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High-Dispersion Spectroscopic Observations of Venus During 1968 and 1969 II. The Carbon-Dioxide Band at 8689Å

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Thirty well-exposed photographic plates showing the spectrum of the carbon dioxide band at 8689A in the atmosphere of Venus were obtained during 1968 and 1969. All spectra were obtained at a dispersion of 2 Å/mm for Venus phase angles varying from 10° to 126°. We find rotational temperatures ranging from 236°K to 274°K. The average value of the rotational temperature is 246 ± 1°K (one standard deviation); for our 1967 observations, the rotational temperatures ranged from 222 to 248°K, with an average value of 238 ± 4°K. The variation of the equivalent width of the 8689A band, with Venus phase angle, was very similar for the two sets of observations (53 plates). The temporal variations, of approximately 30 percent, were comparable with the phase variations over this limited range of phase angle.

I. Introduction

We have made an extensive series of observations of Venus at high resolution (see L.G. Young, 1972) beginning in 1965. The results of observations made at McDonald Observatory, (with both the 82" Struve Reflector and the 107-inch telescope) during 1968 and 1969 are presented here. Previous to our present work there have been only two substantial published sets of observations of the entire CO_2 band at 8689A. Chamberlain and Kuiper (1956) measured 6 plates taken with a dispersion of 9.6 Å/mm and Young, et al. (1969) measured 14 plates taken with a dispersion of 4 Å/mm and 9 plates taken with a dispersion of 2 A/mm. In both cases, the phase-angle coverage was somewhat less than for the present set of observations. Furthermore it was of some interest to see how well our observations of Venus matched from one year to the next. Kuiper (1952) was the first to point out that the equivalent width of this band varies with the location on Venus, and shows fairly large day-to-day variations as well as variations with the Venus phase angle. Young, et al (1973) have studied the day-to-day variations (when the Venus phase angle only varied from 69° to 77°) and reported that the "strength of the CO_2 absorptions in the spectrum of Venus varies by 20 percent in a period of 4 days." One might expect to see variations in temperature from day-to-day if the carbon-dioxide amounts vary by that much, although these temperature variations would be expected to be on the order of a few degrees K, since the CO_2 lines appear to be formed near the tropopause.

II. Observations

The spectrograms used in this study are listed in Table 1. Plates in column 1 prefixed with a C were taken with the 160-cm focal length coudé spectrograph of the 82" Struve Reflector using grating I. This grating, used in the third order, gives a dispersion on the plate of 2 Å/mm. Plates prefixed with an N were taken at the coudé focus of the 107-inch telescope with the 425-cm focal-length spectrograph and grating B used in the first order, resulting in a dispersion of 2 Å/mm on the plate. Thus all of our spectra were obtained with the same dispersion. All exposures were made on ammonia-hypersensitized IV-N plates. Higher order spectra were blocked out using either an RG-10, RG-8 or RG-5 filter. The choice of filter depended upon the contrast of Venus against the sky background. The spectroscopic plates were developed in D-76 for anywhere from 12 to 18 minutes, using continuous agitation in a rocker tray.

These observations were made over a period of a year and the local terrestrial weather varied considerably from plate to plate: 70 percent of the observing days were clear, 20 percent were hazy and 10 percent were partly cloudy; the ambient temperature ranged from 44 to 90°F, with an average temperature of 66°, the relative humidity varied from 9 to 91 percent, with an average humidity of 36 percent; the seeing varied from 1" to 10" with average seeing of 3"-4". Only the 30 best, well exposed plates were included in the following analysis. Table 1 gives the date (column 2), the time of the observation (column 3) and the phase angle of Venus (column 4). Column 5 gives the Doppler shift of the Venus lines at 8700A (Niehaus and Petrie, 1961). Column 6 gives the position of the spectrograph slit on the image of the disk of Venus. An image rotator was used to position the slit at one of the five standard positions we have used in our earlier studies of Venus. For this set of observations we have in fact used only three different positions on the image of the disk. In order to maintain a consistent notation with our earlier series of papers, we will retain the same numbering system as before. Position 1 is pole-to-pole near the terminator; position 2 is pole-to-pole near the limb; position 4 is parallel to the equator near the sub-Earth point.

III. Measurement of Equivalent Widths

All of the plates listed in Table 1 were traced in the density-versus-wavelength mode on the recording microdensitometer at the California Institute of Technology. In all cases the microphotometer slit covered the central 80 percent of the width of the spectrum. In some cases a plate was traced more than once.

Previous work (A.T. Young, 1972) has shown that the density of hypersensitized IV-N plates is a linear function of exposure, apart from the toe of the characteristic curve (see Fig. 1.). Thus a density tracing is equivalent to an intensity tracing, apart from a zero-point shift. As our strongest lines have residual intensities on the order of 80%, a readable intensity tracing would have the zero off-scale. Equivalent-width calibrations were based on the following 22 solar lines and their equivalent widths as reported by Moore, Minnaert and Houtgast (1966): 8668.456 (9 mÅ), 8671.879 (13 mÅ), 8674.756 (113 mÅ), 8679.646 (41 mÅ), 8680.405 (25 mÅ), 8686.368 (54 mÅ), 8693.958 (17 mÅ), 8694.641 (34 mÅ), 8698.717 (20 mÅ), 8699.461 (73 mÅ), 8710.398 (82 mÅ), 8712.701 (57 mÅ), 8713.208 (58 mÅ), 8717.833 (105 mÅ), 8728.024 (107 mÅ), 8736.040 (289 mÅ), 8742.466 (97 mÅ), 8751.198 (14 mÅ), 8752.025 (94 mÅ), 8757.199 (91 mÅ), 8763.978 (99 mÅ), 8770.681 (11 mÅ). As many of these solar lines as appeared in a tracing of the spectrum of Venus were measured and used to calibrate that tracing. Unfortunately, all tracings did not begin and end at the same wavelengths. The majority of the tracings contained 20 solar lines. After finding the conversion from squares on the chart paper to mÅ, we then found the percentage error in our solar line calibration. Previously we had used this error as an estimate of the systematic error in our measurements of the equivalent widths of the CO_2 lines. We now believe that this overestimates our systematic error, since the equivalent widths of the solar lines reported by Moore, et al. refer to direct light from the center of the solar disk and not to integrated sunlight which is what we measure on our Venus plates. The differences in the equivalent widths measured for direct and integrated sunlight have, in some cases, been as large as 50 percent, or much larger than the standard deviations we report for the set of solar calibration lir (where we found a minimum standard deviation of 3.7 percent and an average standard deviation of 6.7 percent). We estimate that our relative systematic error is about equal to our random error, or about 2 percent. (Photoelectric scanner results should improve this situation considerably in the future).

The results of our measurements of the Venus carbon-dioxide lines are shown in Figures 2 to 11. In each figure we have plotted the equivalent width of the individual rotational lines against $|m|$, where m is related to the rotational quantum number J by $m = -J''$ for the P branch and $m = J'' + 1$ for the R branch. Here the double prime refers to the lower rotational energy state. The measurers are identified by the following symbols: circles, LDGY, and triangles, RAJS, as indicated on the figures. The measurements of these two people are usually in good agreement although each individual found his own intensity calibration from his measurements of the solar lines. About a quarter of the measurements show a systematic difference of approximately 10 percent between the two individual measurements. This difference is comparable to the difference found by one person in making measurements of the same plate from two tracings. Thus, our systematic error in determining the absolute value of equivalent widths is estimated to be about 10 percent. The rotational temperatures found from our measurements of equivalent widths are unaffected by the absolute value of measurements; they are only affected by the relative systematic errors (~ 2 percent) which arise from possible errors in judging where to draw the continuum.

IV. Determination of the Rotational Temperature and Other Parameters

As in our previous papers, we assume the curve of growth can locally be approximated by a straight line of slope b, i.e.

$$W(m) \sim S(m)^b \qquad (1)$$

where W is the equivalent width, S is the line intensity and m is the rotational line index mentioned before. Chamberlain and Kuiper's (1956) paper suggested that lines formed in a scattering atmosphere should follow a square root absorption law (b = 0.5). In table 2 we give the results obtained both for a square root absorption law and for a curve of growth; in the latter case, line intensities are calculated for various temperatures and the slope of the curve of growth corresponding to each temperature is computed. The temperature T_0 corresponds to the curve of growth which best fits the measurements (has the smallest standard deviation). Thus, the temperature T_0 is the value of the rotational temperature which gives the best overall fit to the distribution of equivalent widths, W, as a function of line intensity, S. Using the slope, b, found from that fit, we then seek the rotational temperature which gives the best fit to the distribution of equivalent widths, W, with rotational line index, m, from the expression

$$\ln \frac{W(m)}{m^b} = \ln W_o - \frac{0.5614\, m(m-1)b}{T_{rot}} \qquad (2)$$

If our measurements had no systematic errors, then we should find $T_o = T_{rot}$. The quantity W_o would be the same as the equivalent width measured for the R(0) line, if there were no scatter in our data. In the past, we found that the former was more generally true than the latter. Table 2 gives both T_o and T(b) as well as $W_o(b)$. The difference between $W_o(0.5)$ and $W_o(b)$ is due to the fact that, generally, $b \neq 0.5$. Table 3 gives a summary of the rotational temperatures found for each plate. The average temperature found assuming a square root absorption law is $T(0.5) = 215 \pm 1^oK$. For the curve of growth analysis, the average value of $T_o = 236 \pm 2^oK$ and the average value of the rotational temperature is $T_{rot} = 246 \pm 1^oK$.

V. Comparison With Other Measurements in 1968-1969.

Young et al. (1971) reported on a series of measurements of the carbon dioxide bands at 7820 Å and 7883 Å in the spectrum of Venus during this same period. The average temperatures they found were $T(0.5) = 232 \pm 3^oK$, $T_o = 240^oK$ and $T_{rot} = 244 \pm 3^oK$. These temperatures did not vary significantly with time, while our measurements of the CO_2 band at 8689 Å indicate slight temporal variations ($\sigma_{ext} > \sigma_{int}$). If we average all of the curve-of-growth temperatures found for the 1968-1969 observations of Venus, we obtain a temperature of $T_{avg} = 241 \pm 1^oK$, assuming the widths of the CO_2 lines are independent of rotational quantum number. If the rotational line widths are allowed to vary, we found (Young, 1971) the rotational temperature should be increased 4 percent, or $T_{avg} = 251 \pm 1^oK$.

VI. Comparison With Measurements of the 8689 Band of CO_2 Made During 1967.

Young et al. (1969) made an extensive series of measurements of this band the previous year. The average temperatures they found were $T(0.5) = 229 \pm 6^{o}K$, $T_{o} = 240^{o}K$ and $T_{rot} = 238 \pm 4^{o}K$. The present results indicate a noticably lower value for the average temperature found assuming a square-root absorption law, $T(0.5) = 215 \pm 1^{o}K$. The value of $T_{avg} = 239 \pm 2^{o}K$ for 1967 does not differ significantly from the value of $T_{avg} = 241 \pm 1^{o}K$ found for 1968-1969.

Since the same carbon-dioxide band was measured in both sets of observations, we can compare the values of $W_{o}(b)$ found for each set. This is done in Figure 12 where the present observations are indicated by circles and the 1967 observations by triangles. The sets of measurements are virtually indistinguishable and both indicate about the same amount of day-to-day variation in the equivalent widths (or CO_2 abundance above the Venus cloud tops). There does not appear to be much difference in the observations made two years apart; the major effect is in the day-to-day variations.

VII. Apparent Amount of Carbon Dioxide in the Absorption Path

In spite of the large day-to-day variations in the carbon-dioxide abundance, we can still compute the average amount observed above the clouds in 1968-1969. The intensity of the R(0) line is given by

$$S(1) = S_{band}(Q_{rot})^{-1} \qquad (3)$$

where $S_{band} = 0.72\ cm^{-1}/km\ atm_{stp}$ for the 8689Å band of CO_2 and $Q_{rot}(241^{o}K) = 214.7$ (Gray and Young, 1969). Hence

$$S(1) = 3.35\ m\ cm^{-1}/km\ atm_{stp}. \qquad (3a)$$

For both the 1967 and the present observations, we have an average value of $W_o(b) = 21 \pm 1$ mÅ $= 28 \pm 1$ m cm^{-1}. The minimum CO_2 abundance, ηw, (where η is the effective air mass) is found if we assume a <u>linear</u> absorption law, <u>viz.</u> law, <u>viz.</u>

$$W = S\eta w. \tag{4}$$

Hence $\eta w \geq 8.4$ km atm_{stp}. On the other hand, if the absorption is assumed to follow a square-root law (despite our findings to the contrary in the analysis of rotational temperatures) we have

$$W = 2(s\gamma\eta w)^{1/2} \tag{5}$$

for a pressure broadened line of halfwidth $\gamma = \gamma^o p_{eff}$. For CO_2 $\gamma^o = 0.1$ cm^{-1}/bar; for Venus $p_{eff} = 0.09$ w bar/km atm, since the atmosphere consists of 95 percent carbon dioxide. Equation (5) applies when the parameter

$$x = \frac{S\eta w}{2\pi\gamma} > \frac{\pi}{2}, \tag{6}$$

otherwise equation (4) is the appropriate relation. Substituting $\gamma = 9$ w m cm^{-1}/km atm and S(1) from (3a), we see that the square-root absorption law (in the absence of scattering) holds only if $\eta > 26.5$ air masses. It is possible that multiple scattering could increase the effective air mass to this large a value. However, even for a value of $\eta = 20$, equation (4) is still reasonably accurate. It would then indicate, for example, that only $w = 0.42$ km atmos of CO_2 are above the "cloud tops" which are at a pressure of 37 mb, and the R(0) line still follows a nearly linear absorption law. Smaller values of η would have the effect of putting the "cloud tops" deeper in the atmosphere, but would still have the R(0) line follow a linear absorption law.

In order to show how large a day-to-day variation does occur in the CO_2 abundance above the cloud tops, we note that $W_o(b)$ varies between 21.5 and 27.1 mA for the phase angle range $62^o < i < 64^o$. This amounts to a 12 percent change in abundance for a negligible change in the Venus phase angle.

Table 4 gives a comparison of the CO_2 abundance over various areas on Venus. This clearly demonstrates the necessity of making many observations before attempting to draw any conclusions about the distribution of carbon dioxide over that planet. To illustrate this, we have made averages of the abundance over various regions for 45 degree increments in the phase angle (probably a much longer time interval than that of most observations). From these averages one could conclude; a) the CO_2 abundance is maximum at the limb and minimum at the equator; b) the CO_2 abundance is maximum at the terminator and minimum at the equator; c) the CO_2 abundance is greater at the limb than at the terminator; or d) the CO_2 abundance is greater at the equator than at the terminator. We chose only to conclude that the CO_2 abundance varies over the planet and that its distribution does not remain constant with time.

VIII Conclusions

We have found good agreement between the present set of observations and the previous observations of the carbon dioxide band at 8689Å, both as to the average abundance of CO_2 and the rotational temperatures. Similarly there is good agreement between the average temperatures found for this band and the carbon dioxide bands at 7820Å and 7883Å observed over the same time period. There is a slight indication that we are seeing some variation in the rotational temperatures with time, but this is a weak effect compared to the comparatively large day-to-day variations in the CO_2 abundance. The distribution of CO_2

over the planet varies with time and there is no conclusive evidence that one area of Venus consistently has more CO_2 above it than any other area.

IX. Acknowledgement

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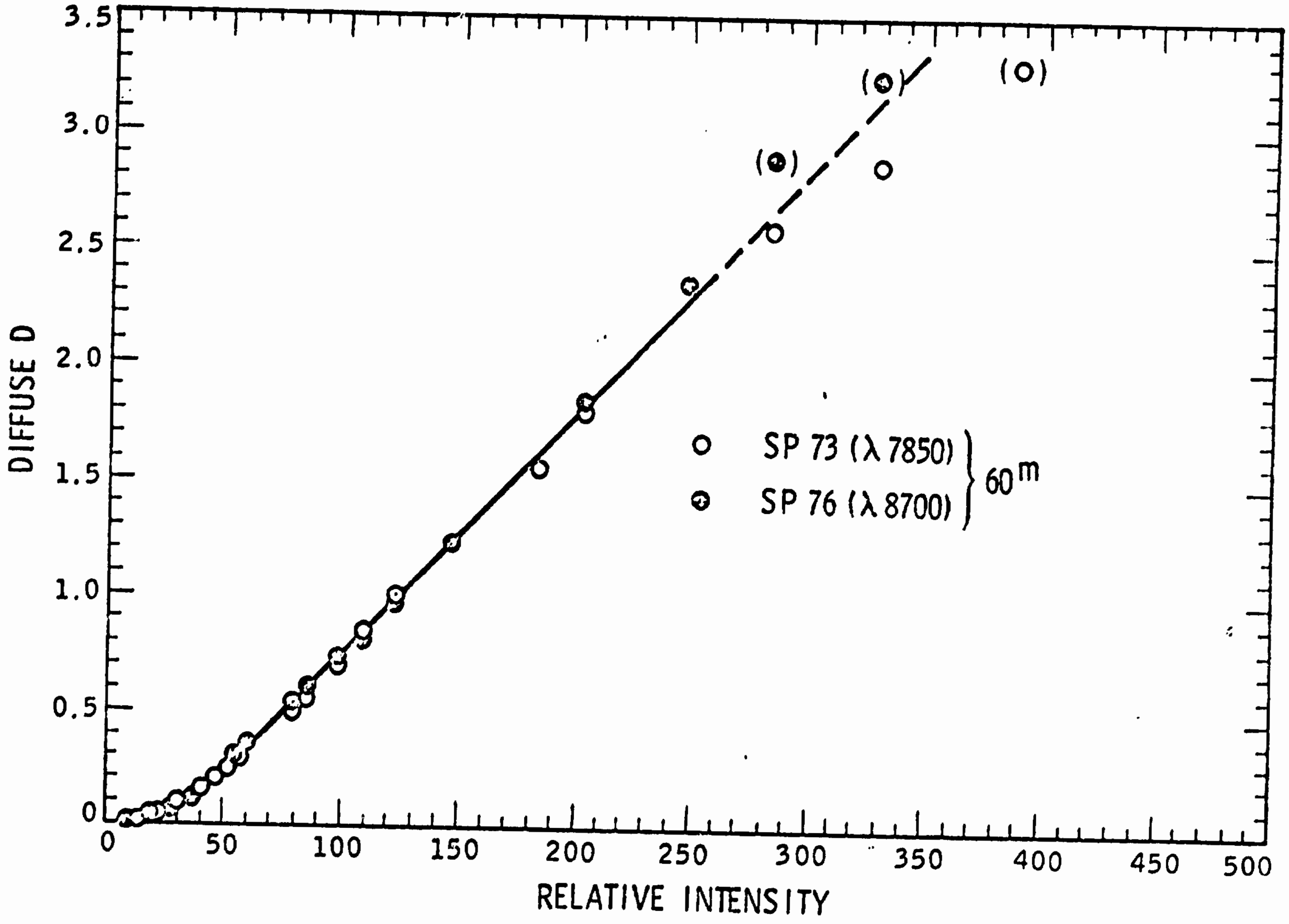
LIST OF FIGURES

Fig. 1. Density - vs. - exposure curve for two typical hypersensitized IV-N plates (spot-sensitometer data). Density is a linear function of exposure, in the normal range of densities.

Fig. 2. Equivalent widths of lines in the 8689Å carbon dioxide band as measured by two people for Venus plates taken on the dates indicated.

Figs. 3-11 (same figure captions as Fig. 2.)

Fig. 12. Intercept of the least-squares fit to a square-root absorption law as a function of Venus phase angle. The quantity $W_o(0.5)$ is a convenient measure of the carbon dioxide abundance. It would be equal to the equivalent width of the R(0) line if the square-root absorption law were valid and the data were completely free from both noise and errors in measurement. The solid symbols refer to spectra when the Doppler shift of the Venus lines was to the red; the open symbols refer to a Doppler shift to the blue.



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3.0
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⊙ SP 76 (λ 8700)
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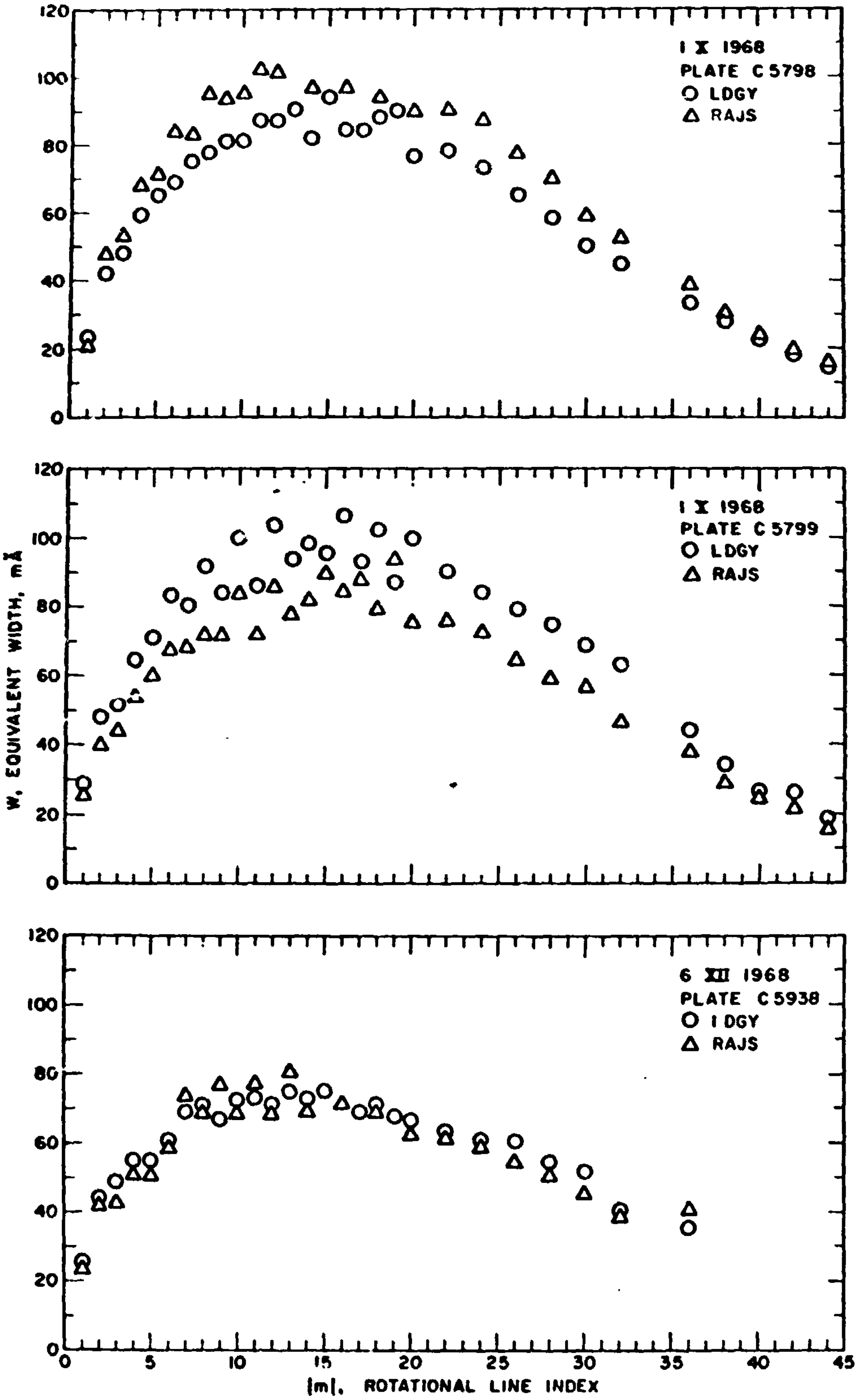

1 X 1968
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O LDGY
Δ RAJS
1 X 1968
PLATE C 5799
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PLATE C 5938
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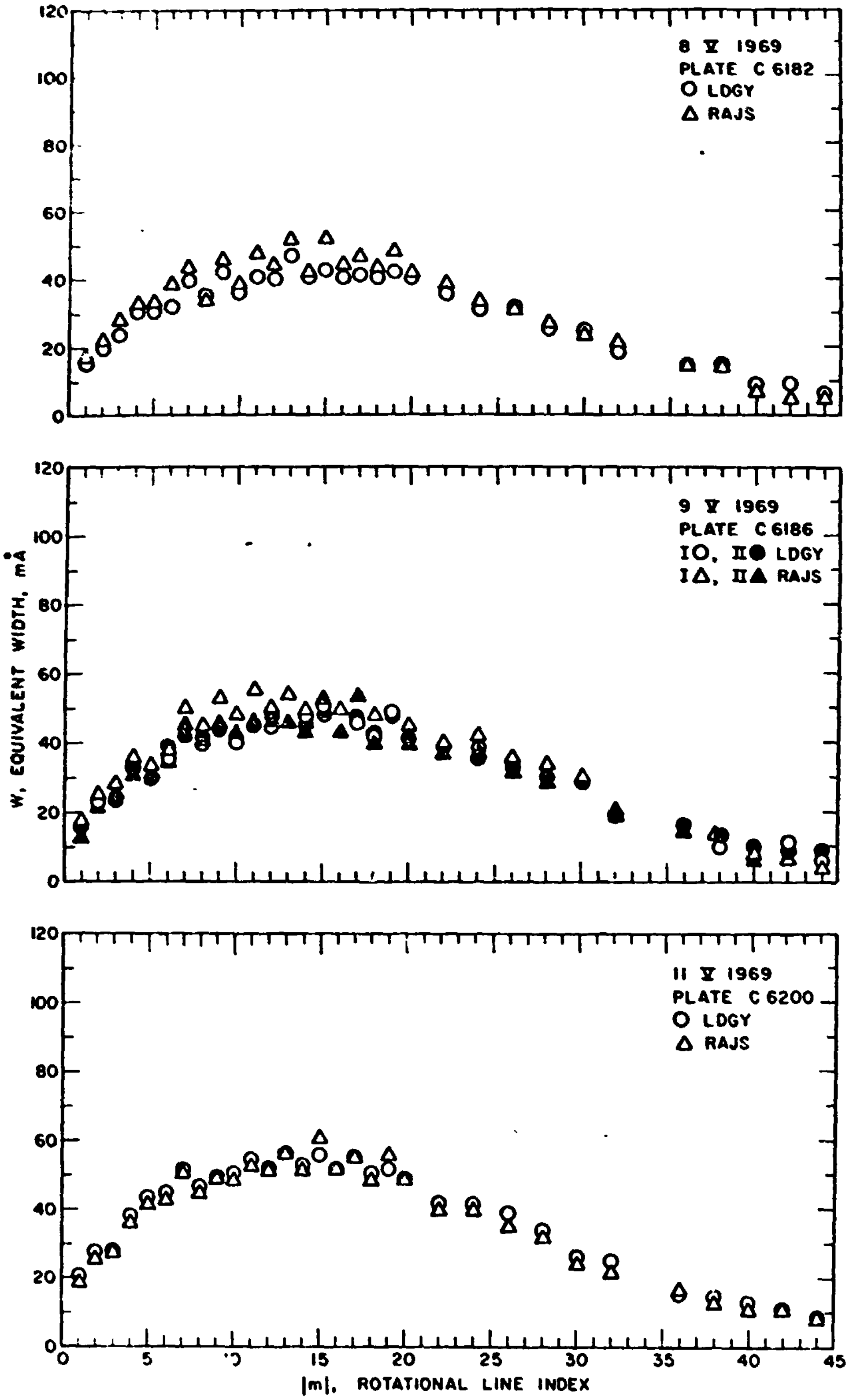
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PLATE C 6182
○ LDGY
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9 V 1969
PLATE C 6186
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I△, II▲ RAJS
11 V 1969
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△ RAJS
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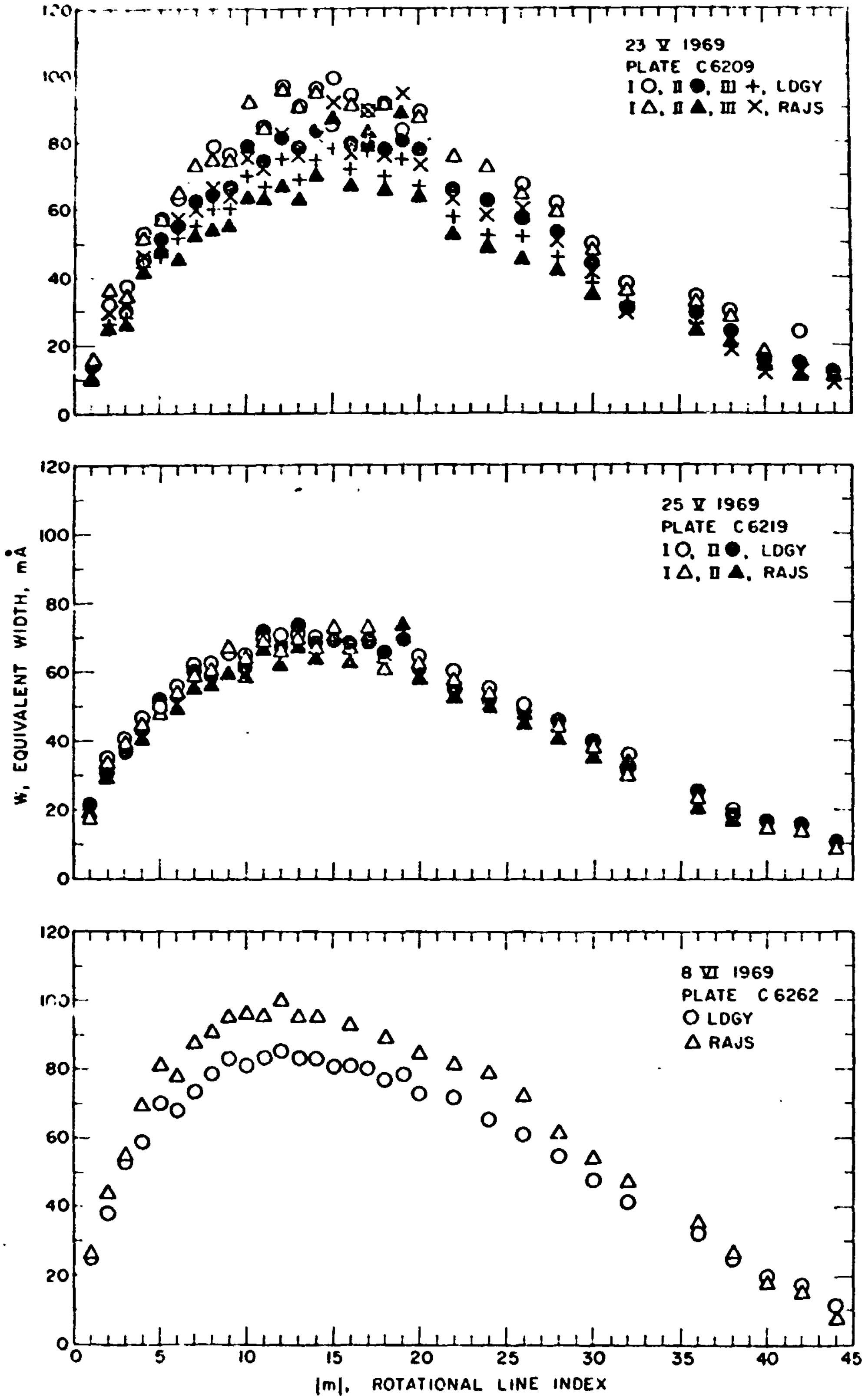
|m|, ROTATIONAL LINE INDEX



120
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PLATE C6209
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I ○, II ●, LDGY
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W, EQUIVALENT WIDTH, mÅ
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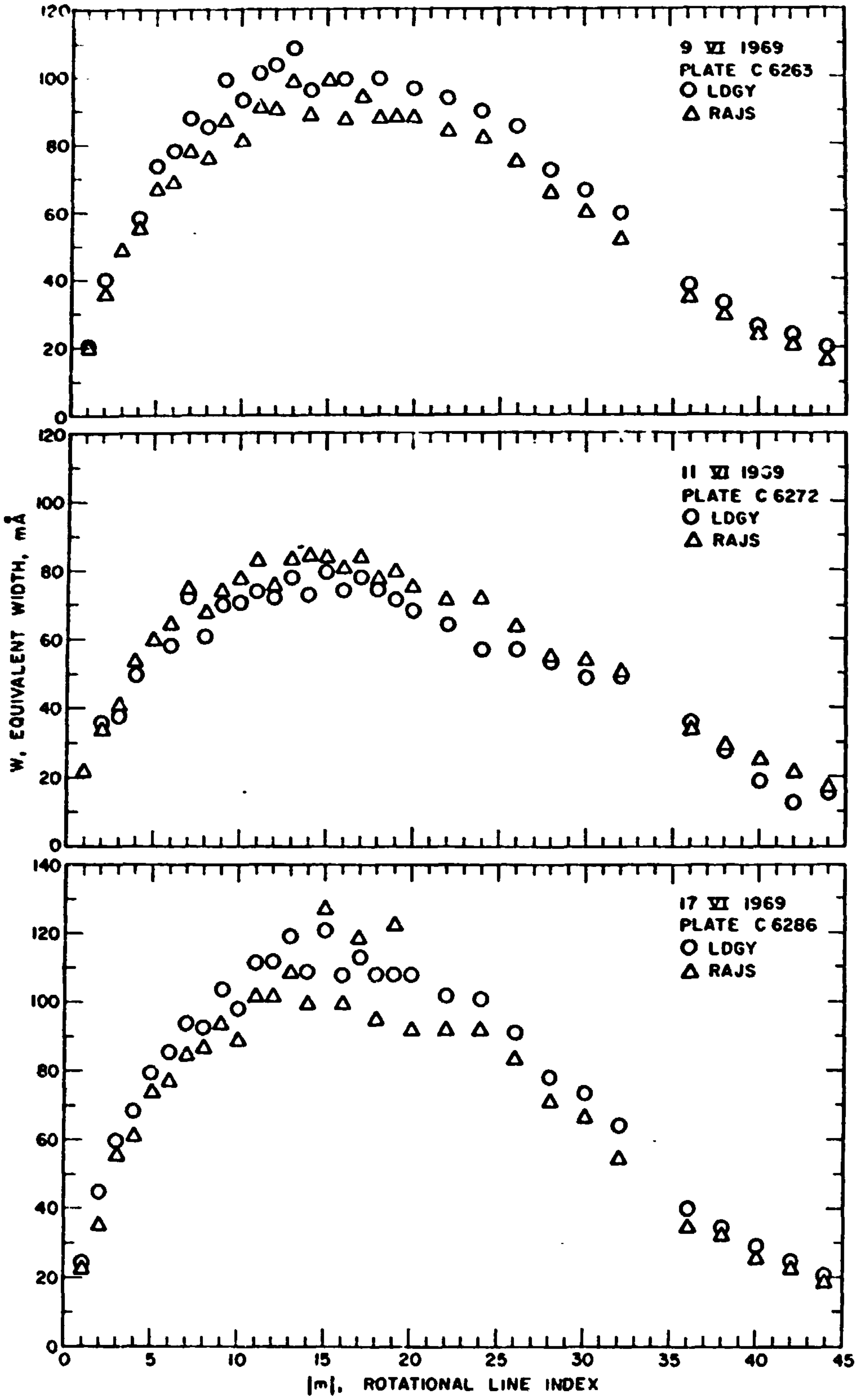
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PLATE C 6272
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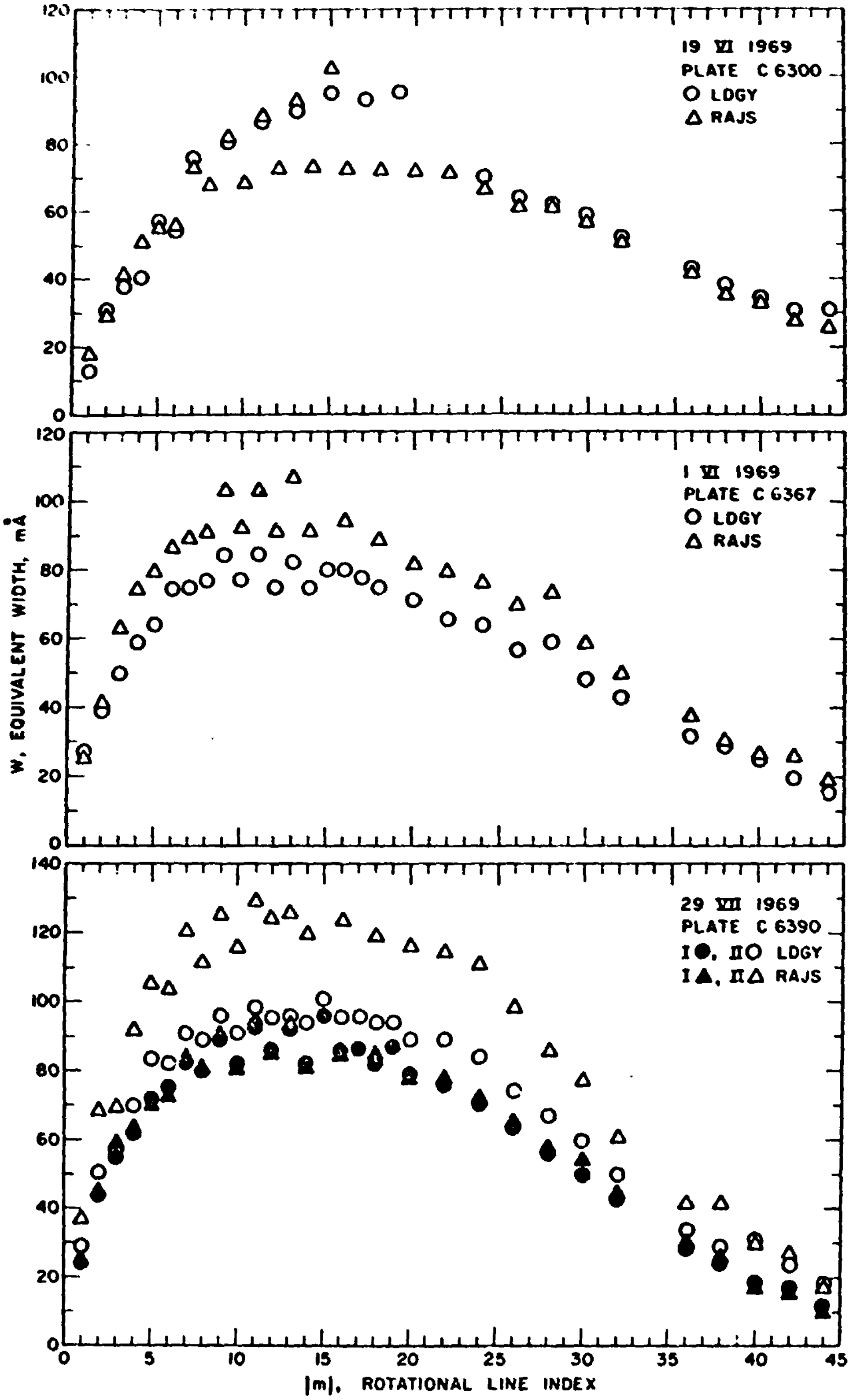
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△ RAJS
1 VI 1969
PLATE C 6367
○ LDGY
△ RAJS
29 VII 1969
PLATE C 6390
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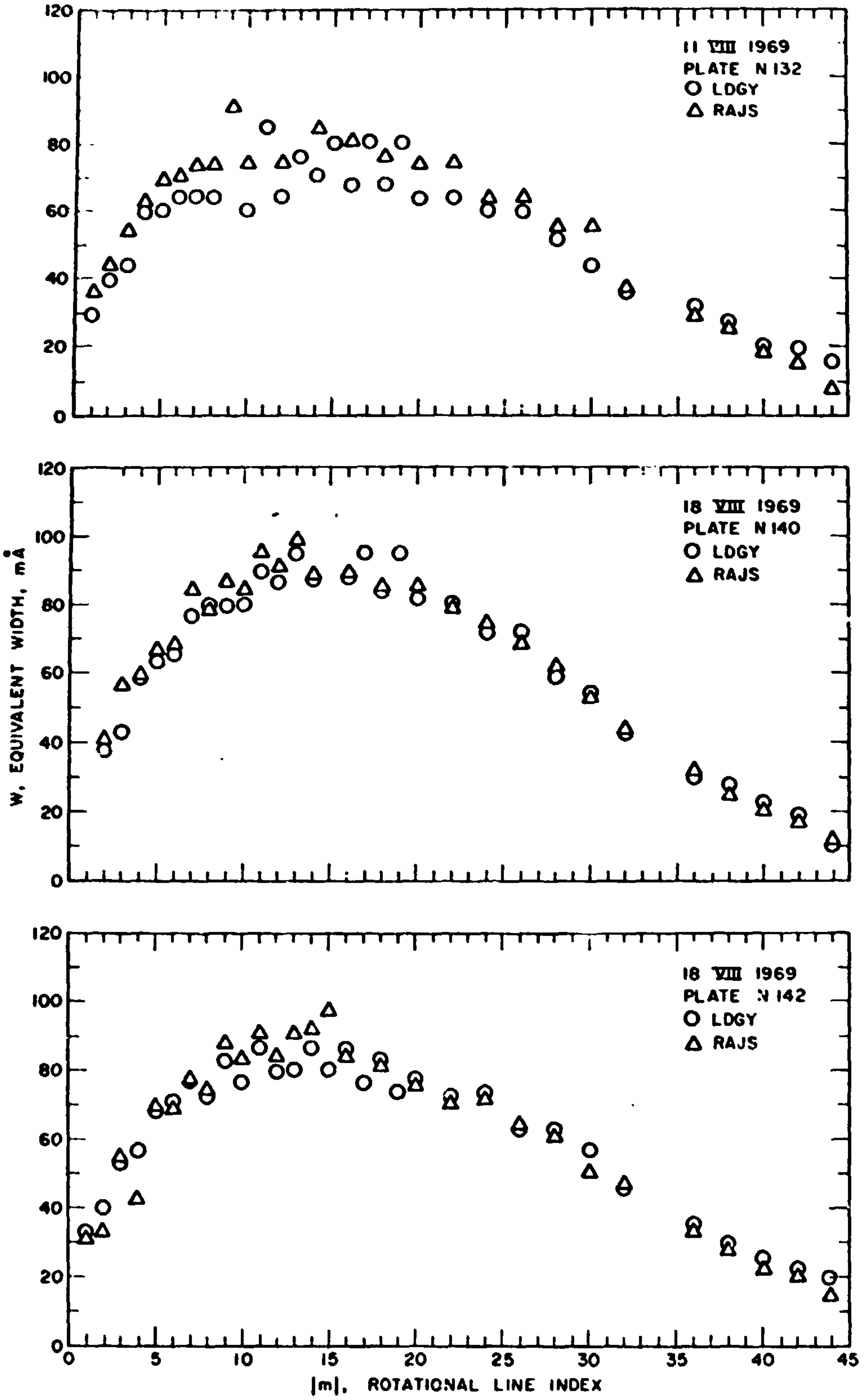
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PLATE N 140
O LDGY
Δ RAJS
18 VIII 1969
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W, EQUIVALENT WIDTH, mÅ
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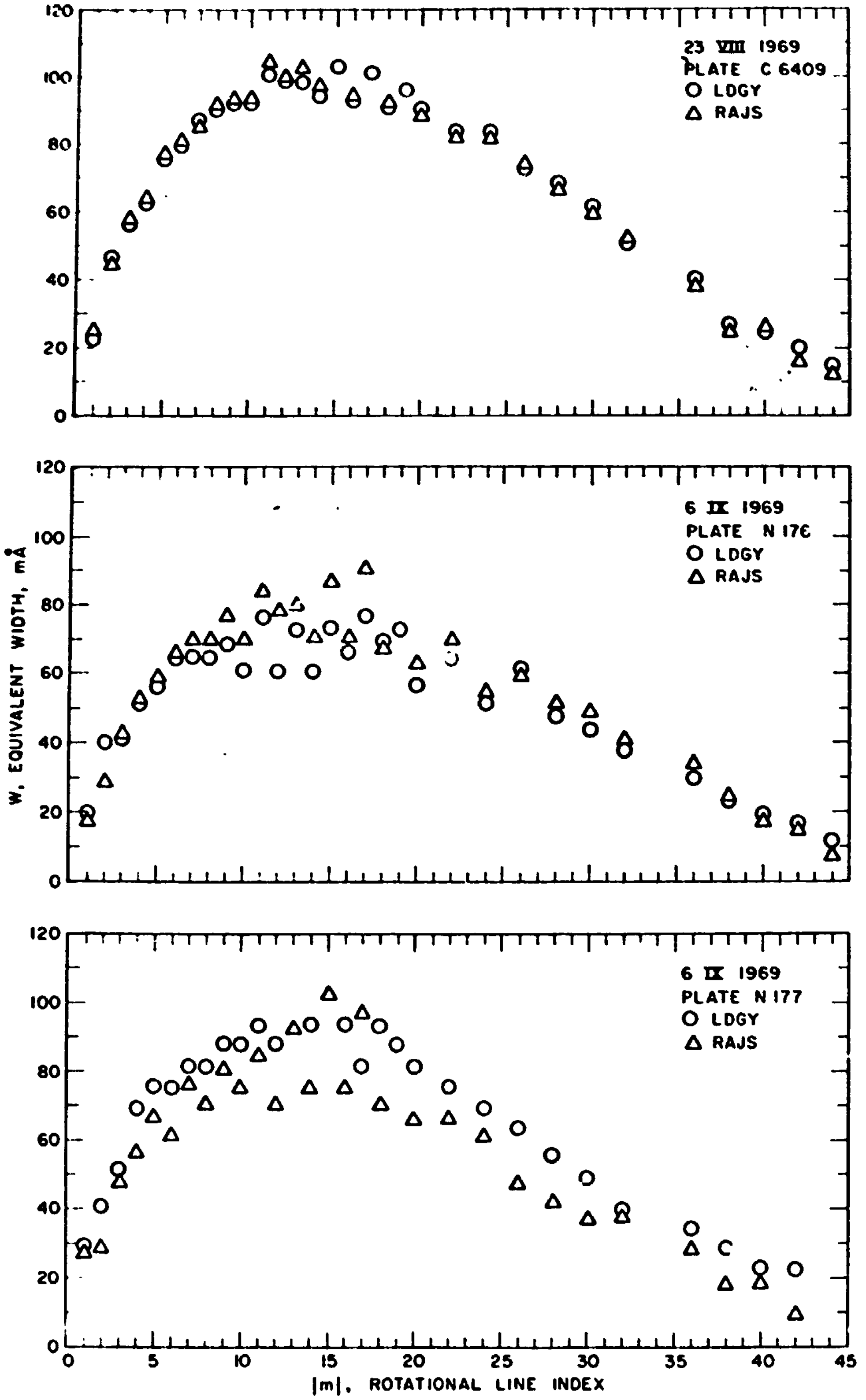
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Δ RAJS
6 IX 1969
PLATE N 176
O LDGY
Δ RAJS
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PLATE N 177
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Δ RAJS
W, EQUIVALENT WIDTH, mÅ
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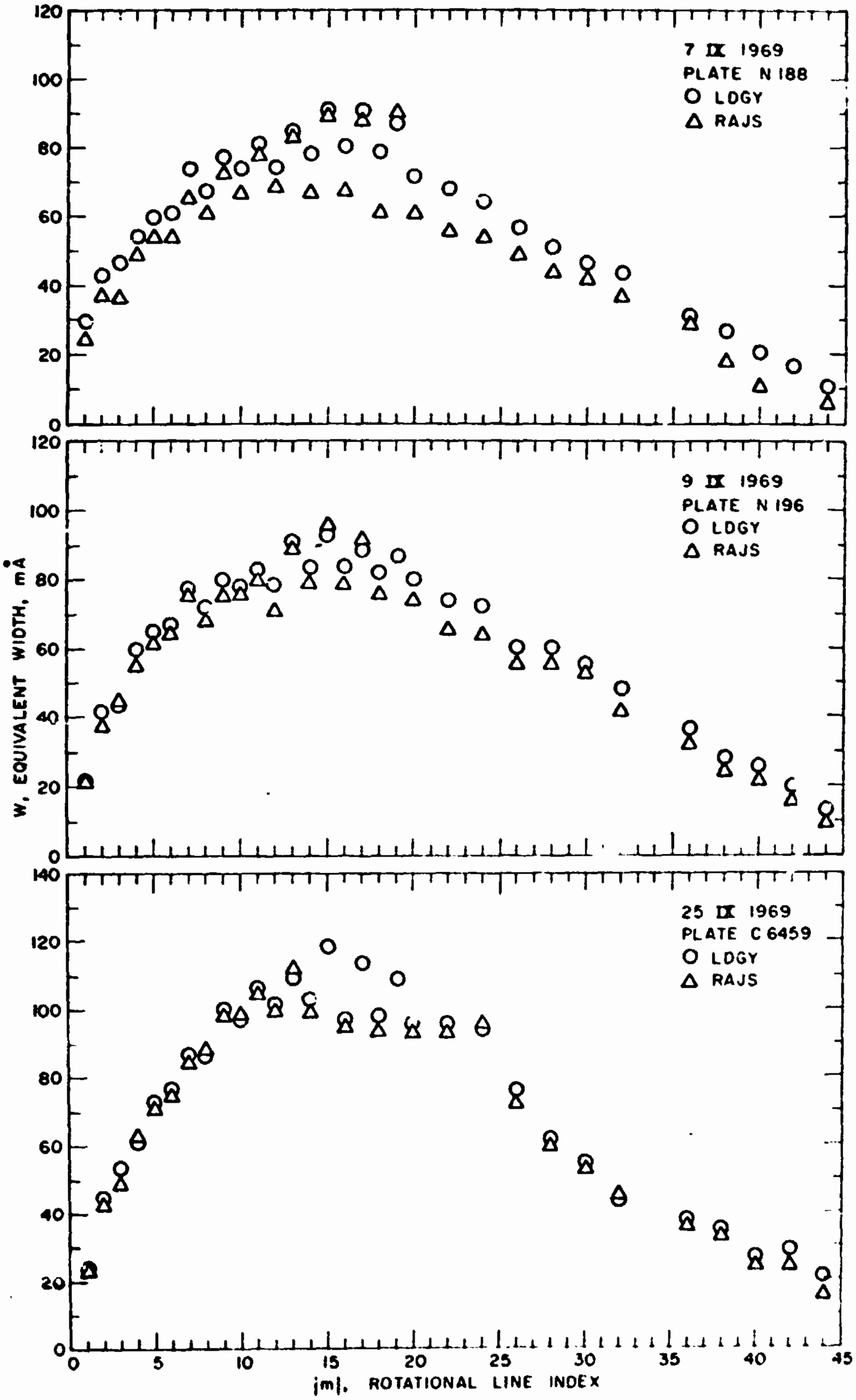
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Δ RAJS
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PLATE N 196
O LDGY
Δ RAJS
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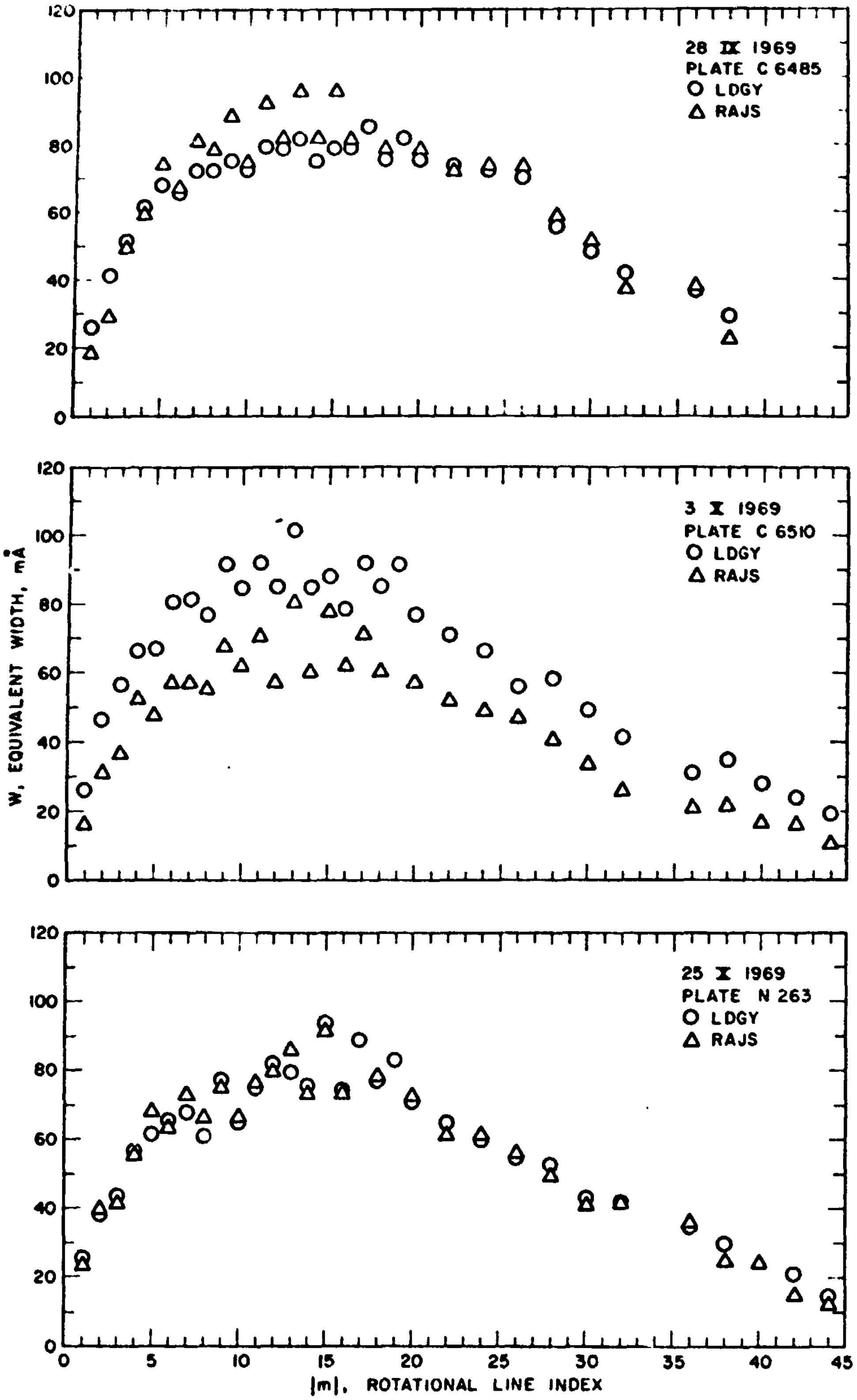
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△ RAJS
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W, EQUIVALENT WIDTH, mÅ
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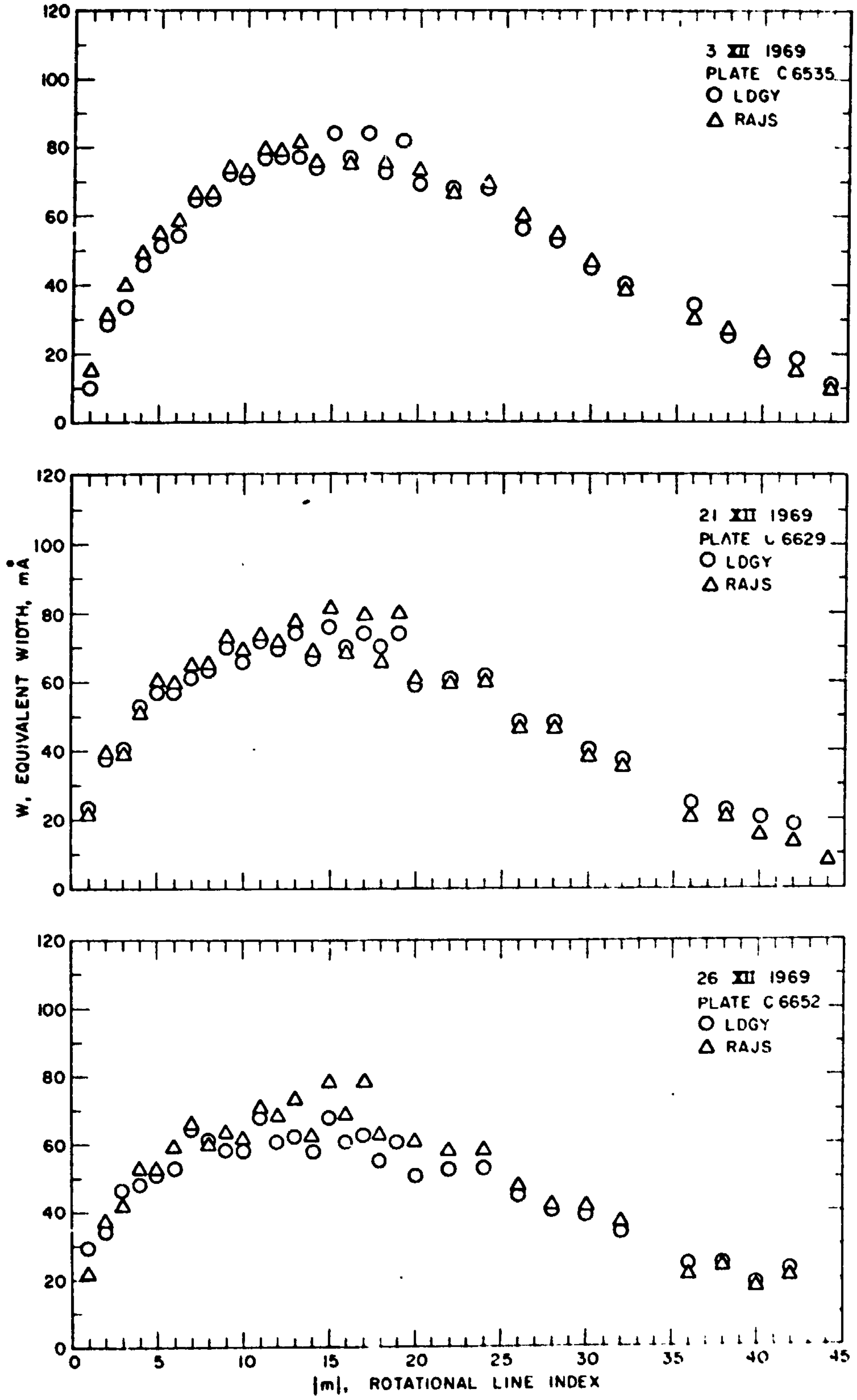
|m|, ROTATIONAL LINE INDEX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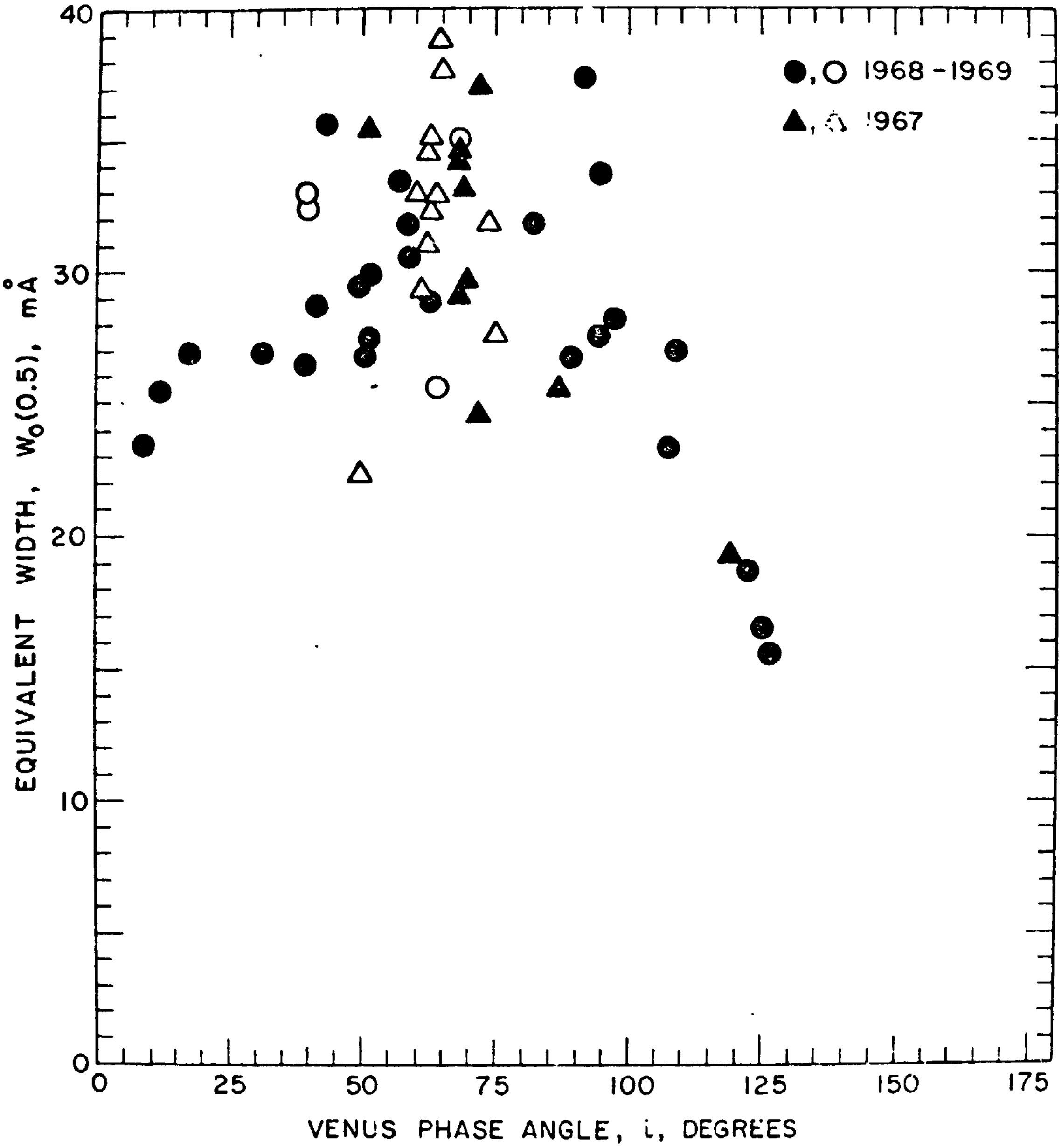
45
|m|, ROTATIONAL LINE INDEX


●, ○ 1968-1969
▲, △ 1967
40
30
20
10
0
EQUIVALENT WIDTH, $W_0(0.5)$, mÅ
0
25
50
75
100
125
150
175
VENUS PHASE ANGLE, i, DEGREES