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IRREGULARITIES OF PLASMA DENSITY IN THE SOLAR NEIGHBOURHOOD

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Summary

Observations of radio scattering in the outer corona and the interplanetary medium were carried out in 1964 using a 38 Mc/s interferometer on a baseline of 10 km. The radial dependence of scattering has been studied over the range 10–100 R_0 and the gradient was found to become progressively less steep at large distances. This result explains some discrepancy between earlier measurements and suggests that the irregularities are caused by plasma instability. The scattering at all distances has decreased by a factor of 5 since 1959.

1. *Introduction.* The angular scattering of radio waves caused by irregularities of plasma density near the Sun has been studied extensively since 1952 and it has been shown that irregularities are a permanent feature of this region during all phases of the solar cycle. More recently the discovery of interplanetary scintillation (**1**), (**2**) has demonstrated that the irregularities extend to distances beyond the Earth's orbit.

Radio observations are important for two reasons. They allow the interplanetary medium to be investigated in the region where optical methods fail and to which space-probe measurements have not yet penetrated; they are also sensitive to irregularities on a much smaller scale than can be detected by other methods. Results from space-probes (**3**) and the cosmic ray anisotropy (**4**) have yielded information about magnetic field irregularities on a scale greater than 10^5 km, while radio scattering is caused by structure on a scale less than a few thousand kilometres (**5**), (**6**).

The magnitude of the radio scattering is governed by three factors: the physical extent of the irregularities, the magnitude of the plasma density variations and the number of irregularities distributed along a line of sight. By themselves, scattering measurements have been used to set an upper limit of a few thousand km to the scale of the irregularities and this has enabled limits to be imposed upon the mean electron density obtained by smearing out the irregularities to fill the whole volume (**5**), (**6**). The greatest uncertainty in this analysis is the extent to which the volume is filled by irregularities, the largest mean density being obtained when the irregularities are close-packed. The density so derived is less than estimates based on optical and space-probe values which suggests that the irregularities account for only about 10 per cent of the total electron content.

Studies of the interplanetary scintillation of the source 3C 48 have given information about the scale of the irregularities and the phase deviation which they introduce for the region 0·4–1 a.u. (**7**). At these distances the irregularities constitute a weak scattering medium (random phase variations less than one radian). It is important to bear in mind, however, that irregularities which cause scintillation must have a scale smaller than the Fresnel zone radius so that the

3C 48 measurements would have been insensitive to irregularities larger than about 750 km. No such limitation applies to the radio scattering measurements.

Little is yet known about the origin of the scattering irregularities. It has been suggested that plasma density variations on a scale smaller than the mean free path might be accounted for by ' frozen-in ' magnetic fields (**8**), (**9**). Evidence favouring this idea is the scattering anisotropy (**9**)–(**11**) which gives support to the concept of filamentary irregularities aligned roughly radially. More recently, space-probe measurements (**3**) have indicated that the interplanetary magnetic field has a filamentary structure whose mean orientation conforms to the spiral pattern predicted by Parker (**12**). The magnetic filaments are, presumably, associated with perturbations of plasma density and while the observed scales are too large to explain the radio scattering a substructure might exist which cannot, as yet, be detected by space-probe measurements.

Another possibility, suggested by the remarkably small scale of the scattering irregularities, is that the density fluctuations are generated by plasma instability. Some attempt to distinguish between the filamentary and instability models may be made if the variation of scattering with distance from the Sun is determined over a sufficiently large range. Previous measurements of the radial variation have been assumed to follow a simple power law and the results have shown some discrepancy. For example, Ericson (**13**) observing at 26 Mc/s in 1961–1962 derived a radial index of $-2{\cdot}0$, while Hewish & Wyndham (**5**) obtained values of $-1{\cdot}46$ in 1961 and $-1{\cdot}41$ in 1962 at frequencies of 38 Mc/s and 26·3 Mc/s. The latter measurements are also in reasonable agreement with observations at 85·5 Mc/s by Slee (**6**).

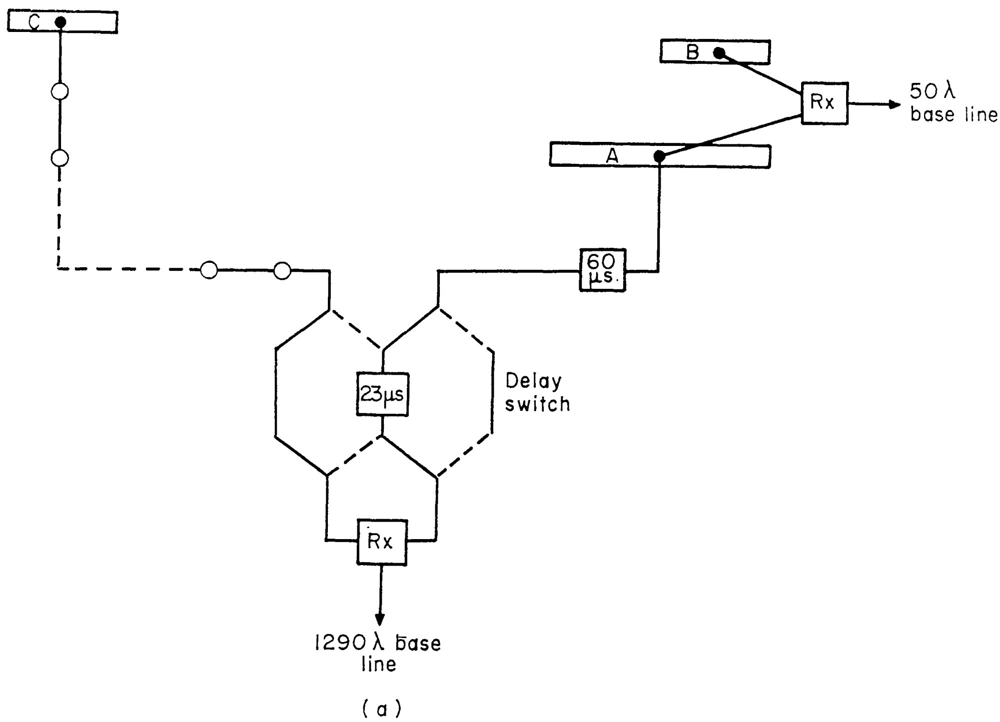
To investigate the radial variation in more detail, and to make an extensive study of radio scattering at sunspot minimum, a new series of observations was carried out in 1964 and the results are presented in this paper. It is shown that the discrepancy between earlier estimates of the radial variation has arisen from the inadequacy of a simple power law model. Our present results give evidence for a radial variation which becomes progressively less steep as the radial distance increases; when this is allowed for the earlier results are found to be mutually consistent. A radial gradient of this kind suggests plasma instability as the most likely origin of the irregularities.

2. *Observations*. The observations were carried out at a frequency of 38 Mc/s using an interferometer on a base-line of 10 km (1290 λ) extended in an east–west direction. The reception pattern of the interferometer was designed to comprise three main responses, one on the meridian and one on either side, so that a radio source could be recorded thrice daily. In this way the effective azimuth of the baseline was varied and it was possible to study the scattering anisotropy. In addition to the 10 km interferometer another arrangement was used which provided a short baseline of 50 λ suitable for studying large scattering close to the Sun. Radio sources included in the observations were 3C 84, 3C 123, 3C 134, 3C 144 and 3C 274.

When the observations were planned it was anticipated that 3C 144 (the Crab Nebula) a source which has been frequently used for scattering measurements, would be of little value owing to its resolution by the narrow fringes of the 10 km interferometer. Fortunately this proved not to be the case, since the nebula was found to contain an unsuspected component of small angular diameter radiating predominantly at low frequencies (**14**).

The 10 km (1290 λ) interferometer consisted of a 3000 ft corner-reflector at the observatory combined with a 720 ft reflector of similar construction at the distant site. An additional 720 ft reflector was constructed in order to provide a short base-line (50 λ) and the arrangement is shown in Fig. 1(a). Each interferometer pair was connected to a similar phase-switched receiver and, in the case of the distant aerial, the signals at 38 Mc/s were conveyed to the main site by way of a buried cable. Attenuation in the cable was compensated by a series of battery-operated pre-amplifiers inserted at intervals of 3000 ft. At the receiver a quartz delay line was used in the connection to the local aerial in order to compensate for the 60 μs delay.

The dipole arrays in each reflector contained elements spaced by 1·4 λ in order to produce three widely-spaced maxima in the reception pattern. The location of these maxima and the corresponding position angles of the interference patterns



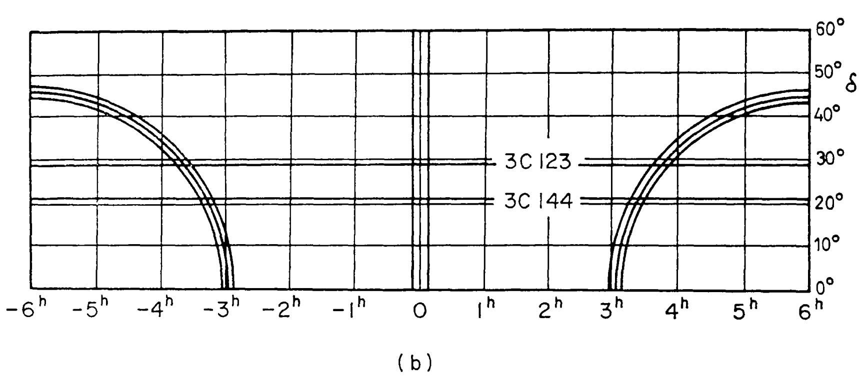


FIG. 1(a). *Schematic diagram of the aerial system. A and B are 3000-ft and 720-ft corner reflectors. The distant aerial C, a 720-ft corner reflector, is connected to the local site via a buried pre-amplifier chain.*

(b) *Sketch of the reception pattern indicating the three responses as functions of declination and hour angle.*

contained within them are shown in Fig. 1(b). A bandwidth of 0·2 Mc/s was used in conjunction with a time constant of 2 s and a selection of either off-meridian response was made by incorporating an additional delay of 23 μs in the cable from one side of the interferometer or the other. During the observations the beam was switched automatically according to a pre-arranged sequence on a clock driven programme disc. The sensitivity of the interferometer was reduced by a factor of about two for the off-meridian transits owing to the reduced gain of the array elements in these directions.

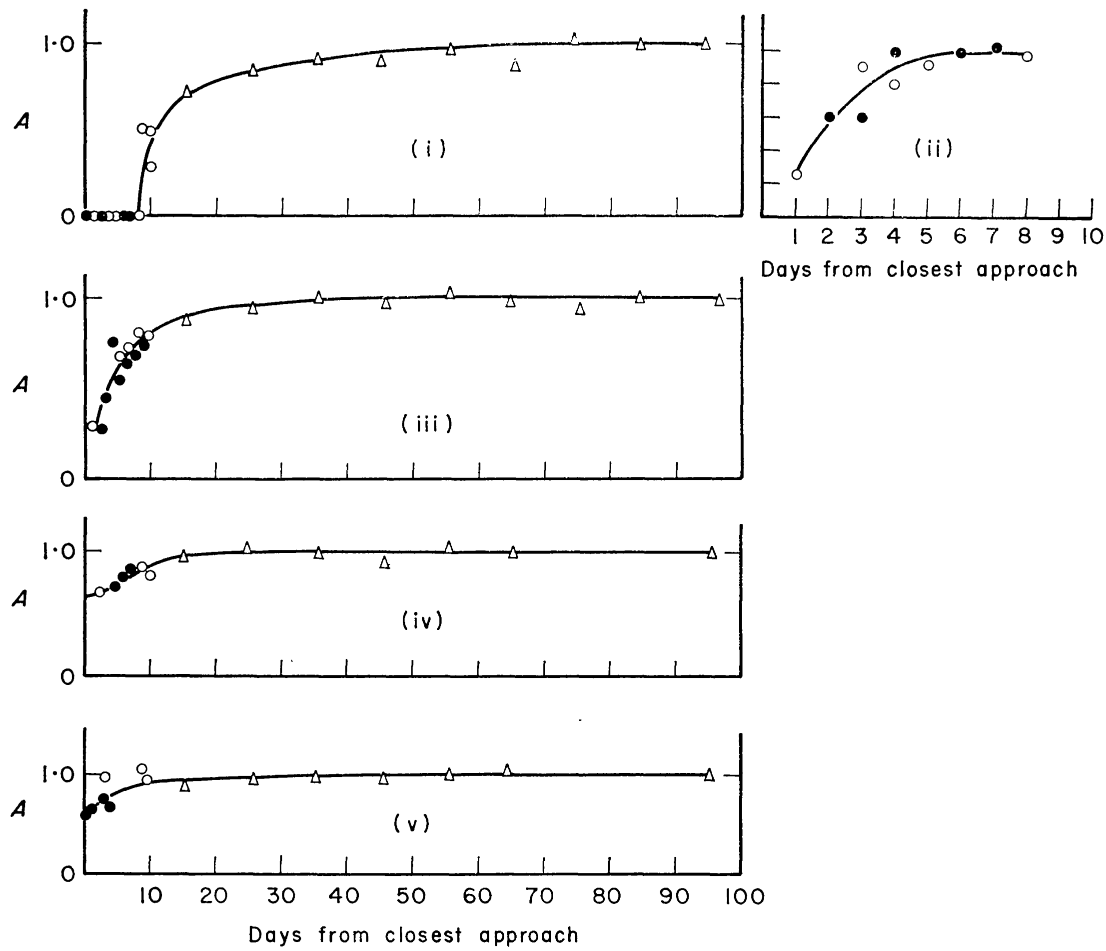


FIG. 2(a). *Observed fringe amplitude (A) as a function of time taking the date of closest approach as origin.*

● *daily observations, source approaching the Sun*
○ *daily observations, source receding from the Sun*
△ *ten-day averages*

(i) 3C 144 *meridian transit* (1290 λ)
(ii) 3C 144 *meridian transit short base-line* (50 λ)
(iii) 3C 123 *meridian transit* (1290 λ)
(iv) 3C 123 *early transit* (*equivalent base-line* 905 λ)
(v) 3C 123 *late transit.*

Daily observations on a routine basis were carried out during February–October 1964, although occasional measurements were made during the preceding six months. In seeking long-period changes of fringe visibility associated with radio scattering at a large distance from the Sun it is essential to maintain a continuous monitor of instrumental sensitivity. For this purpose it was assumed that sources with an angular separation exceeding 90° from the Sun would exhibit negligible reduction of fringe visibility. Sources which satisfied this condition were used as calibration sources and a preliminary analysis of the data showed that 3C 84, 3C 134 and 3C 274 exhibited no significant reduction of fringe visibility as they approached the Sun. This result was unexpected and showed that a considerable decrease of scattering had occurred since the previous measurements in 1962. It demonstrated, however, that these sources could be used for calibration purposes throughout the observations.

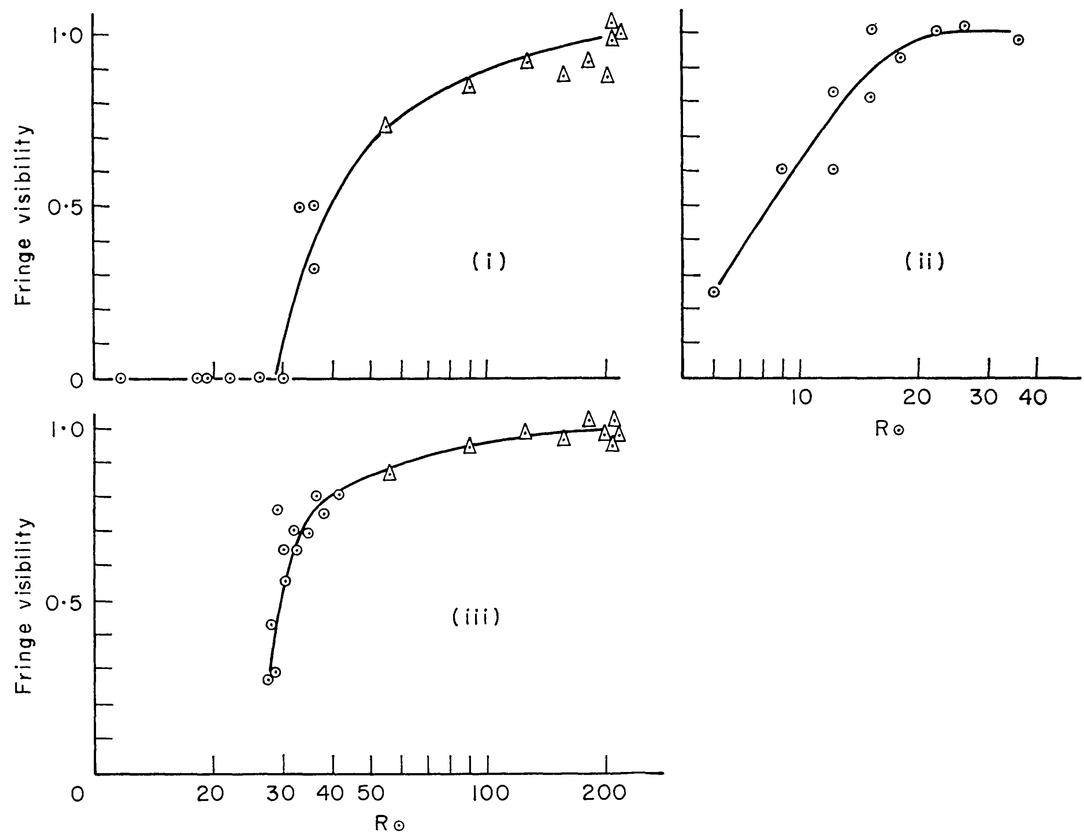


FIG. 2. (b) *Fringe visibility as a function of the distance of the line of sight from the Sun.* (i) 3C 144, (1290 λ), (ii) 3C 144, (50 λ), (iii) 3C 123, (1290 λ).

The observational data for 3C 123 and 3C 144 are shown in Fig. 2(a). Since we are concerned with the average properties of the interplanetary medium, rather than with its day to day fluctuations, the observations are presented as ten-day means except for sources in the immediate neighbourhood of the Sun where the fringe visibility changes rapidly. When a source was observed within 10 days of its closest approach the daily points have been plotted individially. In Fig. 2(b) the fringe visibility is plotted as a function of the perpendicular distance of the line of sight to the Sun.

3. *Interpretation of the data.* To derive the angular scattering from the measured reduction of fringe visibility it is customary to assume an angular spectrum of the form $\exp(-\phi^2/\phi_0^2)$. This assumption is only correct if multiple scattering takes place and it is natural that this supposition be questioned as observations are carried out at greater and greater distances from the Sun. Definite evidence on this

point has recently been obtained from the correlation of interplanetary scintillation at different frequencies (15) which has shown that the interplanetary medium gives only weak scattering at distances greater than about 0·4 a.u. at a frequency of 81·5 Mc/s. Measurements of interplanetary scintillation at 178 Mc/s carried out on many radio sources at different angular distances from the Sun (16) have, on the other hand, shown that multiple scattering takes place at distances $< 0{\cdot}2$ a.u. Scaling these measurements to the lower frequency of 38 Mc/s indicates that, for the present observations, the interplanetary medium must give rise to multiple scattering at radial distances $< 0{\cdot}5$ a.u. Although our observations of 3C 144 show a significant reduction of fringe amplitude beyond 0·5 a.u. no derivation of ϕ_0 beyond 0·5 a.u. has therefore been attempted. It is clear that the above considerations are important if scattering measurements using interferometric methods are to be made at greater angular separations from the Sun, but it may be that interplanetary scintillation provides a more sensitive and reliable technique for study of the interplanetary medium at such large distances.

A further point to be considered is the effect which interplanetary scintillation may have upon the observations of 3C 144, since it is not immediately clear that the concept of fringe visibility has any meaning in the case of a scintillating source. It may be shown, however, that if the random variations of fringe amplitude are averaged, either by the use of a suitable time constant in the receiver, or arithmetically, then the fringe visibility behaves exactly as if the apparent source dimensions were increased by scattering in the usual way.

Smooth curves were drawn through the data points, as indicated in Fig. 2(b) in order to derive the average variation of fringe visibility with radial distance. The corresponding variation of angular scattering ϕ_0 was then calculated assuming an angular spectrum of the form $\exp(-\phi^2/\phi_0^2)$ and the curves for 3C 123 and 3C 144 are displayed in Fig. 3. Results for the off-meridian transits are not included since these gave values of ϕ_0 which were not significantly different from those obtained for the meridian transits. This result agrees with the recent work of Slee (6) who also found little anisotropy during the current period of sunspot minimum. Considerable radio interference was experienced when 3C 123 was close to the Sun and for distances less than 0·2 a.u. observations were possible for only about one half of the available days. The somewhat smaller scattering observed for 3C 123, as compared with 3C 144, can be accounted for by a decrease of scattering with increasing heliographic latitude.

4. *Discussion.* It is of interest to compare the present results obtained at sunspot minimum with earlier results derived at different phases of the solar cycle. Previous measurements carried out at a frequency of 38 Mc/s using interferometers on an east–west baseline are also shown in Fig. 3. These observations have been described before in references (5), (9) and (10). A comparison of the curves suggests that the scattering at all distances from the Sun shows a similar solar cycle modulation, the variation from maximum to minimum being a factor of approximately 5. Observations carried out in different years tended to cover different ranges of radial distance, but all the measurements included a radial distance of 20 R_0 and for this distance a detailed comparison of scattering with smoothed sunspot number can be made. The result is shown in Fig. 4 and it is seen that a close correlation exists between sunspot number and the magnitude of the radio scattering.

In the past, as mentioned in Section 1, attempts have been made to account for the radial variation of scattering in terms of a simple power law $\phi_0 \propto (R/R_0)^{-x}$ and different observers have obtained discrepant results. It is clear, however, from the curves shown in Fig. 3 that a simple power law is inadequate and it appears that earlier disagreements can be largely accounted for in terms of the differing radial

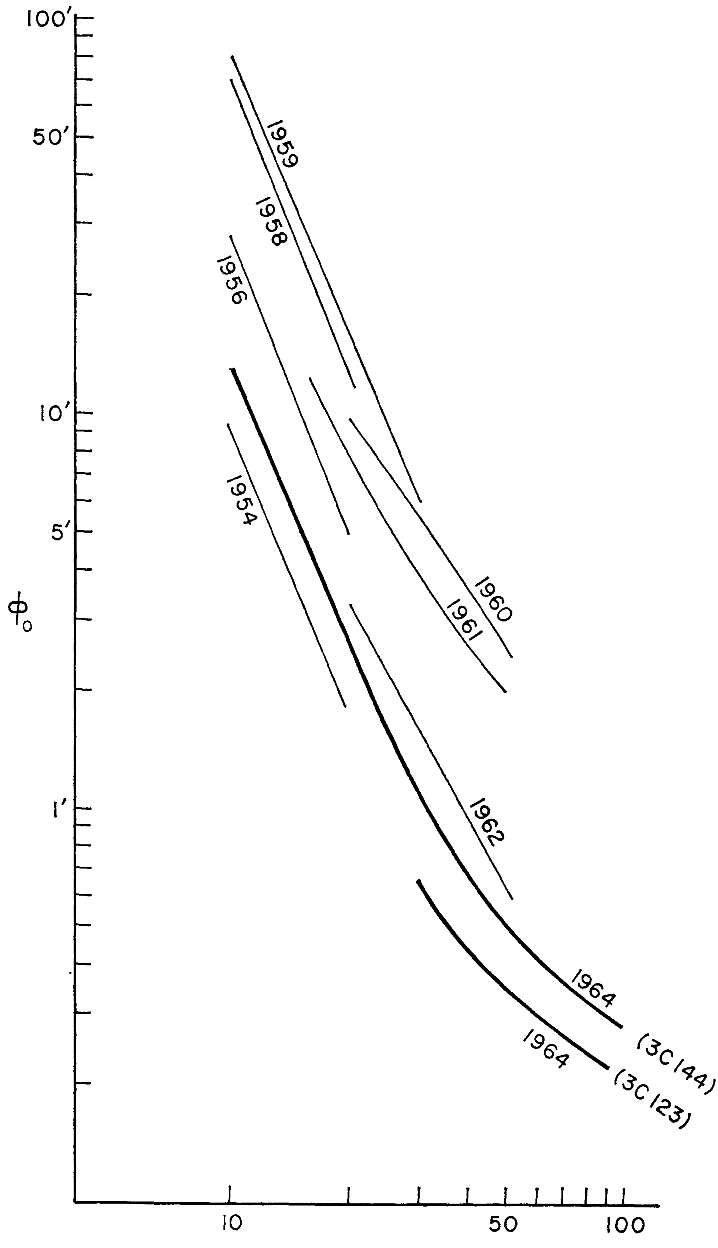


FIG. 3. *Angular scattering ϕ_0 at 38 Mc/s plotted against distance from the Sun (thick lines). Some earlier measurements are shown for comparison (thin lines).*

distance to which the data referred. Estimates of the power law index x derived from the results shown in Fig. 3 and earlier data are displayed in Fig. 5 and it is seen that the index decreases progressively with increasing radial distance from the Sun.

To appreciate the significance of the radial dependence of scattering, particularly with regard to the origin of the irregularities as discussed in Section 1, it is helpful to consider an idealized model. Suppose, for example, that the variation of plasma density is always the same fraction of the mean density and that the scale of the irregularities increases linearly with distance from the Sun, so that the irregularities always occupy the same fraction of the total volume. Then for this case the geometrical similarity of sample volumes requires that the radial variation of scattering be the same as that of the mean plasma density (9).

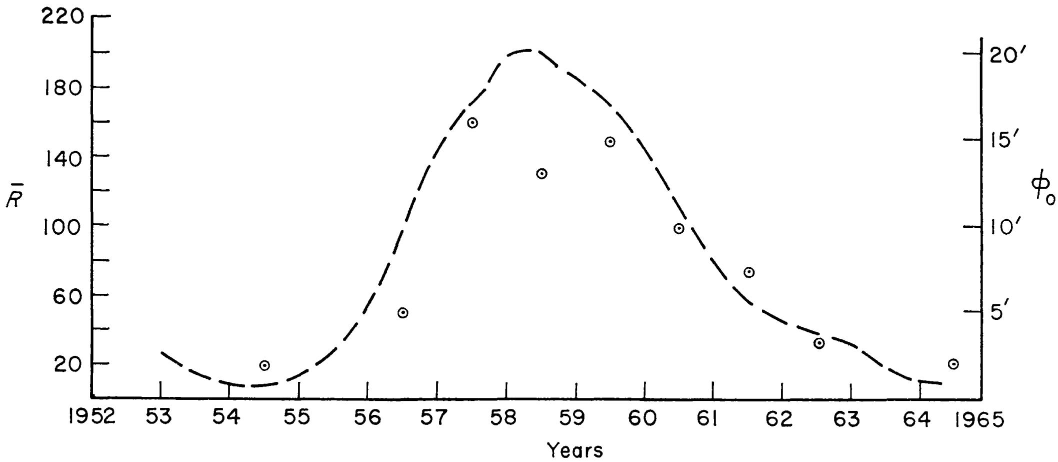


FIG. 4. *Angular scattering (observed at 20 R_0) compared with smoothed sunspot number $\bar{R}$ (broken curve).*

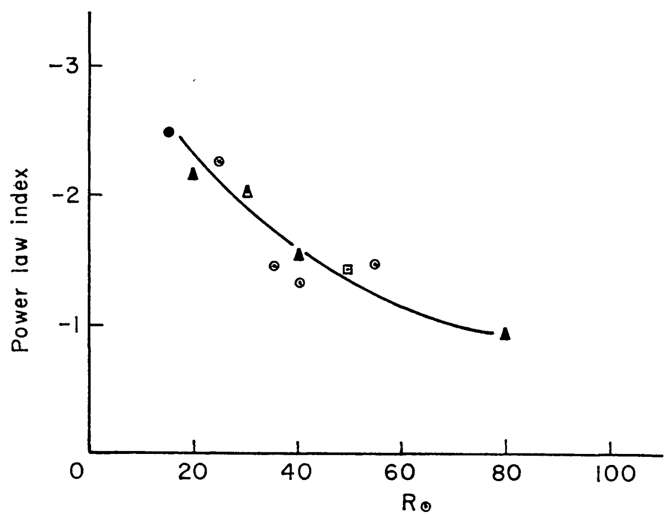


FIG. 5. *The variation of radial power law index (x) with distance from the Sun.*

● *Högbom* (9)	*mean over range* 5–20 R_0 *in* 1958
○ *Hewish & Wyndham* (5)	*mean over range* 10–40 R_0 *in* 1959
	mean over range 20–50 R_0 *in* 1960
	mean over range 20–80 R_0 *in* 1961
	mean over range 20–50 R_0 *in* 1962
△ *Ericson* (13)	*mean over range* 10–50 R_0 1961–62
□ *Slee* (6)	*mean over range* 20–80 R_0 1960–62.
▲ *Present observations.*	

No reliable measurements of the mean plasma density are available beyond 16 R_0, the limit reached by Blackwell & Petford (17), and within 0·8 a.u. where space-probe values have been given. In the presence of a radially symmetric solar wind of constant velocity, however, a plasma density following an inverse law would be expected. Blackwell & Petford obtain a relation $N_e \propto (R/R_0)^{-2\cdot3}$ in the range 5 R_0–16 R_0 and show that an extrapolation of this law gives values in fair agreement with space-probe observations at 1 a.u. We therefore conclude that the density does not vary more slowly than an inverse square law. If the plasma density fluctuations were as postulated in our idealized model the radial variation of scattering should follow the same approximate inverse square law. This is evidently not the case beyond 20 R_0 as shown by Fig. 5. In an earlier attempt to resolve this difficulty a solar wind which converged toward the heliographic equator was postulated (5); this led to a radial variation of mean density $N_e \propto_e (R/R_0)^{-1\cdot7}$ which does not agree with the estimates discussed above and this suggestion must therefore be discarded.

In order to adjust our simple model to fit the scattering measurements it is necessary either to increase the number of irregularities along a line of sight, or to increase the modulation of plasma density. Neither of these possibilities can occur if the density variations are associated with magnetic filaments rooted to the sun as depicted by recent space-probe measurements. Indeed, as shown by Parker (**18**), the balance of magnetic and kinetic pressure between filaments acts in such a manner as to reduce the density perturbation progressively with distance from the sun, so that a filamentary model should give a radial variation of scattering which is steeper than an inverse square law.

It therefore appears that plasma instabilities, which grow progressively as the plasma is swept outwards from the Sun, afford a more reasonable interpretation of the radio scattering data. Parker (**12**) has predicted that instabilities are to be expected; the detailed types of instability which might naturally occur, in the light of recent space-probe data concerning the anisotropic velocity distribution of protons, have been considered by Scarfe *et al.* (**19**). Further evidence favouring the instability hypothesis is the remarkably small scale of the irregularities which has been shown, from interplanetary scintillation data, to be little larger than the ion gyro radius (**7**). If this interpretation of the scattering is correct, then the dependence of scattering upon distance from the sun should provide valuable information concerning the growth-rate of the instability.

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