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日食的射电观测

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摘　　要

日食为射电天文提供了一维高空间分辨率太阳射电观测机会. 日食射电观测在太阳射电物理的发展上起过重要的作用. 文中对日食射电观测的若干重要因素作了介绍和分析. 日食射电观测在我国太阳射电天文发展上也起了重要作用. 文中简要介绍了在我国组织观测的 1958 年、 1968 年、 1980 年及 1987 年的太阳射电日食观测及其主要结果.

关 键 词　太阳: 日食 — 太阳: 射电辐射

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Radio Observations of Solar Eclipse

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Abstract

For radio astronomy, solar eclipse provides a nice opportunity for making solar radio observations with high one-dimension spatial resolution. The radio observation of solar eclipse has played an important role in solar radio physics. Some important factors for radio observation of solar eclipse are introduced and analysed. Solar eclipse radio observation has also played an important role in the progress of solar radio astronomy in China. The solar eclipses of 1958, 1968, 1980 and 1987, which were observed in China, are introduced, and the main results of these observations are briefly shown.

Key words sun: solar eclipse—sun: radio radiation

1 Introduction

1.1 Solar eclipse is one of the most spectacular astronomical phenomena

For the optical astronomer, the eclipse serves to reveal features of the chromosphere and the

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corona. Development in perfecting and utilizing the coronograph has provided a continuous monitoring of coronal activity, but the eclipse still serves in many optical solar studies. For the radio astronomers, the eclipsing process gives resolution to their solar mapping, revealing the temperature and angular diameters of enhanced regions of solar activity associated with sunspots, plages, and prominences. The eclipse gives the radio astronomers data on coronal temperatures and on the extent of the corona at many wavelengths. The development of high resolution radio interferometers has lessened the need for eclipse measurements, but many eclipse measurements continue to add to our understanding of solar physics.

1.2 The eclipsing process in radio observation [1]

As the moon moves in front of the sun, it occults solar features such as sunspots, plages, and prominences, with a knife-edge sharpness (the moon's limb). The radio first contact occurs earlier than the optical first contact, and the radio fourth contact later than the optical one. At totality, between the second and third contacts, only the solar corona is visible (radio residual). After totality the moon moves on uneclipsing the same solar features as during the eclipsing period with a different passing geometry compared with the period between the first and second contacts (Figure 1).

Basically, information can be obtained from solar eclipes relating to the following:

(1) The emissivity of centers of radio activity on the solar disk. The radio diameter and brightness of radio emission regions associated with sunspots, plages, prominences can be obtained. The technique used is to find sudden changes in the solar flux level between the first and second contacts or between the third and fourth contact. The polarized component of the enhanced region, which is very obvious (Figure 6) because of no polarized component in the quiet solar radio emission, can be found as its height and spectrum. A comparison with optical features can be made, and optical data have played an important part in radio data analysis.

(2) Total eclipse of the sun is used to find the radio diameter of the solar corona at various wavelengths and at different periods of the sunspot cycle. At totality, radio residuals, for example, of 25% or more and 15% or more of the solar energy at meter wavelength and 21 cm wavelength, respectively, will show that the solar corona has not been completely eclipsed.

(3) A model of solar brightness distribution can be derived from eclipse records. The observed brightness distribution across the solar disk depends on the variation in intensity of an emergent rays at various position from the center of the solar disk to the limb. At optical wavelengths there is a marked limb-darkening effect. As temperature increases with depth in the photosphere, central direct rays originating at greater depths are hotter than oblique rays at the limb. At centimeter wavelength, the reverse situation applies. The corona is thin but not transparent and there is an increase in temperature from the chromosphere out to corona. Therefore, the direct central rays emerging from the deeper regions in the chromosphere are not as intense as the oblique ray at the limb which originate in higher and hotter regions; This leads to limb brightenning. The situation will change at the meter wavelength. If there is limb brightenning , a sharper decrease will be seen at the time of frist contact as if an enhanced region was eclipsed.

The same effect will be seen near the fourth contact.

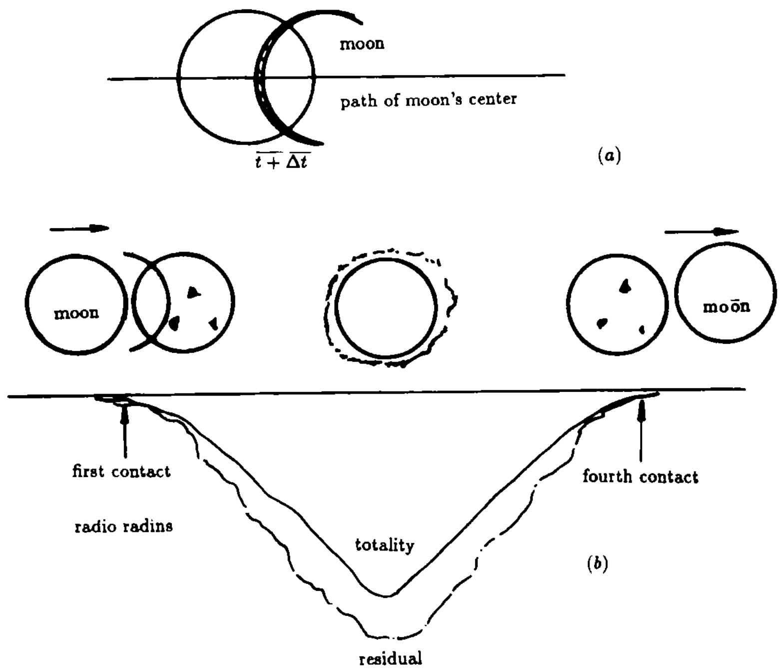

Fig.1. The eclipsing process in radio astronomy

(a) one-dimension spatial resolution

(b) the radio eclipsing process

In the early stage of solar radio study, our knowledge of the radio sun increased rapidly from the results of radio solar eclipse measurement. During the partial eclipse of November 23, 1946, Covington [2] in Ottawa, Canada, observing at 10.7 cm, determined that several bright regions, one with an excess of 1.5×10^6 K above the average surface temperature of 5.6×10^4 K had been detected. This enhanced region had an area equal to 2.2% of the solar disk, but it has 25% flux of the whole solar disk. It was the first observation of the contribution of small areas of solar activity to the total solar temperature. Another bright region, apparently located at the solar limb, caused the signal to decrease 9%, 3 min before the first contact, when the moon's limb eclipsed a prominence.

In this paper we will discuss some factors for radio solar eclipse observation, and present a brief introduction of the radio solar eclipse observations which have been made in China since 1950's.

2 Some factors for radio solar eclipse observation

2.1 Eclipse curve slope analysis

An eclipse curve $P(t)$ (Fig.7) is a record of power as a function of time. The derivative of this curve, $\dot{P}(t)$ is the change in power as a function of time (Fig.3,8). The slope is then proportional to the brightness distribution of circular arcs across the solar disk. Therefore, the slope curve can be used to distinguish the irregularities in solar brightness which show up much more prominently here than on the eclipse curve itself. Knowing the total flux and the residual flux allows one to normalize any point value on slope curve to percentage relative to total flux after correcting for atmospheric attenuation and other factors.

2.2 Spatial resolution available from radio solar eclipse observation

The spatial resolution of radio solar eclipse observation is caused when the moon limb eclipses the solar disk. Therefore, the spatial resolution depends on temporal resolution; the moon's speed relative to the sun; the changing rate of the antenna temperature; and the shortest time interval to cause the antenna temperature's variation which is larger than receiver's sensitivity. And it is relative to the moon's speed and the sensitivity of receiver. The formula for spatial resolution ΔQ is:

$$\Delta Q = \nu \cdot \Delta t \doteq \frac{M(T_{\rm N} + T_{\rm a})}{\sqrt{\Delta f \cdot \tau}} \doteq \frac{a}{\Delta T} \tag{1}$$

where v is the speed of the moon, $M = 5$, $T_{\rm N}$ is the noise temperature of the receiver, $T_{\rm a}$ is the antenna temperature of the radio sun at observing frequency, Δf is the bandwidth of the receiver, τ is the time contant, ΔT is the antenna temperature increment of local emission regions, and a is the dimension of local emission region. According to equation (1), it can be seen that the spatial resolution will increase (ΔQ decrease) if the noise temperature of receiver, $T_{\rm N}$, and the antenna temperature of the radio sun, $T_{\rm a}$, decrease (in the case around totality, and in the case of strong emission regions). Usually, the spatial resolution of 20″—30″ can be reached, some unexpected case will be described as follows.

2.3 Some two–dimension information obtainable

The moon's eclipsing action yields a one-dimensional picture of the variation of solar power with time of passage of the moon across the solar disk. No indication is given where along the moon's arc temperature differences exist. With a group of two or more stations it is possible to create a geometry of intersecting arcs, from which the location of enhanced regions can be found (Fig.2*a*). It can also be obtained with combining eclipsing moon's arc with uneclipsing moon's arc (Fig.2*b*,10).

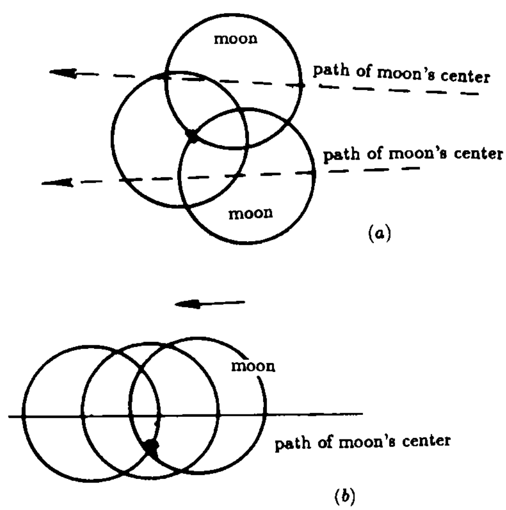

Fig.2 Two-dimension information obtainable
(*a*) with two stations; (*b*) with combining eclipsing moon limb arc with uneclipsing arc

2.4 Radio observation of solar eclipse in multi–frequency

According to the equation(1), the spatial resolution is independent of observing frequency, it causes an important characteristic of radio solar eclipse observation. The spatial resolutions are almost the same to different frequencies, it will be favourable to multi-frequency analysis of enhanced emission regions. At present, multi-frequency radio observations of local emission region are still important to solar eclipse observations.

3 The history of solar radio eclipse observations in China

In the history of radio astronomy, eclipse has played an important role. It is the same to solar radio astronomy in China. Mainly, the radio observations of solar eclipses on April 19, 1958, September 22, 1968, February 16, 1980, and September 23, 1987 are important.

(1) The observations of the annular eclipse of April 19, 1958 were especially interesting since it marked the year of maximum solar activity. The Pulkovo Observatory in Russia in cooperation with Chinese scientists made preliminary measurements in Hainan Island at 5.1, 3.3, and 2.0 cm wavelengths. Their primary purpose was to study the emission regions above sunspots, the size and brightness temperature of polarized and unpolarized components. The main results have been published by Gelfreikh, *et al*[3], Molchanov[4], Su, *et al.*[5], and Peterova, *et al*[6]. It is important that these observations pushed on the foundation of solar radio astronomy in China.

(2) The radio observations of the total eclipse of September 22, 1968 was a comprehenvive

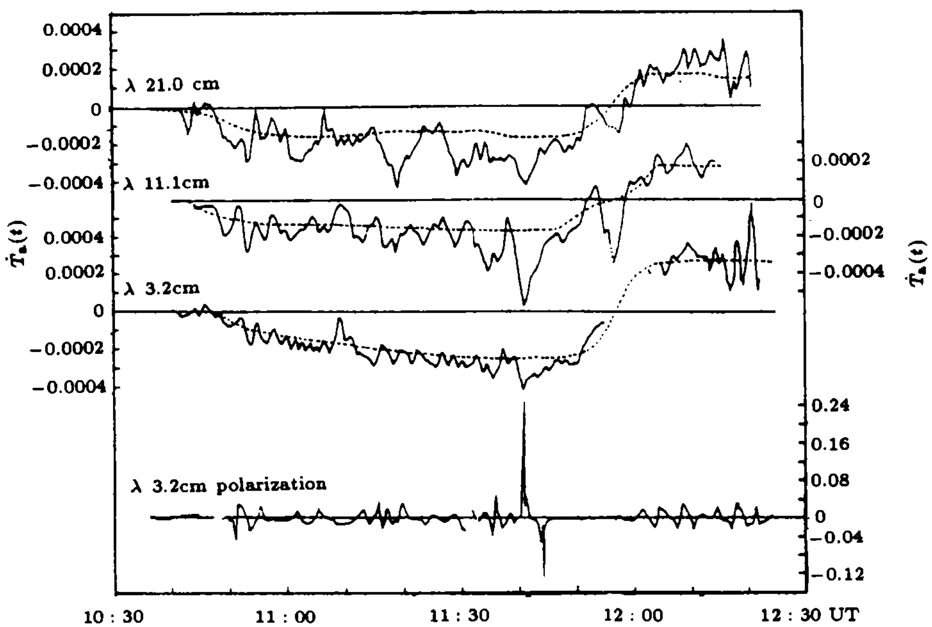

Fig.3 The normalized antenna temperature eclipsing slope curves of the solar eclipse radio observations on September 22, 1968, $\dot{T}_a(t)$ (solid lines), that of quiet sun background $\dot{T}_{ac}(t)$ (dotted lines) [12]

study of solar eclipse in China for the first time. The radio observing team consisted of Beijing Astronomical Observatory, Purple Mountain Observatory, and Nanjing University made observations in Keshe, South Xinjiang (at 3.2, 11.1, and 21 cm wavelengths) and in Yining, North Xinjiang (at 3.2 cm wavelength). Their primary purpose was the same as the Hainan Island solar eclipse of 1958. The eclipsing slope curves observed in Keshe are shown in Fig.3. The following results were obtained [7-12]:

(i) Equivalent radius of the radio sun in solar maximum year amounts to 1.04, 1.07, and 1.085 $R_\odot$ at 3.2 cm, 11.1 cm, and 21 cm respectively (Fig.4).

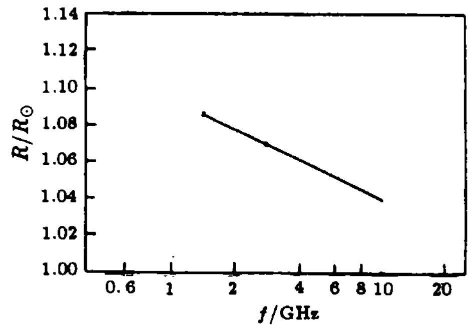

Fig.4 The relation between equivalent radius of radio sun and frequencies obtained in Sept. 22, 1968 solar eclipse [12]

(ii) The ratio between quiet sun to total solar emission is 0.907, 0.71 and 0.65 at 3.2 cm, 11.1 cm and 21 cm respectively.

(iii) Several local radio sources are associated with sunspots, plags and coronal condensations(beyond the solar limb). Although it was the year of maximum solar activity, there were only a few small and one middle active regions on solar disk. The brightness temperature of the middle active region(Wilson No. 16992, E36N17) is 0.45×10^6 K, 2.4×10^6 K and 3.0×10^6 K at 3.2 cm, 11.1 cm and 21 cm respectively.

(iv) The following parameters of the radio sources on solar disk were measured: angular sizes, fiux density, average brightness temperatures and heights. The angular sizes of the sources increase with wavelength, a typical value for a source are 43, 54 and 150 arcsec at 3.2 cm, 11.1 cm and 21 cm respectively. Heights of the sources increase with wavelength from $(2\text{–}3)\times10^4$ km at 3.2 cm to $(5\text{–}7)\times10^4$ km at 21 cm. The flux density spectrum of some radio sources is shown in Fig.5. Some of them have peaks at 11.1 cm. They exhibit an evident effect of the gyro- resonance radiation.

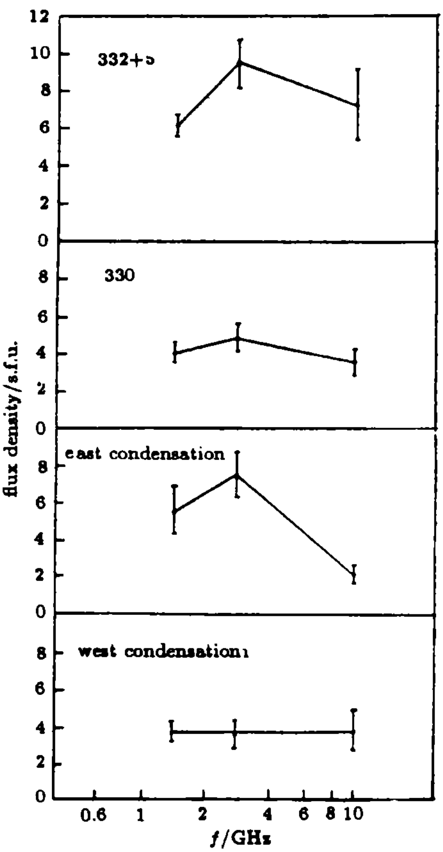

Fig.5 The fiux density spectrum of some radio sources observed in 1968 solar eclipse [12]

(v) Excellent results were obtained in the polarization observation at 3.2 cm [7]. Fig.6 and the bottom of Fig.3 show the 3.2 cm circular polarization flux slope curve when the moon was eclipsing sunspot group No. 332 (Wilson No. 16992). The total circular polarization flux during uneclipsing time is zero, due to the cancellation of the opposite circular polarization from at N pole and S pole of sunspot regions. The circular polarization of solar disk background is zero. The right circular polarization suddenly appeared, when the other sunspot with left circular polarization sense was eclipsed. The opposite process occurred during the uneclipsing interval. From Fig.6, it can be seen that the small spots in the group are resolved, the spatial resolution reaches 2–3 arcsec. The heights of the sources are at 2.0×10^4 and 2.7×10^4 km for polarization sources and unpolarization sources, respectively. Recently, it can be interpreted as follows: the polarization sources are at loop foot regions and the unpolarization sources are at the top of loops, but at that time, the "magnetic loops" was not so familiar to most solar physicsts.

The radio observation of 1968 solar eclipse has trained the Chinese solar radio astronomers of the first generation.

(3) The radio observations of the total eclipse on February 16, 1980 were made by the team consisted of Beijing Astronomical Observatory, Purple Mountain Observatory, YAO (Yunnan Astronomical Observatory, Beijing Normal University and Beijing University in Kunming, Yunan (at 2.0 cm, 3.2 cm, 8.2 cm, 10.3 cm and 21 cm wavelength), and in Ruili, Yunnan (at 8.6 cm wavelength). The eclipsing curves of the observations (solid lines) and the quiet sun background (dotted lines) at different wavelength are shown in Fig.7, and the slope curves in Fig.8. The main results are as follows [13,14]:

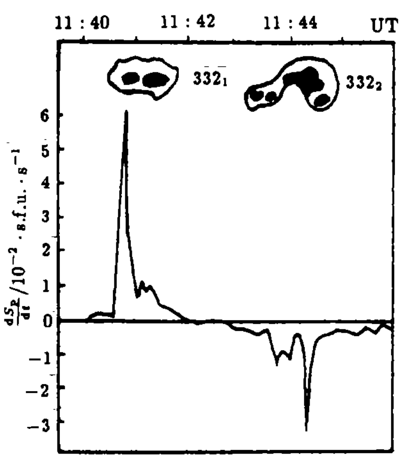

Fig.6 The 3.2cm circular polarization flux slope curve of the moon eclipsing sunspot group No.332 (Wilson No. 16992) [7]. Feb. 16, 1980.

(i) Radius of the radio sun in solar maximum year amounts to 1.007, 1.013, 1.040, 1.067 and 1.090 $R_\odot$ at 0.86 cm, 2.0 cm, 3.2 cm, 8.2 cm and 21 cm respectively.

(ii) The flux density spectra of the quiet sun at several wavelengths between 0.86 cm and 21 cm have been obtained. They are compared with the spectra obtained in the 19th solar maximum years (in the Xinjiang eclipse in 1968) and in minimum year recorded by TYKW of Japan. The flux density of the quiet sun background in the 20th maximum years is higher than that both in minimum years (19th and 20th solar active cycles) and in 1968. The results are shown in Fig.9.

The shaded area gives the contribution of the enhanced emission regions appearing at solar disk on

(iii) The quiet sun shows limb brightening at 0.86 cm wavelength [14]. The calculated distribution of the brightness temperature on the solar disk has shown that there is an apparent brightening in the 2′—3′ range on the inner side of the optical limb. The peak brightening amounts to 18% relative to the central brightness temperature of solar disk.

(iv) Several solar radio sources are associated with sunspots, plages and a coronal condensation region during the eclipse. There is evidence that there were emissions associated with the regions where sunspots had disappeared not long before. Their brightness temperatures were about 1×10^5 K at 2.0 cm, 3×10^5 K at 3.2 cm, 5×10^5 K at 8.2 cm and 5×10^5 K at 21 cm. There may be "cold" source regions associated with filaments and coronal holes.

(v) The following parameters of the radio sources on solar disk were measured: angular sizes (along the direction of the moon center's motion across solar disk), flux density,average

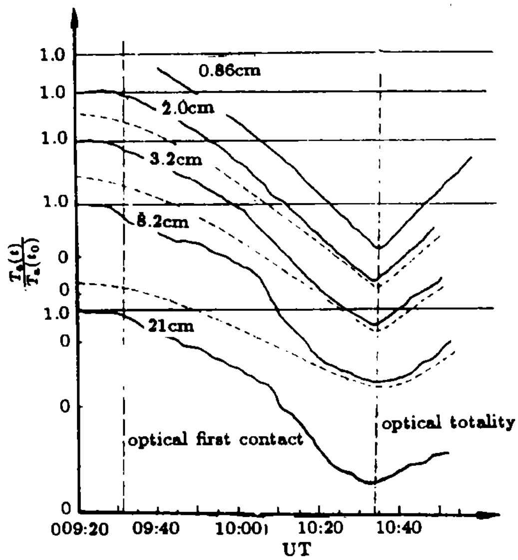

Fig.7 The eclipsing curves of the observations (solid lines) and the quiet sun background (dotted lines) at different wavelength for 1980 solar eclipse [13]

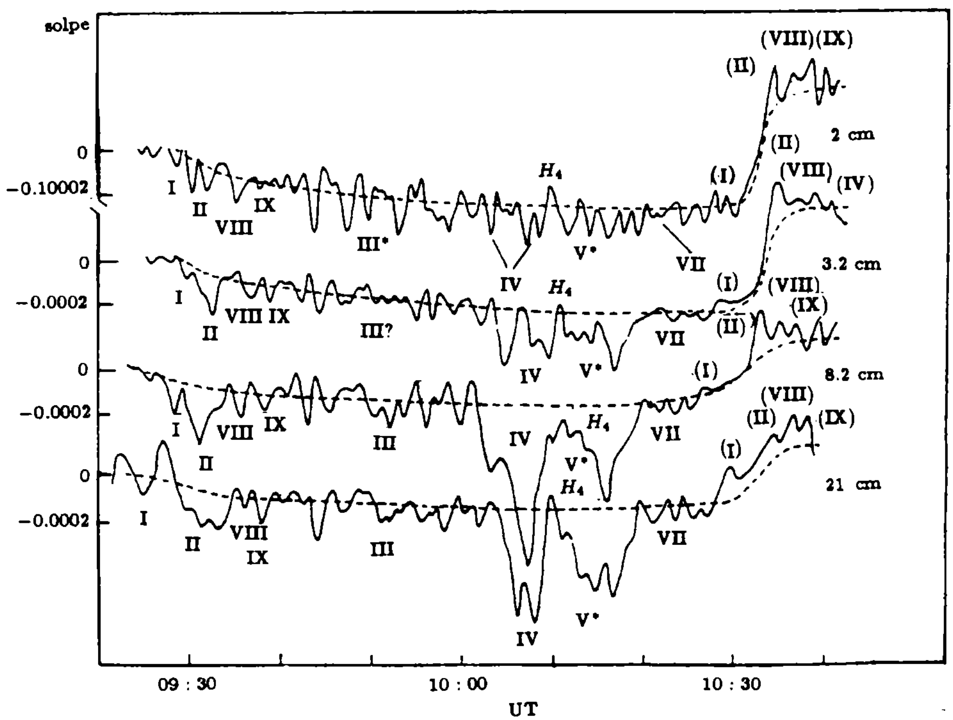

Fig.8 The eclipsing slope curves of the radio sun (solid lines) and the radio quiet sun background (dotted lines) for 1980 solar eclipse [13]. The Roman numerals represent the radio sources

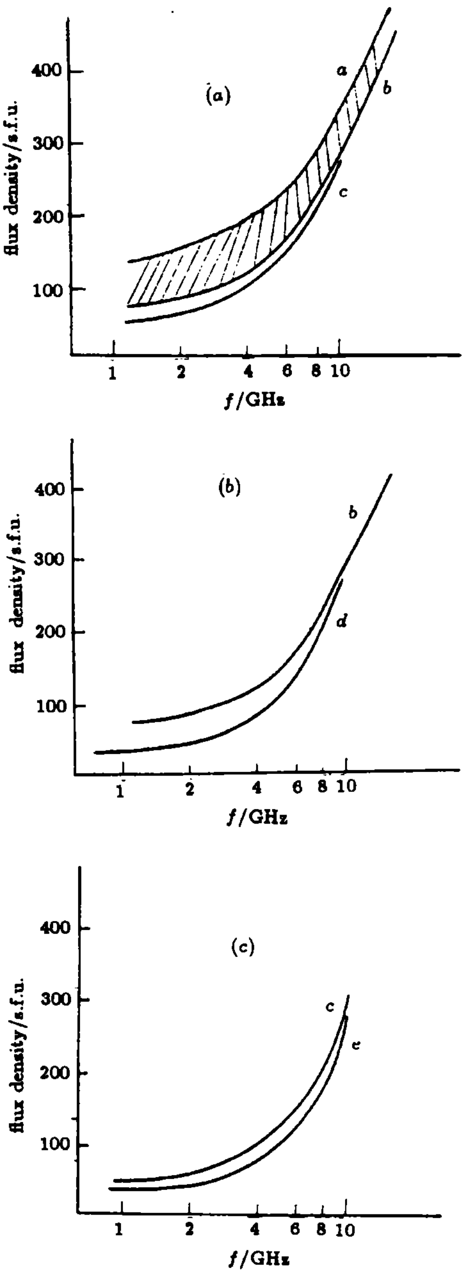

Fig.9 The spectra of radio quiet sun background[13]
a: the total flux spectrum of February 16, 1980 solar eclipse; *b*: the radio quiet sun background spectrum of 1980 solar eclipse (the 20th solar max. year); *c*: the same to '*b*' for 1968 solar eclipse (the 19th solar max. year); *d*: the same to '*b*' for TYKW 20th min. year; *e*: the same to '*b*' for TYKW 19th min. year

brightness temperatures and heights. The angular sizes of the sources increase with wavelength from 0.5 ′ at 2 cm to 1′—2′ at 21 cm, and also show a tendency of increase with the flux density of sources. Heights of the sources increase with wavelength from 0.54×10^4 km at 2 cm to 4.2×10^4 km at 21 cm. The brightness temperatures are from about 0.1×10^6 K for weak sources at 2 cm to about 5×10^6 K for strong sources at 21 cm. Fig.10 shows that by using the moon limb arc at eclipsing and uneclipsing, the positions of radio sources are determined. Fig.11 shows the flux spectra of some sources, it exhibits an evident effect of the gyro-resonance radiation.

(vi) The spacing between two radio peaks of a bipolar spot group decreases with wavelength and this means that there may be a magnetic arch structure above the spots [15].

(4) The multi-frequency joint radio observations of the annular solar eclipse on Sept. 23, 1987 were made with nineteen radiotelescopes located at nine sites at ten wavelengths from 0.86 cm to 21 cm. The parameters about solar radio emission during the quiet period of solar activity were obtained. The main results are as follows [16].

(i) The values of occultation radius of solar disk at each of corresponding wavelengths R_λ were 1.014–1.280 $R_\odot$ while the ones of equivalent radius $R_{e\lambda}$ were 1.007–1.014 $R_\odot$. The $R_{e\lambda}$ were a little smaller than statistical ones obtained by Früst[17], but a little larger than the observation results of total solar eclipse in 1968 and 1980 in China.

(ii) The values of equivalent height of radio emission in solar atmosphere were $(0.5—11)\times10^4$ km, while the ones of average brightness temperature over the quiet solar disk background were $0.9—10\times10^4$ K. From this, the equivalent temperatures changing with height in solar atmosphere were also obtained.

(iii) The percentages of residual flux density at the totality of eclipse were given, and the qualitative conclusions about limb brightening of brightness distribution of solar disk at the most of corresponding wavelengths were obtained.

(iv) It was calculated that the brightness distributions of solar disk at 0.86 cm, 2.0 cm, 2.56 cm and 3.2 cm were limb brightening, and the range of brightening peaks amounted to 5%—20%. The peak bands with width of $0.03 - 0.15R_\odot$ were lying within $0.8 - 1.0R_\odot$ on the inner side of the optical limb. But at 1.46 cm there was a trend of limb darkening.

(v) Some of the local radio sources associated to optical objects such as sunspots, plags and prominences were identified. Furthermore, the main parameters of these sources, such as angular radius, flux density, average brightness temperature and the height above the photosphere, and their change with wavelength, were calculated.

(vi) Observation data also showed that some filaments had absorption effect on radio emission.

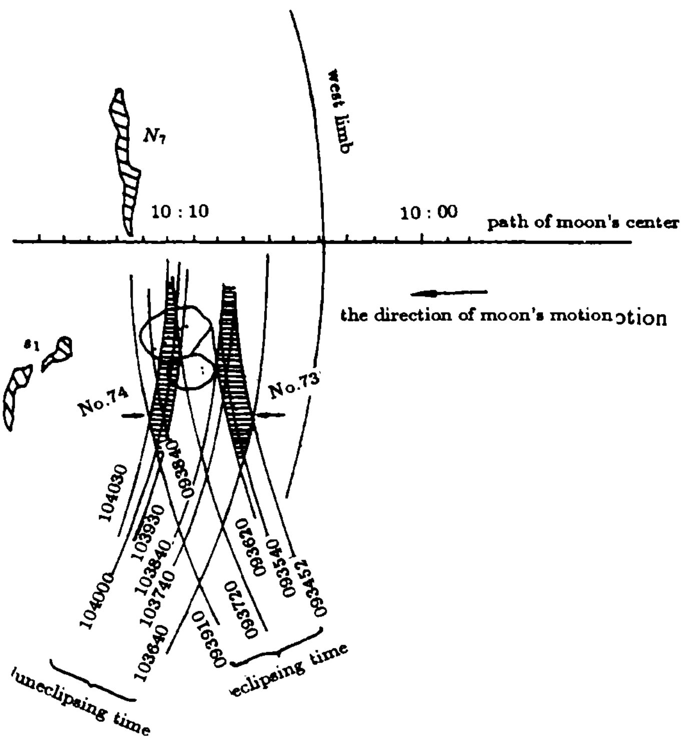

Fig.10 The positions of two radio sources are determined by using the moon limb arc at eclipsing and uneclipsing (at 8.2cm) [13]

4 Conclusion

The radio observation of solar eclipse has played an important role in solar radio physics. It will play a less important role in the future, but it is believed that solar eclipse radio observations will be important in pointing out directions for long-term, systematic observations. In particular, multi-frequency joint observations provide some impotant imformation which can not be displaced by those observations with radio interferometers.

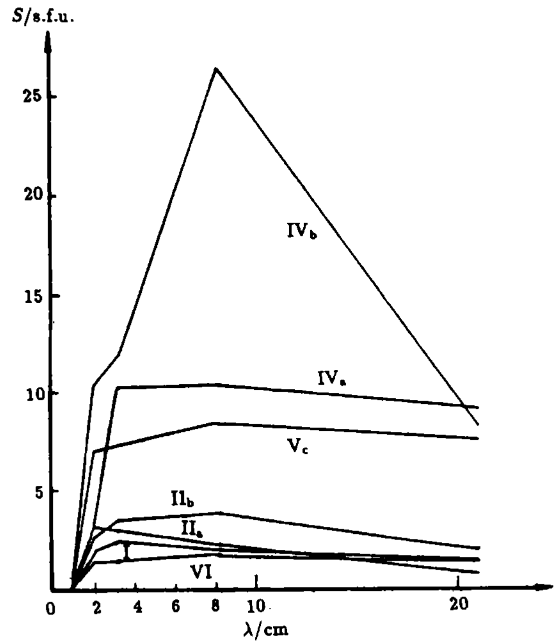

Fig.11 The flux spectra of some sources for 1980 solar eclipse

For the solar eclipse on March 9, 1997 , three teams of the radio observations will work on:

(1) the radio observations at 2.84 GHz in Mohe by Beijing Astronomical Observatory group;

(2) the radio observations at 8.6 mm wavelength in Mohe by Purple Mountain Observatory group;

(3) the multi-frequency observations at 1420, 2130, 2840, 4260, and 9400 MHz in Beijing, Kunming, and Nanjing by Beijing Astronomical Observatory, Yunnan Astronomical Observatory, and Purple Mountain Observatory groups respectively.

The multi-frequency analysis of some radio sources on solar disk will be expected, while the radio distribution of the quiet solar brightness background will be made too.

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References

[1] Castelli J P, Aarons J. In: Aarons J *et al.* Solar System Radio Astronomy. New York: Plenum Press, 1965. Chap. 3

[2] Covington A E. Nature, London, 1947, 159: 405

[3] Gelfreikh G, Kotrolkov D, Rishkov N *et al.* In: 1959 Paris Symposium on Radio Astronomy, Stanford Univ. Press, 1960: 125

[4] Molchanov A P. Soviet Astron.-AJ, 1962, 5: 651

[5] Su S W, Hsiao K C, Wu H W *et al.* Izv. Vysshikh Uchebn. Zavedenii Radiofiz., 1962, 5: 807

[6] Peterova N G, Molchanov A P, Nagnibeda V G. Solar Data 8th, Liningrad: Akademiia Nauk, 1963

[7] Eclipse Observation Group of Purple Mountain Observatory. Acta Astronomica Sinica, 1974, 15: 123

[8] Eclipse Observation Group of Beijing Astronomical Observatory, Eclipse Observation Group of Nanjing Univesity. Acta Astronomica Sinica, 1975, 16: 200

[9] Eclipse Observation Group of Beijing Astronomical Observatoryy. Acta Astronomica Sinica, 1975, 16: 189

[10] Eclipse Observation Group of Purple Mountain Observatory. Acta Astronomica Sinica, 1974, 15: 113

[11] Joint-Observation Group of Xinjiang Eclipse. Acta Astronomica Sinica, 1976, 17: 41

[12] Solar Ellipse Radio Observation Group. Acta Astronomica Sinica, 1981, 22: 254

[13] Fu Qijun, Ji Shuchen, Luo Xianhan *et al*. In: Biao CHEN, Shi-hui YE, Chang-fa LIU *et al* eds. Reports on Observations Made in Yunnan of China on the Total Solar Eclipse of February 16, 1980. Beijing: Science Press, 1983. 64

[14] Group of 8.6 mm Solar Eclipse Observations. Reports on Observations Made in Yunnan of China on the Total Solar Eclipse of February 16, 1980. Beijing: Science Press, 1983., 94

[15] Luo Xianhan, Yao Deyi, Ji Shuchen *et al*. Acta Astronomica Sinica, 1995 26: 51

[16] Liu Yon, Ji Shuchen. In: Tao Shiyan, Wan Lai, Lian Baixian *et al* eds. Observations and Studies of China an Annular Solar Eclipse of Sept. 23, 1987. Beijing: Science Press, 1990. 18

[17] Früst E. In: Kundu M, Gergely T E eds. Radio Physics of the Sun, IAU Symposium, No.86, Dordrecht: Reidel, 1980: 25