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INFRARED RADIATION OF VENUSIAN CLOUDS

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N. V. Temnaya, G. F. Filippov

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16. Abstract
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INFRARED EMISSION OF THE CLOUDS OF VENUS

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The thermal infrared emission of Venus measured by Venera-9 and Venera-10 displays significant asymmetry in the day-night direction. The emission of the night side corresponds to a brightness temperature of 244°K. The brightest temperature of the day side is 233-234°K. The extent of the upper layer of clouds, in which the thermal emission is formed, is 4-6 km. The altitude of the emitting layer above the surface of the planet (64-67 km) is determined from the brightness temperature and the existing models of the atmosphere of Venus. In some cases, correlation is noted between the inhomogeneity and the details of the ultraviolet image. The day side temperatures strangely coincide with the freezing point of sulfuric acid at a concentration of 66-77%.

The two radiometers of the same type mounted on board the Venera-9 and Venera-10 have an angular resolution of 1.2 deg (0.02 rad), and threshold sensitivity of about 70°K and a range of 8-13 and 18-28μ. Rejection of the interval 10-18 μ prevents distortion of the results due to emission of the higher layers of the atmosphere in the carbon dioxide band at 15 μ. The wavelength of the maximum of the emission of Venus occurs at the middle of the radiometer range. /3*

The thermal emission of Venus is formed in the upper layer of the cloud cover of the planet. The brightness temperature of the emitting layer is determined from the measured brightness in the indicated range. The radiation balance of the planet depends on this temperature. Among the problems of the experiment were the study of the limb darkening effect, investigation of local inhomogeneities and

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*Numbers in the margin indicate pagination of original foreign text.

their relation with phenomena observed at other wavelengths and study of longitude and latitude effects.

The altitude of the upper part of the cloud layer, from which the emission received by the radiometer originates, was found on the basis of the brightness temperatures obtained in the experiment with the help of the models of the atmosphere of Venus proposed by Marov and Ryabov [1] and Moroz [2]. This altitude is 64-67 km and refers to the level where the optical thickness in the infrared reaches unity. The physical properties of the emitting medium are tentatively the following: The pressure is 50-130 mb, the density is $(0.13\text{-}0.18)\cdot 10^{-3}$ gm/cm^3. The concentration of particles of the cloud layer is 40-200 cm^{-3} [3], /4
their average diameter is about 2.2 μ, while the dispersion of the sizes is very small [4]. The most probable composition of the particles is sulfuric acid with a concentration of about 75% [5]. Its total concentration with respect to CO_2 is about $3\cdot 10^{-5}$. The infrared emission is formed in a rather extended layer, whose brightness temperature T_B practically coincides with its kinetic temperature [6].

Since the temperature of the outer part of this layer is somewhat lower, the limb-darkening effect arises similar to that described in the literature. It was shown in the work of Pollack and Sagan [7] that within definite limits of the cosine μ_2 of the zenith distance of the observer, all darkening models can be reduced to the law:

$$B_{IR}(\mu_2) = k \cdot \mu_2^{\alpha} \qquad (1)$$

where k and α are constants. Another version of representing $B_{IR}(\mu_2)$ which follows from the approximate solution of the radiation transequation, was used by Chase, et al. [8]. The darkening coefficient D defined by the "boundary temperature" T_0 for $\mu 2 = 0$ was introduced here:

$$B_{IR}(T_0) = B(1,0)\cdot(1 - D) \qquad (2)$$

where B(1.0) is the brightness at the point with $\mu_2 = 1$. Then:

$$B_{IR}(\mu_2) = B(1,0)\cdot[(1 - D) + D\mu_2] \qquad (3)$$

Neglecting scattering, which is evidently valid for this problem, and using the Planck nature of the source function, one can find the absorption coefficient per unity path length. In any case, the contribution of the emission from colder layers increases with decreasing $\mu 2$, which also determines the characteristic form of the curves $B_{IR}(\mu_2)$ or B_{IR} as a function of the distance from the center of the disk of the planet.

A few words about the models with which the altitude of the clouds was evaluated. Figure 1 presents five temperature-altitude curves for various models and also for the measurements of Venera-9, Venera-10 and the radio eclipse data of Mariner-10. Our estimates of the altitudes are based on the section of the curve indicated by /5 points, closest in position to the models of Marov and Ryabov, Moroz and NASA-11. It is possible that the estimate of the altitudes will vary somewhat with further refinement of the models.

It was indicated in the express-communication about our experiment [9], in analyzing the obtained data, that their interpretation leads to the alternative: either to assume the evening temperature to be significantly greater than the day or to use two darkening laws different D for the day and evening sides. The first results obtained with the help of Venera-9 and Venera-10 showed that a temperature of about 233°K is consistently recorded in the day zone for values of $\mu_2 \approx 1$ (Figs. 2 and 3). These measurements practically coincided with the averaged results of previous (ground-based) determinations [6]. However, the radiometric experiment on Mariner-10 in 1974 gave a temperature of 255°K in the range 45μ[8,10], while the first of these works indicated a small probability of significant divergences for the brightness temperatures at 10 and 45μ.

There are evidently two causes of the differences in the determination of the temperatures. One of them was shown in [9] in favor of our measurements. Its sense is that measurements from spacecraft require determination of two unknowns: the brightness temperature of the emitting layer and the law of limb darkening. The temperature can be determined strictly if the cosine of the zenith angle of the craft

μ_2 is unity. As far as we know, this condition was not satisfied on Mariner-1. As was shown later, the darkening law for Venus cannot be determined by an isolated measurement. Another cause of the divergence is the thermal asymmetry of Venus, which is the content of this article.

Two different darkening laws for day and night were used in work [9]. It was learned soon after that this does not eliminate all difficulties. While all remained comparatively favorable from the day zone and the data fit well in dependence (3), this approximation was unsatisfactory in the zone of the night terminator (evening) (Fig. 4). Measurements of Venera-10 of November 6, 1975, are presented here. The temperatures in the day zone lie at the level 233°K. However, with consideration of μ_2, they are higher in the evening zone. Dependence (1) presented in logarithmic form in Fig. 5, $\lg B_{IR}$ as a function of $\lg \mu_2$, shows that the value of α does not remain constant even in narrow zones of μ_2. Further operation of the apparatus of Venera-9 and Venera-10 did not leave doubt about the stable increase in the night temperatures over the day. Figures 6 and 7 show the results of measurements obtained with increasing phase angle of the planet up to 59 and 64° (November 1 and 9, 1975, respectively). Already in Figure 6, the night temperatures sharply increase near the terminator for the same values of μ_2 in the day and night zones. This effect is expressed significantly more strongly in Fig. 6. With consideration of μ_2 in the evening zone, the temperatures reach 236°K for 232°K in the day zone. The asymmetry of the curve is common for all the profiles of Figs. 2, 3, 6 and 7. A completely new pattern can be seen in Fig. 8. The curve is symmetric. This is the night zone of the planet. The values of $\mu_2 = 0.999$ made it possible to determine reliably the night temperature as 244°K with close darkening laws both in deep night as well as in the evening zones. Representation of $B_{IR}(\mu_2)$ in the form of (3) gives a good approximation with: /6

$$B_{IR}(\mu_2) = B(I,0)(0{,}50 + 0{,}50 \cdot \mu_2) \tag{4}$$

for the day zone and:

$$B_{IR}(\mu_2) = B(I,0)(0{,}60 + 0{,}40 \cdot \mu_2) \tag{5}$$

for the night zone, while the approximation is better for the day zone. The form of (1) also represents well the results for the night zone:

$$B_{IR}(\mu_2) = B(I,0) \cdot \mu_2^{0.31} \quad (6)$$ /7

Values of α from 0.30 to 0.43 were obtained on different days for the day part of the planet. The extent of the layer corresponding to an optical thickness of unity is 4-6 km. These results are considered in more detail in [11].

The transition of the cloud layer to the night mode of temperatures begins already for a drop of the sun to 30-85° above the horizon. It still remains unclear what the conditions are in the zone of the morning terminator, there are practically no possibilities for large differences: the left part of the zone represented in Fig. 8 was under night conditions for about 25 earth days. We consider it most likely that because of the great length of the solar day, the temperature distribution is quasi-stationary in nature and is similar for the evening and morning zones. (It would be more speculative to make the same assumption about the high latitude regions.) Thus, the "night mode" probably encompasses significantly more than 180° in longitude. The dependence of the brightness temperature on longitude, latitude and angle of the sun will undoubtedly be of interest. The studied traces encompass a zone of ±35° in latitude. The investigations of the polar zones, which were performed from orbit by Venera-9 and Venera-10 only under conditions of relatively small μ_2 leave the possibility of some ambiguity in interpretation. A satellite of Venus in a circular polar orbit would be the ideal apparatus for solving this problem.

Thus, the thermal emission of Venus is asymmetric (Fig. 9). The temperatures of the day zone in the region of latitudes ±35° are 233-234°K, and 244°K in the night zone at the same latitudes. This is the second reason for the differences in measurements on the apparatus of Venera-9 and Venera-10 on the one hand and Mariner-10 on the other, since the route of Mariner-10 was mainly over the night side of the planet.

The symmetry of both branches of the curves $B_{IR}(\mu_2)$ obtained by Taylor [10] is evidently a consequence of the significant coverage of the planet by the "night mode." In our measurements, this symmetry is observed only in the night zone. There were sequences in which day, evening and night were covered, which gave curves with strongly diverging branches (Fig. 10). /8

The stable difference of the day and night temperatures has an obvious relation with the interception of part of the solar radiation by the cloud layer. We assume a probable cause of the decrease in day temperatures to be the appearance of intense convective currents in the day zone, which carry part of the radiating substance into the zone above the clouds at an altitude of 3-4 km. This leads to a change in the exponent α. It remains unclear whether this cause is natural. There is a strange coincidence noticed by L. Ksanfomaliti. Figure 11 presents the phase diagram of the sulfuric acid solution as a function of its concentration. The curve is taken from the work of A. Young [5]. The level of the day temperature lies precisely at the sharp bend in the curve at the point with the sulfuric acid concentration of 66-77%. The refractive index for the solution with concentration 70% and temperature 233°K is 1.44, which coincides ideally with [4]. However, the temperature of 250°K taken by A. Young distinguishes practically nothing with these points of the curve, whereas, our values (233°K) can be interpreted as evidence that the upper boundary of the clouds of Venus is somehow related just to this point of the phase diagram. There are evidently mechanisms stabilizing this level, at least in temperature. One follows from the temperature-pressure dependence of water vapor over sulfuric acid presented in the same work of A. Young. The pressure of water vapor over the acid with a concentration of 68% is three times greater than for a concentration of 70%. But the freezing point at 68% is above that for 70%. The difference in pressures provides for the motion of water vapor downward to the main mass of the absorber. The freezing drops with lower concentration transmit the excess water vapor to other drops, thereby enriching the acid and maintaining the liquid state /9 (the arrow in Fig. 11). The large latent heat of the phase transition in the drops of H_2SO_4 together with the intense mixing imparts a steady-state nature to the process, which is also aided by the sharp increase in the rate of precipitation of drops from the more rarified upper layers according to the data of [3]: while 10^7 sec are required for their drop by one altitude scale height (5 km) at an altitude of 68 km, only 10^6 sec is required at an altitude of 78 km. The capability of sulfuric acid for intense supercooling is also an important fact noted by Pollack in the discussion to work [12].

The mechanism described above permits a completely independent evaluation of the concentration of water vapor (at the altitude of the emitting layer) from its pressure. This quantity is $0.9 \cdot 10^{-4}$ with respect to the pressure of carbon dioxide above sulfuric acid with a concentration of 70% and coincides well with other determinations, for example, [13]. The temperature of 250°K taken by many American investigators would give an unacceptably high pressure, almost an order of magnitude higher.

Let us now turn to the details in the curves B_{IR}. Extended regions with temperatures decreased by 0.8-1.4° are observed in several sequences. The length of these zones is up to 5000 km; we see such a pattern in Fig. 3. There is not doubt about their nature: these are local elevations of the emitting layer. According to the estimate of A. Young, such elevations can exceed the scale height. It remains surprising in this case that the mechanism stabilizing the temperature operates so effectively.

There is also great interest in the fine-scale details of the curves. They are clearly traced on individual profiles, but are occationally absent on other traces investigated with the same resolution. Their amplitude does not usually exceed 2°K. According to the available statistics, the resolution under orbital conditions permits obtaining details, curves of three types are observed: /10

-- with weakly expressed details (Fig. 7);

-- with a few periodic details (Fig. 3; Fig. 6).

In these cases, the small waves on the curves have a spatial extent of 150-180 km and are separated by intervals of about 1500 km; their correlation with ultraviolet details is observed. As was shown in [9], one can assume a relation between these waves and the dynamics of the atmosphere of Venus;

-- with a large number of details with unclear period. The typical dimension of the details (50-80 km) is an interesting fact. A sharp increase in resolution does not give any additional details (Fig. 8).

Further tasks of the experiment are the study of the night and morning zones and also of the high-latitude regions of the planet.

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Fig. 1. Temperature-altitude curves for different models. The points indicate sections of the curve on which the altitude estimates in the article are based.

Fig. 2. Curve of brightness B_{IR} and brightness temperature T_B in the infrared region according to the data of Venera-10, October 29, 1975. The approximation by two curves of the type (3) indicated by points deviates significantly from the curve at the edges. The lower curve B_{IR} is the reading of the control ultraviolet photometer. The circles in the upper part is the resolution scaled on the time axis in terms of the velocity normal to the sighting line and the slant range. The day temperature is 234°K. The phase angle is 57°.

Fig. 3. October 26, 1975, Venera-9 transmitted measurements of the brightness B_{IR} and temperature T_B after composing the condensed profile with a decrease in temperature by $1\text{-}1.4^{\circ}$. The typical periodic waves on the curve are separated by intervals of about 1500 km. The waves are evidently correlated with details of the ultraviolet profile. The phase angle is 55°.

Fig. 4. Curves of B_{IR} and B_{UV} of Venera-10 for November 6, 1975. The left, evening part of the profile cannot be represented in the form (3). The day temperature is 233°K. The phase angle is 62°.

Fig. 5. Change in the exponent α in formula (1) represented as $\Delta \lg B_{IR}/\Delta(\lg \mu_2 + 1)$. Venera-10, November 6, 1975. B_{IR} in arbitrary units.

Fig. 6. Measurements of Venera-9 of November 1, 1975. The growth in B_{IR} and T_B to the left from the maximum value is well noted. Periodic waves are noted. The phase angle is 59°.

Fig. 7. Sharp growth in B_{IR} and T_B to the left and the maximum value and the terminator. Venera-9, November 9, 1975. The phase

angle is 64°.

Fig. 8. Night side of Venus. The curve is practically symmetric on both sides from μ_{2max}. Venera-9, November 13, 1975, the phase angle is 122°. The maximum value of μ_2 corresponds to 244°K. The measurements were performed with high resolution.

Fig. 9. Diagram of the distribution of the constant components of the brightness of the thermal emission of Venus from the surface of the cloud layer in the region of latitudes $\pm 35^{\circ}$. The variation of the brightness is approximately linear in the transition zone. View from the North Pole. /13

Fig. 10. Day and night branches of the profiles B_{IR}, presented in Fig. 3 and Fig. 6 as a function of μ_2. Curve 1 is the same as in Fig. 8, 2 is the same as in Fig. 4.

Fig. 11. Phase diagram of the water-sulfuric acid system [4]. The day temperatures of 233° coincide with the position of the minimum of the curve at 70-76% solution. The arrow indicates the change in composition of the drops and the decrease in its freezing temperature.

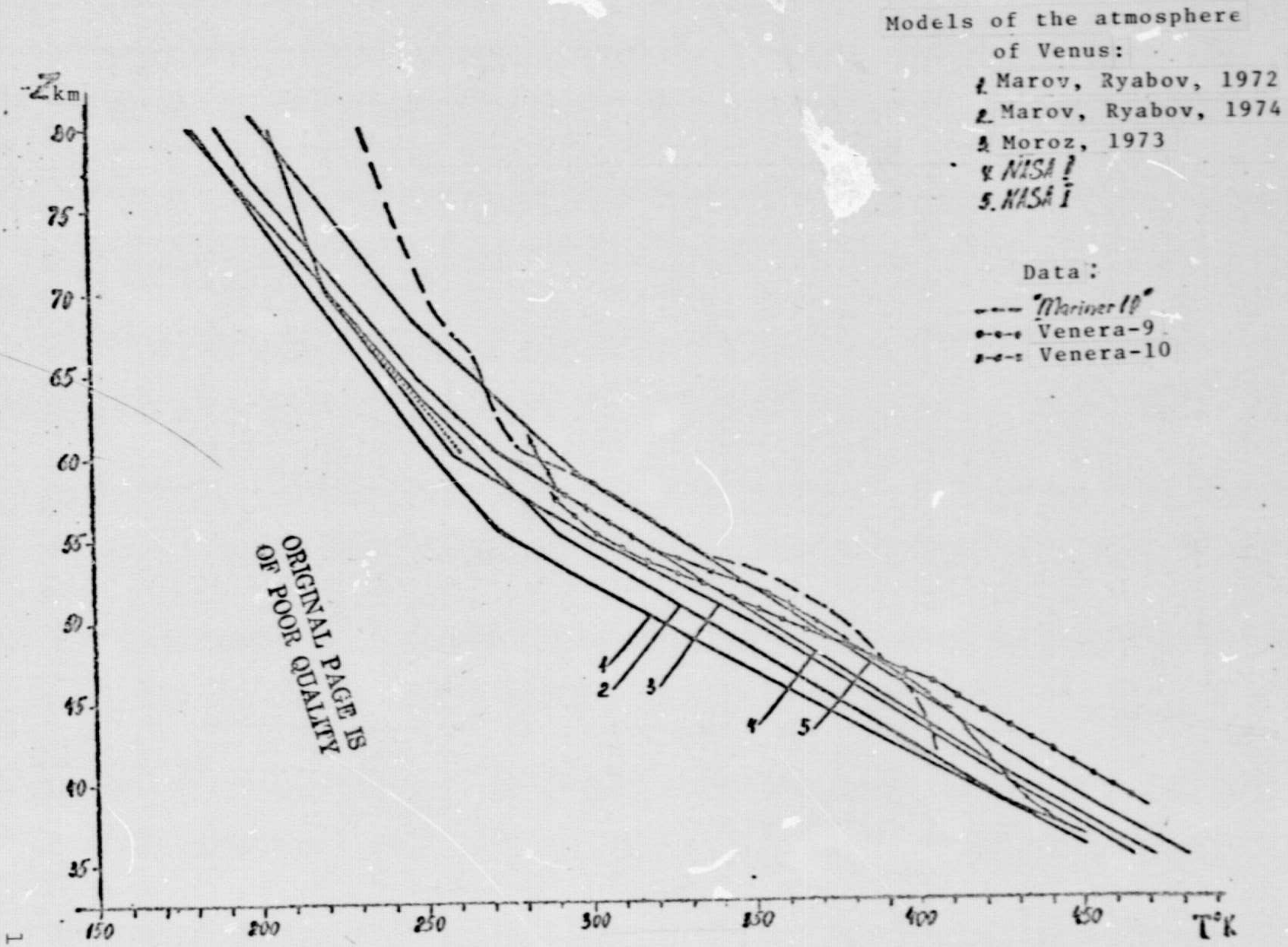

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Figure 1

y.57°c, 94,810, 29.10.75.

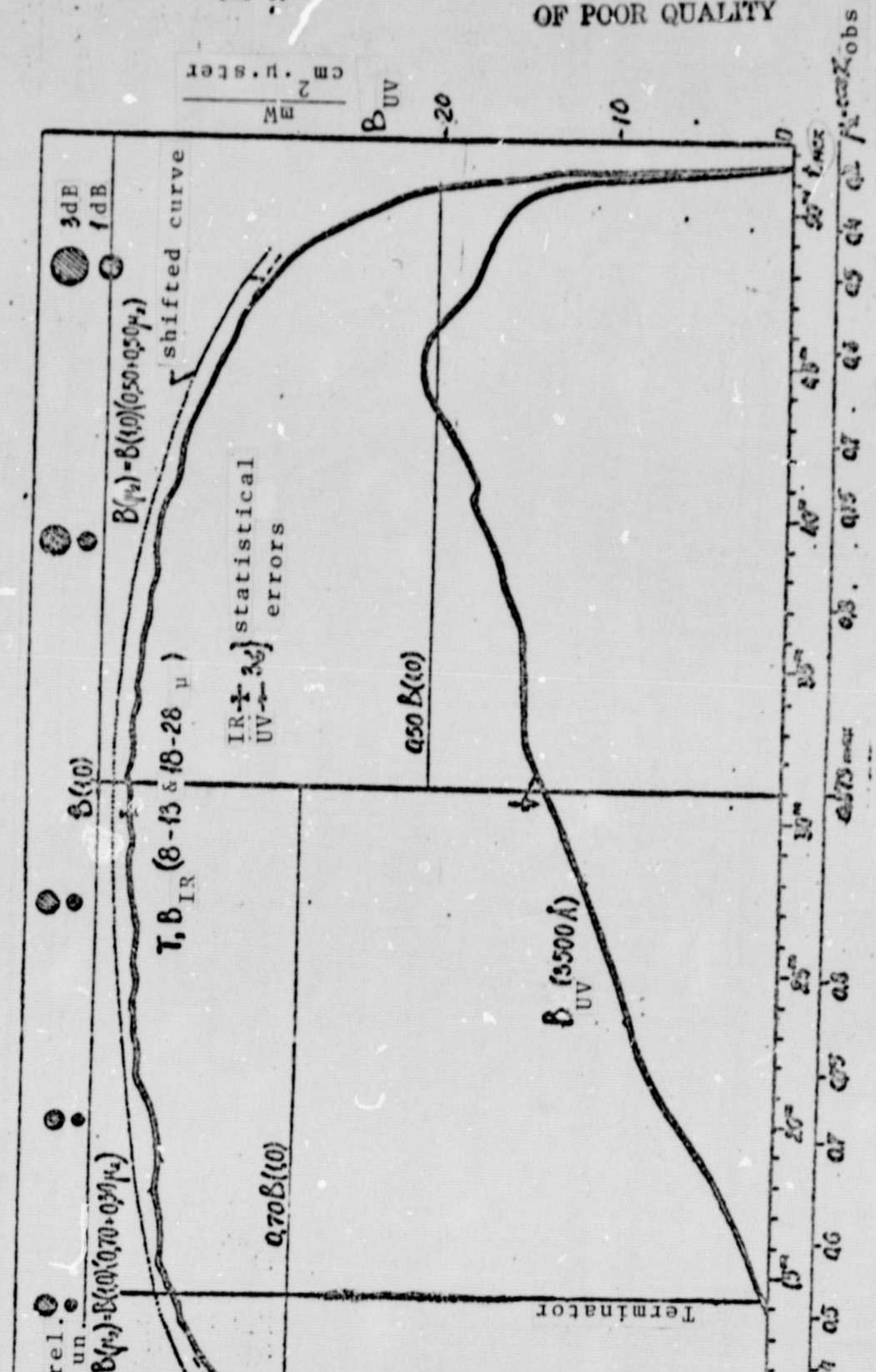

Figure 2

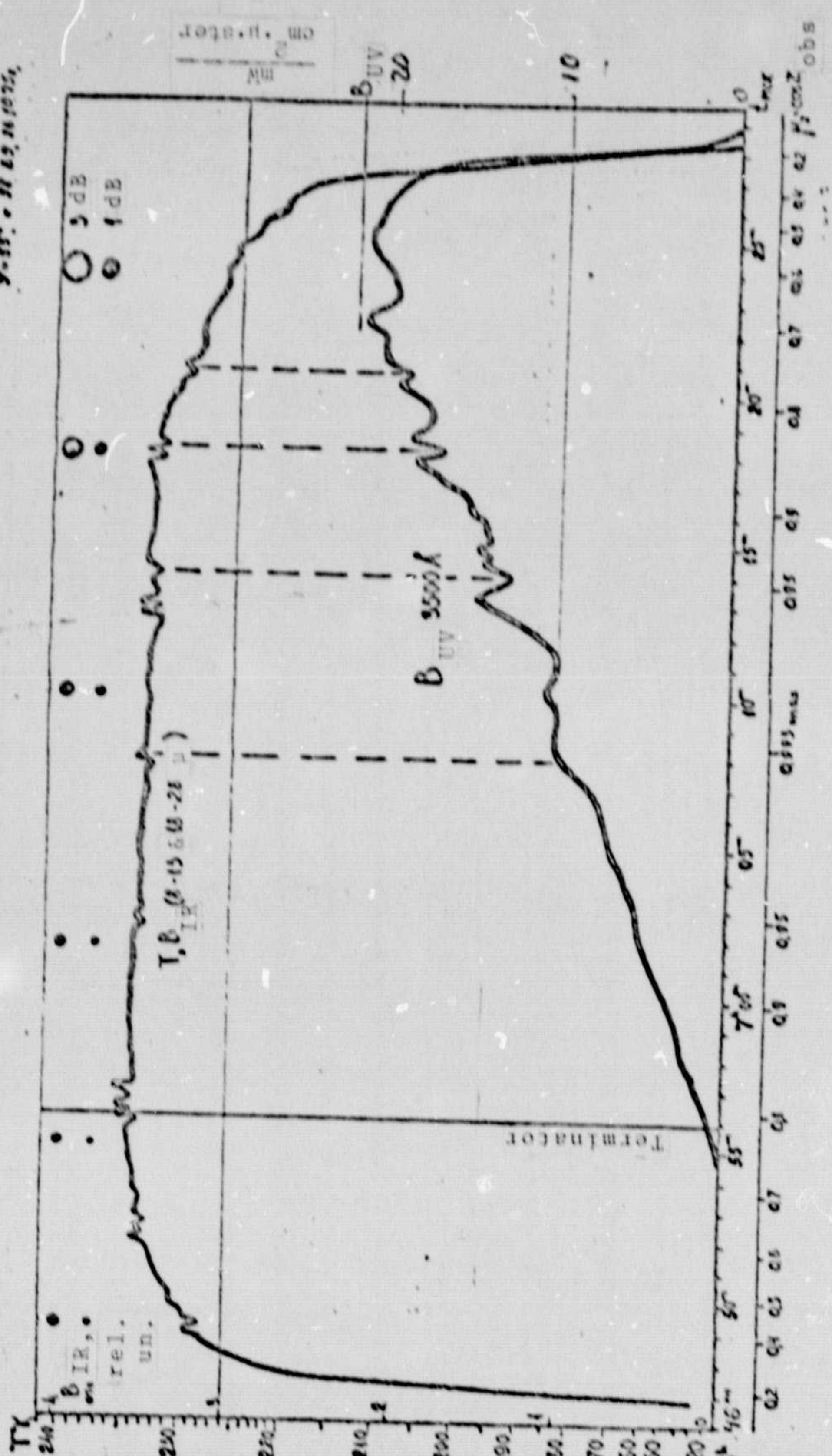
T K
B IR, rel. un.
T, B IR
B UV 3500 Å
B UV
20
10
mW / cm² μ ster
3 dB
1 dB
Terminator
z obs

Figure 3

OF POOR QUALITY

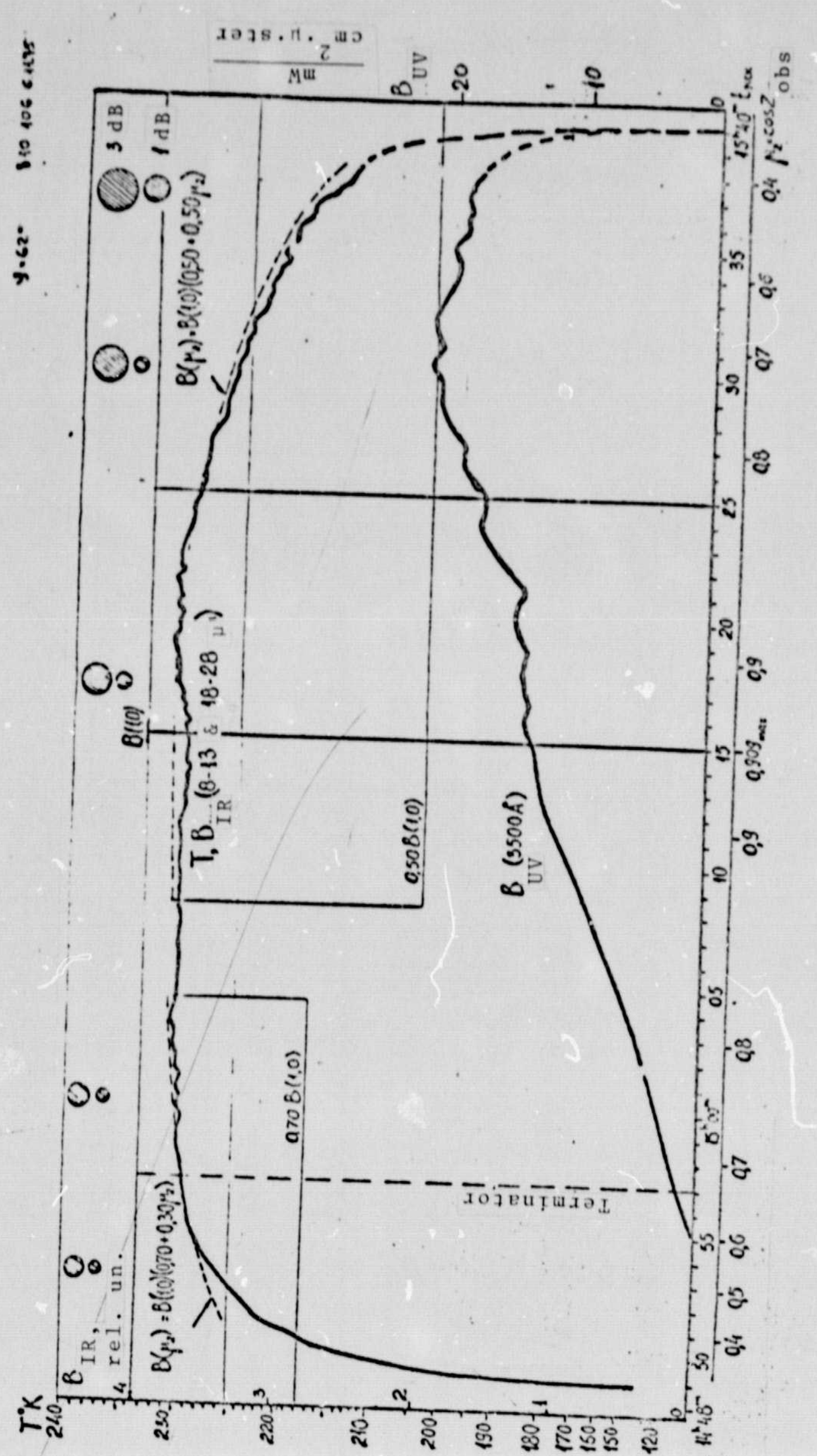

Figure 4

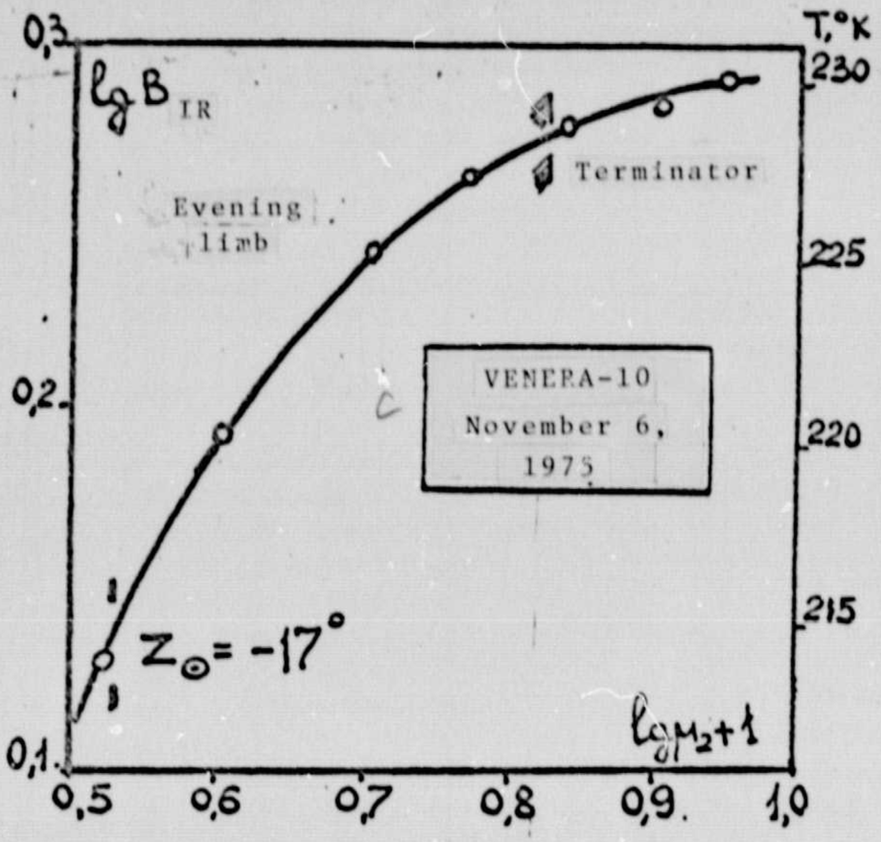
0,3
0,2
0,1
lg B_IR
T, °K
230
225
220
215
Evening limb
Terminator
VENERA-10
November 6, 1975
Z⊙ = -17°
lg μ2 + 1
0,5
0,6
0,7
0,8
0,9
1,0

Figure 5

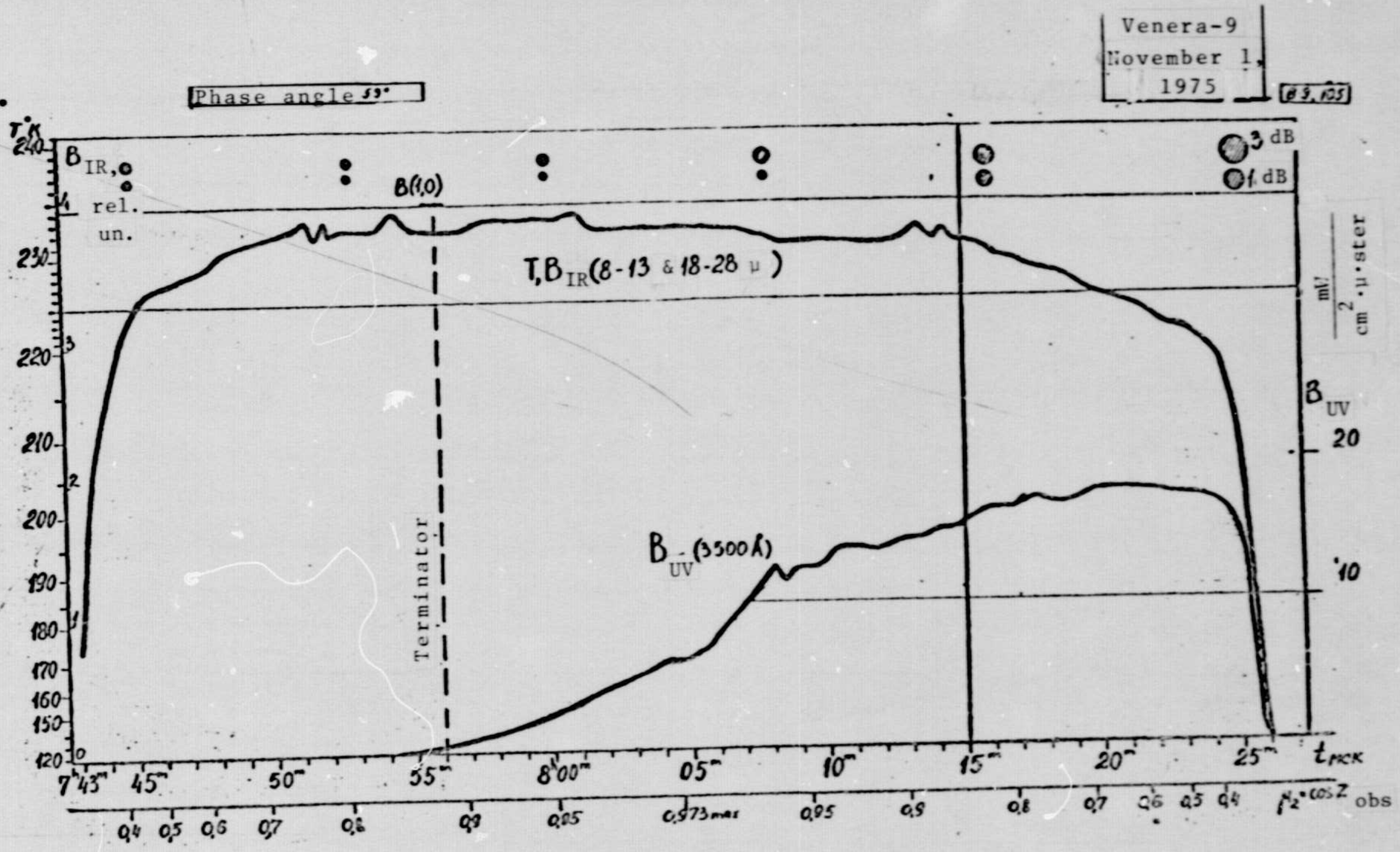

Figure 6

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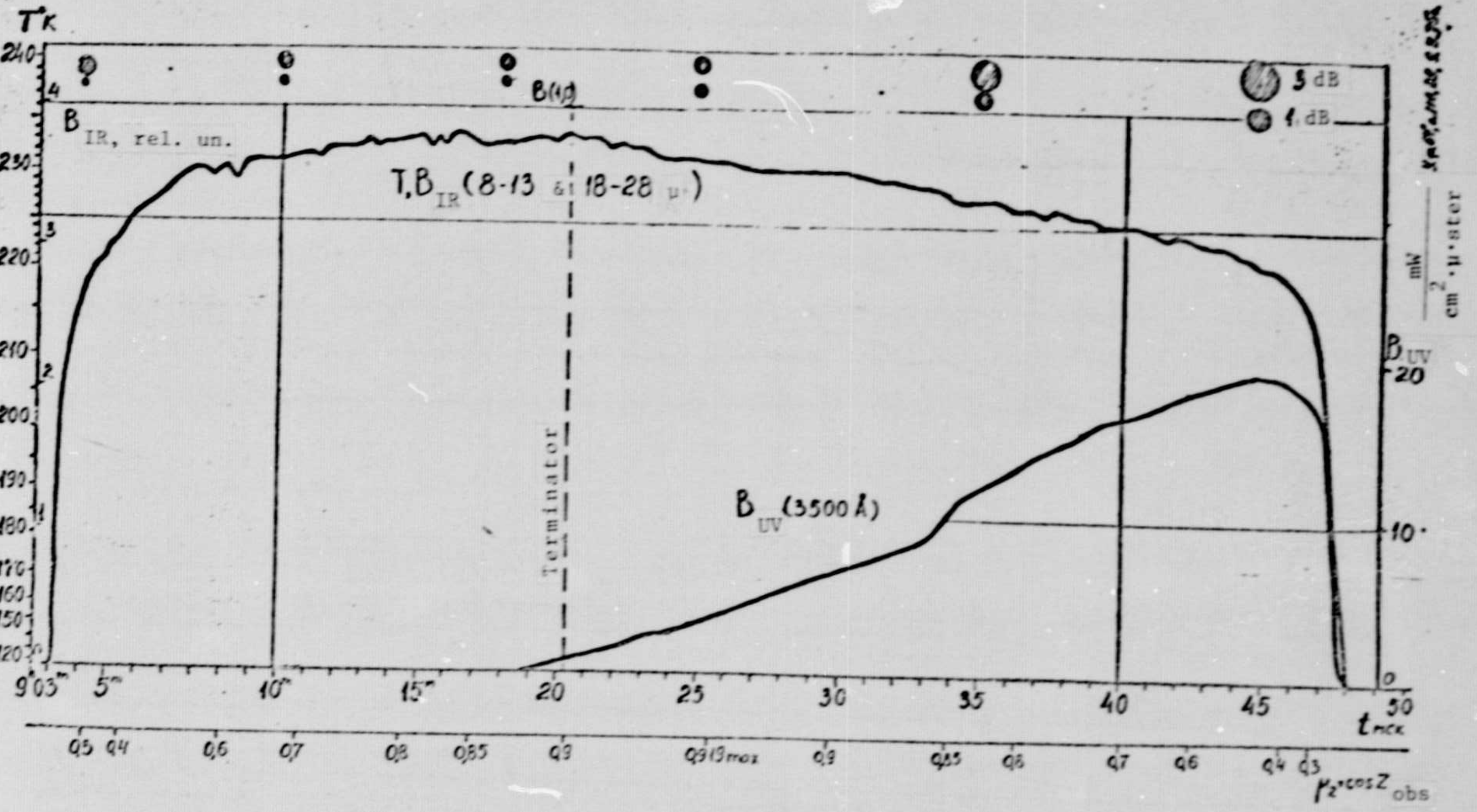
T°K
240
230
220
210
200
190
180
170
160
150
120
4
3
2
1
0
B IR, rel. un.
T,B IR (8-13 & 18-28 μ)
B(1λ)
Terminator
B UV (3500 Å)
3 dB
1 dB
B UV
mW / cm²·μ·ster
20
10
0
9h03m
5m
10m
15m
20
25
30
35
40
45
50
t мск
0,5
0,4
0,6
0,7
0,8
0,85
0,9
0,919 max
0,9
0,85
0,8
0,7
0,6
0,4
0,3
μz = cos Z obs

Figure 7

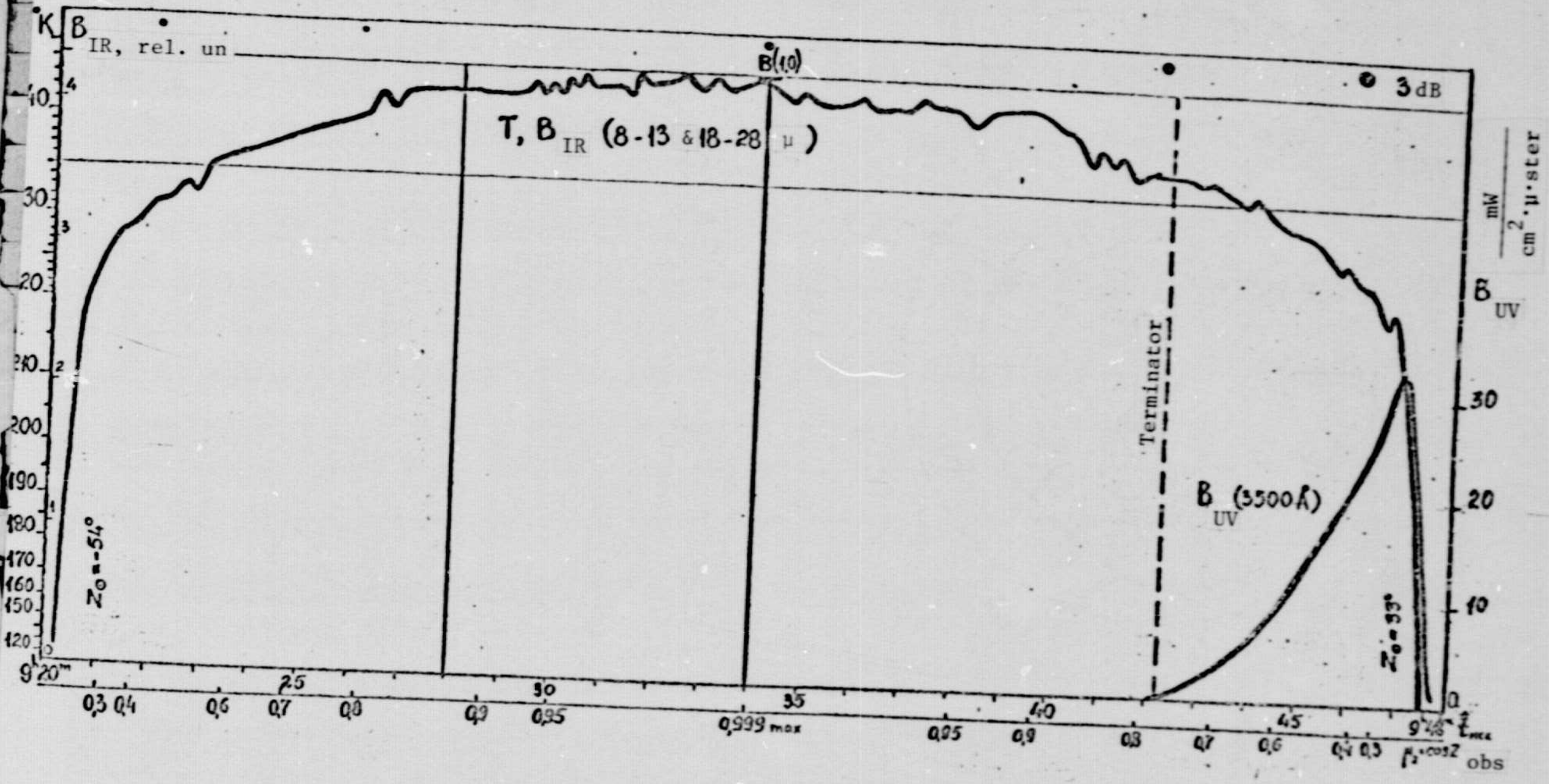
K
B_{IR}, rel. un
3 dB
T, B_{IR} (8-13 & 18-28 μ)
B(1,0)
Terminator
B_{UV} (3500 Å)
B_{UV}
$\frac{mW}{cm^2 \cdot \mu \cdot ster}$
$Z_0 = -54°$
$Z_0 = 33°$
40
30
20
210
200
190
180
170
160
150
120
4
3
2
1
0
30
20
10
0
$9^h 20^m$
25
30
35
40
45
$9^h 48^m$
t_{msk}
0,3
0,4
0,6
0,7
0,8
0,9
0,95
0,999 max
0,95
0,9
0,8
0,7
0,6
0,4
0,3
$\mu = \cos Z_{obs}$

Figure 8

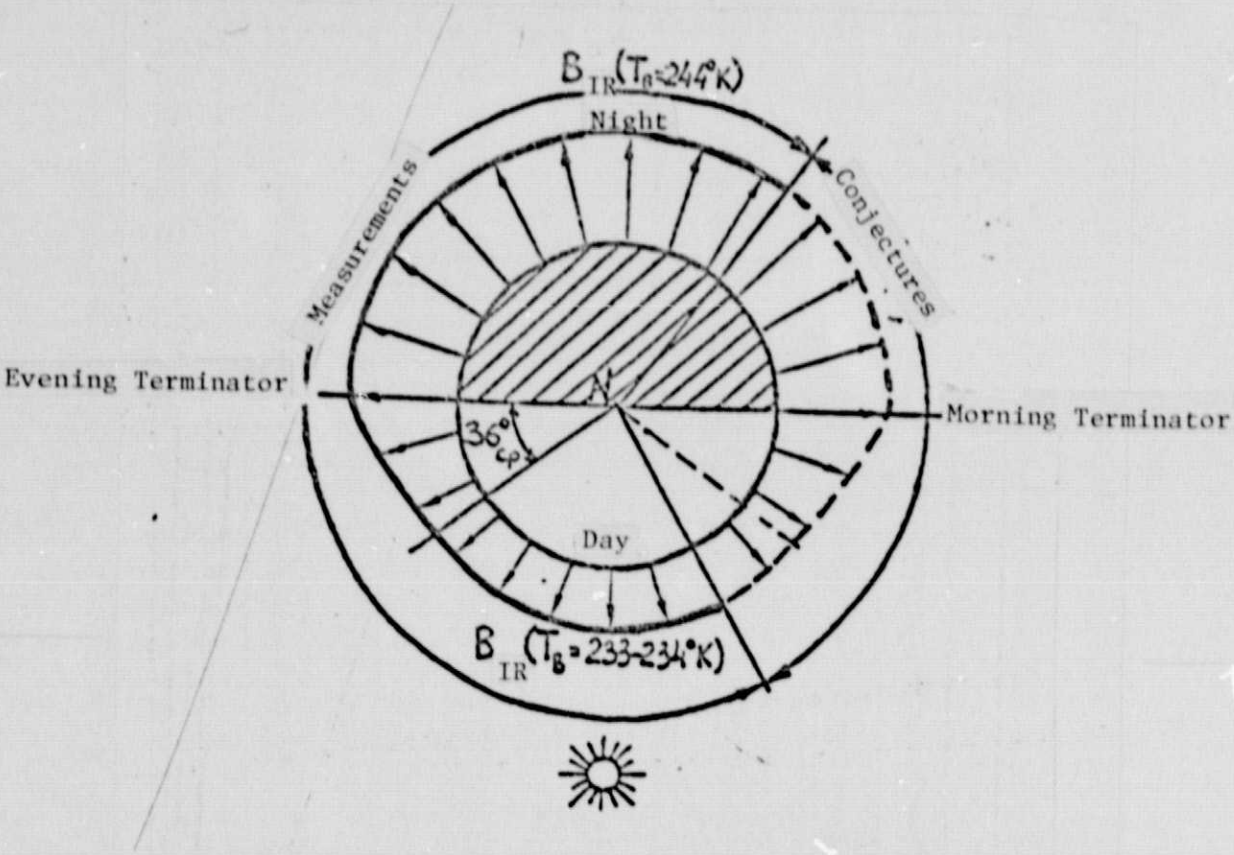
B IR (T_B=244°K)
Night
Measurements
Conjectures
Evening Terminator
Morning Terminator
N
36°
φ
Day
B IR (T_B=233-234°K)

Figure 9

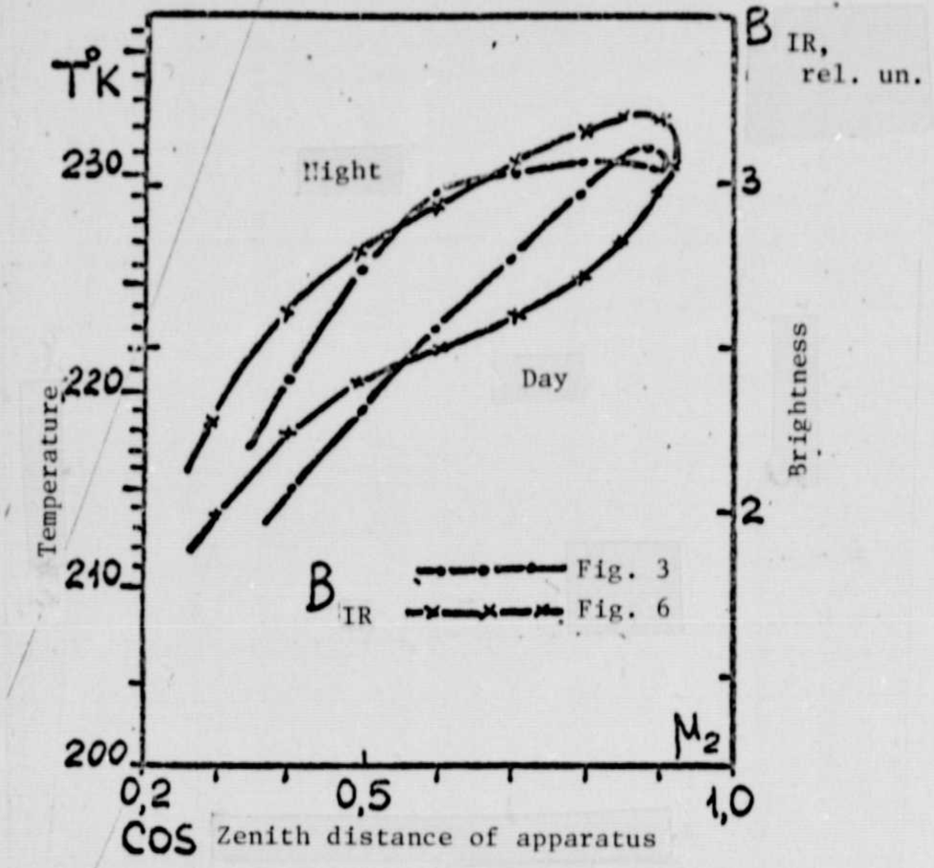
T°K
Temperature
230
220
210
200
B IR, rel. un.
Brightness
3
2
Night
Day
B IR
Fig. 3
Fig. 6
M2
0,2
0,5
1,0
COS Zenith distance of apparatus

Figure 10

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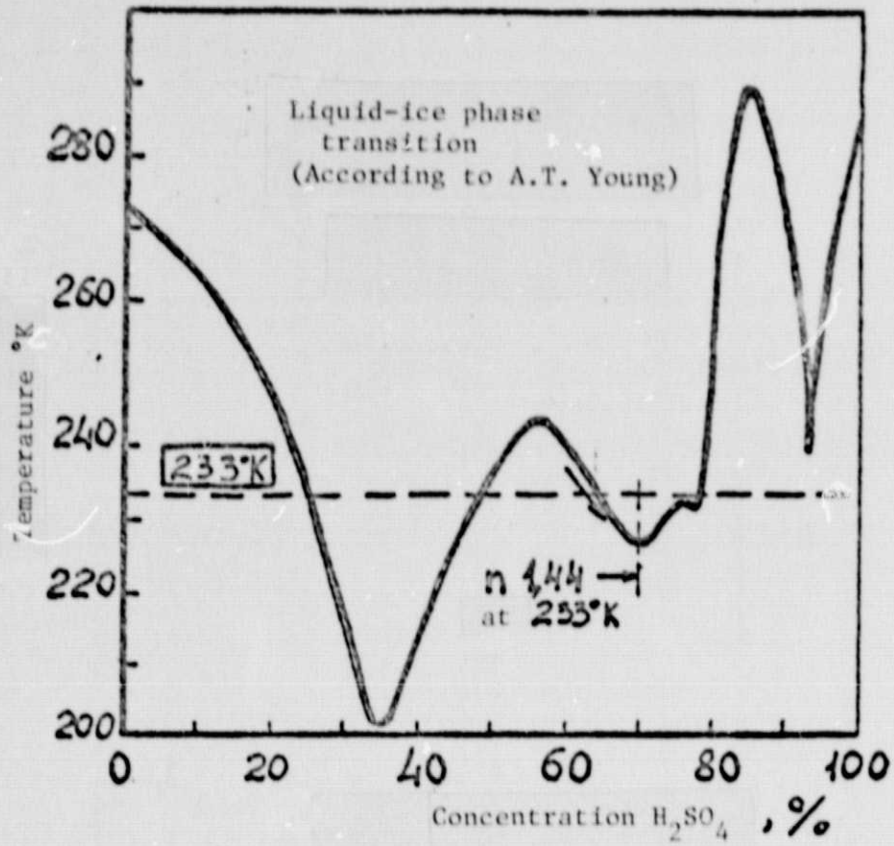

Figure 11