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PRELIMINARY OBSERVATIONS OF INTERPLANETARY SCINTILLATION AT 69.3 MHz

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Abstract

Observations of interplanetary scintillation of radio sources for studying the solar wind have been carried out at two stations, Toyokawa and Fujigane, since June, 1970. The aerial is a square array containing 256 half-wave dipoles. A phase-switching receiver and a recording system which assure the simultaneity of the records taken at the two stations are used. The observational data are analysed by the statistical method. The velocity enhancements of the solar wind which correspond to the Forbush decrease and the geomagnetic storm have been detected by the observation of 3C 48 about 3 days after the solar flare. There is a tendency for the scale of the diffraction pattern to increase with increasing velocity, as pointed out by Vitkevich and Vlasov. The average scale of the diffraction pattern is about 300 km and it appears that the scale of the pattern or the size of the density fluctuations in the solar wind increases with increasing solar activity.

1. Introduction

Interplanetary scintillation (IPS) was discovered by Margaret Clark during a 178 MHz interferometric survey of radio sources at Cambridge and was applied by Hewish et al. (1964) and Cohen et al. (1966) to investigations of angular structure of quasi-stellar radio sources and solar wind. The first 3-station observation of IPS for studying the solar wind was made by Dennison and Hewish (1967) at 81.5 MHz in 1966. They observed IPS of 3C 48 and measured the motion of the diffraction pattern across the surface of the earth produced by the density fluctuations in the solar wind.

According to Dennison and Hewish, the average velocity of the solar wind was about 300 km/sec at a distance of 0.8 a. u. from the sun and 490 km/sec at a distance of 0.36 a. u. when the line of sight crossed the polar region of the solar atmosphere. This variation of the velocity with the distance from the the sun was interpreted as an increase of the velocity associated with heliocentric latitude. The observed direction of the solar wind fitted the expected direction for a radial flow from the sun within the experimental uncertainty of $\pm 15°$ and the scale of the diffraction pattern was found to be 100~200 km.

Vitkevich and Vlasov (1970) also observed IPS of the same source at three stations during nearly the same period, 1966~1967, and, in contrast to Cambridge observations, they found that there was a deviation from the radial motion which was dependent on the heliocentric latitude.

The above two observations were carried out near the minimum of the sunspot cycle and confined to the regions where the line of sight of 3C 48 crossed. Therefore, further observations may be considered to be necessary to derive the three-dimensional model of the solar wind and to study the effects of solar activities on the solar wind. Recently, Dennison and his colleagues (1968) have observed IPS of many scintillating sources with the Calgoora radio telescope and have detected the plasma streams and the flare effects. In Japan, the "SFE" study, which will investigate solar flare effects on interplanetary space and the magnetosphere with ground-based and rocket observations, has been planned as one of the IASY projects and it has been decided that our group will also make IPS observations for studying storms in interplanetary space.

In this report, the results of preliminary observations made during this year are described. For financial reason, we have now only two observing stations, but it may be possible to compare our results with solar-geophysical data and discuss the effects of solar activity in some extent.

2. Equipment and Observations

Two observing stations are now operating for the simultaneous observation of IPS. One station is at Toyokawa and another one is at Fujigane at the foot of Mt. Fuji. These stations are separated by a distance of 126 km, as shown in Fig. 1. Each station is equipped with a 256-element dipole array antenna backed by a reflecting screen, which has the physical dimensions of 40m×40m and is operated at a frequency of 69.3 MHz. This antenna is divided equally into two parts in the east-west direction and operated as a phase-switching interferometer. The half-power beam width is about $3° \times 6°$. By changing the length of the cable, the beam is tilted in the north-south direction so that we can observe the scintillating sources distributed in a declination range from 0° to 70°. Photographs of the antenna are shown in Fig. 2.

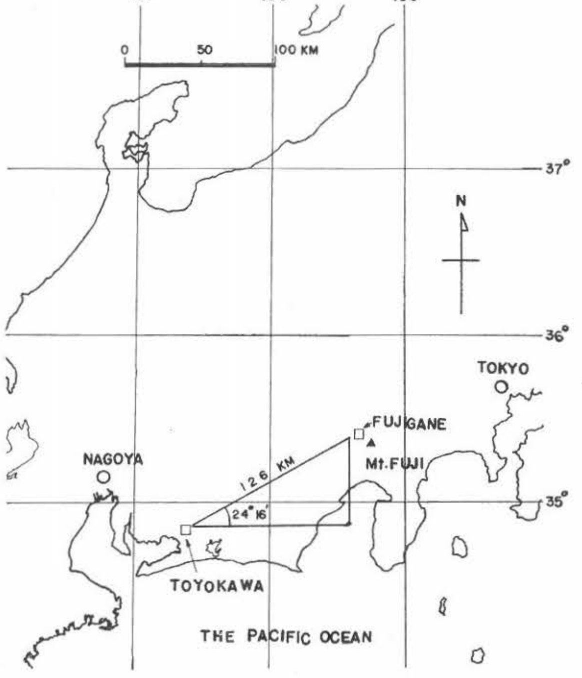
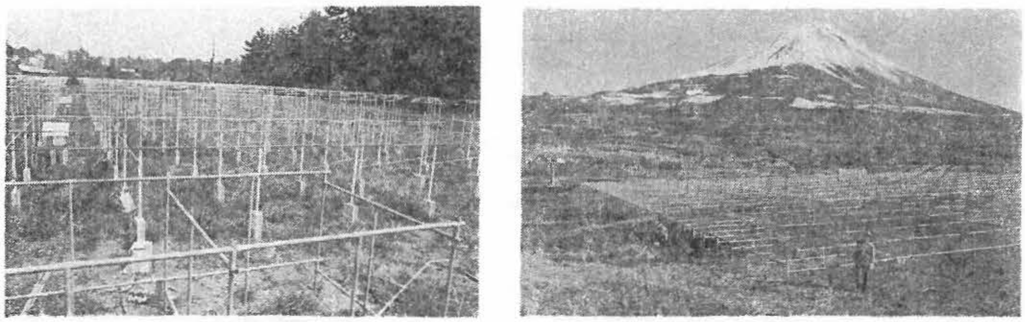


Fig. 1. Geophysical arrangement of two stations. Toyokawa and Fujigane.



TOYOKAWA FUJIGANE

Fig. 2. Photographs of the dipole array antenna.

As a telephone line or radio link is not available, a special recording system is used to assure the simultaneity of two records obtained independently at two stations. This system is shown in Fig. 3(a) and (b). The output of the low frequency amplifier of the receiver is recorded in one channel of the two-channel magnetic taperecorder and the reference voltage of 210 Hz (phase-switching frequency) for phase sensitive detection is recorded in another channel together with the highly stabilized 1 KHz signal. This 1 KHz signal is recorded through the gate which is opened by the minute signal of JJY, Fig. 3(a), at a pre-set time. When the recorded magnetic tape is played back, the 1 KHz signal is separated from the reference voltage and introduced into the system controller of the analog-digital converter. This controller counts the number of pulses of 1 KHz and sends one command signal to the digital voltmeter every 50 counts. The output of the phase-sensitive detector of the playback amplifier is sampled and digitized by the digital voltmeter at intervals of 50 msec and punched on a paper tape. Using this system, we can assure the simultaneity of two records within 10 msec.

Simultaneous observations of IPS at two stations have been carried out since

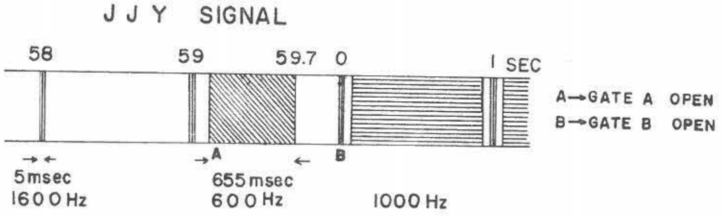


Fig. 3 (a) JJY clock signal.

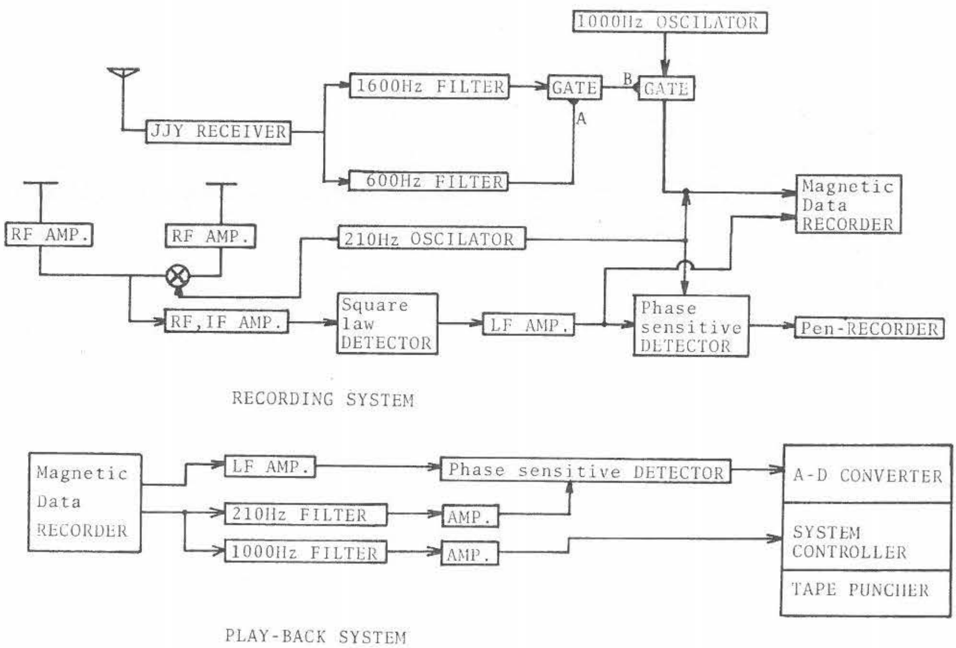
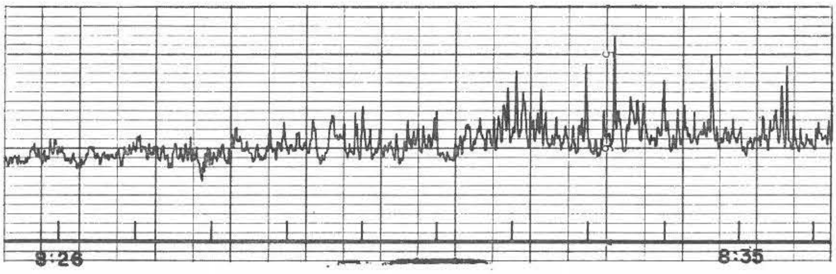


Fig. 3 (b) Recording and play-back systems.

June, 1970. The observed sources are 3C 48 (in June), 3C 147 and 3C 196 (in July and August), 3C 286 (in Sept.) and 3C 298 (from Oct. to Dec.).

An example of the chart record of 3C 48 is shown in Fig. 4. Because of the poor directivity of the antenna, we cannot find the mean flux density of 3C 48, but the intensity fluctuations are clearly seen.



3C48 4 JUNE 1970

Fig. 4. A chart record of scintillation of 3C 48.

3. Data Analysis

The procedures of data analysis are as follows (we referred to Dr. Wiseman's procedure).

i) Inspecting the chart records, we exclude the parts of the records which contain distinct noise such as solar bursts or lightning.

ii) The selected records are divided into blocks which consist of 2048 successive samples (102.4 sec). The terminal sections of each block are weighted by cosine bells to reduce side lobes when applying the Fourier transform. As the duration of our observations is about 5 minutes, we can take three blocks when there is no distinct noise. The residual records which cannot be included in any block are omitted.

iii) By calculation which includes the fast Fourier transform (FFT), program of which was written by Brenner (1970), we get: 1) power spectrum 2) auto-correlation and 3) cross-correlation by averaging the values obtained from each block. The methods of derivation of these elements are as follows.

1) The power spectrum is computed by applying the FFT to each block directly.

2) After passing through the filters, the Fourier transform of the power spectrum is calculated to derive the auto-correlation function. These filters consist of three parts, i. e. high-pass filter, low-pass filter and a filter for the elimination of white

noise. The high-pass filter is applied for eliminating ionospheric scintillation, and the cut-off frequencies of high-pass and low-pass filters are 0.01 Hz and 1.2 Hz, respectively.

3) The cross-correlation function between the records obtained at both stations (Toyokawa and Fujigane) is computed from the filtered records which are obtained from the original data. The filtered records are obtained by the following three processes: the Fourier transform, the high-pass and low-pass filters mentioned above, and the inverse Fourier transform.

4) Besides the three elements mentioned above, the dynamic spectrum is obtained from the original records by computing the power spectrum for successive blocks, each of which contains 2048 samples and is shifted by 6.4 seconds from the next. Examples of these elements are shown in Fig. 5.

Following the idea shown in the book written by Blackmann and Tukey (1959), the variability of spectral estimates can be derived. If we adopt 0.1 Hz for the spectral resolution, the number of equivalent degrees of freedom is about 58 for the average power spectrum which is obtained from three blocks, and about 20 for a dynamic spectrum which is calculated from only one block.

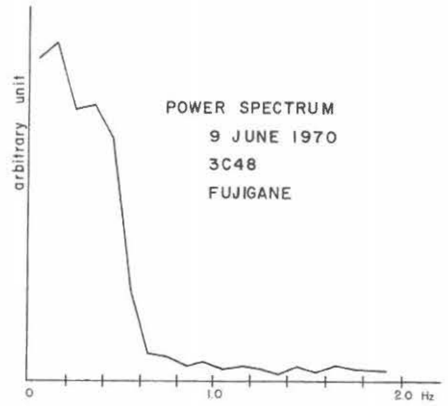


Fig. 5. (a) Power spectrum

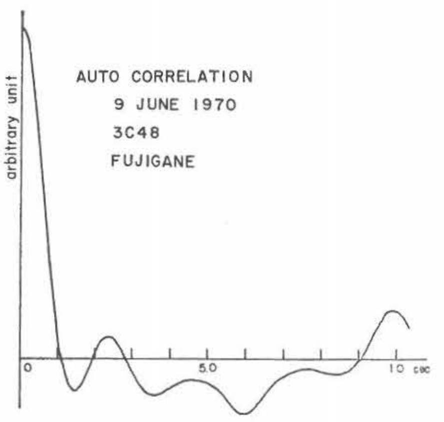


Fig. 5. (b) Auto-correlation

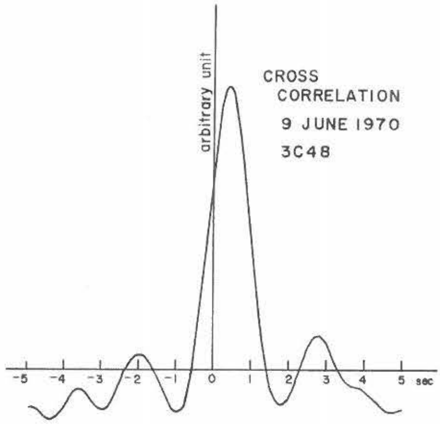


Fig. 5. (c) Cross-correlation

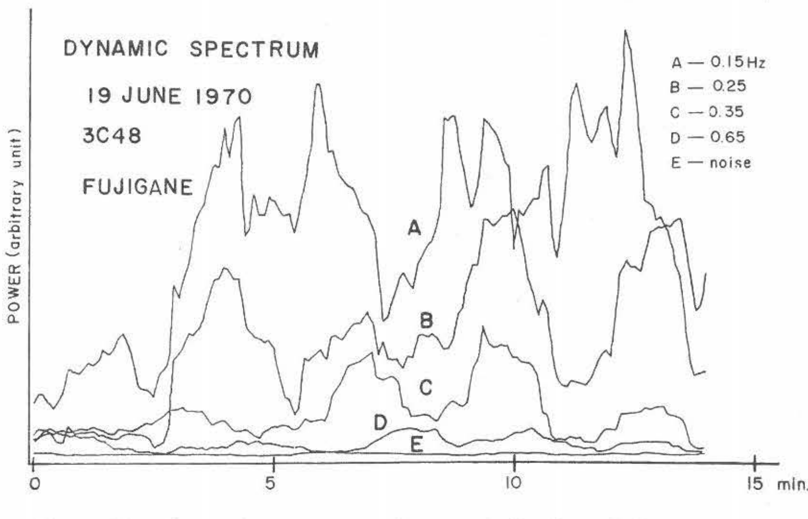


Fig. 5. (d) Dynamic spectrum. Curves A, B, C, and D represent the variation of power at 0.15, 0.25, 0.35 and 0.65 Hz, respectively, and E is the noise level. The initial increase of each curve at about 2.5 min means that the 3C 48 came into the main beam.

4. Results

The apparent drift velocity of the diffraction pattern between Toyokawa and Fujigane can be calculated from the time delay of the apex of the cross-correlation curve and the geographical distance (126 km) between the two stations. The daily variation of the apparent drift velocity obtained from the observations of 3C 48 is shown in Fig. 7(a).

To find the true velocity V of the solar wind, we have to take into account the direction of motion, the shape and the time-change of the diffraction pattern. The shape of the diffraction pattern has been measured by Dennison and Hewish, and Vitkevich and Vlasov. It has been found that the diffraction pattern is slightly elongated in a direction parallel to its motion and the mean axial ratio is less than 2:1. Then we can assume that the pattern is isotropic, as described by Dennison and Hewish (1967).

According to Briggs et al. (1950), when the isotropic pattern changes in form as it moves, the apparent velocity V′ (in the direction of motion) is represented as follows:

$$V' = V + (V_c^2 / V)$$

where V_c is a parameter to describe the random change of the pattern and is the ratio of the scale and the life time of the pattern. As V_c may be considered to approximate to the Alfvén velocity in the solar wind, which is about 40 km/sec at a distance of 1 a. u. from the sun, we may assume $V_c \ll V$. If we neglect V_c and assume an isotropic, unchanging pattern, the apparent velocity V′ is nearly equal to the true velocity V. Finally, we have to make a correction for the difference in direction between the solar wind and the base line. Assuming a radially-flowing solar wind, we can calculate the angle between the base line and the radial flow from the sun. In the case of 3C 48, this angle is about 20 degrees in June, and the correction is about 10 %.

The scale of the diffraction pattern is obtained from the auto-correlation and the power spectrum of the intensity fluctuations. Assuming that the auto-correlation curve is of a Gaussian form such as $\exp(-V^2 \tau^2 / d^2)$, the correlation length d can be calculated from the correlation time τ_e, as $d = V\tau_e$. However, when ionospheric scintillations are included in the data, we cannot use the auto-correlation curve. The observations of Cygnus-A have shown that ionospheric scintillation usually has little power above 0.1 Hz. Therefore, if we cut the low frequency part below 0.1 Hz of the power spectrum and assume that the power spectrum has a Gaussian form such as $\exp(-\pi^2 d^2 f^2 / V^2)$, which is the Fourier transform of the Gaussian auto-correlation function, we can estimate d from the equivalent width f_e $(= V/\pi d)$ of the power spectrum. The calculated values of d are shown in Fig. 7(b) and it is seen that the scale derived from the auto-correlation is nearly equal to that derived from the power spectrum.

5. Discussion

It may be interesting to compare the results of IPS observations with the results obtained by spacecrafts and geophysical observations*.

The geometrical configuration of the sun, the earth, the spacecrafts and the scintillating radio source (3C 48) is shown in Fig. 6 and the velocity and the proton density of the solar wind measured by Vela 3 and 5** are shown in Fig. 7 (d) and (e), respectively.

If we compare Fig. 7 (a) with Fig. 7 (d), it is seen that the variations of the wind velocity derived from IPS observations are very similar to those observed by Velas. The velocity enhancements were detected by both measurements on June 17 and 27. Vela satellites are orbiting around the earth and measuring the solar wind just outside the magnetosphere of the earth. The velocity measured by IPS is considered to be the velocity of the solar wind near the point closest to the sun on the line of sight to the radio source. As shown in Fig. 6, the point closest to the sun was also near the earth during this period and then the velocity enhancement shown in Fig. 7 (a) may be considered to be that of the solar wind in the vicinity of the earth. On the other hand, solar flares of Imp. 3 occurred on June 13 and 24, and successive Forbush decreases of galactic cosmic rays and geomagnetic storms were observed on June 17 and 27. It may be inferred from these observations that the high velocity plasma cloud ejected from the flare region passed through the earth on these days.

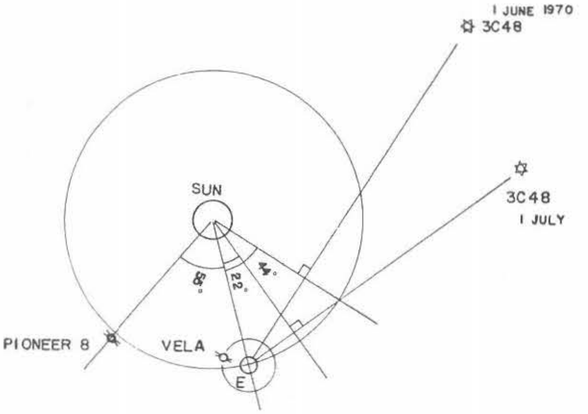


Fig. 6. The geometrical configuration of the sun, the earth, spacecrafts and the line of sight of 3C 48 projected on the ecliptic plane.

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* SUMMARY OF DAILY OBSERVATIONAL RESULTS OF SOLAR PHENOMENA, COSMIC RAY, GEOMAGNETIC VARIATION, IONOSPHERE, RADIO WAVE PROPAGATION AND AIRGLOW, edited by the Subcommittee for Data Illustration, Ionosphere Research Committee of Japan.

** ESSA SOLAR-GEOPHYSICAL DATA (prompt reports), July (1970)

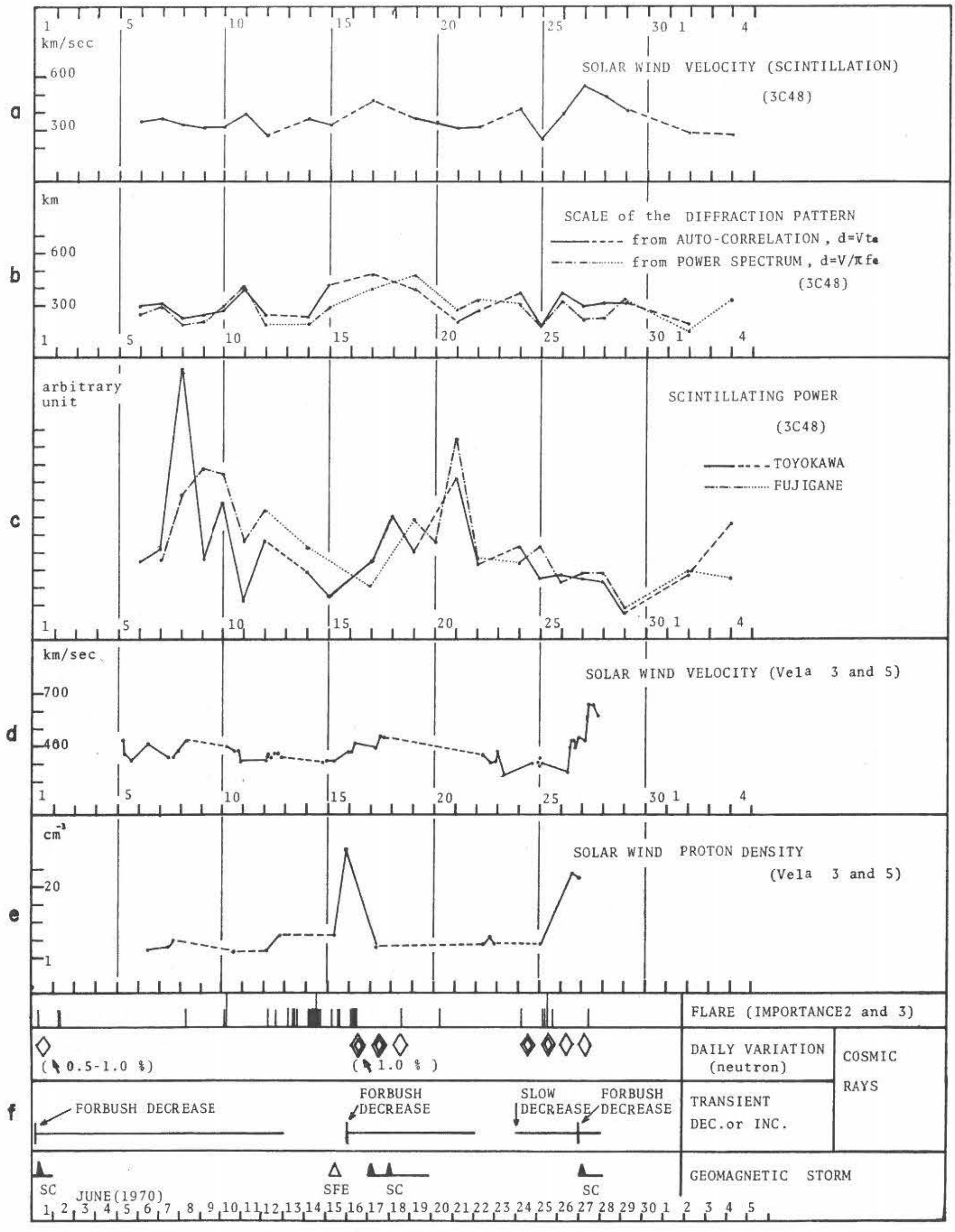

Fig. 7. (a) Observed velocity of the solar wind. (b) The scale of the diffraction pattern. (c) Scintillating power. (d) The velocity of the solar wind (Vela 3 and 5). (e) Proton number density (Vela 3 and 5). (f) Solar-geophysical data.

According to Vitkevich and Vlasov (1967), the scale of the diffraction pattern is larger when the velocity of the solar wind is larger. We have examined the relation between the scale of the diffaction pattern and the velocity of the solar wind. As shown in Fig. 8, there is a tendency for the scale of the diffraction pattern to increase with an increase of the velocity of the solar wind. But, in a few cases (for example on June 27), the scale of the diffraction pattern did not increase. Assuming that the scale of the diffraction pattern varies along the best fit line in Fig. 8, the scale on June 27 should be ~500 km, instead of 300 km. This decrease of the scale may be considered to be caused by a strong scattering effect. When the scattering is strong, the scale of the diffraction pattern is smaller than the size of the density irregularities in the solar wind and is reduced to:

$$d = a / (\sqrt{2}\ \Phi_0) \qquad (1)$$

where d : the observed scale of the diffraction pattern (km)

a : the size of the density irregularity in the solar wind (km)

Φ_0 : r. m. s. phase deviation in the scattering region (radian).

As the observed value of d is 300 km, Φ_0 is estimated to be 1.2 radians. Then we can estimate the electron density fluctuation $\overline{\delta Ne}$ by the formula (Salpeter, 1967):

$$\Phi_0 = 0.46 \sqrt{a L}\ \lambda\ \overline{\delta Ne} \qquad (2)$$

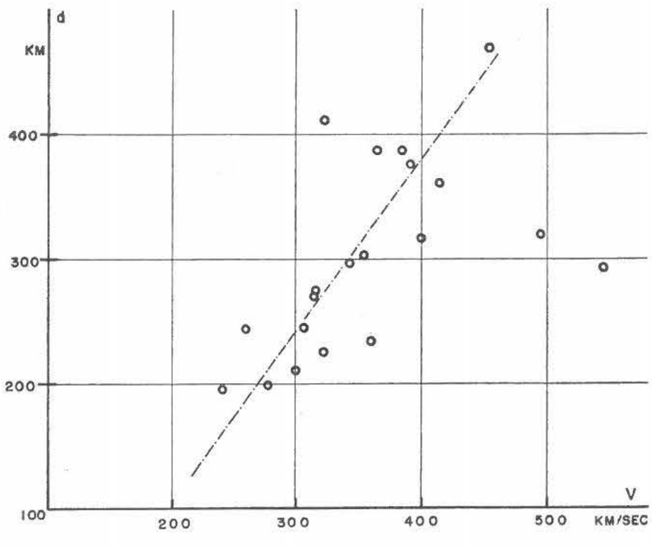

Fig. 8. The relationship between the solar wind velocity V and the scale of the diffraction pattern d.

where a : the scale of the diffraction pattern (100 km unit)

L : thickness of the scattering region (a. u.)

λ : wavelength (meters)

$\overline{\delta Ne}$: r. m. s. density fluctuation (electrons/cm^3)

Assuming L$\sim$0.4 a. u., which is the distance between the earth and the point closest to the sun on the line of sight. The estimated value of $\overline{\delta Ne}$ is 0.46/cm^3, which is about 3 times higher than the value expected from the formula derived by Cohen et al. ($\overline{\delta Ne}$=0.14/(distance from the sun in a. u.)^2). Vela also observed the enhancement of ion density which is about ten times higher than the normal value, as shown in Fig. 7(e). If the size of the density fluctuation is 500 km, the scattering region is within the Fresnel region. In the above discussion, we have assumed that eq. (1) is valid even in the Fresnel region.

Dennison (1969) has reported that the scale of the diffraction pattern was 160 km at a distance of 0.8$\sim$1.0 a. u. from the sun in 1966. The mean value of the scale derived from our observations is $\sim$300 km. It appears that the scale of the pattern, or the size of the density fluctuation, increases with increasing solar activity.

We have noticed that block to block variations of the shape of power spectrum are not small and sometimes beyond statistical ambiguity, then we calculated the dynamic spectrum. We have not yet detected a systematic change in the power spectrum, but expect to be able to find a wave-like phenomena in the solar wind.

Acknowledgements

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