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OBSERVATIONS OF AN INCREASE IN THE FLUX FROM TAU A DURING OCCULTATION BY THE SOLAR CORONA

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ABSTRACT

During the June, 1965, occultation by the solar corona, the radio source Tau A was observed at wavelengths of 74 and 128 cm with the NRAO 300' antenna. Little change in the flux at 74 cm was observed, but at 128 cm the flux increased by 30% during the occultation. Various explanations of this flux increase are considered, but none are found to be very satisfactory.

In mid-June each year the solar corona occults the radio source Tau A. These occultations yield valuable data concerning the radio transmission properties of the corona (Hewish, 1955; Erickson, 1964). At wavelengths above 2 m, the observations appear to be reasonably consistent with the multiple scattering mechanism proposed by Hewish, and the scattering appears to scale proportionally to λ^2. Blum and Boischot (1957, 1959), using the Nancey solar interferometer, have reported observations of 50% increases in the Tau A flux at 177 cm when the source and sun were separated by about $7R_\odot$ in both 1957 and 1958. In June, 1964, Kundu (1965) observed the occultation at 70 cm using the Arecibo radiotelescope, and recently reported a 20% decrease in the flux at $9R_\odot$ separation. Neither of the latter results are in agreement with predictions based on the multiple scattering mechanism. Such discrepancies do not appear at shorter wavelengths, however, since Wyndham and Clark (1963), and Hughes, Downes, and Murray (1964), have observed no effect of the corona upon the radiation from Tau A at 18 cm and 6 cm, respectively. This is in agreement with the multiple scattering theory, for its λ^2 dependence would predict effects far too small for measurement at these wavelengths.

Therefore, the only outstanding discrepancies with the multiple scattering mechanism lie in the 50 to 200 cm wavelength range. In an attempt to elucidate the matter, we instrumented the NRAO 300' transit telescope at 74 cm (405 MHz) and 128 cm (234 MHz) in order to observe the 1965 occultation. To minimize the disruption of the 21 cm line programs in which the telescope was engaged, the 74 cm and 128 cm feeds were mounted off-axis, SW and SE of an on-axis 21 cm feed. Thus, some coma sidelobes are produced, and the beams are about 1° east and west of the meridian plane. The feeds are helicies, giving right circular polarization.

Because of the high antenna temperatures anticipated for Tau A, the receiving system required for these observations was rudimentary. Each frequency channel consisted of a crystal mixer, a filter to block IF interference, a 30 MHz IF amplifier, square law detector, integrator, DC amplifier, and a meter driver. The data were

recorded on a dual-pen strip chart recorder and the integration times were 1^s. Each minute, 500°K calibration signals of 7^s duration were inserted from a gas discharge tube into each mixer through directional couplers. The antenna was set to the declination of Tau A, and drift scans were obtained for about one hour each day.

The principal observational problem in all solar occultation work is contamination due to solar emission. On the day of closest approach, June 14, 1965, Tau A was 79' from the center of the sun. For comparison, the measured beamwidths of the telescope were 50' at 128 cm and 30' at 74cm. The solar flux is orders of magnitude greater than that of Tau A. We thus encountered a moderate solar contribution to the profiles despite the fact that the surface accuracy of the 300' dish is practically perfect for these wavelengths, and sidelobe levels are generally very low. In order to ascertain the solar contribution to the profiles, drift scans of the sun were obtained on days before and after the occultation with the antenna set to the same positions relative to the sun that were used on the seven central days of the occultation. These solar scans established a solar profile for each daily position of the sun during the occultation. The appropriate solar profile was subtracted from each occultation profile, and the response due to Tau A alone was thus determined. These solar profiles were highly stable; they fit together almost perfectly to form a completely consistent picture of the sidelobe structure of the antenna. The solar flux at these wavelengths was apparently constant during the observation period, and solar sidelobe profiles taken about two weeks apart, before and after the occultation, superimposed upon each other with maximum differences in antenna temperature of only about 30°K. As examples, the three sidelobe profiles used to establish the solar contribution to the June 14 record are shown in Fig. 1. On this day, the right ascension of the sun and Tau A differed by only 67^s and the largest solar correction was required on this record. Since the apparent sun moves in the sky more than one beamwidth per day, the corrections on all other days were much smaller.

Fig. 2 presents the profiles obtained each day after

subtracting the solar contribution. The solar contribution was negligible except during the June 11 to 18 period. The magnitude of the solar correction near the peak of each profile is illustrated by the arrow under each profile. It is seen that the profiles obtained during this period represent the antenna's response pattern nearly as well as those obtained when the solar contribution was negligible. This proves that the solar correction must have been accurate, otherwise the profiles would have been lopsided and would have converged before and after transit to some level above or below the true baseline. The broadening of the profiles due to multiple scattering by coronal irregularities is too small to be observable with our beamwidths.

The flux of Tau A obtained each day is illustrated in Fig. 3. The 74 cm flux is fairly constant, or slightly increased during the occultation. This contradicts Kundu's result. The 128 cm flux shows a marked rise of 30% during the occultation period. This is in strong confirmation of Boischot's results, although our results differ slightly in that our fluxes rise monotonically as the separation decreases to $4.96R_{\odot}$, while he found a maximum flux near $7R_{\odot}$. This difference could be easily attributed to our shorter wavelength (128 cm compared to 177 cm) or to the fact that our data pertain to solar minimum, while his were taken near solar maximum. As a crude indication of solar activity, the 2800 MHz solar flux (NBS-CRPL, 1965) is also illustrated in Fig. 3. It is seen to remain constant and there are no other indications of solar activity during the occultation period.

We are extremely fortunate to have optical observations of the corona available during this occultation period. From the total solar eclipse of May 30, 1965, and from Coronoscope II flights* on June 3 and July 1, 1965, we can obtain excellent information concerning the distribution of coronal streamers. In the plane perpendicular to the

* The author is greatly indebted to Dr. Gordon Newkirk, Jr. and Mr. David Bohlin, High Altitude Observatory, Boulder, Colorado, who furnished him preliminary sketches of the distribution of coronal streamers previous to the publication of the Coronoscope II results.

line of observation during the Coronoscope II flights (this is roughly the plane containing heliographic meridian 110° and 290°), the outer corona is dominated by two streamers. One large streamer appears in the direction of heliographic latitude -10° on the 290° meridian plane, the other is smaller and appears in the +10° direction on the 110° meridian plane. The radiation from Tau A passed through the larger steamer on June 18 and 19. (The heliographic coordinates of the points of closest approach along the ray paths were B = -12°, L = 282° on June 18, and B = -9°, L = 268° on June 19.) Fig. 3 shows that an anamolously high flux was observed on these two days. If this correlation is not accidental, it indicates that the radiation was either amplified or focused on the earth by the streamer. The ray paths never traversed the other streamer, and we have no observations definitely indicating the presence or absence of streamers along the ray path to Tau A on June 12, when Fig. 3 also shows a small enhancement of the flux.

We might inquire into the possible causes of the observed flux increase. The simplicity of the instrumentation eliminates most spurious effects of instrumental origin. It is rather unfortunate that on just those days when the solar contamination of the profiles is appreciable, the most striking flux increases occur. However, we can find no reason whatsoever to believe that our corrections for solar contamination were too small, or that they introduced appreciable error, so some physical cause for the flux increase must be sought.

Coronal scattering results in a redistribution of flux in angle. If the scattering region is of finite angular size, this can result in either increases or decreases of the apparent flux at any observing point. However, the increases are small except under highly artificial geometrical conditions (such as an annular ring of scatters with the source and receptors near the axis of the ring). To explain an isolated observation of an enhanced flux, transient coronal scatters of peculiar geometry might be invoked, but decreases in flux are equally probable and it is impossible to explain a general flux increase observed over many days in this fashion. Isolated flux increases

which might be attributed to effects such as this have been observed on several occasions (Erickson, 1965; Gorgolewski, Hanasz, Iwaniszewski, Turlo, 1962; and Vitkevitch, 1956).

Rays passing close to the sun will be strongly scattered and will fall into adjacent regions, causing a small increase in net flux at appropriate angles. This effect has been calculated (Erickson, 1964), and can cause small flux increases when the apparent separation of a source and sun are $3.7R_\odot$ for $\lambda = 124$ cm. The effect is too small and occurs at too small separations to explain either our results or those of Bioschot. Therefore, it does not appear possible to explain the observed flux increases through coronal scattering.

The next possibilities to be considered are the effects of uniform coronal refraction. Such effects have been considered theoretically by Link (1952) and by Bracewell and Preston (1956). In the absence of coronal scattering ray paths throught the corona will bend away from the radius vector. This uniform coronal refraction will cause a shift in the apparent position of the source, and will cause a large increase in apparent flux at the edge of the occulting disk, i.e. at the edge of that angular region of the sky from which no rays can traverse the corona to the earth. The angular size of the occulting disk depends somewhat upon the model of the electron distribution employed in the calculation of coronal ray paths, but all coronal models predict occultation disks at 128 cm whose radii lie between 2 and 3 $R_\odot$. Under these conditions, the flux increase at $5R_\odot$ is negligible. Independently, we have computed ray paths through a Van de Hulst model corona (Van de Hulst, 1953). using both the polar and equatorial electron densities.* These calculations confirm Link's and Bracewell and Preston's results. They indicate that at $5R_\odot$ the apparent position of Tau A would be shifted by less that 1', and its flux should be practically unchanged. Therefore, we see no possibility of explaining the observed increase through coronal refraction effects.

* The author is indebted to Mr. W. M. Cronyn who provided the IBM 7090 computer program for these ray path calculations.

If the increase in apparent flux cannot be explained through a redistribution of the flux in angle, then the only remaining possibility is through an amplification mechanism in the corona. The possibility of negative absorption in various radio astronomical sources has been considered by Twiss (1958). His results were considered in detail for the generation of solar burst radiation by Wild, Smerd, and Weiss (1963). Employing the latter authors' notation, the coefficient of absorption for a medium, such as the corona, can be written as:

$$K = -\frac{c^2 N}{\mu^2 f^2} \int_0^\infty \frac{d F(\epsilon)}{d\epsilon} Q_f(\epsilon)\, g(\epsilon)\, d\epsilon \qquad (1)$$

where

f = the frequency of the wave.

N = the electron density.

μ = the index of refraction.

$F(\epsilon)$ = the electron probability distribution in momentum space (this may be thought of as the effective energy distribution function).

$Q_f(\epsilon)$ = the mean electron emissivity; that is, the mean power emitted spontaneously by each electron of energy ϵ per unit time per unit frequency interval in one polarization per unit solid angle into any direction. $Q_f(\epsilon)$ depends upon the particular microscopic emission process under consideration.

$g(\epsilon)\, d\epsilon$ = the statistical weight of the energy levels. The levels are assumed to be continuous and $h f \ll \epsilon$.

For amplification to occur, we must have $K < 0$, and so we must consider the conditions under which this can occur. If $Q_f(\epsilon)$ consists of one or more well defined resonance peaks, and if $\frac{dF}{d\epsilon} > 0$ across one of them, K can be negative.

However, under thermodynamic equilibrium, $\frac{dF}{d\epsilon} < 0$ for all ϵ; since $Q_f(\epsilon) \geq 0$ by definition, this implies that $K \geq 0$. Therefore, amplification cannot occur when we have thermodynamic equilibrium.

Let us consider the case of a superthermal flux of high energy electrons. Assuming that $F(\epsilon)$ and $Q_f(\epsilon)\, g(\epsilon)$ are well behaved functions and $Q_f(0) \equiv 0$, partial integration of Eqn. (1) yields:

$$K = \frac{c^2 N}{\mu^2 f^2} \int_0^\infty F(\epsilon) \frac{d}{d\epsilon} (Q_f(\epsilon)\, g(\epsilon)) \, d\epsilon \qquad (2)$$

Since $F(\epsilon) \geq 0$ for all ϵ, Eqn. (2) shows that if $\frac{d}{d\epsilon} (Q_f(\epsilon)\, g(\epsilon) > 0$, amplification cannot occur. The case of non-relativistic bremstrahlung was considered by Twiss and by Wild, Smerd, and Weiss who show that $\frac{d}{d\epsilon} (Q_f(\epsilon)\, g(\epsilon)) > 0$. One can easily show that this also holds at relativistic energies, and thus the possibility of amplification in the case of bremstrahlung can be eliminated.

Another microscopic emission process which might be considered is Cherenkov radiation. Direct Cerenkov radiation by charged particles of relativistic energies occurs when the phase velocity of the wave is below the particle velocity. Phase velocities below the velocity of light occur only in the extraordinary mode below the gyro-frequency, and radiation in this mode can neither penatrate nor escape the plasma. Radiation may be generated indirectly by the generation of electron plasma waves via the Cerenkov effect. However, at $5R_\odot$ the plasma frequency is on the order of 5 MHz, and plasma waves of $\approx$ 200 MHz would be evanescent. Thus it appears that Cerenkov effects cannot cause amplification.

Other types of interaction with the radiation field might be through very high quantum number transitions in dust grains (Erickson, 1957) or atomic hydrogen (Kardoshev, 1959). In these cases, we should expect the relative populations of the high quantum states to be determined by a Boltzmann distribution since the corona is assumed to be in collisional equilibrium, and collisonal transitions dominate all others by a large factor. It is difficult to understand how a flux of fast particles could appreciably affect the relative populations and produce the overpopulation of the upper states required for maser-like amplification.

The only other known emission mechanism is that of gyro or synchrotron radiation. For non-relativistic particles, one can obtain amplification at low harmonics of the gyro frequency. The conditions under which amplification can occur are quite strict, and it is very unlikely that they will be fulfilled in the outer corona. First of all,

the observing frequency must be a low harmonic of the gyro frequency. This means that we must assume that regions exist where the magnetic field is on the order of 10 gauss. Due to their tremendous magnetic pressure (≈ 5 dynes/cm^2) compared with the gas pressures ($\approx 10^{-4}$ dynes/cm^2) such regions should rapidly expand and dissipate. Wild, Smerd, and Weiss also show that the magnetic and Doppler spreading of the gyro resonance must be small if amplification is to occur.

For synchrotron emission in a vacuum, Wild, Smerd, and Weiss show that $-\frac{\partial}{\partial \epsilon}\left(Q_f(\epsilon)\, g(\epsilon)\right) > 0$, and that in this case we cannot have amplification. However, their argument concerning synchrotron emission does not generally apply to the solar environment because they neglect the effect of the ambient plasma on the emission. Since the phase velocity of radio waves in a plasma is somewhat greater than the velocity of the highly relativistic particles, the radiation occurs at lower harmonics of the gyro frequency, and is less concentrated to the particle trajectory than it would be in vacuum. Ginzburg and Syrovatskii (1965) show that the effects of the medium can be neglected only if

$$f \gg 20\,\frac{N}{H_\perp} \qquad (3)$$

where N = the electron density and $H_\perp$ is the field component perpendicular to the direction of emission.

At $5R_\odot$, $N \approx 10^5$ cm^{-3} and $H \approx 10^{-2}$ gauss should be reasonable estimates. In this case, plasma effects are negligible only at frequencies far above 200 MHz. At lower levels in the corona, the ratio $\frac{N}{H_\perp}$ may be expected to increase, and condition (3) will become even more restrictive. Therefore, their arguments must be extended to include the effect of the medium. This calculation is carried out in an accompanying paper (Erickson, 1966). The result is that negative absorption can indeed occur, but quantitatively the effect is too small to explain the observed flux increase with reasonable estimates of the density of relativistic electrons in the corona.

Another complication should be noted. The radius of curvature of relativistic particles in the corona is probably much larger than the coronal inhomogeneities. This makes synchrotron emission calculations

which assume helical electron trajectories somewhat questionable. However, we see little hope that a more complicated calculation assuming non-helical trajectories would yield a much larger amplification factor.

To summarize, increases in the Tau A flux have now been observed during three separate occultations by the solar corona. The observations were made at similar wavelengths by completely dissimilar instruments. We also observe an increase in flux which is apparently correlated with the passage of the source behind a large coronal streamer. We can find no reason to doubt the validity of the data except that no plausible explanation of these increases has been found, and any explanation would require the existance of hitherto unsuspected structures in the outer corona. It is obvious that these observations require confirmation by any institutions with appropriate instruments.

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FIGURE CAPTIONS

Fig. 1 Three scans of the solar sidelobes in the relative position of Tau A on June 14, 1965, are shown. The three scans agree excellently with each other, and their average was used to determine the baseline under the Tau A profile of June 14.

Fig. 2 Tau A profiles observed each day after subtraction of the solar component. The assymetry, and displacement of the peaks form the calculated transit time of Tau A are due to the off-axis feed. Occasional interference from terrestrial sources was experienced. This limited the length of useable baseline beside some of the profiles, but fortunately, practically no interference was experienced during the periods when Tau A crossed the response patterns. The magnitude of the solar contribution under the peak of each profile is shown by an arrow.

Fig. 3 The flux received from Tau A each day during the June, 1965, occultation at wavelengths of 128 and 74 cm is illustrated by the solid dots. The X's indicate the 2800 MHz solar flux, a sensitive indicator of solar activity. A definite increase in the flux from Tau A at 128 cm was observed during the central portion of the occultation.

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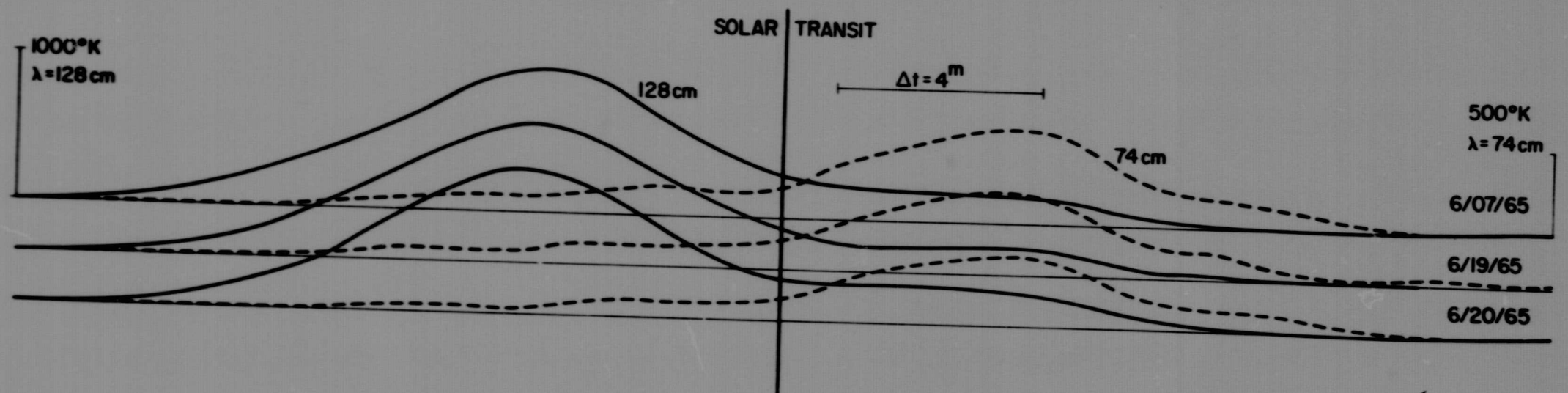
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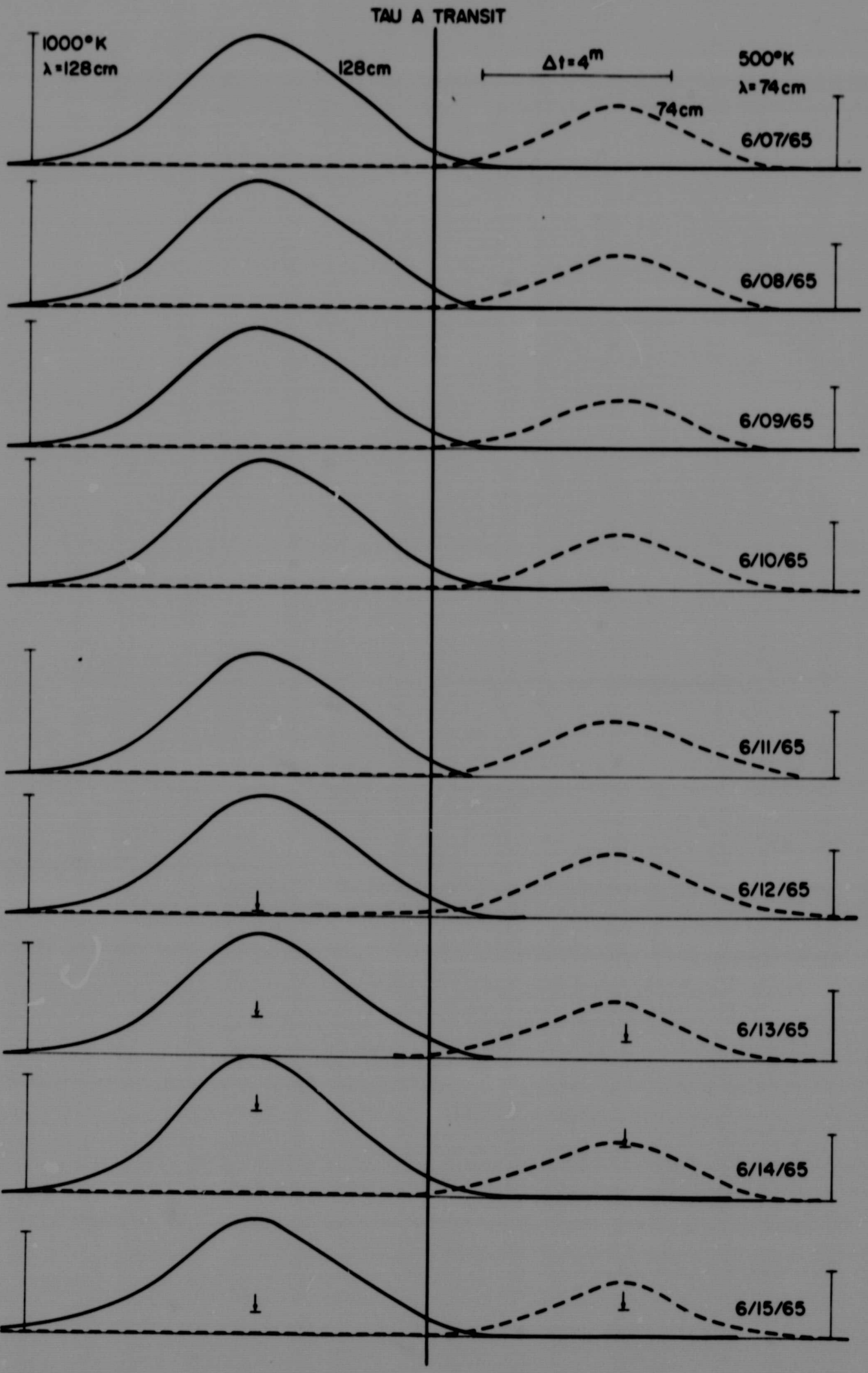
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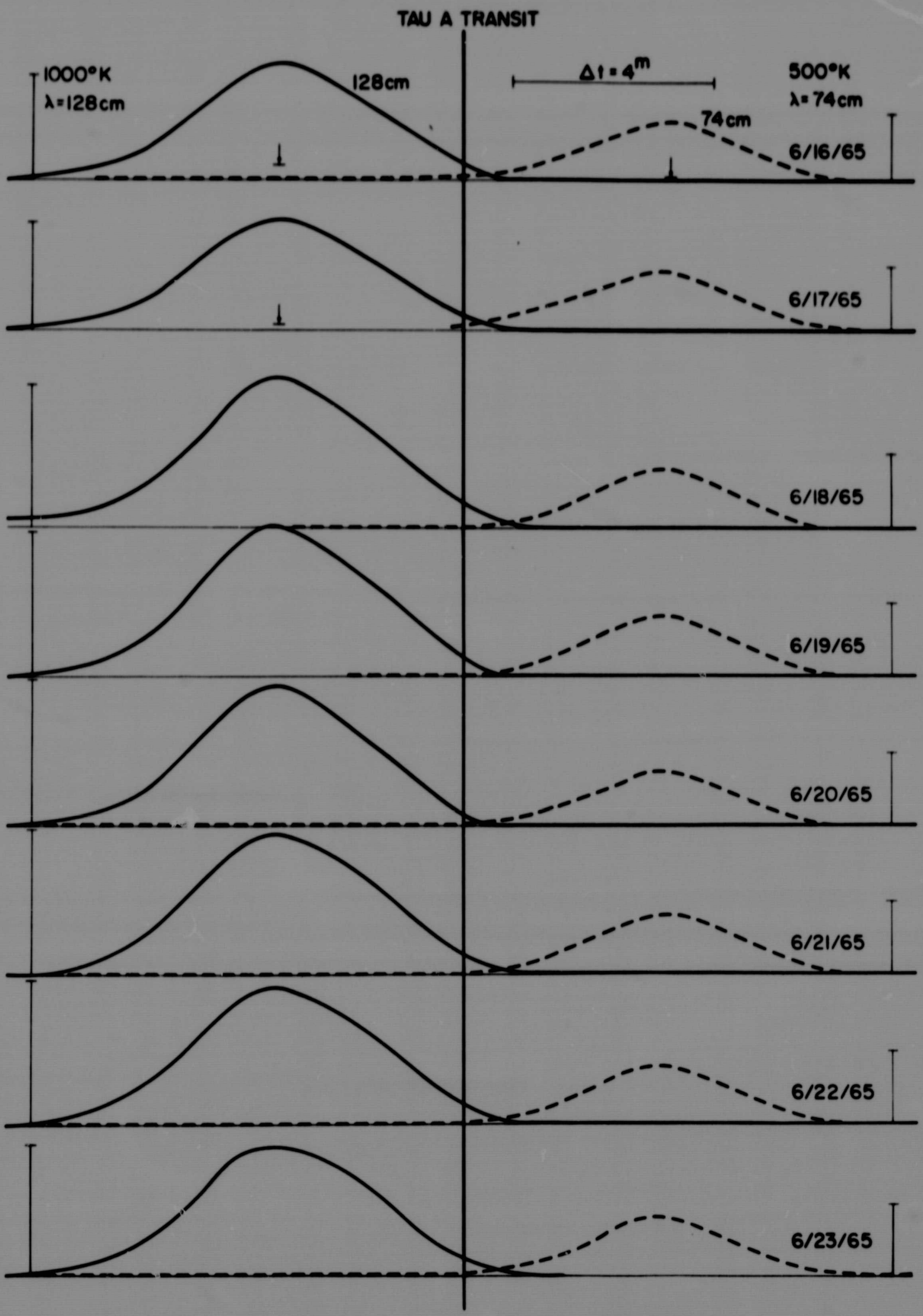
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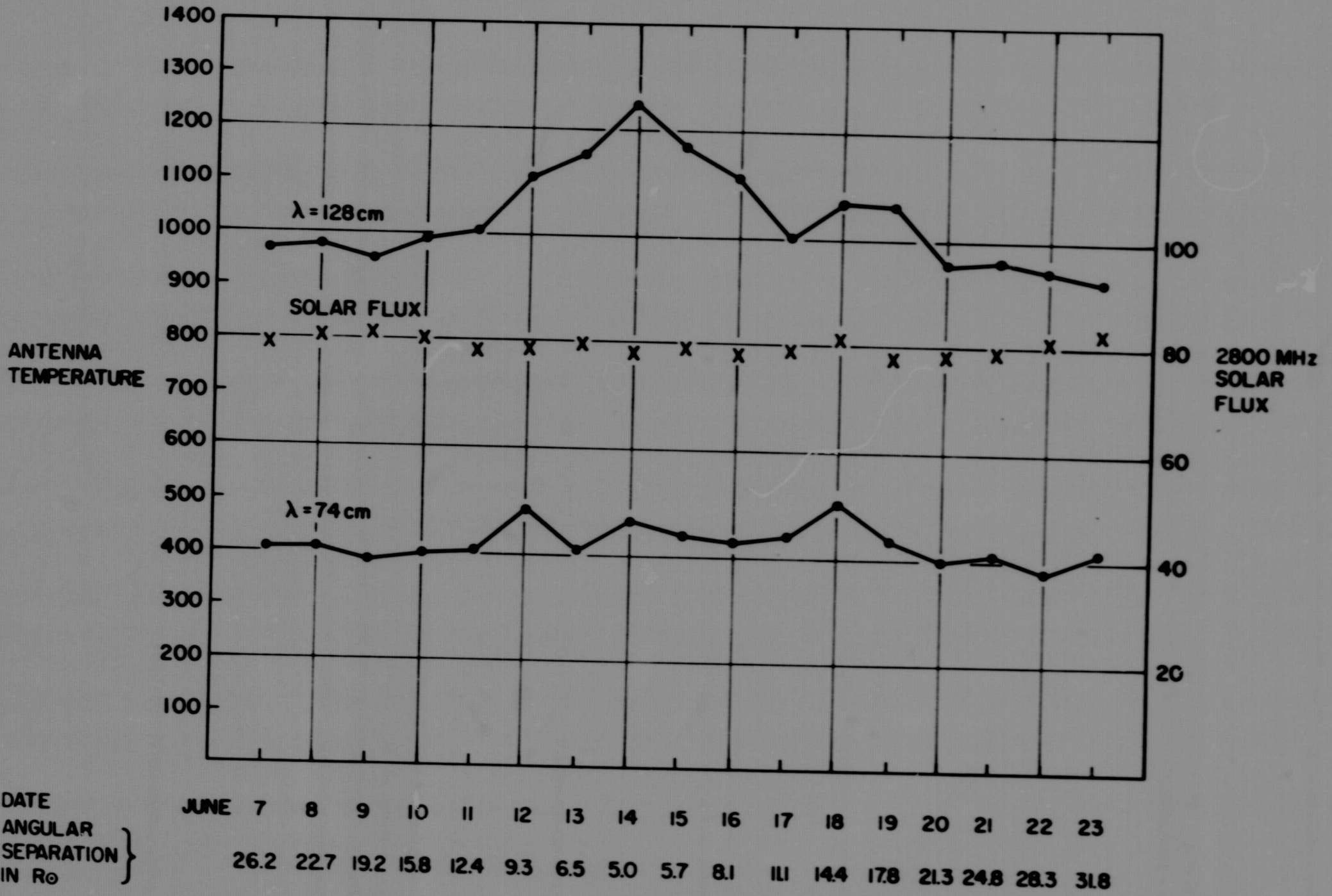
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