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# 3-D Solar Radioastronomy and the Structure of the Corona and the Solar Wind

J.L. Steinberg and C. Caroubalos
Observatoire de Paris, Meudon, 92190, France.

Solar radio bursts are intense radio emissions from localized regions in the corona and interplanetary medium. Their brightness temperature is so much higher than the electron temperature of the ambient plasma that the mechanism which produces them is certainly non-thermal ; the necessary energy is brought into the source region by energetic electrons which can give rise to different types of transient radiation. One of them is the type III radioburst produced by energetic electrons travelling along open magnetic lines of force. Another quite usual form is the type I burst, typical of the meter wave lengths range.

We do not fully understand yet how the non-thermal energy is converted into electromagnetic energy ; but we know that, to be efficient enough, the conversion must take place at frequencies close to the resonant frequencies of the medium. At these frequencies, the refractive index for radio waves takes extreme values : close to 0 for the plasma resonance, much larger than 1 for the gyro-resonances. As electromagnetic waves travel away from their source, those resonance conditions are no longer fulfilled because of the non-uniformity of the electron density or magnetic field ; the refractive index comes back quickly to unity ; such a variation of the refractive index is favourable to beaming effects. The radiation mechanism itself which can involve some amplification may also produce a directive primary emission. In both cases, the beam will be oriented along or at definite angles to the principal directions of the medium : the electron density gradient or the magnetic field.

Using results from the STEREO-1 experiment, it is shown that stereoscopic observations in the deci to decameter $\lambda$ range can provide information on

- the burst emission mechanisms
- the local electron density gradient and magnetic field vector at the source
- the macrostructure of the corona and the solar wind
- the characteristics of small scale electron density inhomogeneities.

Radio bursts of type III can also be used to map solar magnetic field lines of force throughout the interplanetary medium up to the earth orbit and beyond.

Future experiments of these kinds should be carried out between an out-of-the-ecliptic probe and the earth or an earth satellite.

Beaming of the radiation of type I and type III bursts was predicted long ago, but not observed until recently. Rather than giving up the basic mechanisms which seemed capable of explaining many observed properties but implied beaming effects, radio astronomers suggested that random inhomogeneities of the refractive index scattered the radiation.(Roberts, 1959). This suggestion received strong support when scintillations from radio stars seen through the upper corona were discovered. Fokker (1965), Steinberg et al (1971), and Riddle (1972) carried out Monte Carlo numerical computations of the scattering of the radiation from a source embedded in the inhomogeneous medium. These authors used models which were extrapolated to low coronal altitudes from measurements of radio scintillations made for paths which did not cross the corona lower thar 5 solar radii or so. However, these studies were successful in accounting for several observations which could hardly be explained in any other way. They showed that the inhomogeneous medium produces a scattered image broader than the source and appreciably displaced from it ; at the same time, the random propagation tends to suppress any beaming of the radio waves and smoothes the radiation pattern of the source.

Measurements of the angular distribution of the intensity of a source of radio bursts can therefore yield information on :

- the orientation of the principal directions of the medium : $\vec{grad}\ N_e$ or $\vec{B}$, the radiation mechanism and beaming processes.
- the characteristics of small scale inhomogeneities which cannot be obtained in any other way.

To measure directivity, observations from the ground only are inadequate. For many years, authors tried to reach at least a statistical view of the directivity of radio bursts ; for instance, from their E.W. probability of occurence ; but, if the orientation of the radiation pattern of individual bursts relative to the local vertical through the source is not constant, no information on the directivity can be obtained from a single observing site. Simultaneous observations should be made in at least two widely different directions (Steinberg and Caroubalos, 1970).

We have seen that the suprathermal electrons which produce type III bursts are guided along open magnetic lines of force. These lines are carried away by the solar wind into interplanetary space so that type III are observed from low in the corona to the earth orbit and beyond. If we were able to map the successive positions of the type III source, we could also draw 3-D maps of some solar magnetic lines of force.

Stereoscopic observations of radio bursts are powerful tools to study the corona and solar wind. This may be illustrated by some recent results obtained with the STEREO-1 experiment carried out in 1971-1972 at 169 MHz in cooperation between France and the Soviet Union. (Caroubalos and Steinberg, 1974; Caroubalos, Poquerusse and Steinberg, 1974 ; Steinberg, Caroubalos and Bougeret, 1974). At 169 MHz, radio bursts of types I and III occur at altitudes in the range 0.3 - 0.5 solar radius.

STEREO RADIOASTRONOMY OF TYPE I BURSTS

Let $\theta$ be the stereo angle between the two observing directions. When $\theta$ increases, the correlation between the two intensity- VS time -

records taken simultaneously (in the source time scale) decreases in general. Even with $\theta \simeq 15°$, this is clearly visible, but when $\theta \simeq 35°$, the correlation coefficient is less than 0.1. This means that the beamwidth of type I radiation is sometimes smaller than about 25°. However, on some consecutive days, the same intensity may be received at both observing sites and then the beam pattern looks nearly isotropic. Such an apparent contradiction can be resolved if we note that the STEREO-1 observations were carried out in the ecliptic ; so that we are actually analyzing only a plane section of a 3-D beam pattern and we do not know the configuration of the beam pattern out of that plane ; we cannot, for instance, know if the 3-D beam pattern is solid, multilobed or even hollow. It is easy to conceive beam shapes whose cross sections by different planes can be either narrow or broad.

The ratio R of the burst intensity measured in Space $I_S$ to that measured at the earth $I_E$ varies widely from event to event ; so that the beam has to be randomly oriented if its shape is assumed almost constant ; the rms deviation of the orientation is about 0.25 of the beamwidth and this is a rather clear indication that the source does not contain a large number of inhomogeneities.

This is, in turn, connected to an old problem : type I burst intensity can vary by a large factor in 0.1 second ; but the observed source size is about 3 arc min or 0.3 light-second ; so that it was suggested long ago (Högbom, 1960 ; Fokker, 1960) that what we see is actually the scattered image of a deeper and smaller source. In a scattering corona, the assumed small scale inhomogeneities do produce a broad scattered image of a point source but at the same time they broaden the angular distribution of the radiation from that point source. Both effects are intimately connected together via the scattering power distribution along the path. The total rms random angular deviation of the radio rays over their trip from the source to us cannot be larger than half the observed beamwidth ; STEREO observations yield directly a measure of the beamwidth and, thus, an upper limit to the rms angular deviation along the path. This limit is too small for the existing models to account for more than a small part of the image size. Therefore either there is less scattering than generally assumed to account for most of the source apparent size or the inhomogeneities built in the models are inadequate.

In any case it has been demonstrated that very interesting information on the beam orientation and shape can be obtained from stereoscopic observations. To learn more, it is necessary to go out of the ecliptic plane for the following reasons :

- to compare the beam orientation to that of the density gradient we must know the latter and therefore the 3-D electron density distribution in the source region. This can be obtained from coronagraphic measurements on the limb where the electron density distribution as a function of latitude will always be better known than the longitudinal one. It is therefore much more effective to measure the beam orientation in a plane perpendicular to the ecliptic than in the ecliptic.

- operating a stereoscopic experiment between an out-of-the-ecliptic probe and the earth will also provide a larger variety of cross sections of the beam pattern using solar rotation (fig.1); in the ecliptic, solar rotation moves the same cross section of the beam across our lines of sight. Using an out-of-the-ecliptic set-up one should be able to get much closer to a complete descriptinn of the 3-D beam pattern of the bursts.

If the out-of-the-ecliptic probe is on a 1 AU orbit, in a plane tilted to the ecliptic, the stereo angle will also vary quite rapidly and this is again favourable to a detailed description of this beam pattern.

STEREO RADIOASTRONOMY OF TYPE III BURSTS

The spectrum of a type III in a frequency-time domain (dynamic spectrum) shows a band of noise drifting from high to low frequencies. This band is sometimes split in two components which, at a given time, are centered on harmonic frequencies. Some type III's are therefore made of two components which are believed to be produced,one (the "fundamental") at the local plasma frequency $f_p$, the other at twice that frequency. When observed with a single frequency receiver, the first component is recorded first and the second some seconds later, making up a "pair" of type III's.

This interpretation of pairs as fundamental-harmonic pairs has been questioned in recent times but not in a convincing way ; and to settle that question,directivity measurements are important : indeed, the conversion mechanism and the propagation conditions are different for the fundamental and the harmonic ; for instance, the fundamental is generated at about the local plasma frequency so that it should be beamed into a narrow cone ; and if the corona is assumed quasi spherical this cone should be about radially oriented so that few fundamental components should be seen in high longitude events ; this is not the case :

fundamental components are seen nearly all over the disc.

Stereoscopic observations showed that the first (fundamental) component of a pair is systematically more directive than the second (harmonic) and this is a strong argument for the fundamental-harmonic interpretation of pairs (fig.2).

The time profile of a type III at a fixed frequency is also rich in information as it is the convolution of an exciter function by the transient response of the corona which includes the effects of multipath propagation. At 169 MHz, it was found independent from the direction of observation ; therefore propagation conditions do not play an important role in the formation of the time profile.

While the time profile is independent of the direction of observation the intensity ratio $R = I_S / I_E$ can take values very different from unity ; the rate of change of the intensity with the observing directions can reach ± 10 dB and more over 30°. This proves, again, that coronal scattering is less effective than previously thought ; even less effective than necessary to account for some other observations ; for instance, scattering has been invoked to explain that, at a given observing frequency f, the fundamental component (local plasma frequency $f_p = f$) and the harmonic component ($2f_p = f$) are observed at the same position although the first should take place at the f critical level and the second at the f/2 critical level, higher up in the corona. This observation is indeed explainable in a scattering corona (Riddle, 1972 ; Leblanc, 1973) but the scattering power has to be larger than the one deduced from directivity measurements.

Another result from STEREO observations is that the directivity ratios of various type III's can be very different. This can be interpreted if the observed directivity is produced by coronal macro-structures mostly in the form of streamers. On Nov.14, 1971, for instance type III have been observed through a streamer ; the overdense streamer material reflects, absorbs and scatters the type III radiation, away from its source and produces the observed directivity. If this interpretation is correct, the streamers or "lames coronales" detected by Axisa et al (1971) do control the type III image size and shape as a piece of ground glass or a light shade. Observations of these images with radioheliographs together with Stereoscopic observations can be used to study the streamer structure which is hard to resolve optically because of line of sight integration effects. We still do not know where are the type III sources located as compared to streamers ; to settle that question 2-D position measurements at radio frequencies are necessary but at the present time, they are no more accurate than 1 arc min or so. Occultation effects are only detectable with Stereoscopic observations but they are very sensitive to the position of the source relative to the occulting structure. They open up new ways to localize the path of the type III electrons relative to streamers and the site where these electrons are accelerated in the active region. Here again the stereoscopic observations should be carried out on an out-of-the-ecliptic probe because the macro-structure of the corona is better known from optical observations as a function of latitude than of longitude.

One of the most useful properties of type III's is that they are produced over trajectories which span the interplanetary medium. At each altitude the 10-100 keV electrons induce plasma waves which are scattered into electromagnetic waves at the local plasma frequency f. or at twice that the frequency. Therefore from the measurement of the position of type III's at several frequencies, a map of the electron density along the trajectory and a map of that trajectory itself can be drawn.

As the energetic electrons travel most probably along magnetic lines of force, we have a way of plotting such sun-rooted lines of force up to the earth orbit and beyond even out of the ecliptic.

Such an experiment should be carried out at frequencies lower than 10 MHz if we are interested in the coronal and solar wind structure higher than 10 $R_{\odot}$ ; this means that observations should be made from space as radiation of these frequencies do not reach the earth. As a matter of fact IMP-6 has just done that (Fainberg and Stone, 1974). IMP-6 was spin stabilized around an axis perpendicular to the ecliptic and carried a dipole perpendicular to that axis. Using the nulls in the receiving pattern of a short electric dipole it is quite possible to measure the direction of a source as projected on the ecliptic plane. An experiment jointly designed and built by Paris Observatory and Goddard Space Flight Center teams will measure the direction of the type III source at 24 frequencies on ISEE-C. Using a spin plane and a spin axis dipole, the experiment will measure a complete direction (two angles) at each frequency and will produce 3-D maps of some magnetic lines of force from 10 $R_{\odot}$ altitude to the earth orbit and beyond. It will, however, be necessary to assume that these lines of force rotate with the sun as a solid body. The use of a second remote satellite equipped in much the same way as ISEE-C could eliminate this restriction.(fig.3).

There are some indications from the radioastronomy experiments on IMP-6 and other experiments that few type III have been detected far out from the ecliptic. This might very well be due to some directivity of the radiation, but this difficulty can be overcome by going out of the ecliptic.

One of the main purposes of any out-of-the-ecliptic mission will certainly be to explore the 3-D topology of the interplanetary magnetic field and more specifically its latitude variation ; the role of solar active regions in the determination of this topology will be studied. Equipments designed to measure the local magnetic field vector will be flown to achieve this goal but it will be very hard to reconstruct the magnetic configuration in the whole heliosphere from local measurements only. Type III tracking at several frequencies can provide the overall description of this field topology which will be essential to the interpretation of most local measurements made on the O/E probe : for instance the modulation of cosmic rays by the interplanetary magnetic field cannot be understood without a description of this magnetic field in the whole heliosphere.

CONCLUSION

Stereoscopic observations of solar radio bursts are not needed only to improve our knowledge of the physics of these transient radio emissions. In the deci- to decameter-λ range, they can be used to probe the macro and microstructure of the corona. In the hm to km-λ range, type III's are natural tracers of sun-rooted magnetic lines of force ; tracking them as a function of frequency will give a 3-D map of some lines of force from low in the corona to the earth orbit and provide an overall picture of the interplanetary medium which is essential to the interpretation of local measurements.

The choice between the two wavelength ranges depends upon the scientific objectives of the mission ; but it has been shown that, in [illegible]es, observations should be carried out from an out-of-ecliptic probe.

**ACKNOWLEDGMENTS**

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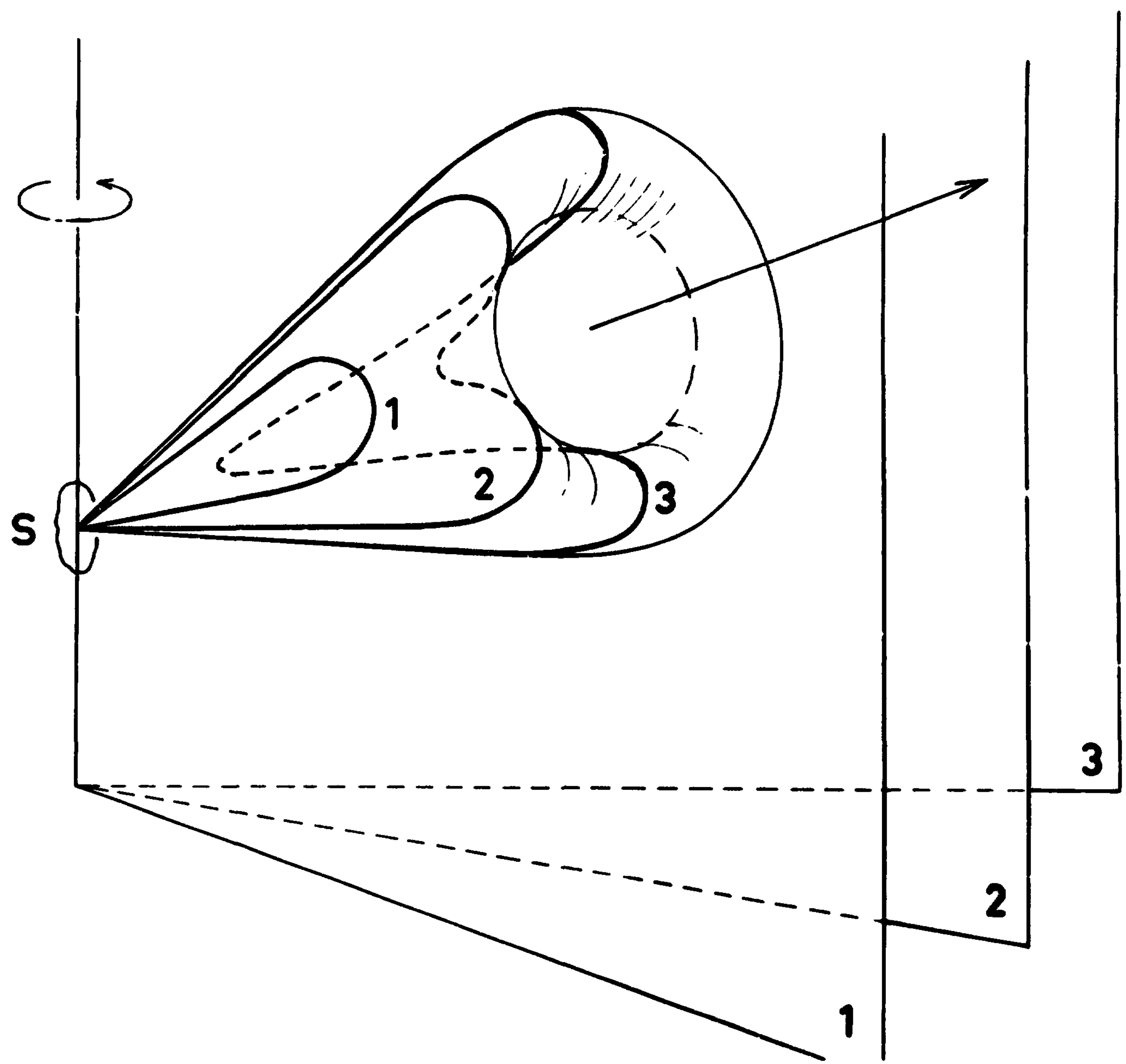
**3-D Solar radioastronomy**

**Figure Captions.**

**Fig.1** Exploration by stereoscopy in a plane perpendicular to the ecliptic of the radiation pattern of a radio burst using solar rotation. The plane sections 1 to 3 are analyzed at different times. If the exploration was carried out in the ecliptic, only one plane section would be studied.

**Fig.2** A typical pair of type III bursts at 169 MHz as recorded from the earth (top) and from the Mars-3 Soviet space probe on Nov.14, 1971. The intensity ratio $I_{Space}/I_{Earth}$ first component (fundamental) is always greater than that of the second component (harmonic).

**Fig.3** 3-D mapping of a solar magnetic line of force using a type III burst as a tracer.



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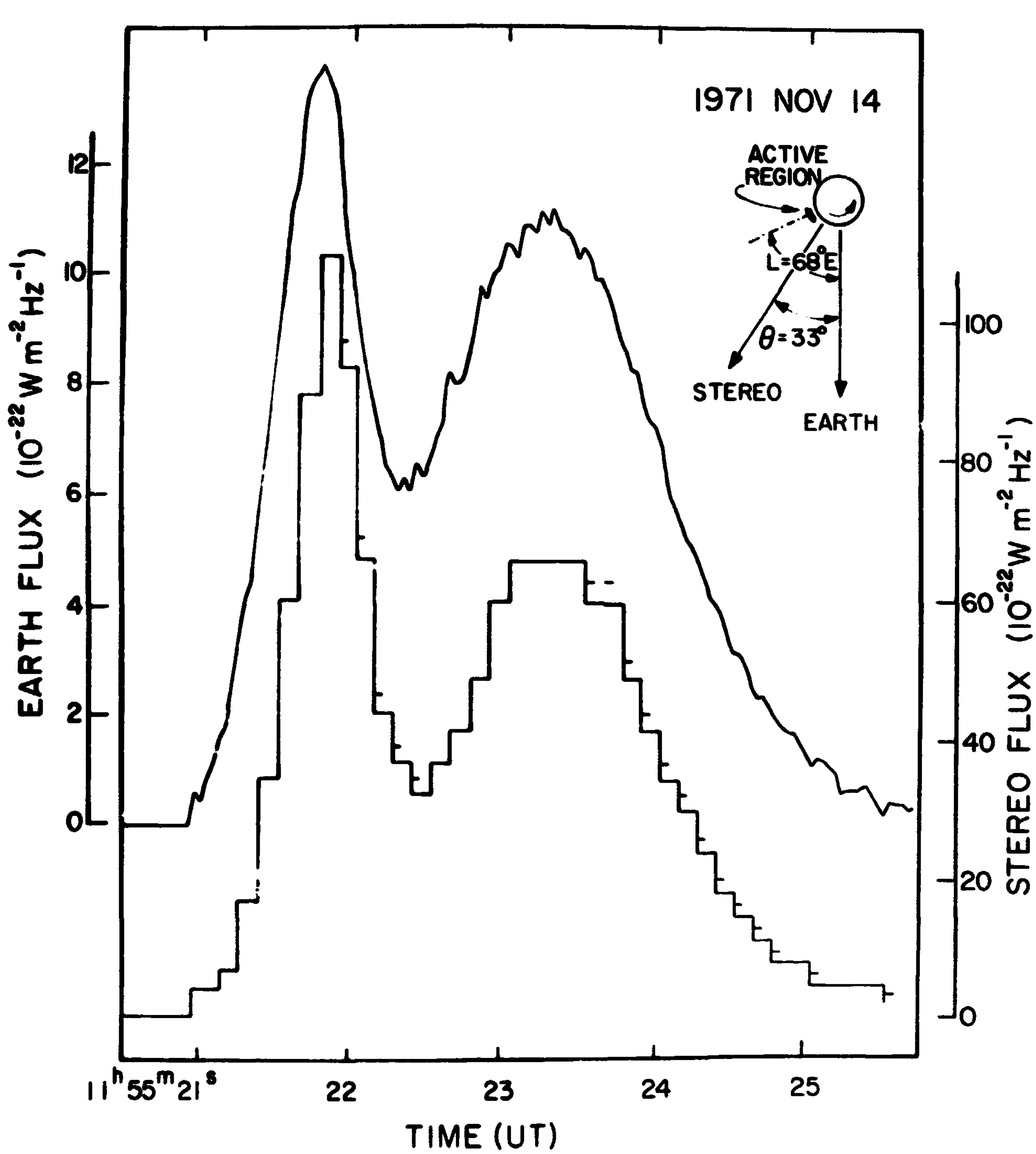
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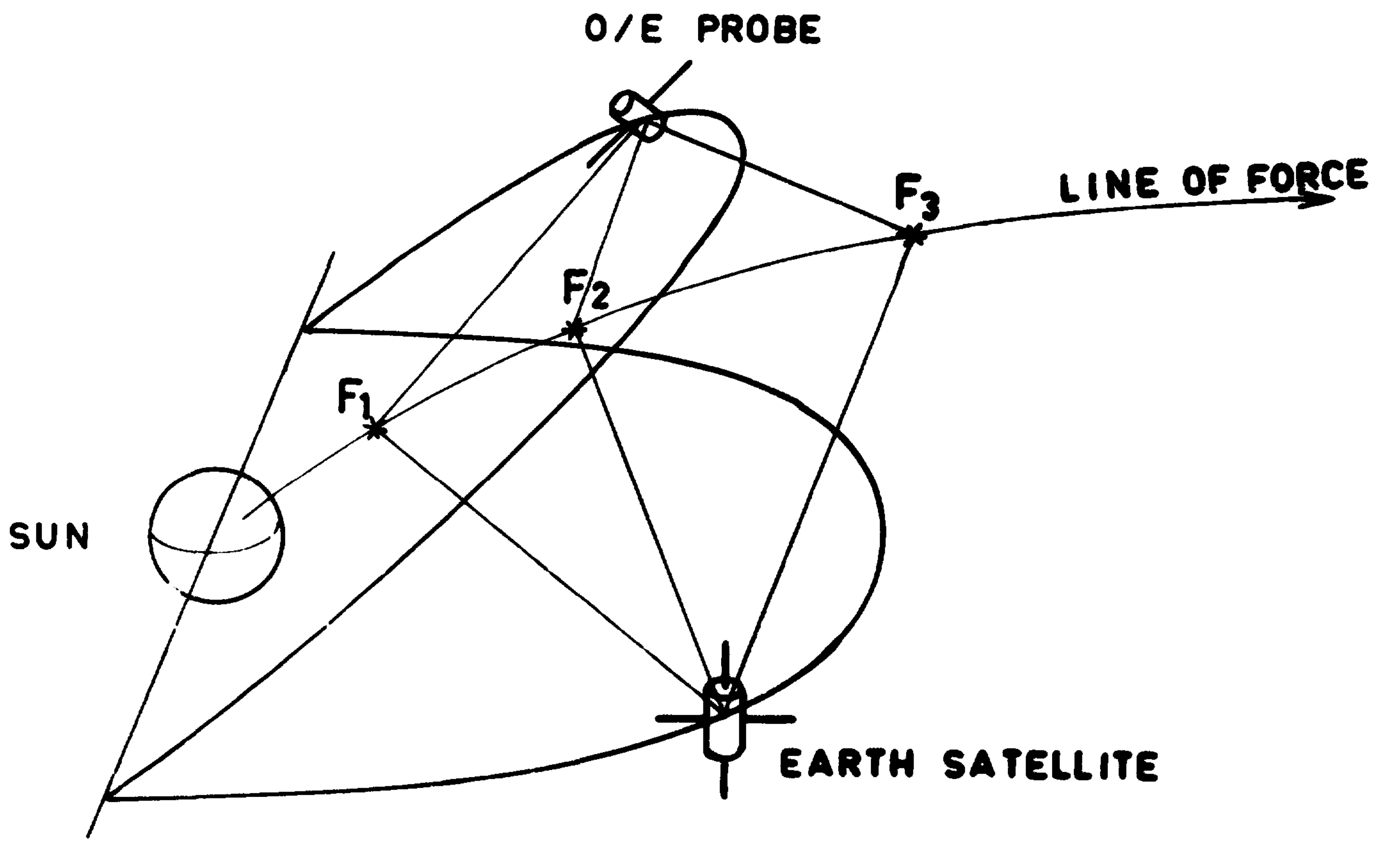
O/E PROBE
F3
LINE OF FORCE
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