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INTERPLANETARY SHOCK WAVES ASSOCIATED WITH SOLAR FLARES
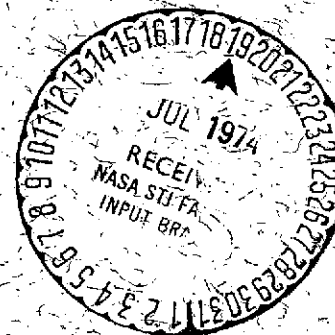
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The earth, on which we are living, is immersed in the hot
ionized gas continuously flowing out of the sun. This gas
flow, now called the solar wind, varies with the solar
activity. The average speed, temperature and plasma density
of this wind near the earth's orbit are 400 kilometers a
second, 100,000 degrees Kelvin and 6 particles a cubic centi-
meter, respectively.

This hot gas flow, however, does not directly reach
the atmosphere nor the surface of the earth because the
earth's magnetic field, called the geomagnetic field, plays
a role as a barrier preventing this gas from reaching this
surface and its very environs. Since this ionized gas is
stopped by the geomagnetic field, a cavity free from this
gas forms around the earth. At present, this cavity is
called the magnetosphere, and its size is about 10-15 earth's
radii on the sunlit side. The magnetosphere in the night
side extends far out to several tens or more of earth's
radius like the tail of comets.

The geomagnetic field is sometimes disturbed by the
change of the property of the solar wind. This change is
generated by disturbances associated with the solar activity.

Solar flares are currently described as the sudden brightening of an optically visible emission called the hydrogen Balmer alpha line, the wavelength of which is 6563 Angstrom (red in color). These flares, which are often called the "Hα-flares", occur in actively changing sunspot groups on the solar surface.

Two or three days after these flares, the geomagnetic field is sometimes highly agitated (Fig. 1). This phenomenon is now called "geomagnetic storm". During this storm, aurorae are often seen in the high latitude regions, both north and south, and world-wide disturbances are observed in the ionospheric F2 regions. These disturbances gradually fade away about a week or so.

The occurrence of these storms was first explained by considering some agents such as ionized gas clouds or corpuscular streams which were ejected from the flare regions. It was thought that geomagnetic storms started simultaneously with the arrival of these clouds or streams at the earth.

At present, it is thought that the sudden commencement of a geomagnetic storm (SSC) begins with the arrival of the

shock wave generated in solar flare through interplanetary space. These shock waves are often associated with solar flares accompanying the emission of type II radio bursts, the wave frequency of which drifts to lower frequencies with time (e.g., ~ 1 MHz per second in metric frequency range). The plasma density in the solar atmosphere, often measured by the number of electron in one cubic centimeter, decreases with distance from the photosphere. Thus the plasma frequenc which is proportional to the square root of the electron density, also decreases with this distance. It is now though that, while propagating outward in the solar atmosphere, these shock waves excite the longitudinal plasma waves which oscillate at local plasma frequency and its harmonics. Since the shock waves propagate outwards through the solar atmosphere, the frequency of these plasma waves necessarily decreases with time: this mechanism produces a drift from high to low frequencies, although we do not know fully yet the emission mechanism of type II bursts which is necessarily related to the mechanism for the transformation from longitudinal plasma to transverse electromagnetic waves. At any rate, this frequency-drift shows that the emission

mechanism of these bursts is closely related to the propagation of shock waves in the solar atmosphere.

1. Basic Processes in the Solar Atmosphere and Interplanetary Space

The solar wind continuously flows out of the solar corona, the outermost atmosphere of the sun. The coronal region is located a few 10,000 kilometers or beyond above the photosphere which is seen as the solar disk by the visible continuum emissions. There exists the chromosphere between the photosphere and the corona.

Various solar phenomena such as sunspots, prominences and flares occur in the solar atmosphere, but the most important factor which controls these phenomena is connected with the magnetic fields associated with sunspots. The origin of these magnetic fields is long known to be related to the general magnetic field of the sun, which is supposed to be similar to that of the earth's dipole, but until now, no explanation has been successful for the origin of this field.

Most flares occur in the sunspot groups which are actively changing both spatially and temporarily. These flares are usually observed by the monochromatic hydrogen Balmer alpha

line emission (Hα line), but, generally, the intensity of the emission is much lower than those of the visible background continuum called the white light emission, so that flares are usually invisible in white lights. Various emissions are associated with solar flares: Hα and many other atomic line emissions, continuum emissions, X-ray and gamma-ray bursts, radio bursts of spectral type II, III, IV and V, particle emissions (10 Mev - 10 Bev protons and other nuclei, and 10 Kev - 10 Mev electrons), plasma clouds and shock waves. Most flare energies are shared by optical emissions and shock waves, and they amount to several times 10^{32} ergs for a typical flare of important 4. This amount of the energy is emitted in various emissions such as mentioned above from the flare into the outer space (Fig. 2).

Shock waves propagate into interplanetary space, and then sometimes produce geomagnetic storms SSC a few days later after flares. In this space, there exists the magnetic field, which is transported from the photospheric surface by the solar wind because this wind, consisting of ionized gases, tends to freeze the photospheric field lines within it. This property of ionized gases is now often called the

frozen-in theorem of Alfven," who discovered such nature

of these kind of gases in 1942. When we consider the mean

speed of the solar wind as mentioned before, about 4 or 5

days are needed for this wind to transport the photospheric

field to the earth's orbit from the sun. Because of the

solar rotation, these magnetic lines of force, stretched

outwards from the sun, produce a spiralling pattern for the

configuration in the ecliptic plane. This type of the

magnetic configuration was predicted by Eugene N. Parker,

of University of Chicago, in 1958 and later experimentaly

verified by John M. Wilcox, now at the Standford University,

and Norman F. Ness of the NASA, Goddard Space Flight Center.

Thus it became clear that the interplanetary space between

the sun and the earth is filled with the magnetic lines of

force originated in the photosphere of the sun. These field

lines influence the propagation of solar flare particles,

both 10 Mev - 10 Bev protons, heavier nuclei and 10 Kev -

10 Mev electrons, and perhaps affect the propagation of

shock waves produced by flares.

The observed pattern of the shock waves near the earth's

orbit is, therefore, important to find out the propagation

characteristics of these waves in interplanetary space. Rcently, the method for estimating this pattern has been developed by Norman Ness and his colleagues, based on the analysis of two or more satellite data for interplanetary shock waves. In doing so, the geomagnetic data on the earth's surface are also used to estimate the time which these shock waves arrive at the earth's orbit.

2. Historical Background

Relationships between solar flares and geomagnetic storms were first investigated by Carrington, an astronomer at the Greenwich Observatory, in the year 1859. Charles Darwin, in this year, published a famous book entitled "The Origin of Species by Means of Natural Selection...," which opened up the new era for the study of biology because this book established biology as science. Carrington observed a white light flare, although, in his time, the technique to observe any spectral line emission like the Hα line had not been found out yet. This flare, really, was one of the biggest flares in the history of solar research, for this type of a flare is only observable when the brightness of flare continuum emissions is greater than that of the

photospheric background emissions. Such flares have been
observed about 10 times since the systematic observations
of the sun started about 30 years ago.

Carrington further remarked that a great geomagnetic
storm occurred about one day after this flare, and then
suggested that this flare was responsible for this storm,
although he did not know what mechanism produces the storm.

Since then, the cause of geomagnetic storm was sought
for by scientists such as Birkeland and Stormer, both
Norwegian physicists. They had been trying to find out
the cause of auroral phenomena which were only seen in the
high latitude regions of the earth. They interpreted these
phenomena by assuming that corpuscular beams emitted by
flares bombarded these regions and then excite the atmospheric
gases. According to them, auroral phenomena were produced
as a result of these processes. Birkeland made the experi-
ment by using a big magnetized iron sphere which was exposed
to the electron beam shot by the electron gun. This is now
well known as the "terrella experiment". In order to explain
the result of this experiment, Stormer made extensive numerical
calculation for the orbits, in the dipole geomagnetic field,

of the electrons emitted from the sun. Later, it became cle:

that these results were not applicable to the auroral partic

but, with the discovery of cosmic ray particles, they were

shown to be useful to study these particle orbits in the

geomagnetic field. At present, the theory of the motion of

these particles is well known as the "theory of geomagnetic

effect" of cosmic rays.

It should be noted here that, at the Hale Solar Observa-

tory in Pasadena, California, G.H. Hale could first watch a

solar flare by his spectrohelioscope in the early 1926. On

24 January 1926, a tremendous eruption outbreak suddenly

appeared in a large sunspot group. He watched in wonder thi

flare-up of the brilliant jet and the associated cloud masse

which occurred while he was testing his spectrohelioscope

between 11^h40^m and 12^h15^m Pacific Standard time. He had

further observed that this flare-up occurred near a great

sunspot at about 22 degrees north in latitude, which was the

close to the central meridian of the sun.

When Carl Stormer observed a large-scale auroral phenome

on 26 of the same month, he wrote Hale: "I have been most

fascinated by a remarkable aurora here the 26th of January

of exceedingly red color, like the aurora in 1870. I should

like to know from which active part of the sun this aurora

was coming." He was so delighted to receive a letter from

this famous Norwegian physicist because "by a piece of rare

good fortune," he could note, "I was able to answer this

question with some chance of certainty." This flare-up

on 24th of January was the first observation of solar flares

by selected spectral lines. This accidental observation by

him thus opened up the new era for the study of solar and

terrestrial physics.

While Birkeland and Stormer were investigating auroral

phenomena, no one knew that the interplanetary space is filled

by plasma and magnetic field transported out of the sun. When

Sydney Chapman and V.C.A. Ferraro, both British, proposed a

new theory of geomagnetic storm in 1931, they also did not

notice that there exist ambient plasmas in this space. The

view that matter existed in this space was first critically

considered by a German physicist, Ludwig F. Biermann, in

1951 based on the detailed analysis of the form of comet tails.

In the field of the physics of interplanetary space, he made

a pioneering work that showed an evidence of the ionized

continuous gas flow from the sun. In order to explain the formation of some comet tails, he showed that some agent other than the sun's light pressure must necessarily be taken into account. This agent was identified by him as the ionized gas continuously flowing out of the sun. Since his theory appeared, it became soon accepted that the space near the sun (< 0.5 A.U) was filled by ionized gases, consisting mainly of proton and electron. This view was furthermore supported by the observations of the zodiacal light.

Thus the interplanetary space was no longer considered as vacuum. When anyone would discuss solar and terrestrial relationships, he had to take into account the existence of the ambient plasma in this space. This situation suggested a possibility of the generation of shock waves in this space if the gas clouds are ejected by solar flare with the speed of ~ 1000 kilometers a second, for instance. At the first international symposium on the hydrodynamic phenomena in astrophysics, which was organized by Professors J.M. Burgers and J.H. Oort, this possibility was taken up immediately by Tommy Gold, presently at the Cornell University, to

explain the sudden commencement (SSC) of geomagnetic storm.

In this case, he explained that the main phase of the storm

was produced by the interaction of the ionized gas from the

sun with the geomagnetic field extending into the space

surrounding the earth, e.g., with the magnetosphere. He,

furthermore, invented a model of expanding magnetic bottles,

ejected by flares, which transport the ionized gas such

as those mentioned above.

In order for his idea to be accepted, the physical state

of interplanetary space had to be understood both theoretic-

ally and observationally in more detail. The first important

step was put forward in 1957 by Sydney Chapman, who was a

founder of the solar terrestrial physics. He considered a

problem on the hydrostatic equilibrium state of the solar

outer corona and then obtained that this corona extends into

the space beyond the earth's orbit. According to him, the

plasma temperature at the earth's orbit was about 100,000

degrees Kelvin. It was found by Parker in 1958 that Chapman's

conclusion did not fill the condition necessarily required

about the pressure balance between the extended solar

corona and the interstellar plasmas. Later, this defficiency

was taken away by Parker himself when considering the theory

of the hydrodynamic equilibrium in the solar outer corona.

This theory led necessarily to the conclusion that there

exists the "solar wind" in interplanetary space. According

to this, the speed and plasma density of the solar wind at

the earth's orbit are highly dependent on the temperature

of the solar outer corona, which is about equal to a million

degrees Kelvin: for instance, for the coronal temperature

of 10^6 degrees Kelvin, the theory of Parker predicts that

the speed and proton density in the solar wind at the earth's

orbit are 500 Km sec^{-1} and 7 protons per cm^3, respectively.

The result deduced from this theory was established to be

correct by the direct observation for this wind by the Marine

2 spacecraft launched to explore the planet Venus and its

vicinity in 1962.

The progress of the research for the plasma and magnetic

field in interplanetary space has thus provided much important

informations on the formation and propagation of shock waves

in this space.

3. <u>Hydromagnetic Disturbances Associated with Solar</u>
   <u>Flares</u>

Before we consider the behavior of these shock waves in
interplanetary space, it may be better to take a look at
various phenomena associated with solar flares. A typical
flare of importance 4 is usually accompanied by particle
and electromagnetic emissions: cosmic ray particles such
as 10 Mev - 10 Bev protons and 10 Kev - 10 Mev electrons,
optical spectral and continuum emissions, radio bursts of
spectral types II, III, IV, and V, X-ray bursts and some-
times, gamma-ray bursts (see Fig. 2). It has been shown
that most SSC geomagnetic storms are associated with flares
which produce both type II and type IV radio bursts. In
this case, the metric wave emission of type IV bursts,
following type II bursts, is important as an indicator that
a parent flare produces shock wave into interplanetary space
(Fig. 3).

This fact suggests that the emission mechanism of these
shock waves is closely related to those for both of these
bursts. Wild and his colleagues, in 1953, showed the first
observational evidence on the high-speed movement of the
radio source for type II bursts from the sun into outer

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space: the speed of this source was 500-1000 Km sec^{-1}, which seemed to explain reasonably the time interval between flares and SSC geomagnetic storms. Therefore, they later proposed a model that type II bursts are generated by shock waves propagating outwards in the solar atmosphere, and that these waves sometimes reach the earth and its vicinity.

If we accept this idea, it is led that these shock waves must propagate, with the speed of 500-1000 Kmsec^{-1}, through interplanetary space. It is known that by following the source for type II bursts the source for the metric component of type IV bursts tends to move outwards. Therefore, it seems that the outward movement of the former is closely associated with the passage of the shock waves in the solar atmosphere. At present, we have many supporting observational results for these associations. Since those type IV bursts are now known to be emitted by the electrons of 10 Kev – 10 Mev energy by gyro-synchrotron mechanism due to their interaction with sunspot magnetic field lines being stretched outward in the coronal region by hot ionized gases, trapped by these field lines, which are heated up during the explosive phase of flares.

Moreton discovered wave phenomena, on the solar surface, which are produced during the explosive phase of flares. Using a special technique, he took many pretty pictures for the waves propagating outwards from the flare regions (Fig. 4). These waves are now known as the "Moreton waves". In general, they did not propagate isotropically along the solar surface from the flare region, but it seems that the pattern of this propagation is well controlled by the configuration of sunspot magnetic field lines in and around the flare region. The magnitude of the estimated speed for these waves had the same order as that obtained from the movement of type II radio sources. This indicates that the origin of the Moreton waves is closely related to that for the shock waves responsible for type II bursts. Recently, more definite support has been obtained for the association of shock waves with type II bursts: analyzing the radio records obtained by the Culgoora radioheliograph in Australia, Paul Wild and his colleagues have detected that the emission of type II bursts is accompanied by shock waves propagating mainly along the sunspot magnetic field lines extending into the outer corona and interplanetary space. The shock

waves emitted by flares seem to propagate under the influence

of these field lines in this space and, 2 or 3 days later,

reach the earth and its vicinity. When the geomagnetic

field extended into the magnetosphere is disturbed by the

shock waves, an SSC geomagnetic storm will be observed by

the magnetograph located on the earth's surface.

The magnetometers and plasma measuring apparata on-board

satellites or deep space probes beyond the reach of the

earth's magnetosphere also would detect these shock waves

passing through interplanetary space.

The study of the propagation pattern of these shock

waves in this space seems to be useful for the understanding

of the interplanetary dynamical processes induced by solar

flares and for the study of the mechanism of SSC geomagnetic

storm. It is now clear that solar flares are the emitters

of shock waves propagating with supersonic speed in inter-

planetary space. Using the magnetic and plasma data taken

in this space, we shall next consider the behavior of these

shock waves in this space.

4. The Observations on the Earth and Their Relation to
    Solar Flares

Solar flares accompanying type II bursts usually generate

shock waves propagating into interplanetary space. Some-
times, these waves can reach the earth or its vicinity and
produce SSC geomagnetic storms on the earth two or three
days later. Since the longitudinal positions of these
flares are distributed randomly over the solar disk, it is
possible to investigate the dependence on the flare positions
of the characteristics of these shock waves such as their
transit times, SSC amplitudes and the magnitudes of the
main phase of the storms. Akasofu and Yoshida, of University
of Alaska, investigated this dependence to find out whether
or not flare positions are a main factor determining these
characteristics of the flare ejecta, and obtained that the
shape of these ejecta is not spherical and forms under the
influence of the interplanetary magnetic field.

Sinno and later, Sakurai considered the effect of these
flare positions mentioned above on the magnitude of the
Forbush decrease of galactic cosmic rays. Their results
indicated that this magnitude is highly dependent on the
longitude position of a responsible flare; this magnitude
tends to increase as the flare position moves eastward
over the solar disk. They concluded that this result is

explained by taking into account the configuration of the interplanetary magnetic field deformed by the shock waves propagating through the space between the sun and the earth. In this case, they tacitly assumed that these waves do not propagate spherically in this space, but are strongly controlled by the interplanetary magnetic field during their propagation.

Using the dependence of the SSC amplitude on the flare position, Joan Hirshberg, in 1968, now at the High Altitude Observatory of NCAR, investigated the propagation pattern of a shock wave in interplanetary space, and estimated the geometrical shape of the shock front: the average shock front has a smaller radius of curvature centered at 0.5 AU from the sun, but stay as a spherical shape when projected onto the ecliptic plane. This result suggests that the shock wave does not propagate isotropically through inter-planetary space: this characteristic is quite different from a concentric pattern produced by dropping a pebble in pond water. Although it has been found that the transit time of the shock wave between the sun and the earth is dependent on the longitudinal position of the responsible

flare, it seems useful to estimate an average speed of its

propagation in a distance of 1 AU. Using the solar and

geophysical data for a few decades, it has been found that

this average speed is around 600 kilometers a second; in

other words, a shock wave takes two and a half days to travel

the distance of 1 AU. In some cases, however, the speed

can be as high as more than 1500 kilometers a second or as

low as less than 350 kilometers a second.

As mentioned above, it seems difficult to estimate

exactly the shape of shock fronts based on the statistical

analysis of geomagnetic data. If we can find out a series

of prominent events of SSC's, which are generated by flares

which occur in the same active region during its passage

over the solar disk, these events will be a good example

capable of finding a geometrical pattern of the shock front

being propagated out of a flare. Sakurai investigated a

series of these events associated with the active region

which passed over the solar disk during 23 October to 4

November 1968. This region, defined McMath No. 9740, was

quite active in the production of proton flares accompanying

type II and type IV radio bursts. This series of events

suggests that a shock wave tends to propagate along the interplanetary magnetic field lines and, therefore, that this wave does not propagate spherically symmetric with respect to the central meridian across the flare position.

The geometry of the shock front in the plane perpendicular to the ecliptic plane can be obtained when the direct observations of shock normals in interplanetary space are deduced. A few of such studies will be given later.

5. Observational and Theoretical Problems of Interplanetary Shock Waves

Since the space era started in 1958, so much data about the interplanetary space in the vicinity of the earth have been collected. The first interplanetary shock wave was identified using the direct observational data of the Mariner 2 spacecraft by Charles P. Sonett of the NASA Ames Research Center and his colleagues. The data revealed that when an interplanetary shock passed by the spacecraft, the measured proton number density, temperature and magnetic field strength increased in their magnitude. In this event, the so-called shock-jump conditions were satisfied. The local shock speed, and the Mach number could also be estimated for this shock, although a more quantitative test of this shock wave was

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not possible because of the quality of the data.

The interplanetary space is filled with protons, electrons and a small portion of ionic components such as He^{++} and partially ionized O, Si, Fe and others. The temperature of this interplanetary medium is so high and the density is so low that the collision rate for the particles between one another is almost negligible. In fact, the mean free path for the proton-proton binary collision at the condition near the earth orbit (or at 1 AU from the sun) is of the order of 1 AU. Hence, if we study any physical phenomena on the scale much less than 1 AU, the solar wind plasma can be treated as collisionless.

For the collisionless solar wind plasma, the velocity distribution for particles is not necessary to be isotropic and the component of different species can maintain different temperature because the collisions between particles are so rare. It has been verified by direct spacecraft observations that solar wind plasmas are indeed anisotropic with different temperatures for protons, electrons and helium ions.

To study the shock waves in this kind of medium, the theory of magnetohydrodynamics (MHD) should be carefully

modified before applying to such a collisionless plasmas.

After 1962 many spacecrafts have been launched to collect the interplanetary data. The interplanetary plasma and magnetic field have been systematically analyzed, and many interplanetary shock waves have been then identified. All these observations have confirmed the existence of inter-planetary (IP) shocks which can be described approximately by the MHD theory if the gross picture of the shocks is to be studied.

A few such studies reported, in general, indicate that the shock-jump equations for conservation of mass, momentum flux and Maxwell's equations are fulfilled in the MHD theory. However, the energy flux conservation equations is not necessarily satisfied, for, because the IP shock waves usually propagate with speed not much different from the solar wind speed, a small uncertainty of the measured solar wind speed or the estimated shock speed and normal direction may invalidate the energy conservation equation. The thermal anisotropy of the plasma also contributes to the imbalance of energy flux conservation.

Nevertheless, a few dozen of interplanetary shocks carefully analyzed have been reported using the data of plasma and magnetic field obtained by multiple spacecraft observations. Thus, the physical parameters derived for these shock waves should be more accurate than the previous studies. The physical parameters which are most interesting to us are the shock propagation direction, speed, the Mach number and the angles between the ambient magnetic field and the shock normal direction.

The earlier studies using limited amount of data found that the shock front originated from the associated flare does not remain as a spherical shape centered on the sun. Recently Jerry Chao and Ron Lepping, of the NASA Goddard Space Flight Center, collected the data for four years from 1968 to 1971, taken by eight different spacecrafts, and selected 22 shock waves with better determined shock parameters than earlier collections. The shock front from this statistical study seems to be more consistent with a spherical shock wave originated from the solar surface, although the selection of the solar origin was somewhat subjective to the authors' opinion. However, more than 75 per cent of

these 22 shocks are associated with radio bursts of type II and type IV, and flares of importance $\geq$ 1 B.

The question is whether the statistically deduced shock front is considered as a representative of the individual shock wave front. Recently, George Siscoe, of University of California, Los Angeles and others investigated that a given shock wave front near the sun propagates into the interplanetary medium which is inhomogeneous in magnetic field and plasma density fluctuations, in addition to solar wind streams interacting with one another. The shock front reached the distance of 1 AU will be very much distorted from the original shape. Then, the statistically deduced shock front may not represent the individual one, but merely show a collective effect due to interplanetary scattering and deflection of the shock front.

A few studies of the individual shock front have been made using widely separated spacecraft observations. B. Bavasano, F. Mariani of the University of Rome and N. Ness used the Pioneer 8 and other earth orbiting satellite data to deduce a shock front which is elongated in the direction along the ambient spiral magnetic field, which is different

from the spherical shape. Recently, R. Lepping and J. Chao also found a shock front similar to the Pioneer 8 observation by using Pioneers 6,7 and other earth orbiting satellites. These two shock fronts deduced from the spacecraft observations are similar to that deduced by K. Sakurai from the data of the radio bursts and geomagnetic storms SSC which originated from the same active region on the sun.

The shock direction out of the ecliptic plane are also being scattered very symmetrically with respect to this plane. A statistically deduced surface would be also a spherical front in this meridianal plane. However, no individual observation with multiple spacecraft is available to estimate the shock front geometry.

The average propagation speed from the sun to 1 AU is about ~600 Kilometer a second. The local speed at 1 AU deduced from the spacecraft data is slightly less than the average speed. This indicates the shock wave may have decelerated during the propagation through interplanetary space.

In order to explain the propagation of these shock waves, E.N. Parker first gave a theoretical description by using

the blast wave, originated from a flare region, which propagates to the earth's vicinity. This wave is very similar to that which is generated as a result of nuclear explosion in the earth's atmosphere. Parker assumed a simple model of the solar atmosphere and computed the shape and the characteristic of the blast wave propagating through interplanetary space. Extensions of Parker's model have been carried out by many others by considering more realistic models on ambient solar wind and shock strength. The flow patterns behind the shock have been estimated as well. However, no experimental evidence for this kind of shock was found.

Another type of flare associated shock was originally suggested by T. Gold and later ellaborated and corrected for more realistic solar wind condition by A.J. Hundhausen. The flare was assumed to accompany a flare ejecta which may last for a period much longer than the explosive phase of a flare. This flare ejecta can push the ambient solar wind resulting in a solar wind disturbance when it has traveled well out into interplanetary space. The ambient solar wind plasma and magnetic field lines are compressed and pushed

aside by the expanding flare ejecta. If the speed of the
flare ejecta exceeds the wave speed of the ambient plasma,
a shock will form in front of the ejecta. If some of the
ejected material moves outward more rapidly than that near
a tangential discontinuity separating the shock and the
flare ejecta, a shock might form within the flare ejecta and
moving toward the sun relative to the ambient plasma. This
would be a "reverse" shock which would be convected outward
by the rapid move of solar wind. A few reverse shock and
two shock pairs have been observed in solar wind.

The flow patterns behind the shock produced by the flare
ejecta are different from that of a blast shock wave. A.J.
Hundhausen and others have identified the typical post-shock
flow and concluded that a high-speed plasma (or flare-ejecta)
is emitted by the corona for at least several days after a
solar flare. This seems more like the flare ejecta produced
shock rather than the blast wave.

6. On the Origin of Interplanetary Shock Waves

As given in the last section, the two types of flare-
produced interplanetary shocks: the "blast wave" and
driven wave, which are distinguished by their generation

mechanisms. The post-shock parameters of plasma and magnetic field should vary in different manner for these two types of shocks.

A.J. Hundhausen has selected about a dozen of interplanetary shocks and tried to differentiate this post-shock conditions by studying the plasma parameters of the kinetic energy flux. If this kinetic energy flux continued to rise after the abrupt jump observed at the shock passage, these shocks can be said to be associated with the driven type. If this parameter is characterized by a steady fall after the abrupt jump at the shock, it resembles the blast type of shock. Although this analogy is tempting and reasonable, all features of observed shocks do not always fit qualitatively the expected patterns for blast or driven waves. These observations suggest that flare-produced shocks are more complicated than those types of shocks theoretically predicted.

Since the observations cannot trace the passage of an IP shock through the entire space from the flare-site to 1 AU, an assumption has to be inevitably made that shocks are formed at the flare region and then propagate continuously through interplanetary space. However, this association of an observed IP shock wave to a flare is still not very

satisfactory. Because the flare phenomena occur a few days earlier and is very common on the sun, such an association of an IP shock to a flare is always found though sometimes not properly identified.

There is however, another mechanism which can generate interplanetary shock wave. This is associated with the overtaking action of high speed flow to the back ground low speed flow in the solar wind, because this wind is emitted at a different speed from different portion of the solar surface. In interplanetary space within the ecliptic plane, a number of the "high speed streams" are, therefore, observed. And these streams usually persist for a period of more than the solar rotation period of 27 days. Because of the rotation of the sun, the high speed stream flows radially from the sun will interact with the lower speed solar wind in front of it. If the difference in speed between this speed and lower one is greater than the characteristic wave speed of the solar wind, the high speed solar wind will act like a supersonic object moving in the air, and then, a shock wave will form at the leading edge of the high speed stream. If the high speed streams do not persist for more than a

solar rotation period, the shock waves produced at the leading edge of the stream will be difficult to be distinguished from the shocks produced by solar flares.

The interplanetary observations show that behind most of the shock waves, the high speed streams exist for more than one day. If these shocks are all flare-produced, then, the increase in flow speed and density or mass flux must also be associated with the flares. It seems still unclear whether all these high speed streams are associated with flares. Since many flare-ejecta as seen in interplanetary space are very similar to the high speed streams of the life time less than 27 days, probably the driven type of shocks are equally probable produced by flare and non-flare ejecta.

Another interesting question is how far an intermediate strength of shocks can propagate through interplanetary space before dissipated. Because of the dissipation mechanism for a collisionless plasma like the solar wind is still not very clear, it is very difficult to estimate the dissipation distance for a collisionless shock wave. A few observations may give a clue to answer this question and also suggest a new mechanism for shocks propagating through interplanetary space.

Mariner 5 spacecraft was sent to the planet Venus in

1967. The plasma and magnetic field data were also collected

to yield some information concerning the physical state of

interplanetary space within the earth's orbit. Since the

Mariner 5 was almost in the same solar longitude as that of

the earth, it offered a unique situation to watch the develop-

ment of any interplanetary phenomena in this space. Fortunately,

two interplanetary events were recorded in the Mariner 5 data

when the spacecraft was at a distance 1/50 AU and 1/7 AU,

respectively, from the earth toward the direction of the sun.

The data of these two events have the characteristics of the

interplanetary shock waves. However, the magnetic field

data which has a higher resolution than the corresponding

plasma measurements, showed that the widths of the transitions

from the up-stream state to the down-stream state were too

much wide as being a collisionless shock wave. At the earth's

vicinity other spacecraft observed the same events, but the

widths of the transitions were much narrower than that at

the Mariner 5 positions. This suggested that, at the Mariner

5 positions, large amplitude waves were observed, and these

nonlinear waves were in the process of steepening into shock

waves (see Fig. 5). The computed steepening time for the waves to propagate from the Mariner 5 positions to the earth agrees with the measured time. This checks the hypothesis that nonlinear waves in the vicinity of the earth steepen up into shocks. The origin of these nonlinear waves is not very clear, but these two events can be associated with very prominent solar events two to three days before the spacecraft observations. These solar events consisted a class 1B importance solar flare followed by radio bursts of types II and IV. Lockheed solar observatory also reported the observation of the chromospheric wave phenomena, called the Moreton wave, associated with these two events. The world data center listed these two events as "Major Flare" which ranks flares according to their H-alpha, radio burst and x-ray effects. Such solar events are not very often to be observed. If the observed interplanetary non-linear waves are of the solar origin, the above mentioned solar events are the best candidate for their association. In addition to these two events, a study of interplanetary data from 1968 to 1971, found that 30% of the interplanetary shocks near 1 AU have the thicknesses of the transition

much larger than the thicknesses predicted from the plasma theory. Unfortunately, no spacecraft is separated far enough to be able to watch whether these structures are really in the process of steepening into shocks. If we adopt the collisionless shock theory which has been tested and checked for laboratory experiments, these observed thick shocks are not shocks, but nonlinear waves in the process of steepening. Most of these "thick shocks" can also be associated with flares and radio bursts. Then, the question is why the shocks were not formed even very close to 1 AU. Before attempting to answer this question, another interesting observation will be described in the following.

The radio bursts of type II are thought to be associated with the passage of the shock wave in the solar corona or far distant space. The IMP-I spacecraft was equipped with an instrument which could measure the radio burst of frequency down to 30 kHz. By using the interplanetary model for the electron density, this lowest frequency corresponds to the position of the shock wave which arrives almost near 1 AU. Hence, the IMP-I measurements can trace the passage of a shock wave from the vicinity of the sun to a distance almost near 1 AU.

A distinct event detected in August 1972 from the data of IMP-I was first studied by H.H. Malitson and her colleagues of GSFC, NASA (Fig. 6). The type II burst was first observed very near the sun by ground-based stations. The first IMP-I observation of type II burst started at 2600 kHz but disappeared at 1630 kHz which corresponds to 10 to 15 solar radii from the sun. Then, the type II burst re-appeared again in the frequency range of 1270 kHz to 600 kHz. It disappeared again until at the frequency 155 kHz corresponding to the distance of about 60 solar radii. Again it disappeared at the frequency about 55 kHz. Such a discontinuous appearance of the type II bursts may manifest that the same interplanetary shock waves are not continuously propagating through interplanetary space, even though they are flare-associated. In addition, the shock speed deduced from the type II bursts for each interval seemed to be faster than the average speed for a disturbance propagating from the sun to 1 AU. This suggests that the radio source moved faster than the mean speed of the disturbance sporadically generating shock waves.

The specific model of shock propagation in IP space,
which we like to propose, will be as follows: Near the sun,
a flare ejecta or high speed stream following a flare will
interact with the pre-flare ambient plasma. During this
interaction, a nonlinear wave can be generated at first.
This nonlinear wave will then steepen into a shock wave.
When shock waves have formed, the radio bursts of type II
and/or type IV will be observed. Since the shock wave
propagates much faster than the flare-ejecta or the piston,
the shock will separate itself from the piston. Furthermore,
the expansion of the shock wave from the flare-site will
weaken the shock strength. This shock will dissipate out
in the ambient plasma, perhaps within a few solar radii.
However, the flare-ejecta continuously interact with the
plasma in front of it, and another IP nonlinear wave will
be produced in front of the flare-ejecta. By this time,
the flare-ejecta may have travelled to a few tenths of 1 AU.
This nonlinear wave will steepen into a shock wave, and
again propagate away from the piston. At this position,
because the interplanetary plasma is moving uniformly and
less turbulent, the spherical expansion effect of the shock

front is slower than near the sun, this shock will be able to propagate for a larger distance say on the order of 0.1 AU before fully dissipated again. A radio burst will be only observed during the actual propagation of the shock through this part of space.

The next nonlinear wave may not be generated until the flare-ejecta reaches a distance of 0.5 AU and the wave steepens into a shock propagating for a distance of a fraction of an AU, say ~0.2 AU. The shock will become very weak and merge with the ambient plasma as a magnetoacoustic wave and be damped out. Another nonlinear wave may have been generated again just in front of the earth and steepened into a shock in the vicinity of the earth at about 2300 UT of 8 August, 1972 (see Fig. 6).

The general picture of shocks repeatedly generated by the flare-ejecta and disappearing in interplanetary space is schematically given in Fig. 7. The well-developed IP shocks occur only at the space between $(x_o - x_1)$, $(x_2 - x_3)$, $(x_4 - x_5)$, and $(x_6 - x_7)$... The number of times and the positions where the shocks existed in interplanetary space depends on the strength of the flare-ejecta and the ambient

solar wind condition and the plasma associated with the flare-ejecta.

The flare-ejecta may be maintained strong enough to generate shock wave in interplanetary space for only a fraction of an AU to a few AU. Using remote space observations, this model of shock propagation may be verified.

Caption for Illustrations

Figure 1.   An example of geomagnetic storm with SSC (Storm
            Sudden Commencement). A typical storm starts with
            the increase of the horizontal intensity of the
            geomagnetic field. Several hours later, then a
            sharp decrease of this intensity is observed,
            which is called the main phase of the storm.

Figure 2.   Various phenomena such as hard and soft X-rays,
            radio bursts at wide-band frequencies, classified
            into microwave, type II, type III and type IV
            bursts and solar cosmic rays are emitted by a
            typical flare. The source of the energy released
            to these phenomena is generated during the
            explosive phase of the flare. Type II radio burst
            is generated as a result of the passage of shock
            waves through the solar atmosphere. Measures
            in the ordinate are arbitrarilly indicated.

Figure 3.   The time sequence for various radio bursts is
            indicated in a function of emitted frequencies.

Figure 4.   A typical example of the Moreton wave is shown.
            This event was observed on 20 September 1963,
            when a proton flare occurred (Courtsey from Sara
            Martin).

Figure 5. A profile of nonlinear wave steepening into

an interplanetary shock wave. A profile with

thickness ΔX_o Steepens into a shock wave with

a thickness ΔX_1.

Figure 6. Type II solar radio burst generated by the

3B flare of August 7, 1972. The burst has

been observed down to 30 kHz by Goddard Space

Flight Center - NASA radio instrument on board

IMP-6 satellite. Notice that the observations

are not continuous but sporadic.

Figure 7. A new model of propagation of interplanetary

shock waves associated with solar flares.
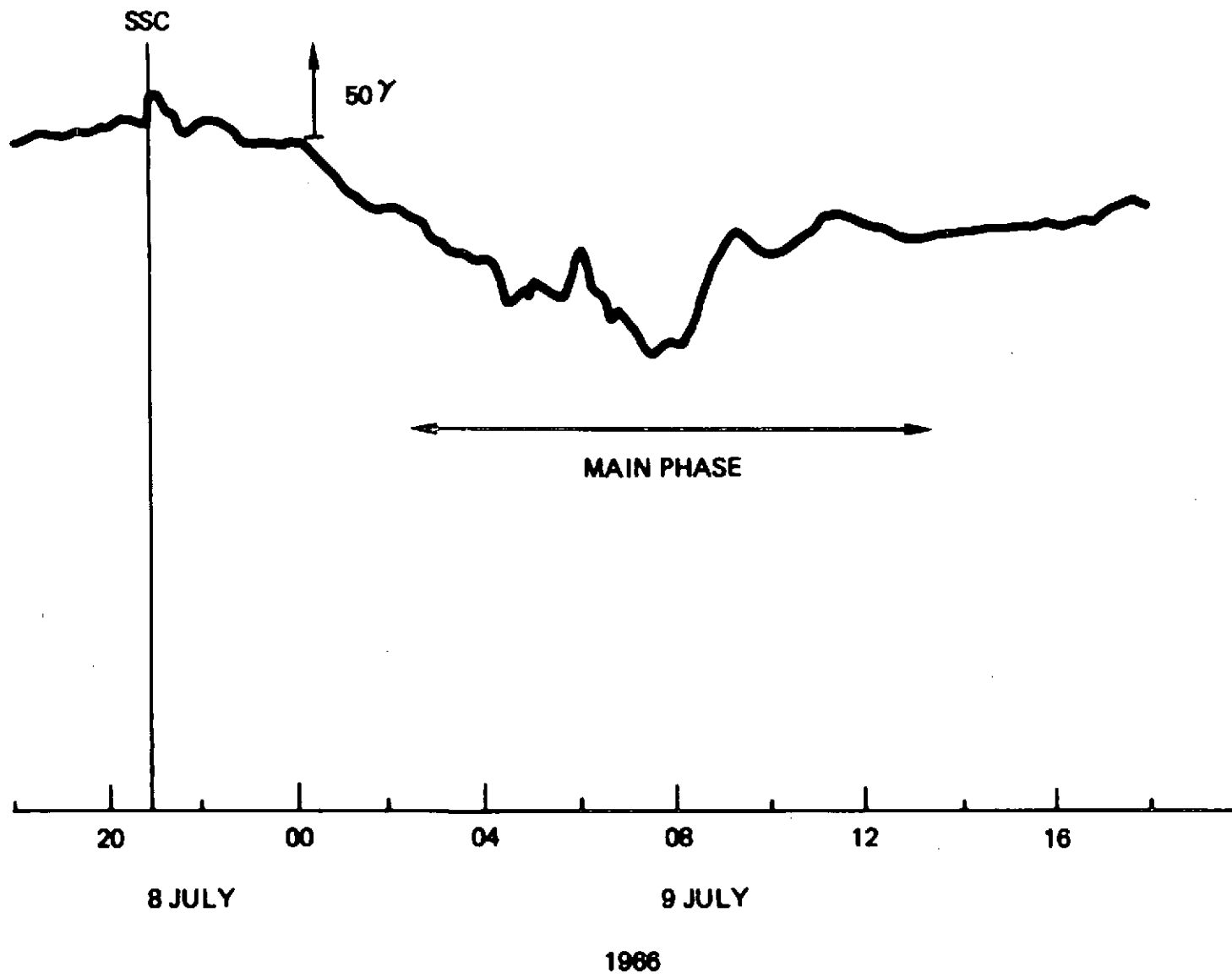
HORIZONTAL COMPONENT OF GEOMAGNETIC FIELD
HONOLULU, HAWAII

Fig. 1
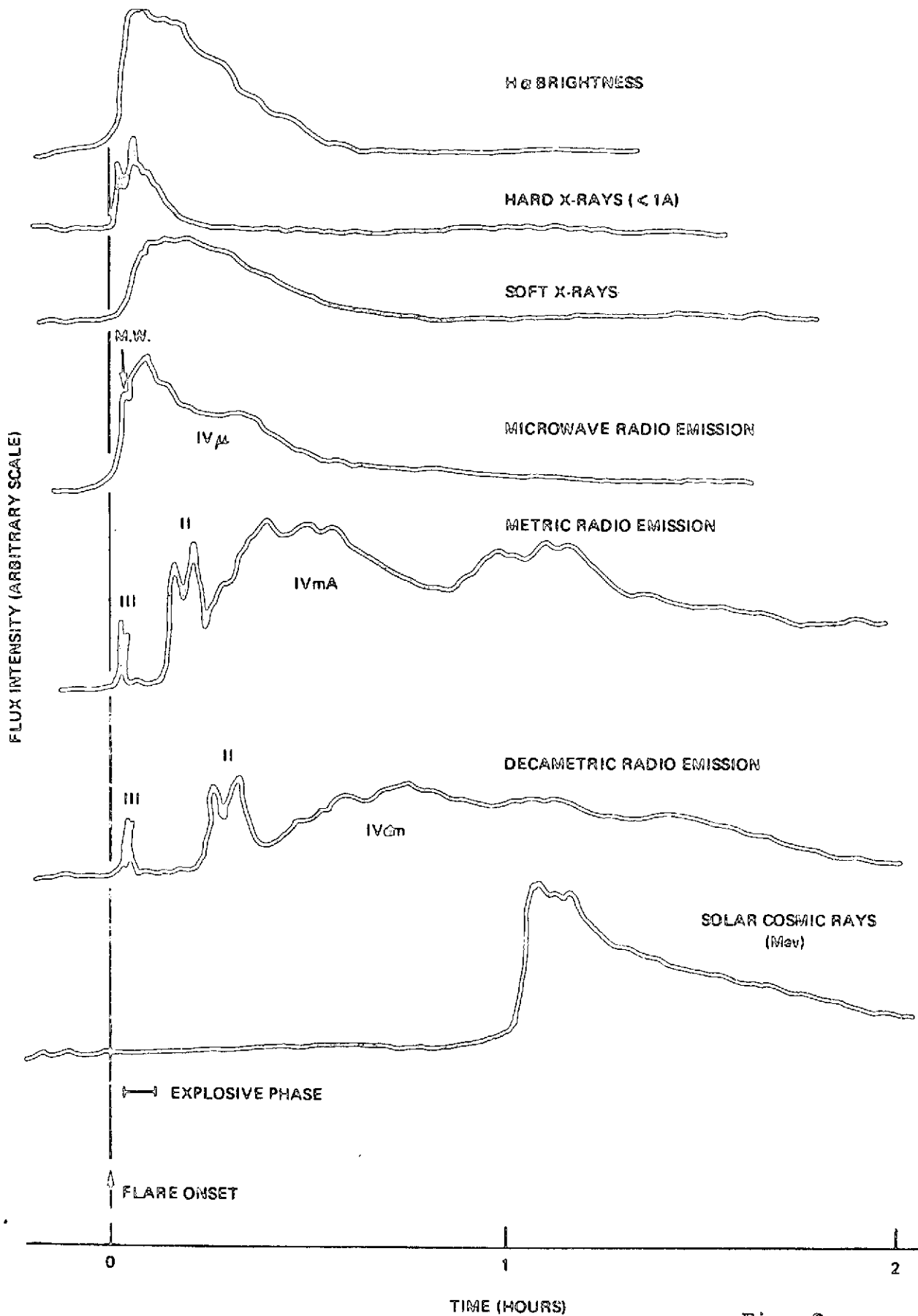
Fig. 2
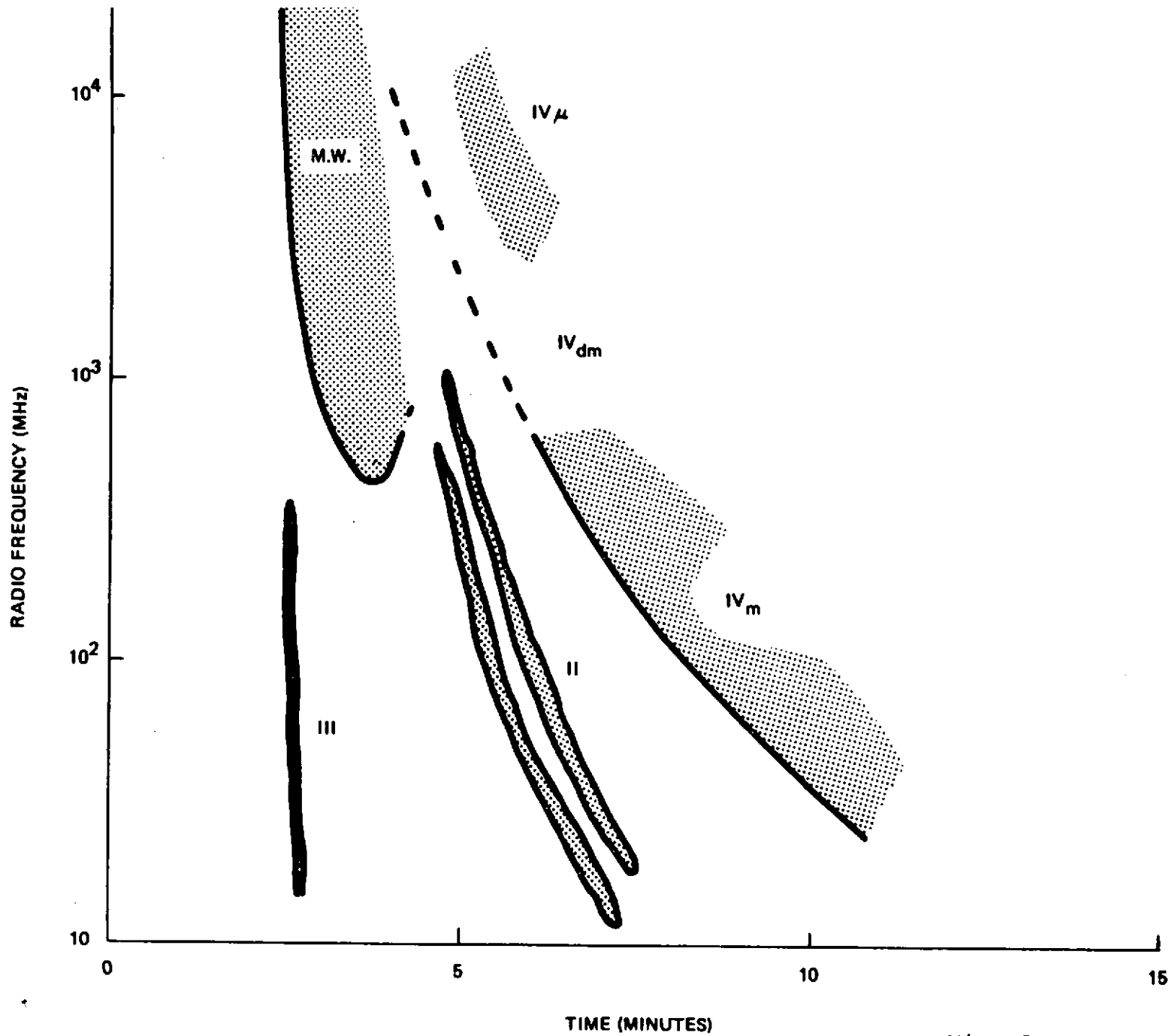
Fig. 3

$\vdash \rightarrow$ $\vdash\hspace{-2pt}\leftarrow$ 3×10^5 KM
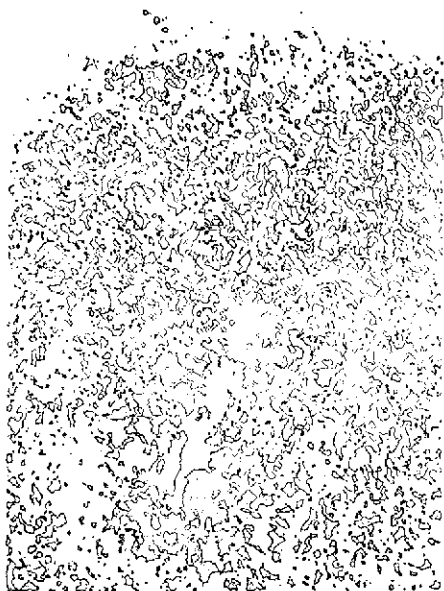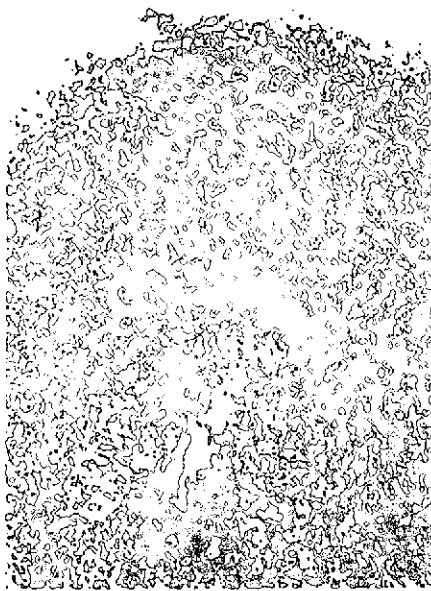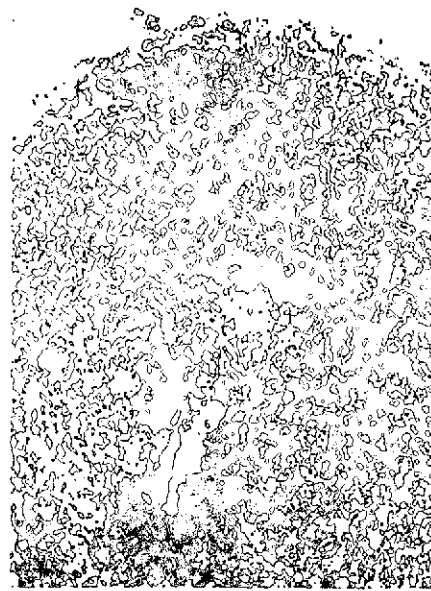
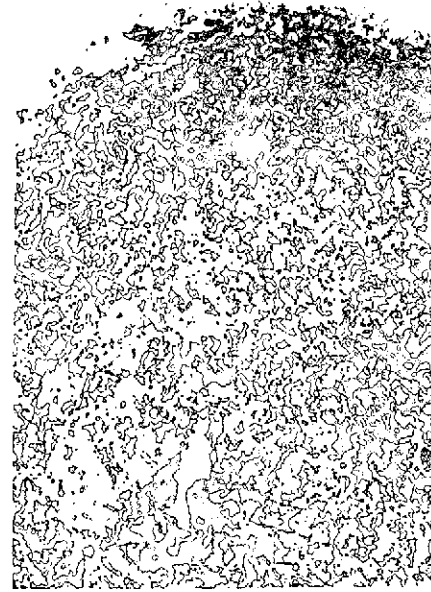2359:25   2400:25   2401:25

2402:25   2403:55   2404:55
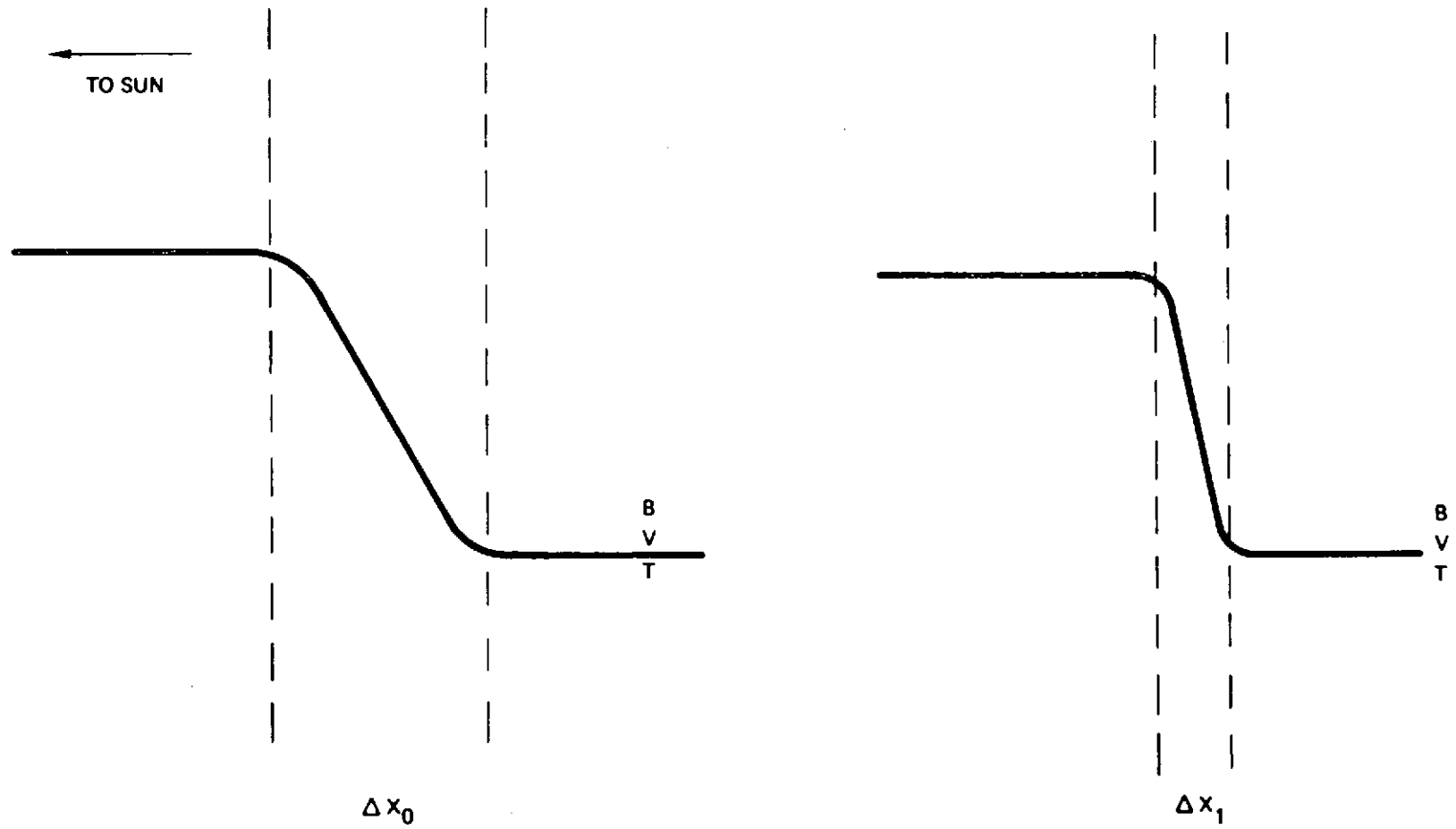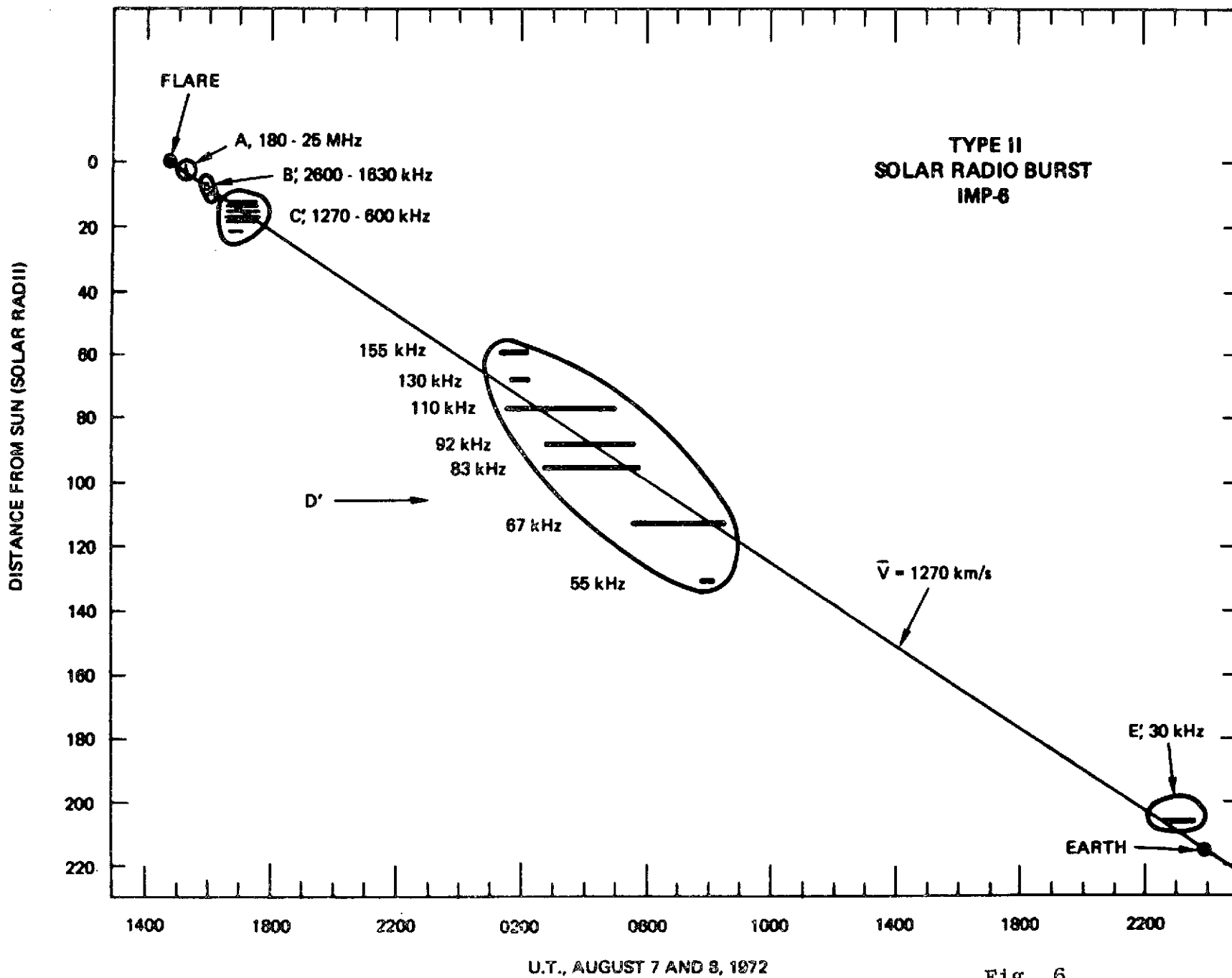
Fig 4
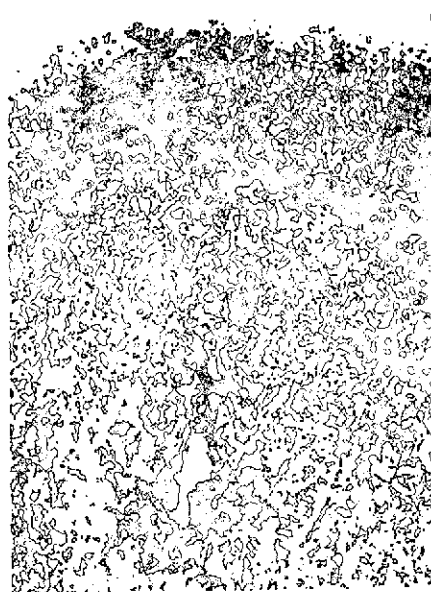
FORMATION OF SHOCK WAVES

Fig. 5

Fig. 6

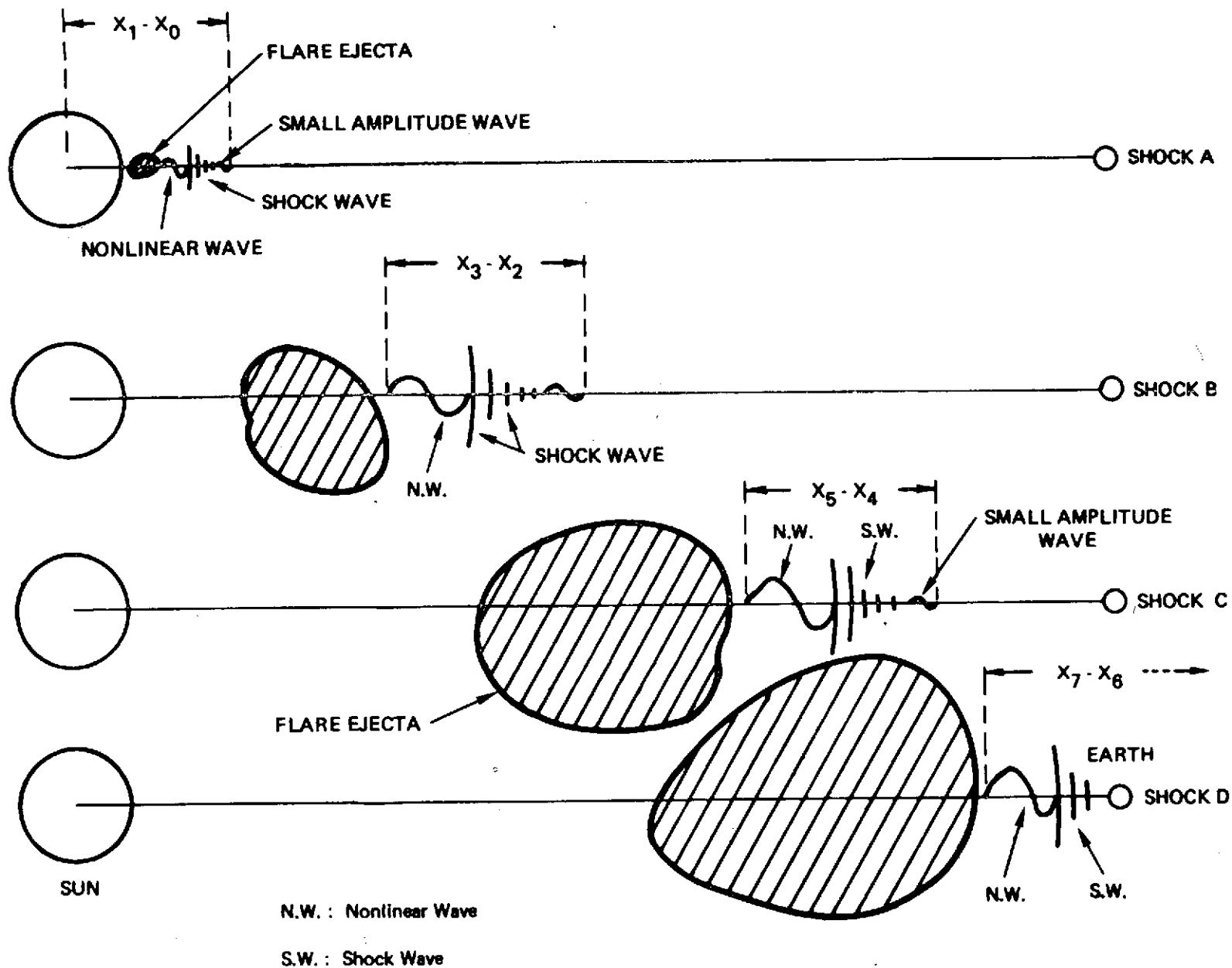A QUALITATIVE SKETCH OF SHOCKS PROPAGATION
IN INTERPLANETARY SPACE

Fig. 7