# Solar Radio Flux and Temperature of the Upper Atmosphere[1]

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*Abstract.* A general analysis of solar radio fluxes between 1000 and 10,000 Mc/s has been made for an entire solar cycle. It is shown that a correlation between a solar radio-flux index and the temperature of the thermopause can be found in the range of 8–10 cm if its basic component is associated with a 27-day mean value. A linear correlation is found between the 27-day mean value of the 8-cm radio flux and the thermopause temperature. However, there is a departure from linearity at 10.7 cm for fluxes of less than 150 units. The oscillation during a so-called 27-day period has a value that is about 50 per cent that of basic component. It is shown that no corpuscular effect is needed in addition to the normal heating of the thermosphere by ultraviolet radiation. A table is given to deduce the relationships between radio fluxes at 8 and 10 cm and average nighttime and daytime temperatures. Finally, the maximum, mean, and minimum temperatures have been deduced for nighttime and daytime conditions between 1952 and 1962.

*Introduction.* The correlation between the orbital deceleration of an artificial satellite and the solar radio flux in the decimeter range has led to relationships between the atmospheric density at various heights and the 10.7- and 20-cm radio fluxes. Considering that the density variation is due to a temperature variation, it can be concluded that the solar ultraviolet radiation is responsible for the heating of the upper atmosphere and that heat conduction is responsible for its cooling. A change in the ultraviolet radiation can be correlated with a change in the radio flux just as with the sunspot number, which is a well-known index of solar activity.

Since all solar ultraviolet radiations do not vary with the same amplitude during a complete solar cycle, it appears logical to consider that a specific radiation in the radio range cannot be a perfectly reliable index [*Nicolet*, 1960]. Furthermore, various spurious correlations, or lack of correlations, may occur if the published values of the radio fluxes are subject to drifts of instrumental origin [*Nicolet*, 1961*a*]. There is no way to account for a special behavior, for example at 5000 Mc/s, when the entire spectrum between 1000 and 10,000 Mc/s varies in exactly the same manner. Consequently, before analyzing the various causes of the temperature variations of the thermopause, it is desirable to obtain reliable data on the variations of the solar radio fluxes.

*Variations of solar radiations.* Extensive solar observations have been conducted at a wavelength of 10.7 cm (2800 Mc/s) [*Covington*, 1958] at Ottawa by the Radio and Electrical Engineering Division of the National Research Council of Canada. The series of observations began in 1947, and the errors, which have been discussed by *Medd and Covington* [1958] and *Covington* [1959], should be of the order of ±2 per cent, or not more than ±3 per cent in the monthly measurements. Intensive calibration measurements have been made at Ottawa with two radiometers calibrated from two fixed points, one for the ambient temperature and the other at the temperature of the sky, taken to be 8°K. A possible systematic error may be introduced, therefore, with an assumed constant sky temperature apparently leading to a seasonal periodic variation proportional to the solar flux.

Routine observations at 8 cm have been carried out at Nagoya by the Institute of Atmospherics since November 1951 [*Tanaka and Kakinuma*, 1953], also with an estimated accuracy of the order of ±2 per cent. A comparison of the 10.7-cm and 8-cm fluxes made by *Tanaka* [1955] during the period of sunspot minimum shows that the ratio is almost constant within ±3 per cent. The ratio 10.7 cm/8 cm, which has a minimum in July and a maximum in January,

[1] Presented at the Fourth Symposium of Cospar, Warsaw, June 1963.

indicates, however, the possibility of a periodic variation in the monthly average values which is dependent on the calibration. Other observations have also been conducted at Nagoya [*Tanaka and Kakinuma,* 1956] at 3.2 cm since May 1956 and at 15 and 30 cm since the beginning of the International Geophysical Year [*Tanaka and Takinuma,* 1958]. Because an attenuation due to the lower atmosphere may occur in the radio fluxes, particularly for the shortest wavelengths, systematic errors may be introduced in the published data, since the transmission through unit atmosphere is subject to several variations. Such variations, generally proportional to the solar fluxes, may introduce periodic oscillations in the basic correlations between radio fluxes and upper-atmospheric parameters, these in addition to sporadic fluctuations not related to the solar emission.

The significance of radio observations for studying the physical conditions in the upper atmospheres of planets is well established, since such observations provide indices of solar activity in addition to the Zurich sunspot number (see, for example, *Kundu* [1960]). It is clear that a solar activity index can be chosen in the 1000- to 10,000-Mc/s spectral range, but it appears that the spectral variation must be considered in the study of correlations with atmospheric phenomena. Since the radio flux is composed, without considering the burst emissions, of a quiet component (basic radio flux) and a slowly varying component, the variation of ultraviolet radiations that heat and ionize the planetary atmospheres must be compared with that of the X radiations. *Friedman* [1962] has clearly shown that the X-ray spectrum between 40 and 60 A varies by a factor of approximately 7 during a solar cycle, while the variation in the range 8–20 A attains a value of about 50 and is several hundred in the 2–8 A wavelength range. Consequently, the behavior in the 3- to 30-cm interval cannot be taken as representative of the solar X-ray flux or of the integral of the ultraviolet flux. The radio flux in the neighborhood of 10 cm can be compared during a certain period of the solar cycle with an ionospheric index, such as the ionization of the $E$ region, but cannot be expected to fit all such observations during an entire solar cycle. There is always a relationship between solar radio emissions in the 3- to 30-cm interval, X-ray, and UV emission and atmospheric parameters, but the correlations vary during the solar cycle.

*Allen* [1957] and *Covington and Harvey* [1960] have found that the quiet-sun radio flux should have a significant variation with solar activity, which can reach a factor of about 2 for the minimum-to-maximum variation in the 10-cm flux. The slowly varying component, which is associated with disturbed regions on the solar disk and is closely correlated with sunspot numbers, leads, in the same spectral region, to a minimum-to-maximum variation of at least a factor of 4. A recent analysis by *Das Gupta and Basu* [1962] shows that, during the International Geophysical Year (July 1957 to December 1958, maximum of solar activity), there is a close correlation between the sunspot number and daily flux between 3 and 30 cm, and, furthermore, that the maximum variation occurs near 8–10 cm.

*Solar-cycle variations.* Since the solar radio emissions in the range of wavelengths from 3 to 30 cm show similar variations with a so-called 27-day cycle, it is of interest to plot the 27-day average value of the Zurich relative sunspot number and of the solar radio flux at 10 cm from 1957 until 1962. The plot (Figure 1) of the Wolf number[2] $\bar{R}_{27}$ with the radio flux[3] $\bar{S}_{27}$ (10.7 cm) shows that, for $\bar{R} \geq 50$, there is a linear relationship between these quantities which, with an error of $\pm 10$ per cent, takes into account the variations of the radio flux for values greater than $S = 100$ units, i.e.

$$\bar{S}_{27}(10.7 \text{ cm}) = 50 + 0.967\bar{R}_{27}$$

But for $\bar{S} < 100$ or $\bar{R} < 50$, a linear variation would be

$$\bar{S}_{27}(10.7 \text{ cm}) = 68 + 0.607\bar{R}_{27}$$

Thus, the close association of the 10-cm radiation with sunspots cannot be expressed during a whole cycle with the same linear relationship. Furthermore, the dispersion of the daily values is larger than the 27-day mean values. Figure 2, which shows a plot of daily values with a variation reaching $\pm 20$ per cent, indicates how such

[2] 27-day geomagnetic period (Bartels) deduced from Zurich Observatory data.

[3] Deduced from Ottawa data in units of $10^{-22}$ watt/m²/cycle/sec.

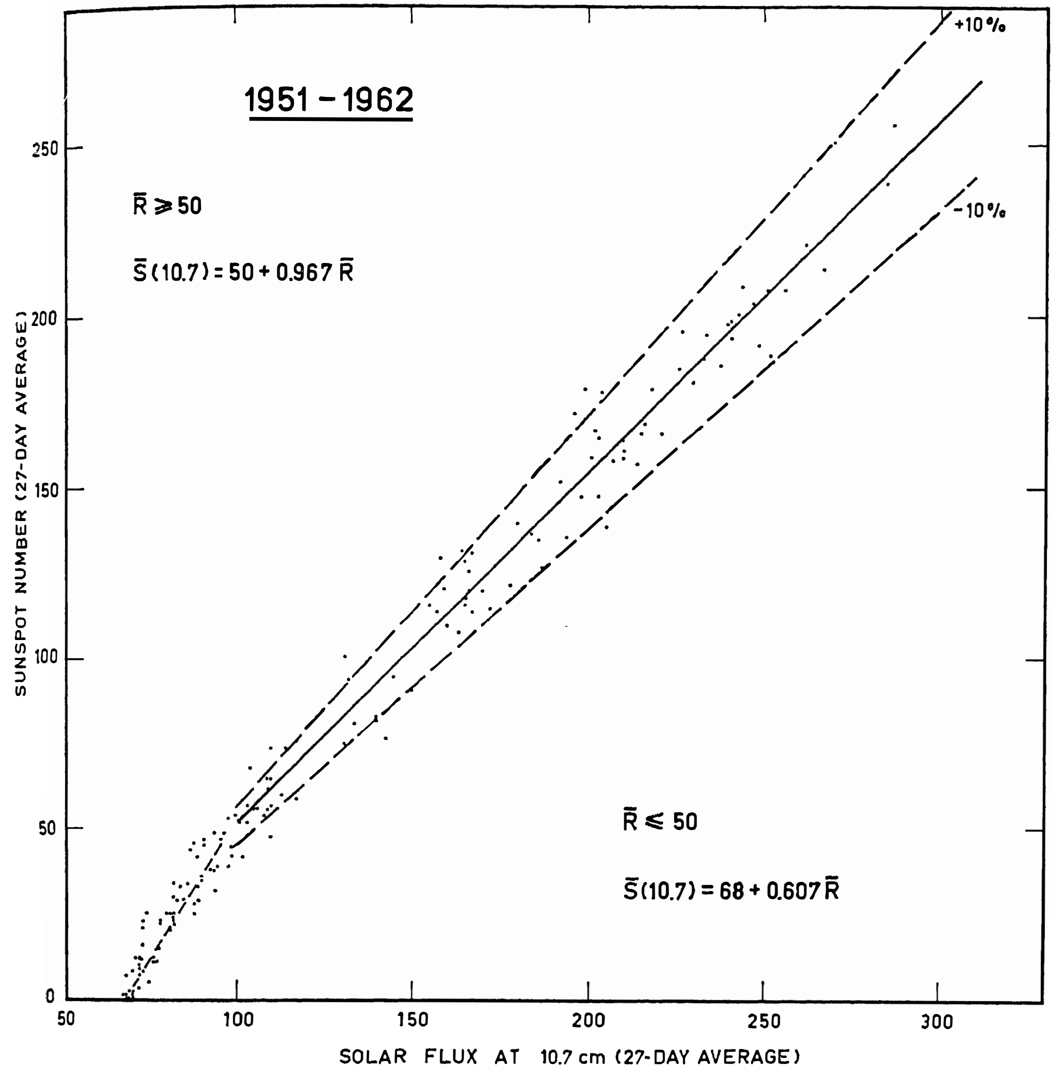
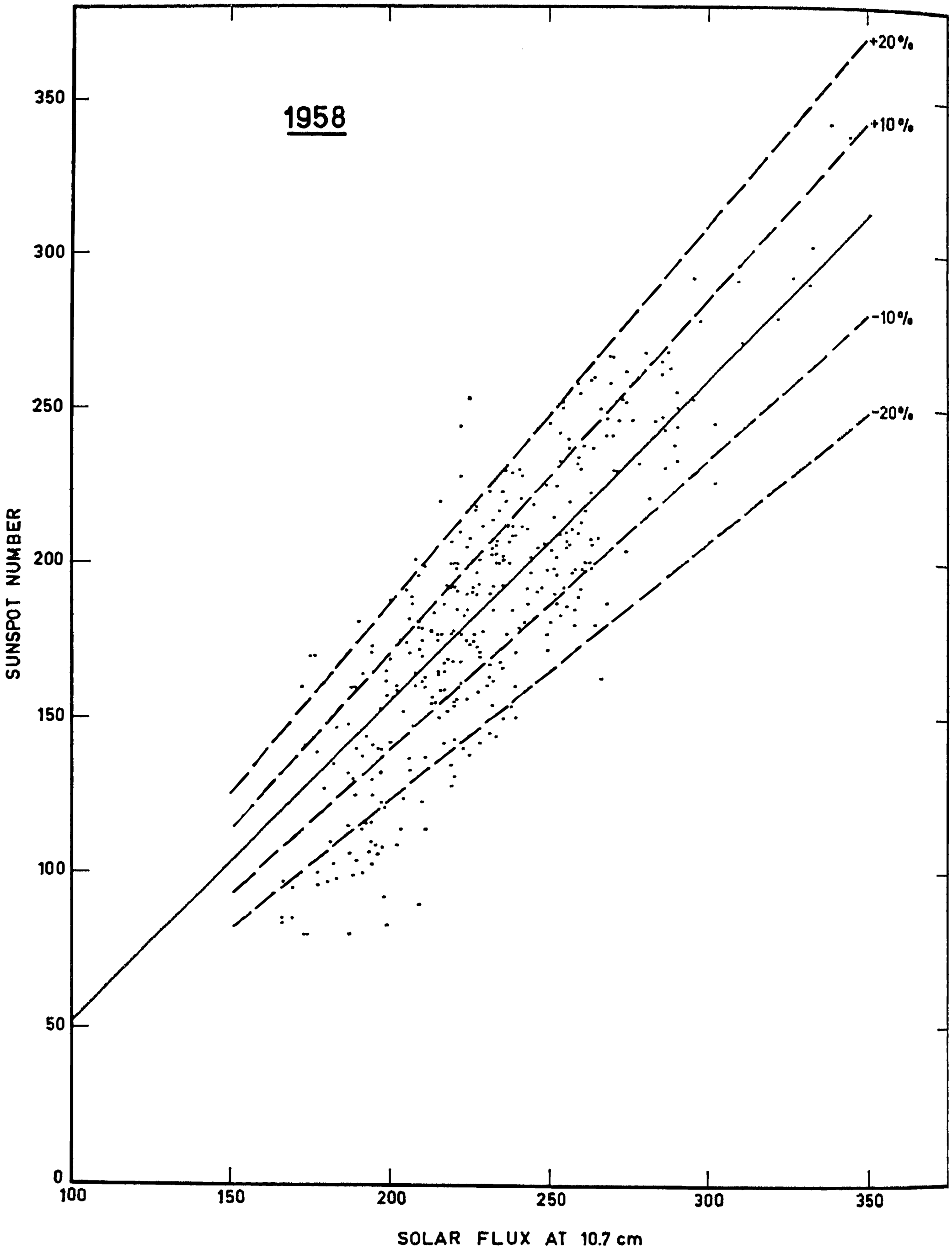



Fig. 1

a solar index may lead to important errors in deducing any empirical correlation with atmospheric parameters.

To determine the differences between two radio emissions, we can compare, first, the 27-day mean values of two wavelengths, such as 8 and 10.7 cm, for which data are available since 1952. Even if the absolute measurements of radio fluxes are estimated with an error of $\pm 7$ per cent, and can deviate by such a percentage from a ratio of unity after normalization, the general variation during a whole solar cycle should be significant [*Covington,* 1961]. Figure 3 shows the gradual difference in the ratio of the 27-day mean values of solar fluxes at 10.7 cm and 8 cm. Near 200 units, both fluxes are identical, i.e. $\bar{S}_{27}(10.7) = \bar{S}_{27}(8)$. For the lower values $\bar{S}_{27}(8) > \bar{S}_{27}(10.7)$, whereas the ratio is reversed, $\bar{S}_{27}(10.7) > \bar{S}_{27}(8)$, for the higher values. It is clear that the ratio $\bar{S}_{27}(10.7)/\bar{S}_{27}(8)$ varies during a solar cycle, even if the emissions at these two wavelengths originate from almost identical levels in the solar atmosphere.

If we compare the variation of fluxes for two years of high and low solar activity (Figures 4 and 5, 1958 and 1961), the annual mean values are



1958
SUNSPOT NUMBER
SOLAR FLUX AT 10.7 cm
+20%
+10%
-10%
-20%
0
50
100
150
200
250
300
350
100
150
200
250
300
350


Fig. 2

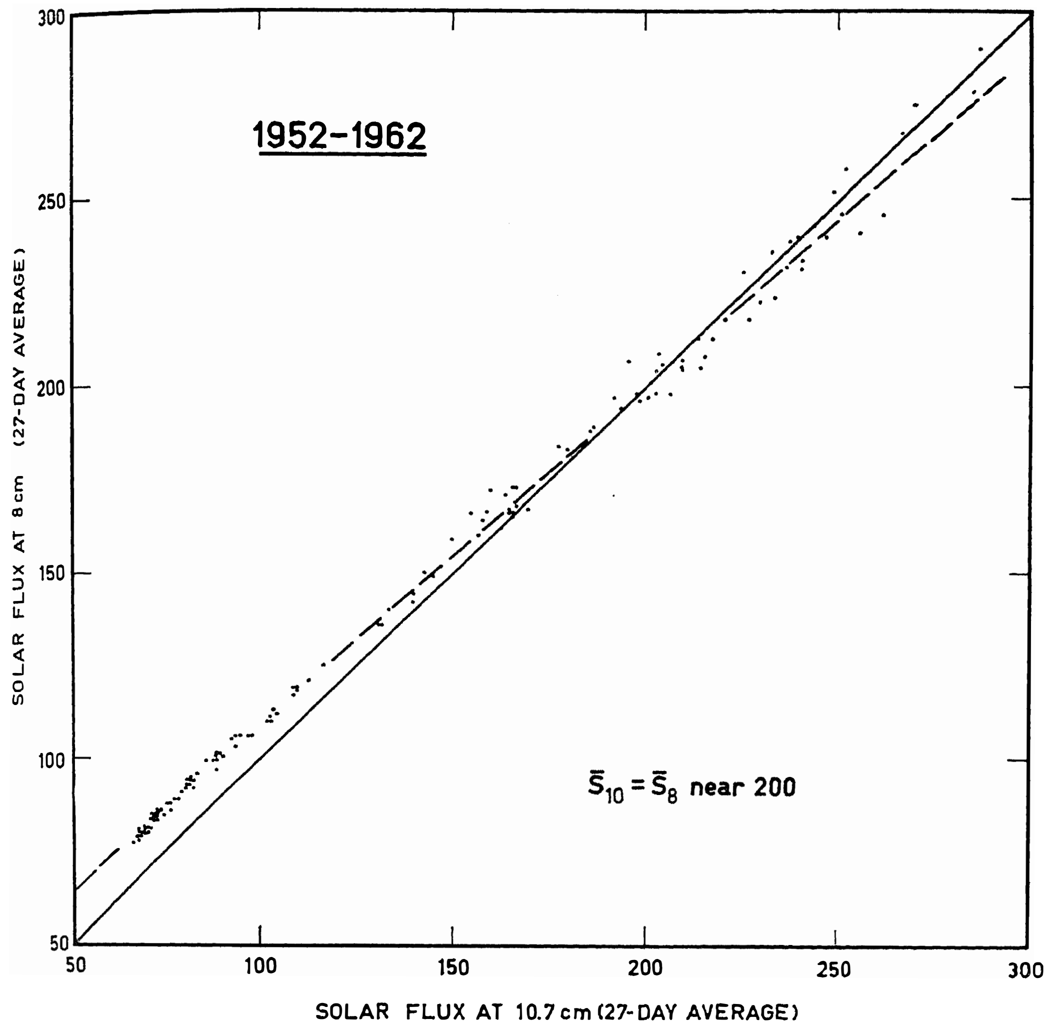



Fig. 3

$$\frac{\bar{S}_{1958}(8)}{\bar{S}_{1958}(10.7)} = \frac{224.8}{230.6} = 0.975$$

and

$$\frac{\bar{S}_{1961}(8)}{\bar{S}_{1961}(10.7)} = \frac{114.9}{113.9} = 1.09$$

There is, therefore, a reversal in the ratio of the 8-cm and 10.7-cm radio fluxes when there is a variation of a factor of about 2 in the absolute values of the fluxes. Furthermore, the maximum amplitude of the variation of daily fluxes, compared with the annual mean value, is, in both cases, of the order of $\pm 30$ per cent. At sunspot maximum (1958, Figure 4) the fluctuations of the ratio $[S(8)/\bar{S}_{1958}(8)]/[S(10.7)/\bar{S}_{1958}(10.7)]$ are generally less than $\pm 5$ per cent and always less than $\pm 10$ per cent. However, the same ratio in 1961 (Figure 5) is represented by scattered values reaching $\pm 15$ per cent but with systematic differences when the ratio is greater than or less than unity. In fact, the amplitude of the variation at 8 cm appears to be less than that at 10 cm. Thus, it can be concluded that the systematic differences occurring in the annual average, 27-day average, and daily values of fluxes measured at 10.7 cm (Ottawa) and at 8 cm (Nagoya) are a clear indication of real variations in the spectrum of the solar radio fluxes between 2800 and 3750 Mc/s.

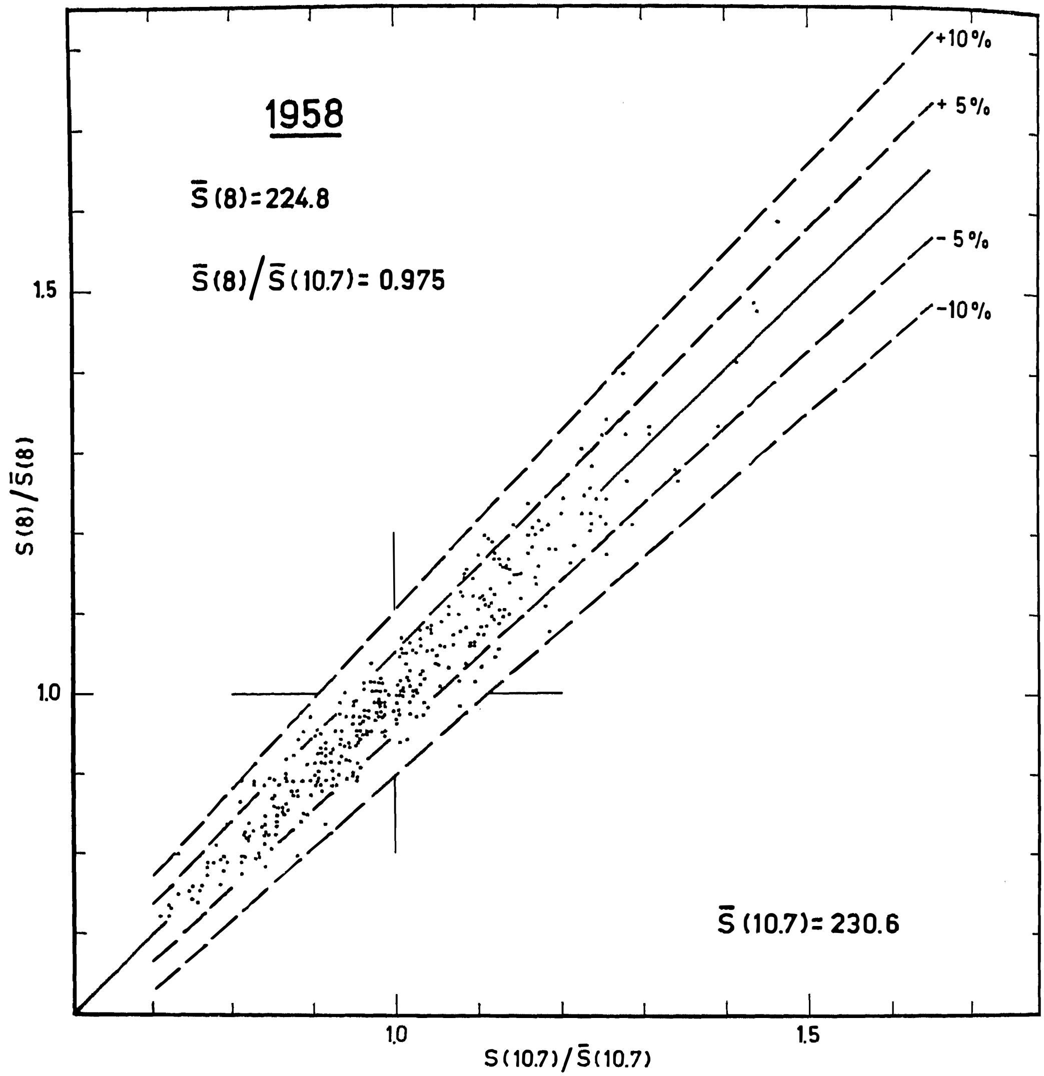



Fig. 4

*Spectrum from 1000 to 10,000 Mc/s.* A comparison between the fluxes at 15 and 30 cm, which are also measured at Nagoya, and the 10.7-cm flux does not show systematic differences such as those noted between 8 and 10.7 cm. From Figure 6 it appears that the ratios have the following median values:

$$\bar{S}_{27}(15)/\bar{S}_{27}(10.7) = 0.72 \pm 0.08$$

$$\bar{S}_{27}(30)/\bar{S}_{27}(10.7) = 0.55 \pm 0.07$$

In other words, the fluctuations, of the order of $\pm 10$ per cent, are of sufficiently small magnitude to be explained by experimental errors without showing real spectral differences. In any event, such a variation of the ratios cannot be indicative of a systematic difference associated with the solar cycle as has been found for 8 cm. In fact, the ratio of two radio fluxes really becomes sensitive to the solar cycle when the radiation is at a wavelength shorter than 10 cm.

The ratios $\bar{S}_{27}(3.2)/\bar{S}_{27}(8)$ and $\bar{S}_{27}(3.2)/\bar{S}_{27}(10.7$ cm) are considered in Figure 7. The two curves lead to the median value of $\bar{S}_{3.2}/\bar{S}_{10.7} = 1.5$ for $\bar{S}_{27}(10.7) > 200$ with a maximum fluctuation of $\pm 10$ per cent. The ratio increases with a decrease

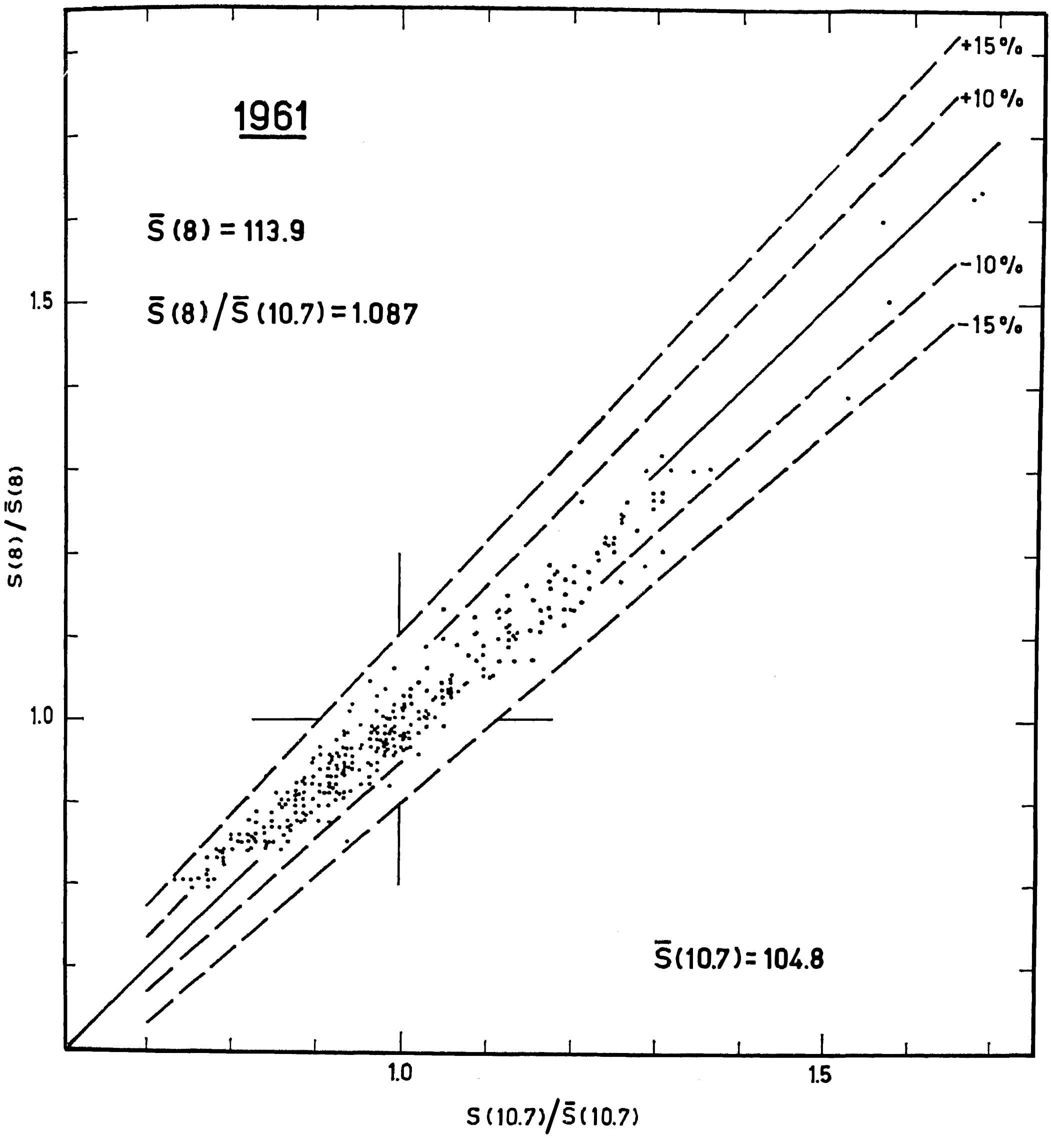



Fig. 5

of solar activity. It is so sensitive to solar activity that its fluctuations follow the variations of the solar flux. Peaks in the ratio correspond to decreasing fluxes, and the minimum value of the ratio, namely 1.3, is real and is associated with the highest activity of the sun in 1957. Thus the variation of radio fluxes with solar activity in the spectral range 1000–10,000 Mc/s is always expressed as follows:

$$\frac{\bar{S} < 10 \text{ cm}}{\bar{S} \geq 10 \text{ cm}} \quad \text{decreases when } S \text{ increases}$$

It is evident that an adequate solar radio index may be chosen at 10 cm or at shorter wavelengths. However, a more complete analysis must be made before we can adopt a general law for the entire solar cycle. Figure 8 shows how the ratio $\bar{S}_{27}(8)/\bar{S}_{27}(10.7)$ varies between 1952 and 1962. The ratio reaches a maximum at the minimum of the solar cycle with a median value of 1.15 ± 5 per cent and decreases to a median value of 0.98 ± 5 per cent at the maximum of the solar cycle, i.e. a difference reaching 20 per cent for the minimum-to-maximum variation

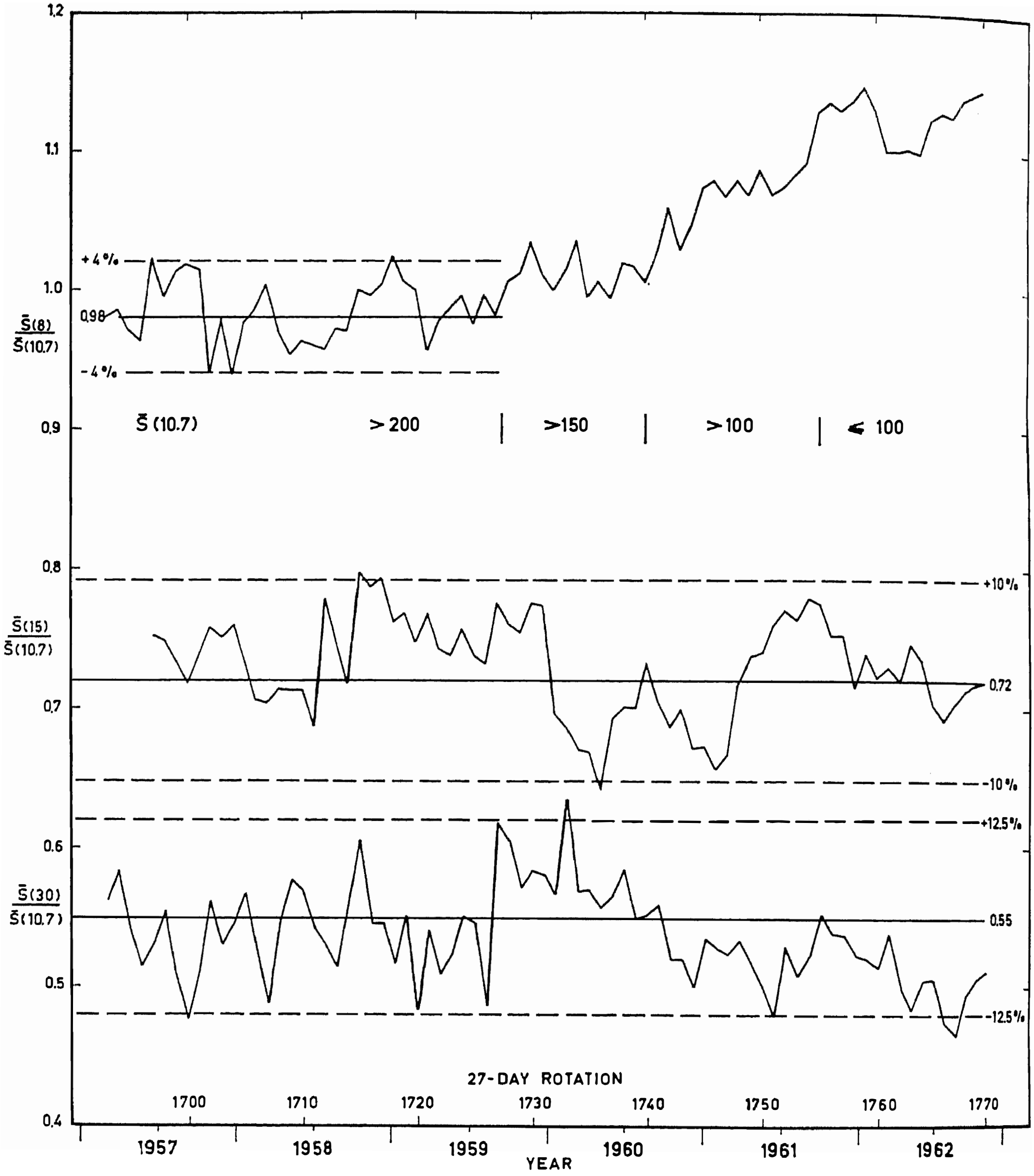



Fig. 6

of a solar cycle. It is clear, therefore, that the absolute fluxes must change as indicated by this ratio.

To give an idea of the amplitude of the 27-day variation of the slowly varying component, Figures 9 and 10 show the ratios $S_{max}/S_{27}$ and $S_{min}/S_{27}$, representing the highest and lowest values of the daily fluxes for each 27-day period. No systematic difference can be immediately detected with the solar cycle for 10 and 8 cm. It is clear that the amplitude of the 27-day cycle at 3 cm is always less than that at 8 cm. As far as 15 cm is concerned, it appears that for $S(8) \geq 200$ units, i.e. for high solar activity, $\Delta S(15\ \text{cm}) \leq \Delta S(8\ \text{cm})$, whereas $\Delta S(15\ \text{cm}) > \Delta S(8\ \text{cm})$ at low solar activity, i.e. when $S(8) < 120$. The same law seems also to be adequate for 30 cm, since $\Delta S(30\ \text{cm}) < \Delta S(8\ \text{cm})$ when $S(8) > 150$ and $\Delta S(30\ \text{cm}) \geq \Delta S(8\ \text{cm})$ when $S(8) < 120$. Such striking features ex-

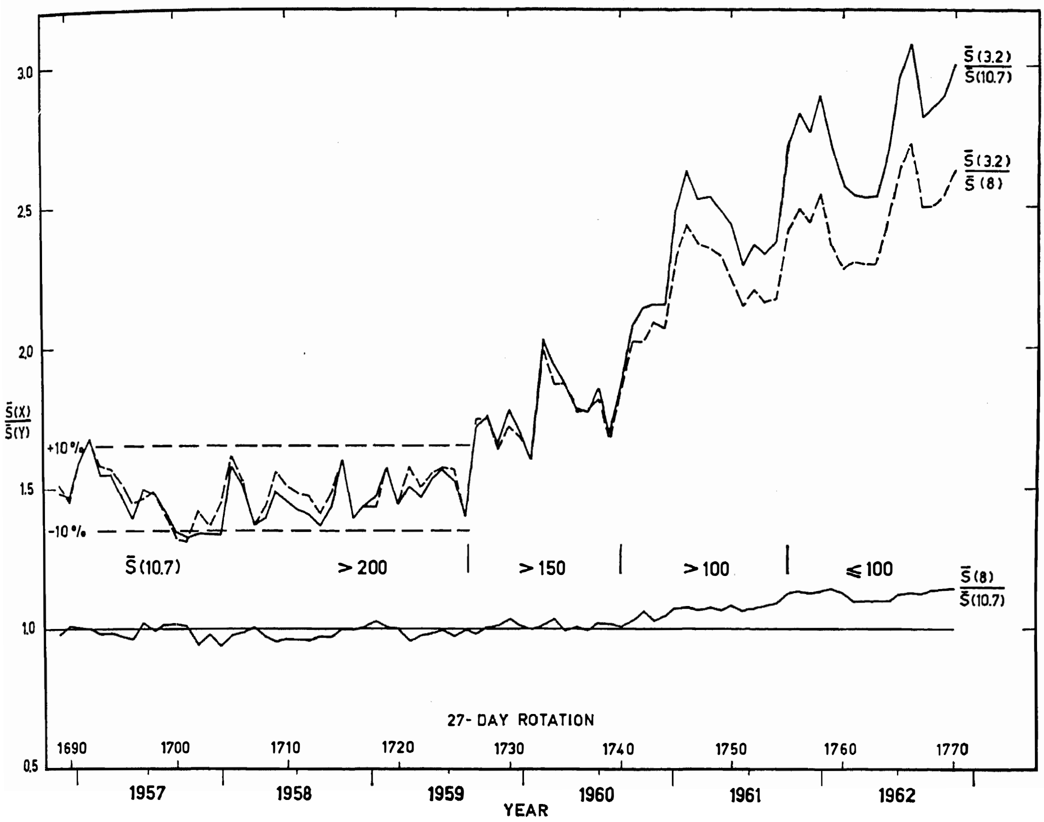

S̄(3.2)/S̄(10.7)
S̄(3.2)/S̄(8)
S̄(X)/S̄(Y)
+10%
-10%
S̄(10.7)
> 200
> 150
> 100
≤ 100
S̄(8)/S̄(10.7)
27- DAY ROTATION
YEAR

Fig. 7

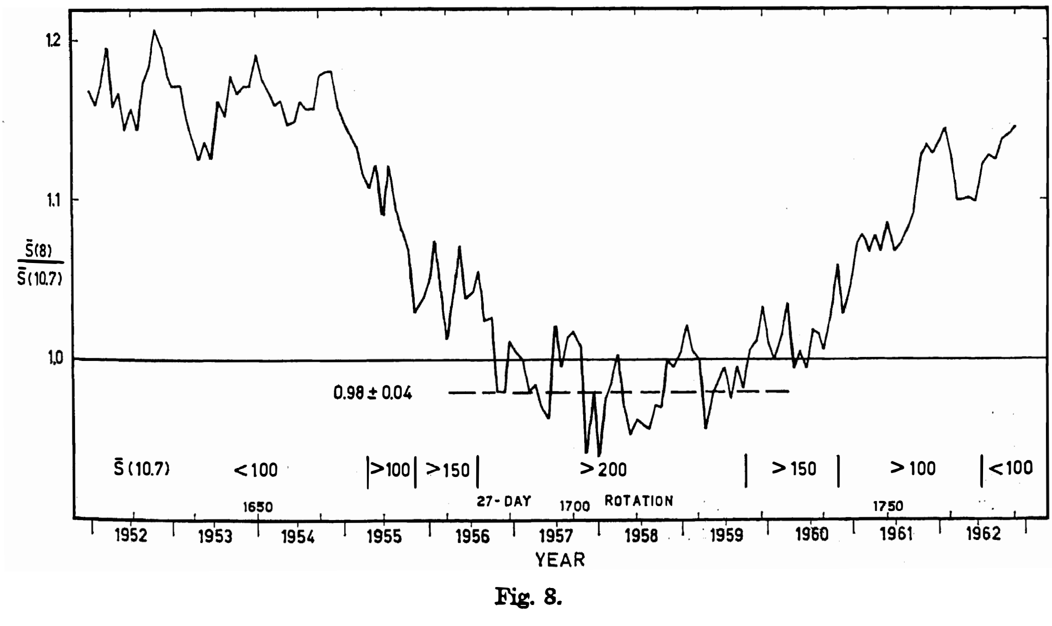

S̄(8)/S̄(10.7)
0.98 ± 0.04
S̄(10.7)
< 100
> 100
> 150
> 200
27-DAY ROTATION
YEAR

Fig. 8.

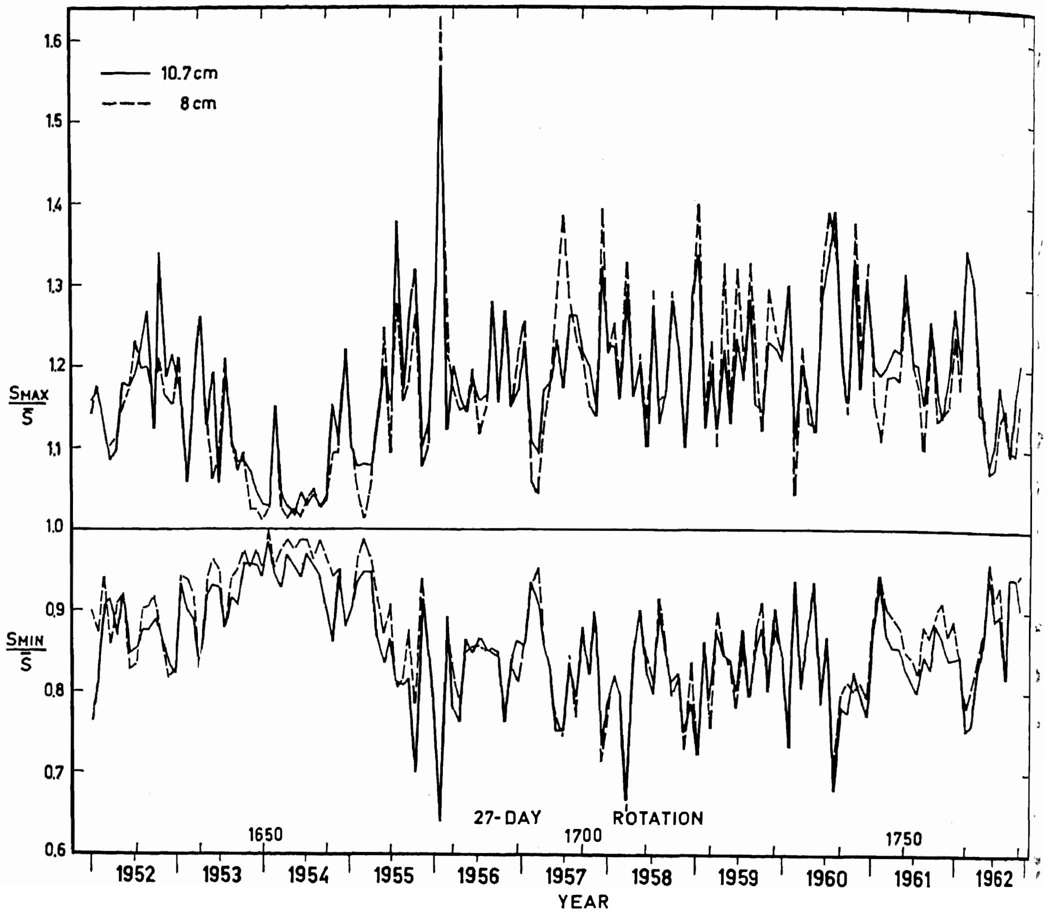



Fig. 9

hibited by the 27-day cycle between 8 and 30 cm indicate that its maximum-to-minimum amplitude, as detected by the daily mean fluxes, cannot be subject to simple laws related to the frequency. A systematic variation is found at high solar activity during the International Geophysical Year period [e.g., *Das Gupta and Basu,* 1962] but is completely different in 1961 and 1962, as is shown in Figure 9.

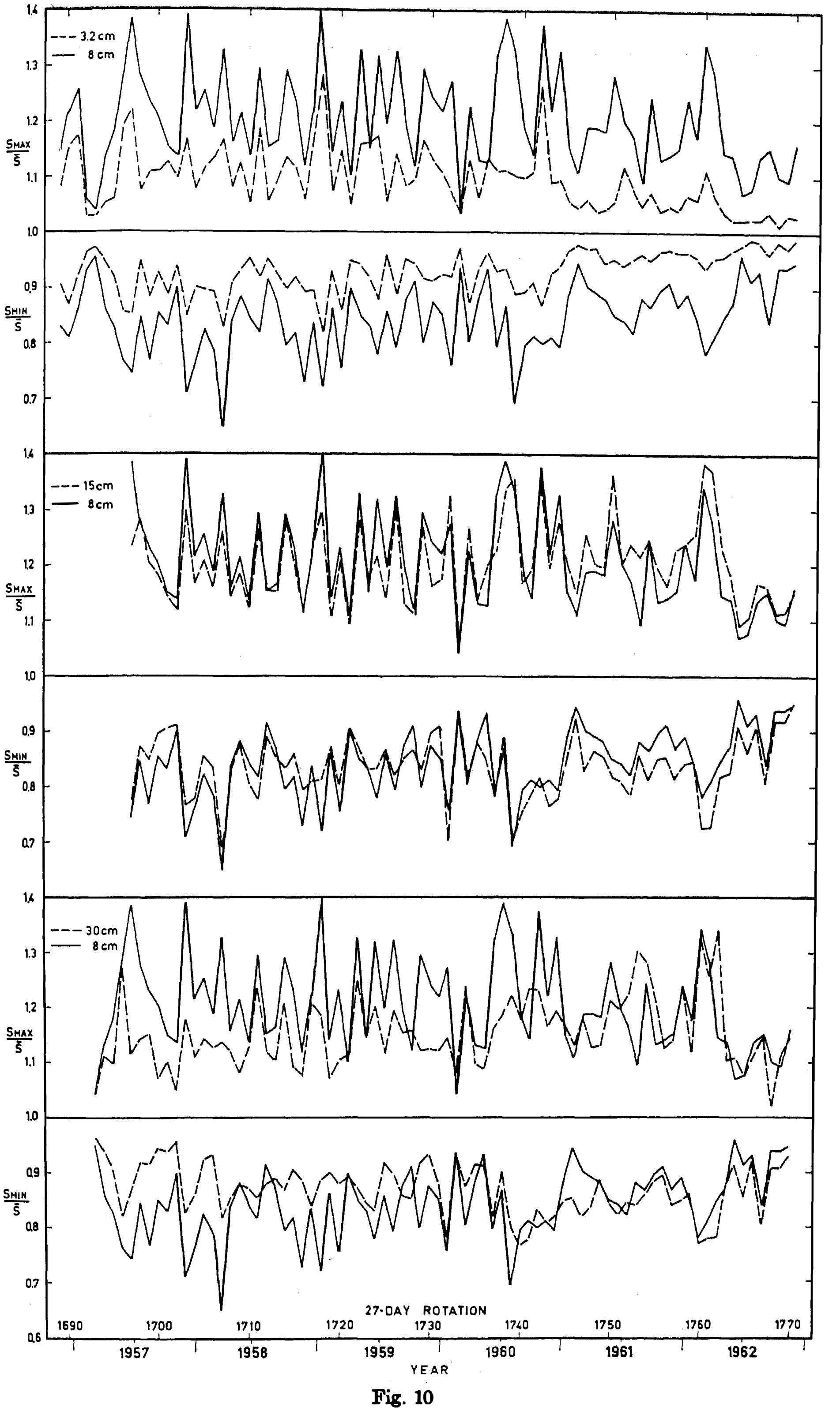
Thus a complete analysis of the solar radio fluxes should be made at wavelengths shorter than 10 cm, since no clear conclusion (systematic errors or spectral differences) can be reached for the spectral range of wavelengths greater than 10 cm.

*Atmospheric temperatures and solar fluxes.* Since the increase of the atmospheric scale height with altitude is due to a normal decrease of the molecular mass and not to an increase of the temperature [*Nicolet,* 1960], and the thermopause temperature is related to the ultraviolet heating and conduction cooling, a relationship can be found between the solar radio flux and the thermopause temperature. *Jacchia* [1961], after adopting *Nicolet*'s [1961*b*] atmospheric model, deduced an equation having the form:

$$T = T_0 + aS \qquad (1)$$

in which the temperature of the thermopause $T$ is related to the solar flux $S$ with $dT/dS = a$; and $T_0$ a constant. Linear relationships such as (1) have also been adopted by *Harris and Priester* [1963] and *Paetzold* [1963].

From the preceding discussion it is clear that the adoption of a radio index at different wavelengths will modify the value of the coefficient $a$ in (1). Further, different coefficients will be obtained, depending on the wavelength chosen.



--- 3.2 cm
— 8 cm
--- 15cm
— 8cm
--- 30cm
— 8 cm
SMAX / S̄
SMIN / S̄
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
27-DAY ROTATION
1690
1700
1710
1720
1730
1740
1750
1760
1770
1957
1958
1959
1960
1961
1962
YEAR


**Fig. 10**

Let us again consider the 5 monochromatic radio fluxes at 3.2, 8, 10.7, 15, and 30 cm for which the analyses made in the preceding paragraphs have shown the general behavior for a complete solar cycle. The following ratios were determined:

1. Ratio of the maximum 27-day mean value reached in 1957 (period 1701 or 1703) and the minimum 27-day mean value reached in 1954 (periods near 1655) or, when no continuous observations are available, individual values during 1766 in August 1962.
2. Ratio of the minimum daily fluxes reached in 1957 (periods between 1695 and 1715) and the minimum 27-day mean value.
3. Ratio of the maximum of maximum daily fluxes reached in 1957 (period 1703) and the minimum 27-day mean value.

The first ratio $R_1$ will give the maximum amplitude during a solar cycle of the 27-day mean value of the radio flux. The second ratio $R_2$ corresponds to the maximum possible variation of the quiet sun during a solar cycle, and the third ratio $R_3$ corresponds to the minimum-to-maximum variation which can be reached.

TABLE 1. Ratios of Various Maximums of Solar Fluxes to the Minimum Values for a Quiet Sun at Minimum Solar Activity

| Mc/s | 9400 | 3750 | 2800 | 2000 | 1000 |
|---|---|---|---|---|---|
| λ, cm | 3.2 | 8 | 10.7 | 15 | 30 |
| $R_1$ | 1.6 | 3.7 | 4.2 | 4.5 | 4.5 |
| $R_2$ | 1.2 | 2.2 | 2.5 | 2.8 | 3.0 |
| $R_3$ | 2.0 | 5 | 5.5 | 5.9 | 5.4 |

The various ratios are shown in Table 1. A factor of about 6, which represents the minimum-to-maximum variation $R_3$ near 2000 Mc/s, corresponds to an extreme case. It is still, however, less than the variation of the X-ray flux [*Friedman*, 1962] absorbed in the ionospheric *E* layer. In fact, a factor of 7 in the X-ray emission must be compared with the maximum ratio $R_1$ of 4.5 representing the 27-day mean ratio. The ratio $R_2$, which varies from 1.2 at 3.2 cm to 3 at 30 cm, shows how difficult it is to determine the amplitude of the quiet-sun variation which should be related, first of all, to the ultraviolet flux associated with the solar heating of the upper atmosphere.

Nevertheless, since the ratio $R_3/R_1$ is of the

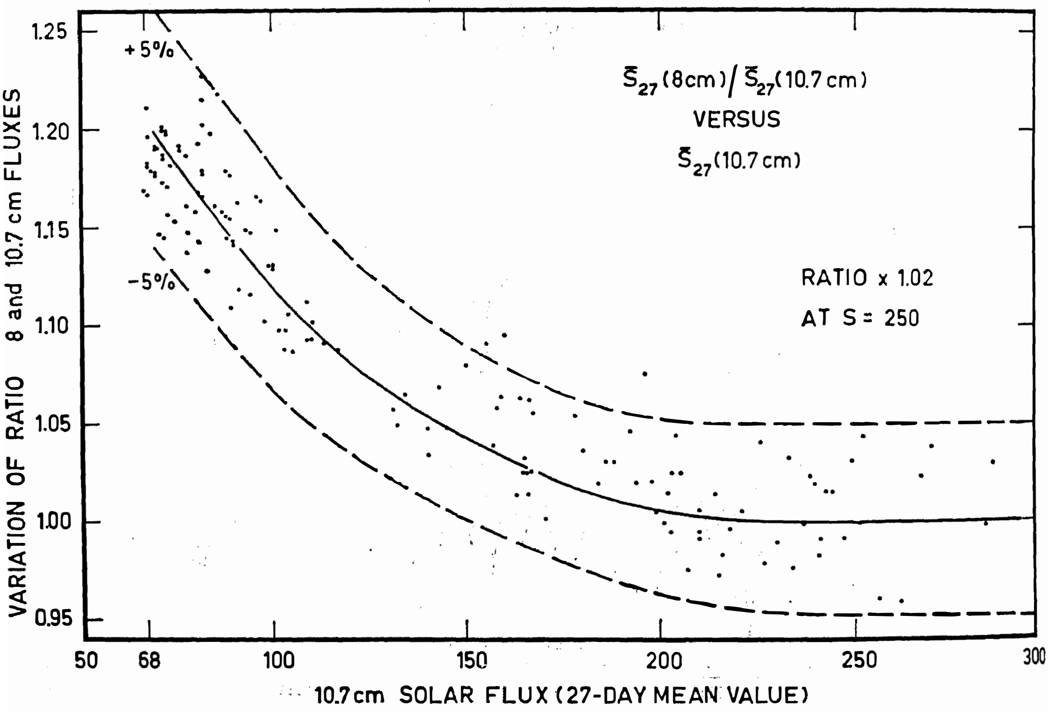



Fig. 11

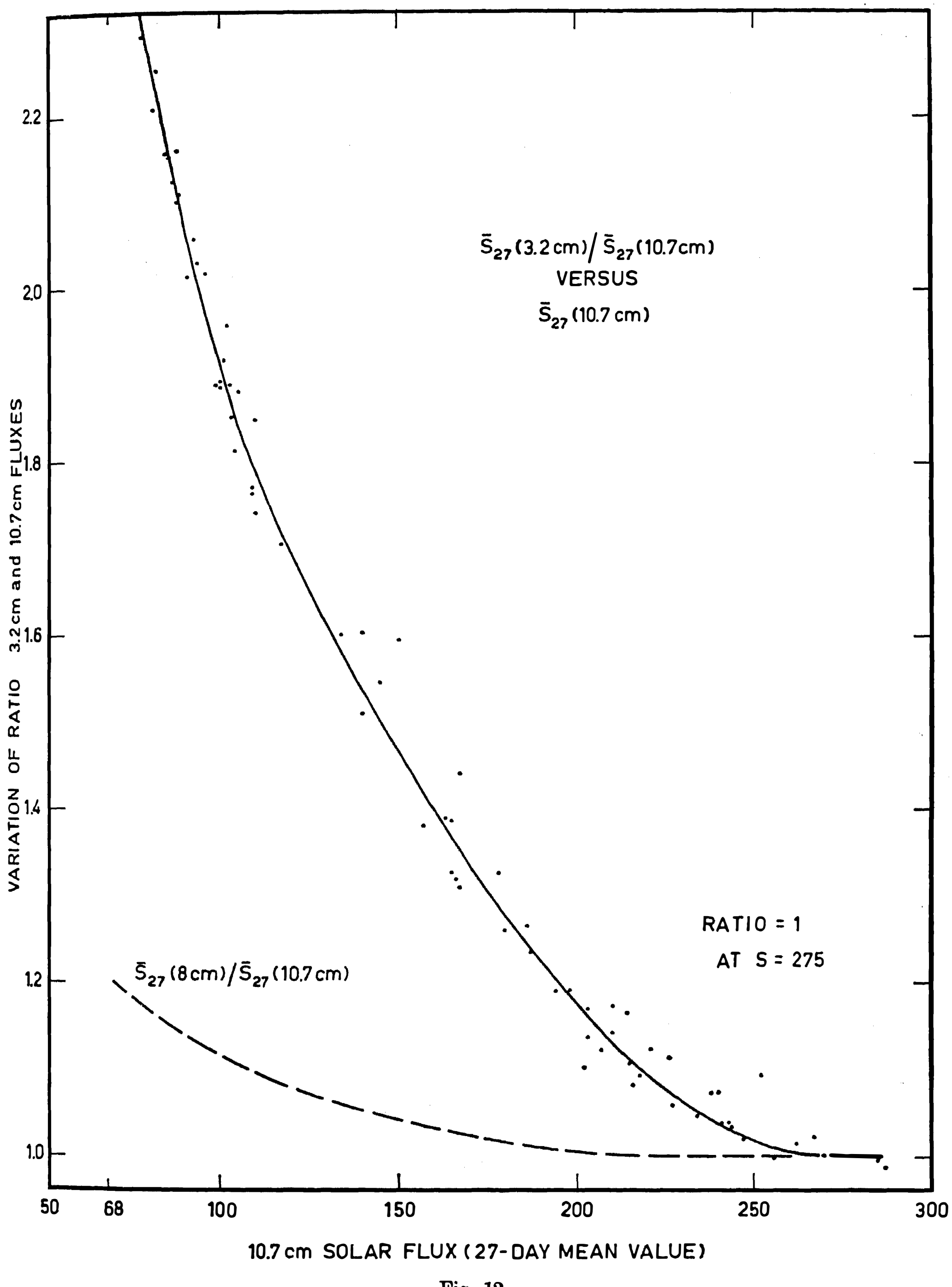

$\bar{S}_{27}$(3.2 cm)/ $\bar{S}_{27}$(10.7cm)
VERSUS
$\bar{S}_{27}$(10.7 cm)
RATIO = 1
AT S = 275
$\bar{S}_{27}$(8cm)/$\bar{S}_{27}$(10.7 cm)
VARIATION OF RATIO 3.2 cm and 10.7 cm FLUXES
2.2
2.0
1.8
1.6
1.4
1.2
1.0
50
68
100
150
200
250
300
10.7 cm SOLAR FLUX (27-DAY MEAN VALUE)

Fig. 12

order of 1.3 and the ratio $R_2/R_1$ is of the order of 0.6 between 8 and 15 cm, (1) is used in a different form in which a basic component corresponds to the mean value $\bar{S}_{27}$ for a 27-day period and a varying component $\Delta S$ represents the oscillation during such a period:

$$T = T_0 + a\bar{S}_{27} + b\Delta S \tag{2}$$

where

$$\Delta S = S - \bar{S}_{27} \tag{3}$$

or

$$T = T_0 + (a - b)\bar{S}_{27} + bS \tag{4}$$

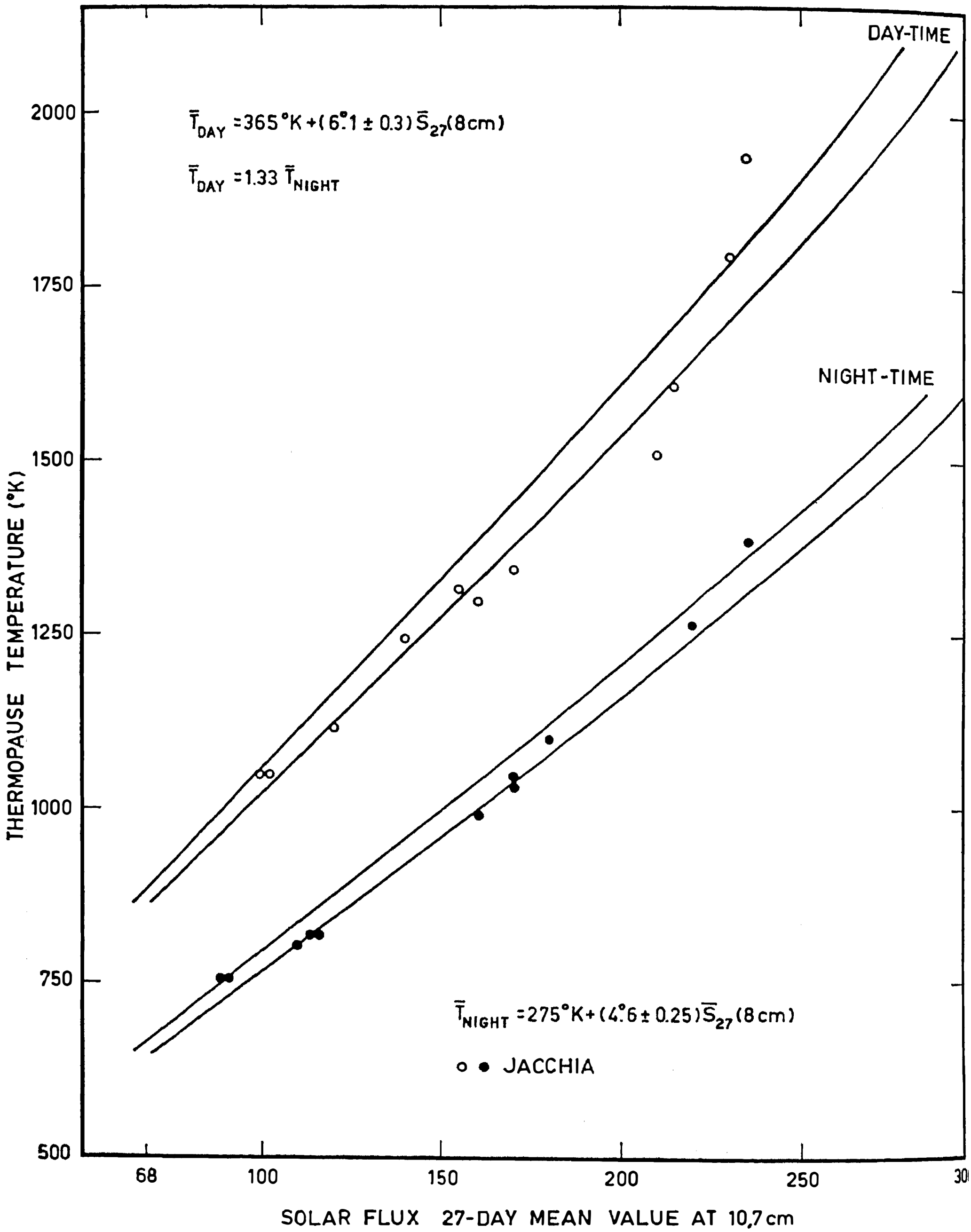



Fig. 13

The coefficients $a$ and $b$ will have different values. $a$ will be greater than $b$, since it must take into account the basic component of the solar flux primarily associated with the ultraviolet flux. The factor $b$ represents the 27-day oscillation of a radio flux that is less important for the ultraviolet variation. In other words, considering the ratios $R_1$ and $R_3$, the term $a\bar{S}_{27}$ in (4) is associated with the variation of $R_1$ during a whole solar cycle and the term $b\Delta S$ corresponds to the fluctuations $(R_3 - R_1)$ during a 27-day period.

To determine the variations for an entire solar cycle, we can compare the ratios of $R_1$ for 3.2, 8, and 10.7 cm, since the variation for the ultraviolet heating must be associated with this spectral range. The variation of $\bar{S}_{27}(10.7 \text{ cm})$ is plotted against the ratio $\bar{S}_{27}(8)/\bar{S}(10.7)$ in Figure 11 with the unit ratio at $S(10.7 \text{ cm}) = 250$. A smoothed relation is drawn and indicates that the slope is steeper for lower activity. The correction factor reaches 20 per cent at sunspot minimum; it should be mentioned that we would not expect a severe departure for the smooth curve, since the individual ratios are affected with a maximum error of $\pm 5$ per cent, i.e. not more than the possible errors in the absolute values. Figure 12 represents the characteristic difference in the 27-day mean fluxes of 3.2 and 10.7 cm. The normalization of the ratio $\bar{S}_{27}(3.2)/\bar{S}_{27}(10.7)$ is made for $250 < \bar{S}_{27}(10.7) < 300$ units. There is a significant change with the solar cycle, reaching a factor of 2.6. The dashed curve, corresponding to the ratio $\bar{S}_{27}(8)/\bar{S}_{27}(10.7)$, compared with the 3.2-cm curve

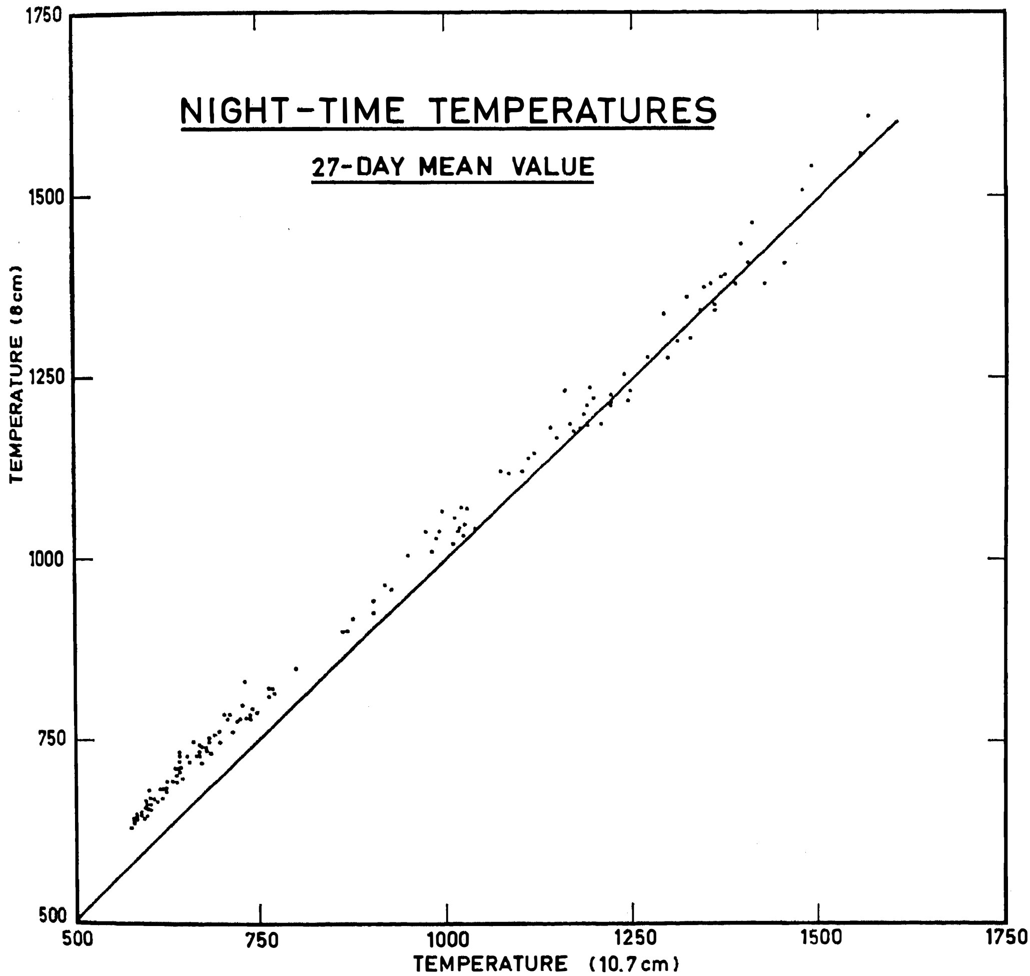



Fig. 14

shows how the spectrum varies with solar activity between 3000 and 10,000 Mc/s. The conclusion arrived at from such an analysis is that the variations of the ultraviolet radiation can be correlated with a radio flux in the range 10–30 cm during the maximum of the solar cycle. However, the relative change of flux is systematically less for higher frequencies and can be regarded as being more representative of the change of the ultraviolet spectrum related to the heating of an upper atmosphere. Since there are no measurements available between 10,000 and 3750 Mc/s, a complete analysis can be made only at 8 and 10.7 cm.

*Jacchia* [1963], using a smoothed value $\bar{S}$(10.7 cm) such that

$$\bar{T} = T(S = 200) + 2.5°\bar{S}(10.7 \text{ cm}) \quad (5)$$

has determined average nighttime and daytime temperatures corresponding to an average value for the diurnal bulge. The result is that, except for the lowest values of $\bar{S}$, a linear correlation with an average slope of 4.5° between nighttime temperatures and $\bar{S}$(10.7 cm) may be found. The same linear relationship is also used by *Harris and Priester* [1963], i.e.

$$T_{\text{night}} = 275°\text{K} + 4.5°\bar{S}(10.7 \text{ cm}) \quad (6)$$

Adopting the same formula for 8 cm, we see (Figure 11) that (8) below can be used if we adopt for the average slope of the variation of the nighttime temperature:

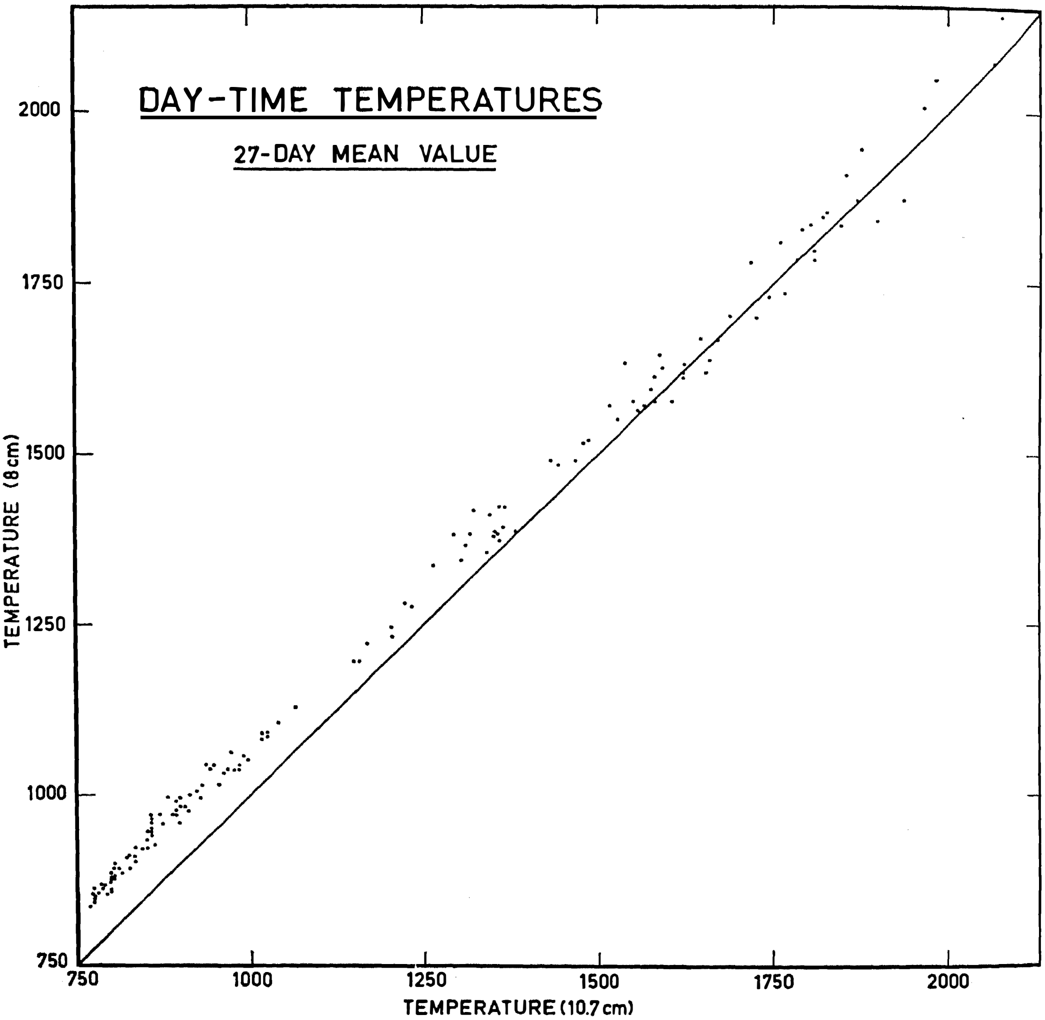



Fig. 15.

$$d\bar{T}(\text{night})/d\bar{S}_{27}(8 \text{ cm}) = 4.6° \quad (7)$$

The use of the 8-cm flux as a solar index leads to a basic correlation between the temperature and the flux at 10.7 cm that is no longer linear. Taking into account the differences of ±5 per cent occurring between 8- and 10-cm fluxes, we use, instead of (6),

$$\bar{T}_{\text{night}} = 280°\text{K} + (4.6° \pm 0.25)\bar{S}_{27}(8 \text{ cm}) \quad (8)$$

The variation of ±5 per cent in the second term of (8) shows that differences of at least $\pm 0.25S$ should be expected in any determination of a correlation between the temperature and the 27-day mean value of any observed radio flux.

To fit the temperatures of the daytime bulge, we use Jacchia's relation

$$\bar{T}_{\text{day}} = \bar{T}_{\text{night}} \times 1.33 \quad (9)$$

leading to

$$\bar{T}_{\text{day}} = 370° + (6.10 \pm 0.3)\bar{S}_{27}(8) \quad (10)$$

The maximum daytime temperature may require a factor a little greater than 1.33, but the following expression, equivalent to that used by *Harris and Priester* [1963],

$$\bar{T}_{\text{daytime maximum}} = \bar{T}_{\text{night}} \times 1.35 + \bar{S}(10.7 \text{ cm}) \quad (11)$$

is not adequate, since it leads to diurnal amplitudes that are too large and, furthermore, to systematic differences, depending on the level of solar activity, with temperatures that are too high.

Thus (8) and (10) have been used to determine the diurnal oscillation with the variation of $\bar{S}_{27}(8 \text{ cm})$. In Figure 13 the temperature variation is plotted against the usual 10.7-cm solar flux utilizing a reconversion from 8 cm which shows the nonlinearity of the relationships. The minimum-to-maximum variation of the average nighttime temperature during a solar cycle is from about 650°K for the completely quiet sun to 1600°K for the highest solar activity. The same variation for daytime temperatures corresponds to the range of 850°K to 2100°K.

To use the 27-day mean values of the 10.7-cm radio flux for conditions of low solar activity, the following formulas can be adopted instead of (8) and (10):

$$\bar{T}_{\text{night}} = 380°\text{K} + (4° \pm 0.25)\bar{S}_{27}(10.7 \text{ cm}) \quad (8a)$$

$$\bar{T}_{\text{day}} = 500°\text{K} + (5.3° \pm 0.3°)\bar{S}_{27}(10.7 \text{ cm}) \quad (10a)$$

if $\bar{S}_{27}(10.7 \text{ cm}) < 200$ units.

*Jacchia and Slowley* [1962] have made a precise analysis of the 27-day oscillation deduced from the drag of several satellites. The temperature variation can be expressed by a relation such as

$$T = \bar{T} + b\Delta S \quad (12)$$

with values of the coefficient $b$ that may be of

TABLE 2. Thermopause Temperatures and Solar Radio Fluxes*

| Temperature, °K | Nighttime $\bar{S}_{27}$(8 cm) | Nighttime $\bar{S}_{27}$(10.7 cm) | Daytime $\bar{S}_{27}$(8 cm) | Daytime $\bar{S}_{27}$(10.7 cm) |
|---|---|---|---|---|
| 650 | 80 | 68 | | |
| 700 | 91 | 80 | | |
| 750 | 102 | 93 | | |
| 800 | 113 | 105 | | |
| 850 | 124 | 118 | 79 | 68 |
| 900 | 135 | 130 | 87 | 76 |
| 950 | 146 | 143 | 95 | 85 |
| 1000 | 157 | 155 | 104 | 94 |
| 1050 | 167 | 168 | 112 | 104 |
| 1100 | 178 | 180 | 120 | 113 |
| 1150 | 189 | 193 | 128 | 122 |
| 1200 | 200 | 205 | 136 | 132 |
| 1250 | 211 | 217 | 145 | 141 |
| 1300 | 222 | 228 | 153 | 151 |
| 1350 | 233 | 239 | 161 | 160 |
| 1400 | 244 | 250 | 169 | 169 |
| 1450 | 255 | 261 | 177 | 178 |
| 1500 | 265 | 272 | 186 | 188 |
| 1550 | 276 | 282 | 194 | 197 |
| 1600 | 287 | 293 | 202 | 206 |
| 1650 | 298 | 304 | 210 | 215 |
| 1700 | 309 | 315 | 218 | 223 |
| 1750 | | | 227 | 232 |
| 1800 | | | 235 | 240 |
| 1850 | | | 243 | 248 |
| 1900 | | | 251 | 257 |
| 1950 | | | 259 | 265 |
| 2000 | | | 268 | 273 |
| 2050 | | | 276 | 282 |
| 2100 | | | 284 | 290 |
| 2150 | | | 292 | 298 |
| 2200 | | | 300 | 306 |

* Solar radio fluxes given with precision of $\pm 0.25S$ corresponding to differences in observational data.

the order of 2.5; extreme values of the order of 2° and 3° could be used for nighttime and daytime conditions. However, it is not yet certain that there is a real difference between dark and sunlit atmospheres, since Jacchia and Slowley considered the possibility of a constant value of $b = 2.2$.

The final formula can be written, according to (2), (4), (8), and (12), and neglecting the possible error of ±5 per cent,

$$T_{\text{night}} = 280°\text{K} + 4.6°\bar{S}_{27}(8 \text{ cm}) + 2.5°\Delta S \quad (13)$$

or

$$T_{\text{night}} = 280°\text{K} + 2.1°\bar{S}_{27}(8 \text{ cm}) + 2.5°\Delta S(8 \text{ cm}) \quad (14)$$

This relation holds, as a general relation, between the solar flux at 8 cm and atmospheric temperature over a complete solar cycle and including the 27-day oscillation. Consequently, there is no need for an explanation of atmospheric heating involving a solar wind or any other corpuscular effect. In fact, the term involving $\bar{S}_{27}$ is the basic component for the ultraviolet heating, whereas the other term incorporating $\Delta S$ involves, with a smaller weight, the effect of the 27-day oscillation. When both $S$ and $\bar{S}$ are used in the same formula, however, the coefficients are of the same magnitude as those deduced from the observations.

There are other effects which have also been introduced, such as the semiannual or annual variations detected by *Paetzold* [1963], for which an origin has been suggested as an effect of a solar or an interstellar wind, respectively. The fact, however, that a solar index such as 8-cm instead of 10.7-cm flux has removed an essential difficulty, such as a lack of a linear correlation at low solar activity and also a systematic drift in the atmospheric temperature from 1958 to 1962, leads to other possible explanations for such effects that may be detected only after several reductions of observational data. Several factors must be kept in mind: (1) Any atmospheric model may lead to systematic differences in the temperature of the thermopause of at least ±50°K. (2) The boundary conditions in the thermosphere cannot be kept constant for an entire year. (3) A steady state of diffusion conditions cannot be assumed in a detailed study of the diurnal variation. (4) The absolute value of any solar radio flux may lead to an undetectable error of ±5 per cent. (5) Depending on the type of calibration, systematic drifts due to seasonal atmospheric effects can occur. Thus, fluctuations may occur that lead to possible singular behavior of certain parameters. In spite of these difficulties, the solar radio flux at 8 cm establishes a simple pattern that is suitable for representing the average temperature conditions of the earth's upper atmosphere at various stages of the solar cycle. This requires a heating by ultraviolet radiation and a cooling by heat conduction without postulating any essential corpuscular process. The latter would lead to an absorbed energy of not less than 0.2 erg $\text{cm}^{-2}$ $\text{sec}^{-1}$, whereas the normal atmospheric conditions show that it cannot exceed 0.05 erg $\text{cm}^{-2}$ $\text{sec}^{-1}$. These influences must be found in the auroral zone and are important during magnetic storms through hydromagnetic heating.

*Temperature variations during a solar cycle.* Since the ratio $\bar{S}_{27}(8)/\bar{S}_{27}(10.7)$ varies with solar activity and there is no general relation that is applicable, numerical values must be used. To show how the differences can be dealt with, a calculation has been made for average nighttime and daytime temperatures corresponding to the 27-day mean values of solar radio fluxes at 8 and 10.7 cm by using (6) and (8). Figure 14 shows how the nighttime temperatures deduced from the 10.7-cm radio flux would be systematically too low when the temperature is less than 1250°K; the difference increases with the decrease of the solar activity. Figure 15 gives the daytime temperatures from 850°K to 2100°K with a systematic difference below 1750°K. The scatter of the various points represents differences in the measured solar fluxes. These must be interpreted as fluctuations representing possible errors when use is made of a solar radio index that is measured with very great precision.

The possible error of about ±0.25$S$ was not included in Table 2, which gives, for various temperatures of the thermopause, the corresponding nighttime and daytime radio fluxes. These fluxes correspond to 27-day mean values at 8 and 10.7 cm. Table 3 gives all 27-day means of the temperature values from 1952 to 1962, including the minimum-to-maximum values for each period. They are based on the linear relationships deduced in the preceding paragraph

TABLE 3. Daytime and Nighttime Temperatures at the Thermopause

| Rotation | Date, ±13 days | Daytime Max. | Daytime Ave. | Daytime Min. | Nighttime Max. | Nighttime Ave. | Nighttime Min. |
|---|---|---|---|---|---|---|---|
| | 1952 | | | | | | |
| 1623 | January 17 | 1092 | 1045 | 1013 | 821 | 786 | 762 |
| 1624 | February 13 | 1043 | 990 | 951 | 784 | 744 | 715 |
| 1625 | March 11 | 942 | 910 | 895 | 708 | 684 | 673 |
| 1626 | April 7 | 978 | 966 | 924 | 735 | 726 | 695 |
| 1627 | May 4 | 986 | 947 | 920 | 741 | 712 | 692 |
| 1628 | May 31 | 964 | 923 | 903 | 725 | 694 | 679 |
| 1629 | June 27 | 1055 | 1001 | 948 | 793 | 753 | 713 |
| 1630 | July 24 | 1065 | 996 | 947 | 801 | 749 | 712 |
| 1631 | August 20 | 1109 | 1045 | 1013 | 834 | 786 | 762 |
| 1632 | September 16 | 1003 | 947 | 920 | 754 | 712 | 692 |
| 1633 | October 13 | 1003 | 959 | 935 | 754 | 721 | 703 |
| 1634 | November 9 | 1032 | 971 | 932 | 776 | 730 | 701 |
| 1635 | December 7 | 1045 | 996 | 940 | 786 | 749 | 707 |
| | 1953 | | | | | | |
| 1636 | January 2 | 1015 | 971 | 922 | 763 | 730 | 693 |
| 1637 | January 29 | 966 | 910 | 895 | 726 | 684 | 673 |
| 1638 | February 25 | 879 | 867 | 852 | 661 | 652 | 641 |
| 1639 | March 24 | 914 | 879 | 859 | 687 | 661 | 646 |
| 1640 | April 21 | 996 | 923 | 879 | 749 | 694 | 661 |
| 1641 | May 17 | 904 | 860 | 846 | 680 | 647 | 636 |
| 1642 | June 13 | 887 | 872 | 863 | 667 | 656 | 649 |
| 1643 | July 10 | 875 | 855 | 843 | 658 | 643 | 634 |
| 1644 | August 6 | 946 | 892 | 863 | 711 | 671 | 649 |
| 1645 | September 2 | 899 | 872 | 858 | 676 | 656 | 645 |
| 1646 | September 29 | 916 | 899 | 887 | 689 | 676 | 667 |
| 1647 | October 26 | 903 | 879 | 874 | 679 | 661 | 657 |
| 1648 | November 22 | 872 | 867 | 855 | 656 | 652 | 643 |
| 1649 | December 19 | 872 | 867 | 862 | 656 | 652 | 648 |
| | 1954 | | | | | | |
| 1650 | January 15 | 864 | 862 | 850 | 650 | 648 | 639 |
| 1651 | February 11 | 860 | 855 | 855 | 647 | 643 | 643 |
| 1652 | March 10 | 918 | 879 | 867 | 690 | 661 | 652 |
| 1653 | April 6 | 860 | 855 | 850 | 647 | 643 | 639 |
| 1654 | May 3 | 851 | 848 | 846 | 640 | 638 | 636 |
| 1655 | May 30 | 848 | 843 | 838 | 638 | 634 | 630 |
| 1656 | June 26 | 839 | 836 | 834 | 631 | 629 | 627 |
| 1657 | July 23 | 858 | 848 | 846 | 645 | 638 | 636 |
| 1658 | August 19 | 874 | 862 | 852 | 657 | 648 | 641 |
| 1659 | September 15 | 867 | 862 | 859 | 652 | 648 | 646 |
| 1660 | October 12 | 902 | 892 | 883 | 678 | 671 | 664 |
| 1661 | November 8 | 910 | 886 | 871 | 684 | 666 | 655 |
| 1662 | December 5 | 910 | 886 | 874 | 684 | 666 | 657 |
| | 1955 | | | | | | |
| 1663 | January 1 | 1003 | 947 | 912 | 754 | 712 | 686 |
| 1664 | January 28 | 964 | 935 | 908 | 725 | 703 | 683 |
| 1665 | February 24 | 922 | 910 | 900 | 693 | 684 | 677 |
| 1666 | March 23 | 888 | 886 | 883 | 668 | 666 | 664 |
| 1667 | April 19 | 907 | 892 | 883 | 682 | 671 | 664 |
| 1668 | May 16 | 963 | 928 | 904 | 724 | 698 | 680 |
| 1669 | June 12 | 1057 | 984 | 946 | 795 | 740 | 711 |
| 1670 | July 9 | 986 | 959 | 932 | 741 | 721 | 701 |
| 1671 | August 5 | 1067 | 984 | 926 | 802 | 740 | 696 |
| 1672 | September 1 | 1043 | 996 | 940 | 784 | 749 | 707 |

TABLE 3. (Continued)

| Rotation | Date, ±13 days | Daytime Max. | Daytime Ave. | Daytime Min. | Nighttime Max. | Nighttime Ave. | Nighttime Min. |
|---|---|---|---|---|---|---|---|
| 1673 | September 28 | 1071 | 1015 | 976 | 805 | 763 | 734 |
| 1674 | October 25 | 1200 | 1106 | 1031 | 902 | 832 | 775 |
| 1675 | November 21 | 1228 | 1198 | 1174 | 923 | 901 | 883 |
| 1676 | December 18 | 1253 | 1198 | 1158 | 942 | 901 | 861 |
| | 1956 | | | | | | |
| 1677 | January 14 | 1415 | 1283 | 1190 | 1064 | 965 | 895 |
| 1678 | February 10 | 1734 | 1418 | 1237 | 1304 | 1066 | 930 |
| 1679 | March 8 | 1487 | 1382 | 1329 | 1118 | 1039 | 999 |
| 1680 | April 4 | 1470 | 1387 | 1297 | 1105 | 1043 | 975 |
| 1681 | May 1 | 1486 | 1412 | 1305 | 1117 | 1062 | 981 |
| 1682 | May 28 | 1455 | 1382 | 1309 | 1094 | 1039 | 984 |
| 1683 | June 24 | 1462 | 1368 | 1298 | 1099 | 1029 | 976 |
| 1684 | July 21 | 1483 | 1424 | 1351 | 1115 | 1071 | 1016 |
| 1685 | August 17 | 1722 | 1632 | 1541 | 1295 | 1227 | 1159 |
| 1686 | September 13 | 1807 | 1644 | 1553 | 1359 | 1236 | 1168 |
| 1687 | October 10 | 1673 | 1571 | 1483 | 1258 | 1181 | 1115 |
| 1688 | November 6 | 2071 | 1871 | 1705 | 1557 | 1407 | 1282 |
| 1689 | December 3 | 1885 | 1785 | 1670 | 1417 | 1342 | 1256 |
| 1690 | December 30 | 2068 | 1907 | 1766 | 1555 | 1434 | 1328 |
| | 1957 | | | | | | |
| 1691 | January 26 | 1782 | 1626 | 1541 | 1340 | 1223 | 1159 |
| 1692 | February 22 | 1523 | 1491 | 1452 | 1145 | 1121 | 1092 |
| 1693 | March 21 | 1595 | 1571 | 1544 | 1199 | 1181 | 1161 |
| 1694 | April 17 | 1641 | 1565 | 1487 | 1234 | 1177 | 1118 |
| 1695 | May 14 | 1721 | 1613 | 1511 | 1294 | 1213 | 1136 |
| 1696 | June 10 | 1975 | 1785 | 1626 | 1485 | 1342 | 1223 |
| 1697 | July 7 | 2040 | 1780 | 1607 | 1534 | 1338 | 1208 |
| 1698 | August 3 | 1760 | 1596 | 1506 | 1323 | 1200 | 1132 |
| 1699 | August 30 | 1971 | 1810 | 1649 | 1482 | 1361 | 1240 |
| 1700 | September 26 | 2212 | 2048 | 1931 | 1663 | 1540 | 1452 |
| 1701 | October 23 | 2269 | 2140 | 1996 | 1706 | 1609 | 1501 |
| 1702 | November 19 | 1938 | 1841 | 1770 | 1457 | 1384 | 1331 |
| 1703 | December 16 | 2391 | 2072 | 1835 | 1798 | 1558 | 1380 |
| | 1958 | | | | | | |
| 1704 | January 12 | 2027 | 1871 | 1701 | 1524 | 1407 | 1279 |
| 1705 | February 8 | 1772 | 1620 | 1515 | 1332 | 1218 | 1139 |
| 1706 | March 7 | 1818 | 1700 | 1563 | 1368 | 1278 | 1175 |
| 1707 | April 3 | 2264 | 2006 | 1730 | 1702 | 1508 | 1301 |
| 1708 | April 30 | 1904 | 1797 | 1685 | 1432 | 1351 | 1267 |
| 1709 | May 27 | 1749 | 1620 | 1549 | 1315 | 1218 | 1165 |
| 1710 | June 23 | 1721 | 1638 | 1541 | 1294 | 1232 | 1159 |
| 1711 | July 20 | 1887 | 1700 | 1583 | 1419 | 1278 | 1190 |
| 1712 | August 16 | 1835 | 1736 | 1680 | 1380 | 1305 | 1263 |
| 1713 | September 12 | 1948 | 1834 | 1744 | 1465 | 1379 | 1311 |
| 1714 | October 9 | 1920 | 1730 | 1596 | 1444 | 1301 | 1200 |
| 1715 | November 5 | 1709 | 1577 | 1472 | 1285 | 1186 | 1107 |
| 1716 | December 2 | 1938 | 1853 | 1660 | 1457 | 1393 | 1248 |
| 1717 | December 29 | 1983 | 1827 | 1713 | 1491 | 1374 | 1288 |
| | 1959 | | | | | | |
| 1718 | January 25 | 2246 | 1944 | 1734 | 1689 | 1462 | 1304 |
| 1719 | February 21 | 1698 | 1613 | 1531 | 1277 | 1213 | 1151 |
| 1720 | March 20 | 1998 | 1834 | 1661 | 1502 | 1379 | 1249 |
| 1721 | April 16 | 1636 | 1577 | 1519 | 1230 | 1186 | 1142 |

TABLE 3. (Continued)

| Rotation | Date, ±13 days | Daytime Max. | Daytime Ave. | Daytime Min. | Nighttime Max. | Nighttime Ave. | Nighttime Min |
|---|---|---|---|---|---|---|---|
| 1722 | May 13 | 1874 | 1669 | 1576 | 1409 | 1255 | 1185 |
| 1723 | June 9 | 1722 | 1632 | 1530 | 1295 | 1227 | 1150 |
| 1724 | July 6 | 1869 | 1669 | 1532 | 1405 | 1255 | 1152 |
| 1725 | August 2 | 1692 | 1577 | 1495 | 1272 | 1186 | 1124 |
| 1726 | August 29 | 2077 | 1846 | 1700 | 1562 | 1388 | 1278 |
| 1727 | September 25 | 1480 | 1387 | 1326 | 1113 | 1043 | 997 |
| 1728 | October 22 | 1452 | 1394 | 1350 | 1092 | 1048 | 1015 |
| 1729 | November 18 | 1685 | 1522 | 1410 | 1267 | 1144 | 1060 |
| 1730 | December 15 | 1623 | 1491 | 1423 | 1220 | 1121 | 1070 |
| | 1960 | | | | | | |
| 1731 | January 11 | 1636 | 1516 | 1434 | 1230 | 1140 | 1078 |
| 1732 | February 7 | 1708 | 1552 | 1415 | 1284 | 1167 | 1064 |
| 1733 | March 5 | 1252 | 1234 | 1208 | 941 | 928 | 908 |
| 1734 | April 1 | 1539 | 1424 | 1325 | 1157 | 1071 | 996 |
| 1735 | April 28 | 1418 | 1357 | 1301 | 1066 | 1020 | 978 |
| 1736 | May 25 | 1443 | 1382 | 1350 | 1085 | 1039 | 1015 |
| 1737 | June 21 | 1531 | 1375 | 1275 | 1151 | 1034 | 959 |
| 1738 | July 18 | 1526 | 1345 | 1283 | 1147 | 1011 | 965 |
| 1739 | August 14 | 1664 | 1486 | 1322 | 1251 | 1117 | 994 |
| 1740 | September 11 | 1472 | 1382 | 1282 | 1107 | 1039 | 964 |
| 1741 | October 7 | 1338 | 1277 | 1194 | 1006 | 960 | 898 |
| 1742 | November 3 | 1514 | 1338 | 1245 | 1138 | 1006 | 936 |
| 1743 | November 30 | 1339 | 1246 | 1168 | 1007 | 937 | 878 |
| 1744 | December 27 | 1357 | 1222 | 1137 | 1020 | 919 | 855 |
| | 1961 | | | | | | |
| 1745 | January 23 | 1141 | 1088 | 1049 | 858 | 818 | 789 |
| 1746 | February 19 | 1073 | 1039 | 1021 | 807 | 781 | 768 |
| 1747 | March 18 | 1112 | 1051 | 1019 | 836 | 790 | 766 |
| 1748 | April 14 | 1106 | 1045 | 1011 | 832 | 786 | 760 |
| 1749 | May 11 | 1097 | 1039 | 1000 | 825 | 781 | 752 |
| 1750 | June 7 | 1150 | 1057 | 1008 | 865 | 795 | 758 |
| 1751 | July 4 | 1204 | 1130 | 1072 | 905 | 850 | 806 |
| 1752 | July 31 | 1140 | 1081 | 1020 | 857 | 813 | 767 |
| 1753 | August 27 | 1125 | 1093 | 1052 | 846 | 822 | 791 |
| 1754 | September 23 | 1178 | 1093 | 1047 | 886 | 822 | 787 |
| 1755 | October 20 | 1056 | 1015 | 983 | 794 | 763 | 739 |
| 1756 | November 16 | 1025 | 984 | 958 | 771 | 740 | 720 |
| 1757 | December 13 | 1055 | 1008 | 967 | 793 | 758 | 727 |
| | 1962 | | | | | | |
| 1758 | January 9 | 1048 | 978 | 946 | 788 | 735 | 711 |
| 1759 | February 5 | 1094 | 1039 | 990 | 823 | 781 | 744 |
| 1760 | March 4 | 1177 | 1063 | 990 | 885 | 799 | 744 |
| 1761 | March 31 | 1129 | 1039 | 978 | 849 | 781 | 735 |
| 1762 | April 27 | 1085 | 1039 | 990 | 816 | 781 | 744 |
| 1763 | May 24 | 1076 | 1032 | 991 | 809 | 776 | 745 |
| 1764 | June 20 | 998 | 978 | 966 | 750 | 735 | 726 |
| 1765 | July 17 | 943 | 923 | 899 | 709 | 694 | 676 |
| 1766 | August 13 | 939 | 904 | 887 | 706 | 680 | 667 |
| 1767 | September 9 | 1015 | 971 | 924 | 763 | 730 | 695 |
| 1768 | October 6 | 1000 | 971 | 954 | 752 | 730 | 717 |
| 1769 | November 2 | 986 | 959 | 942 | 741 | 721 | 708 |
| 1770 | November 29 | 984 | 940 | 926 | 740 | 707 | 696 |

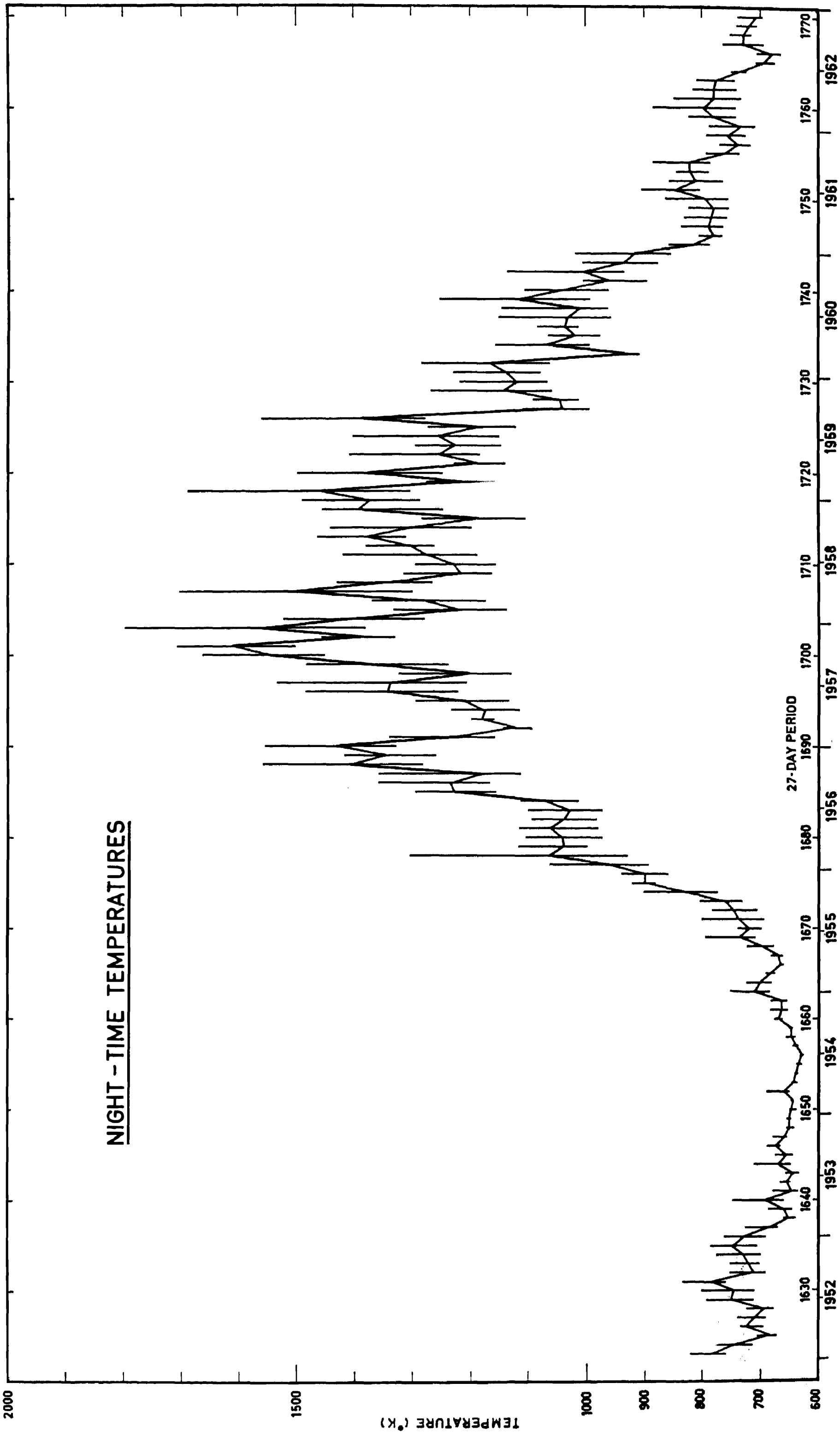

NIGHT-TIME TEMPERATURES
TEMPERATURE (°K)
2000
1500
1000
900
800
700
600
27-DAY PERIOD
1630
1640
1650
1660
1670
1680
1690
1700
1710
1720
1730
1740
1750
1760
1770
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962

Fig. 16

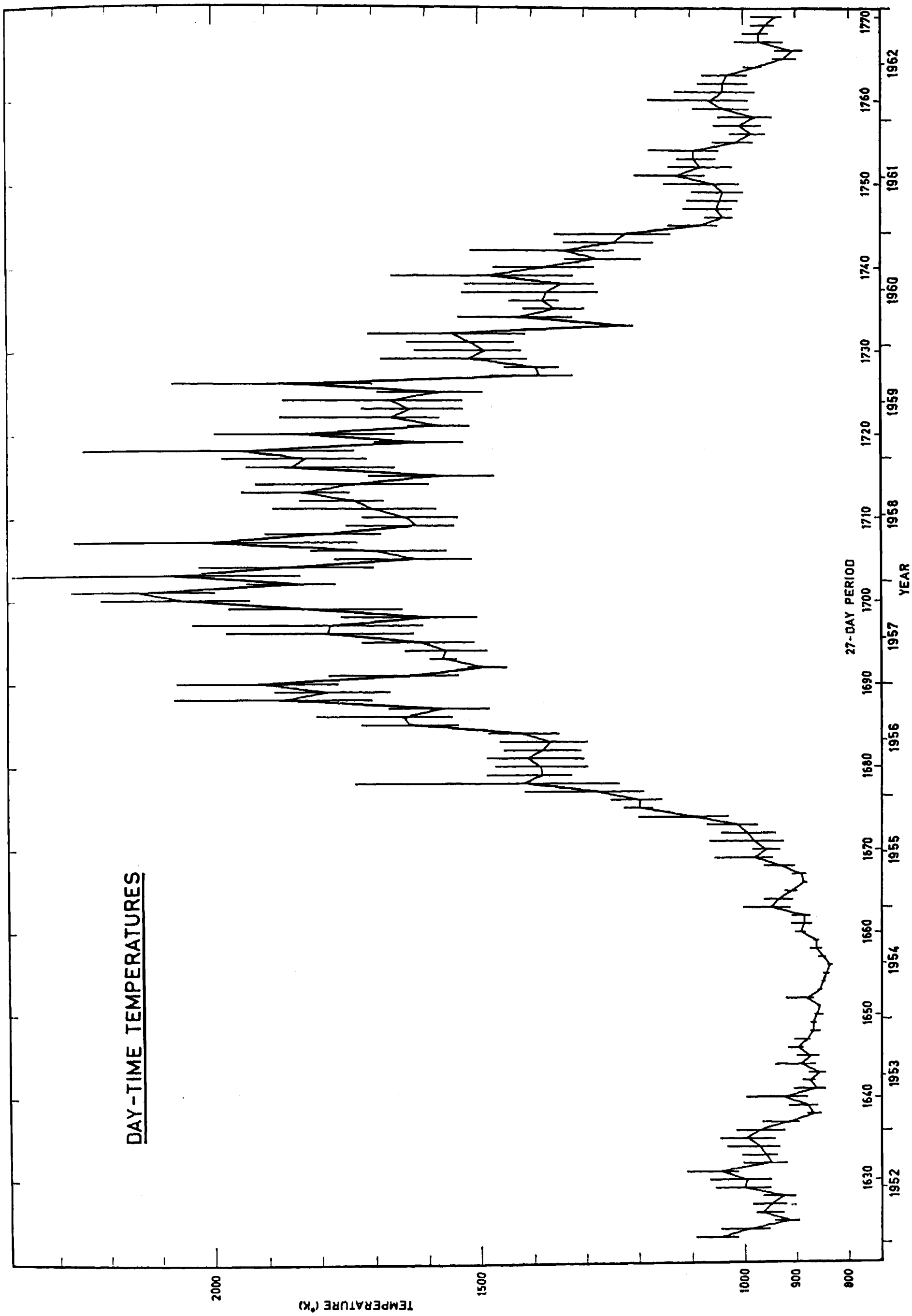

DAY-TIME TEMPERATURES
27-DAY PERIOD
YEAR
TEMPERATURE (°K)
2000
1500
1000
900
800
1630
1640
1650
1660
1670
1680
1690
1700
1710
1720
1730
1740
1750
1760
1770
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962

Fig. 17

by using the 8-cm radio flux. Figures 16 and 17 yield a clear representation of the average temperatures at the thermopause level for a 27-day period. The vertical lines indicate the extreme minimum and maximum temperatures that have been reached during each period. The minimum temperatures are 650°K and 850°K for daytime and nighttime temperatures, respectively. The highest 27-day mean value for nighttime conditions, reached in 1957, is of the order of 1600°K. The maximum nighttime value, of the order of 1800°K, was also attained during that period. The highest 27-day mean value for daytime conditions is of the order of 2150°K, and the maximum daytime value reached 2400°K.

In conclusion, it should be noted that the effect of magnetic storms has not been introduced and should be incorporated in the determinations of temperature by using Jacchia's formula along with $A_p$ indices.

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