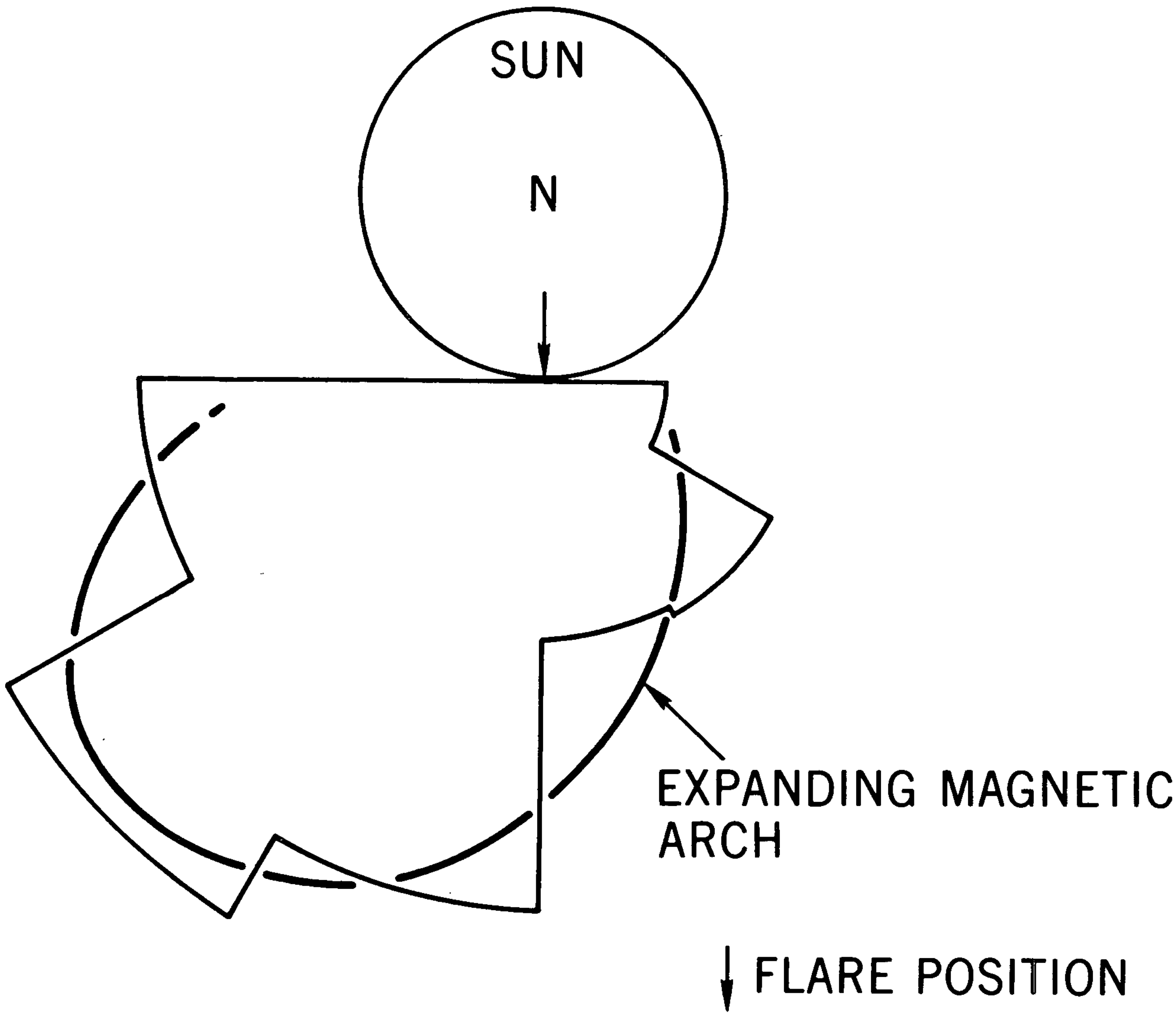

Fig. 8. - Expanding pattern of a magnetic bottle estimated from the result in Fig. 7. This shows an arch-like structure for magnetic field lines.

* U.S. GOVERNMENT PRINTING OFFICE: 1972-735-968/648