CALIBRATION OF STANDARD STARS USING

A VIDICON SPECTROMETER

by

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Abstract

Precision studies of planetary reflectivities
require the calibration of the energy distribution of standards of spectral class similar to the sun. Present standards, however, are of spectral class A or earlier. A
first attempt has been made to calibrate a new set of standards relative to Alpha Lyrae using a vidicon spectrometer
system. This system offers a number of advantages over previous photometer systems, particularly for planetary work.

Spectra were obtained from a number of stars, including
previously calibrated standards. A comparison of these measurements with previous results for these standards gives
fair agreement over only limited wavelengths. The desired
accuracy of a few per cent error has not been achieved;
however, the results of these observations indicate that in
the future accurate measurements can be made at least for
the region $.4-.7\mu$. To obtain reliable calibrations in the
near infrared, however, requires the use of a new spectrometer with a more linear dispersion function than the present one has.

ACKNOWLEDGEMENTS

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I. Introduction

The absolute calibration of the energy distributions of a sequence of standard stars spaced throughout the sky has a wide number of uses in spectrophotometry. In particular, for reflectivity studies of objects in the solar system it is desirable to know the energy distribution of a star relative to the sun. Measurements of an object and a standard star can be made and the relative reflectivity can be derived. (1).

The establishment of a sequence of standard stars involves two tasks: 1) absolute calibration of one or more primary standards; 2) comparison of secondary standards with the primary standard. An absolute calibration of α Lyra to 2% accuracy has recently been done by Oke and Schild (8) and Hayes (4). Secondary standards have been observed by Oke (7), Hayes (4), and Oke, Schild, and Peterson (9). Unfortunately, these stars are all spectral class A or earlier, and thus poor standards for the infrared region, which is of great interest for planetary work. Therefore, the need exists for the calibration of new standards of spectral class similar to the sun (2).

This thesis is the report on the first attempt at calibrating such standards. The instrument used was a vidicon spectrometer, and observations were make at MIT's Wallace observatory using the 24 inch telescope. As this system had never been accurately tested before, the observations were

concentrated on measuring previous standard stars to demonstrate the ability of the system. The vidicon spectrometer has a number of advantages over photometer systems previously used, including simultaneous measurement of an entire spectrum, fairly wide wavelength response, excellent linearity, and (important for planetary work) good spatial resolution. The following sections cover a brief discussion of the system, a description of the observations that were made, and the method of data reduction. Results are given for two stars and a comparison with previous observations. Finally, a discussion of the problems with the system and suggestions for improvement are given.

II. System function and operation

The vidicon imaging system has been described previously
(5,6) and only the relavent aspects are discussed here. The
data processing system used was the Mark III. The face of
the vidicon tube is divided into 250 rows by 256 columns. As
spectra are oriented horizontally on the tube, there exists a
maximum possible resolution of 256 elements, although in prac-
tice a spectrum covers fewer elements. In typical operation,
the tube is first erased by exposing it to saturation and
then scanning it sixteen times. An exposure is then make, and
upon completion the image is scanned and stored on magnetic
tape.

The spectral response curve for the vidicon is given in
Figure 1. The useable range is seen to be about .38 to 1.1μ.

A diagram of the vidicon spectrometer system is given in
Figure 2. A detailed diagram of the spectrometer is given in
Figure 3. Light from the telescope is focused on a silvered
mirror with a slit. Light not passing through the slit is
reflected out the side of the spectrometer for visual guiding
and photographing. After passing through the slit the light
is reflected off a circular mirror, passed through a prism,
reflected off the circular mirror again, and finally reflect-
ed off a flat and onto the vidicon face. Adjustments are
used to position the spectrum on the vidicon and to focus the
image. A neon-argon calibration lamp is used to provide a
reference spectrum, with lines visible in the blue and red
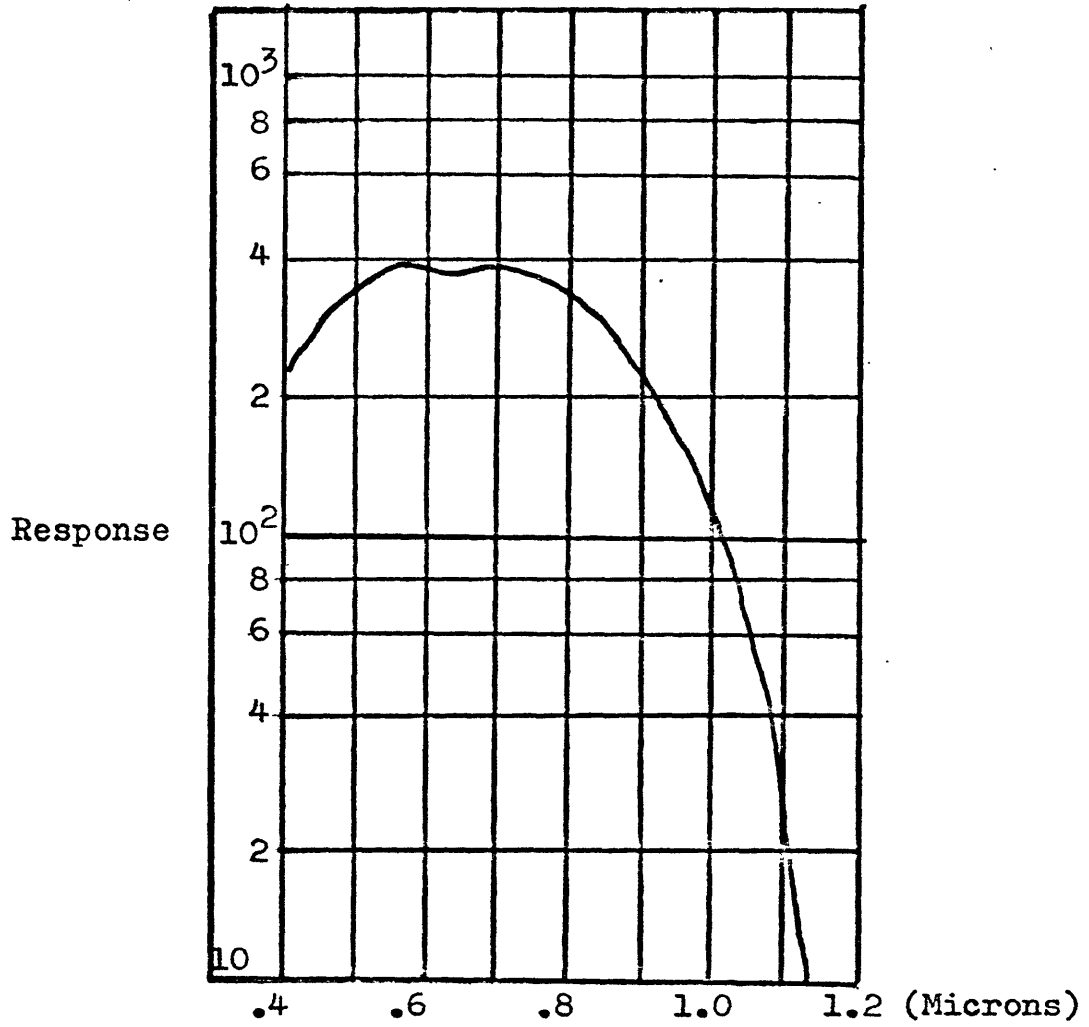
FIGURE 1: Vidicon response function

SPECTROMETER

TELESCOPE

SHUTTER

DIODE ARRAY

X

Y

FOCUS

GRID

CATHODE

6.3V

POWER SUPPLY

A/D

FORMATTER
converts to
tape format
2-12 bit words
→3-8 bit words

TAPE

SCAN
GENERATOR

SCAN
CONVERTER

SHUTTER
CONTROLLER

MONITOR
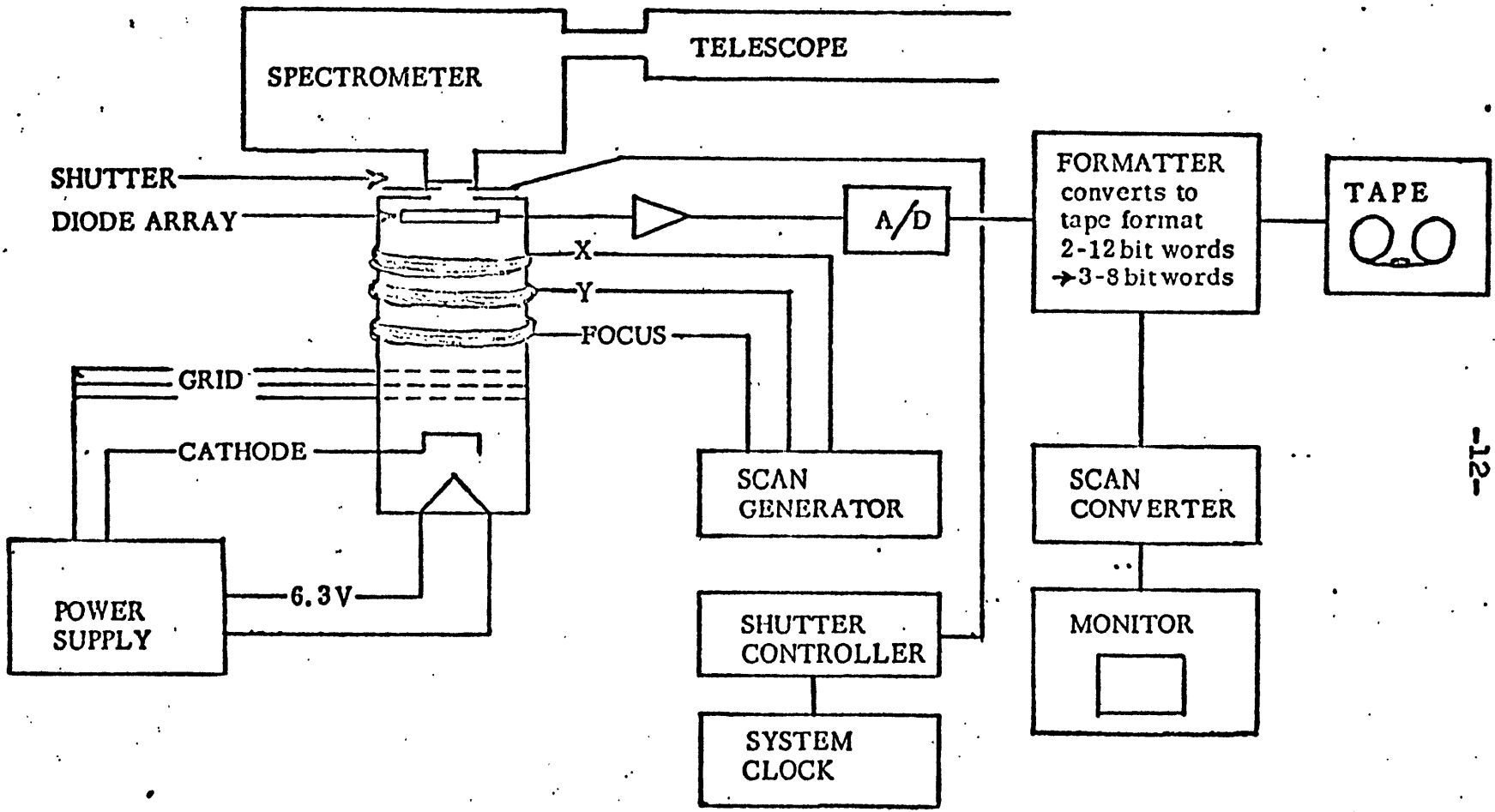
SYSTEM
CLOCK

FIGURE 2: SYSTEM SETUP

FIGURE 3: Spectrometer Schematic

CAMERA

image is
in focus
here

TELESCOPE

BAFFLES

SPHERICAL
MIRROR

LOW
DISPERSION
PRISM

BAFFLES

VIDICON

image is
in focus
here

-13-
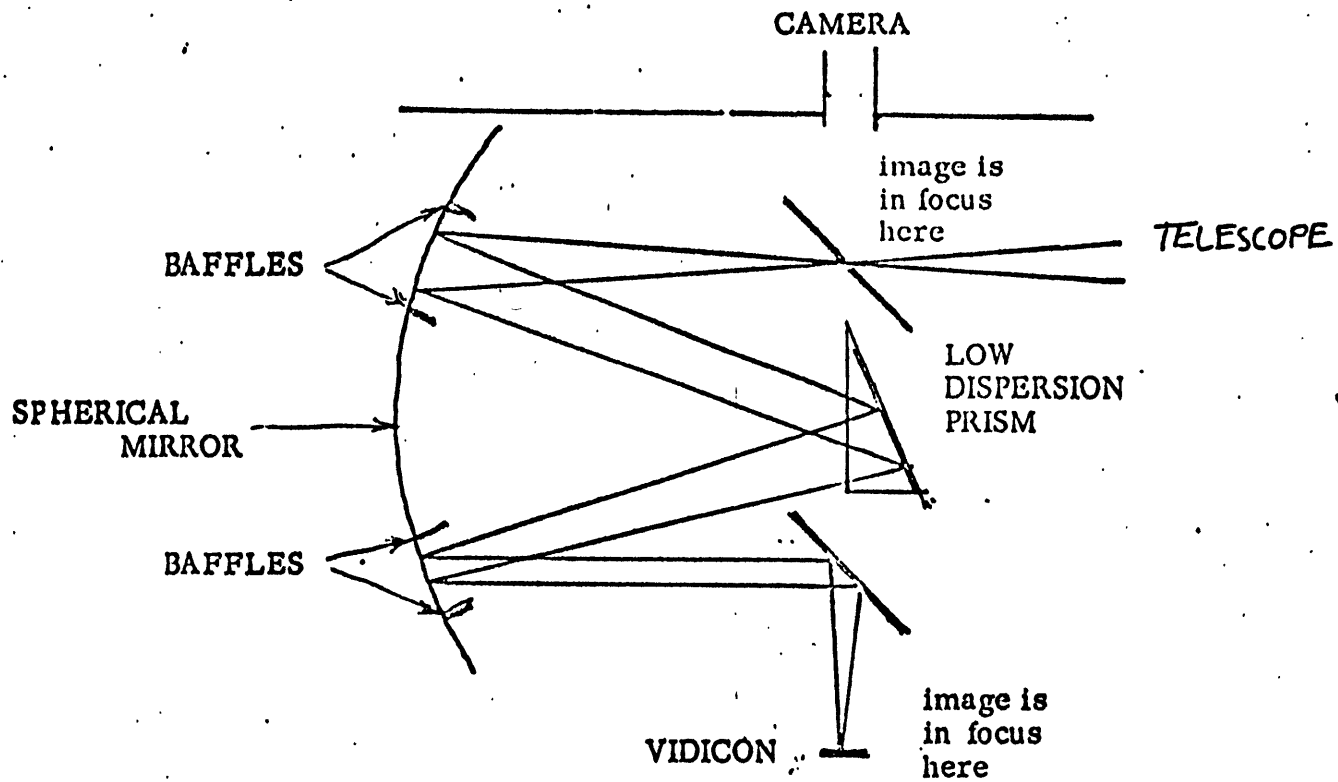
parts of the spectrum. The slit width used is 100μ , giving an intrinsic resolution on the vidicon face of about 2 elements.

The spectrum produced by the instrument is not at constant dispersion, but is highly skewed, with high dispersion in the blue but low dispersion in the red. In order to obtain the complete spectrum of an object one must usually make several exposures to bring out the various parts of the spectrum. Thus the non-linear dispersion function combined with the large variations in spectral response of the vidicon make it difficult to obtain spectra with uniform accuracy.

III. Observations

The vidicon spectrometer was used at Wallace Observatory for two usable nights of observations. The stars observed included a number of previous standard stars as well as others that were of interest as possible candidates for new standard stars. The stars were selected with a variety of spectral types and magnitudes. Table I lists the stars observed the first night and table II the stars observed the second night. On both nights all stars were observed near meridian crossing. In addition, α Lyra and α Boo were observed at a number of different air masses in an attempt to determine atmospheric absorption corrections. Seeing conditions were unfortunately not ideal, being about 10" the first night and about 4" the second.

In general several exposures of a star were made at a number of different exposure times. Calibration spectra were taken periodically, usually after the vidicon dewar was iced. Icing was done about once every 2 hours.

It was found that due to erratic seeing which led to difficulty in tracking the star on the slit, the intensity of a spectrum was only roughly proportional to the exposure time; thus any absolute measurement of spectral intensity was impossible. In addition, in an attempt to record the fainter parts of a spectrum long exposures were sometimes made. However, it has been found that when too much of an image is saturated, it becomes difficult to relate the intensities of

TABLE I

Stars observed first night

Name	Magnitude	Spectral Class
δ Leo	2.6	A4
α Boo	0.2	KO
β Boo	3.6	G5
η Boo	2.8	GO
γ Lib	3.9	G8
α Lyr	0.0	AO

TABLE II

Stars observed second night

Name	Magnitude	Spectral Class
α Boo	0.2	KO
α Leo	1.3	B8
109 Vir	3.7	AO
ζ Oph	2.6	O9
α Lyr	0.0	AO

the weaker parts to the intensities of the stronger parts.
Thus very long exposures were found to be useless in bring-
ing out the weak parts of a spectrum.

After the first night of observations it was apparent
that only stars of magnitude 4 or brighter could be observed
with reasonable exposure times (e.g. about 20 minutes for 4th
magnitude). Thus on the second night only bright stars were
observed. In the future the choices for standard stars will
be restricted by the need for bright standards.

Observations from the second night were marred by the
presence of noise spikes in the images caused by an unknown
source. These spikes could be removed in most cases in the
subsequent computer processing, but not always. In addition,
a new vidicon tube was being used which was not properly ad-
justed; an excessively high background was introduced into
the data, reducing the dynamic range of the tube.

A standard part of processing vidicon images is to ob-
tain dark field and flat field exposures, a dark field being
a read-out of the tube with no image, and a flat field being
an exposure of a uniform illumination. By subtracting the
dark field from an image and dividing by the flat field it is
expected to be possible to remove a constant background inten-
sity (dark current) and correct for variations in the sensi-
tivity of the individual vidicon elements. For the star spec-
tra it was found that a satisfactory dark field could be ob-
tained by using an average intensity of elements far away from
the spectrum image; in such a manner it was also possible to

remove any sky background present. These synthesized dark fields proved to be more suitable than separate dark field images. More difficult, however, was the problem of flat fields. With the present system it is impossible to make flat field exposures; the best that can be done is to obtain the spectrum of a flat field object. In fact, no flat fields of any sort were obtained. Thus a potentially serious source of error could not be removed from the data. To minimize this error, spectra were positioned on the vidicon face in as nearly the same spot as possible.

IV. Data reduction

Each image was recorded on magnetic tape as 250 rows by 256 columns with the spatial direction direction (direction of the slit) being aligned vertically and wavelength horizontally (thus 1 column has 250 spatial elements at one wavelength.) Intensities in the Mark III system range from 0 to 4095 (saturation). The data was initially processed by the Digital Image Processing System (DIPSYS) and the section of each image containing the star spectrum and surrounding elements was passed to a second program written to reduce spectrometer data. This program performs 5 stages of processing: 1) obtains dispersion functions from calibration spectra; 2) averages the star spectra spatially to obtain an integrated intensity at each wavelength; 3) averages each star spectrum in wavelength according to an associated dispersion function to yield intensities per unit wavelength with constant resolution across the spectrum; 4) averages all the spectra for each star together to obtain an overall spectrum; also solves for atmospheric corrections if desired; 5) computes ratios to a reference star spectrum. The details are as follows:

1) Calibration spectrum. The dispersion function for the spectrum is given approximately by

$$\lambda_s = \lambda_0 + C/(S + S_0)$$

where λ_s =wavelength of element S (S=1 to 256) and λ_0, C and S_0 are constants. These constants are determined by measuring the values for S of several lines of the calibration

source and adjusting the constants by a least squares fit.

Determining the wavelengths of the lines in the calibration source proved to be a problem. The source produces a number of lines in the blue and red, all from argon. A spectrum was made in the laboratory which provided the wavelengths of all lines to an accuracy of 20 Å; however, better accuracy was desired. The lines in the red were identified in wavelength tables for argon; however, argon produces numerous lines in the blue, and those that were being seen could not be identified. The problem was partially resolved when spectra of α Lyra were obtained. These spectra contained numerous absorption lines of hydrogen which could be identified. These lines were used to calibrate the associated dispersion functions, and from these the wavelengths of the lines of the calibration source could be determined. The adopted wavelengths are given in table III.

2) Star spectra. The spatial distribution of starlight as recorded by the vidicon is a complicated function of a number of factors, such as the focusing of the telescope, the optics of the telescope and spectrometer, and seeing conditions. One would expect the convolution of all these effects to lead to a spatial distribution of intensity that was approximately Gaussian. This hypothesis was tested by fitting Gaussians to a selection of columns of data from a number of spectra (each column would correspond to the spatial distribution at one wavelength). The function fitted was

$$I_x = B + Q e^{-\left(\frac{X-X_0}{\sigma}\right)^2}$$

TABLE III

Calibration Spectrum

| Wavelength	Relative intensity (approx.)
3370	4095
3539	1400
3566	3500
3745	1200
3789	1900
3973	670
4028	890
6965	450
7504	1600
8115	1150
8420	920

where I_x is the intensity at element X, X_o is the element of maximum intensity, Q is the amplitude of the Gaussian, σ the width, and B is a constant offset to account for dark current and sky background. In a number of cases, the Gaussian provided an excellent fit. Figure 4 shows some of these cases, with the observed and theoretical profiles superimposed. In other cases, however, the fit was much poorer; in such cases the peak of a profile tended to be flatter than a Gaussian. Therefore, a second procedure was adopted to get the intensity. The elements far from the peak of a profile were averaged together (usually 20 elements) to get an average background intensity; this number was subtracted from the intensity of each element of the profile, and the resulting numbers were simply added together to get the total integrated intensity.

3) The intrinsic resolution per element of the dispersion function ranged from about 10 Å at .35 μ to about 200 Å at 1.1 μ. Thus at a constant resolution of 50 Å (the resolution of previous standard star calibrations) several elements would be averaged in the blue while individual elements would be selected in the red for further processing. This non-uniformity in averaging lead to several problems as is discussed below.

4) In order to average together all the spectra for a particular star it was necessary to normalize each spectrum to unity at a particular wavelength. Air mass corrections were
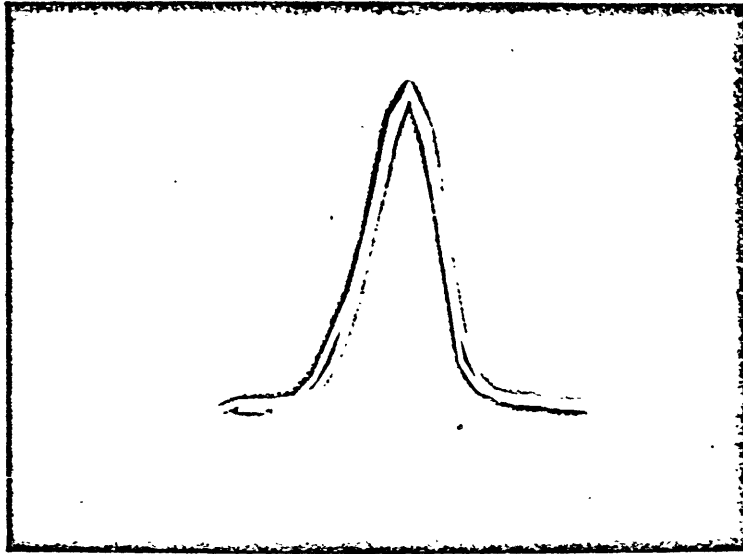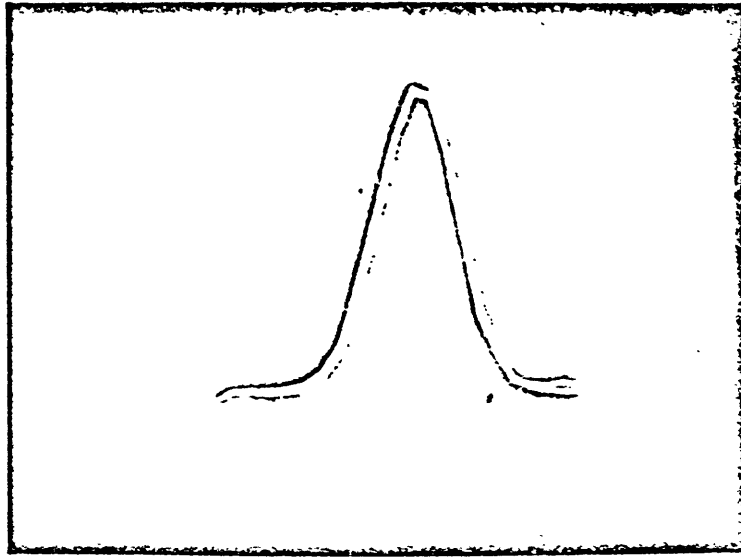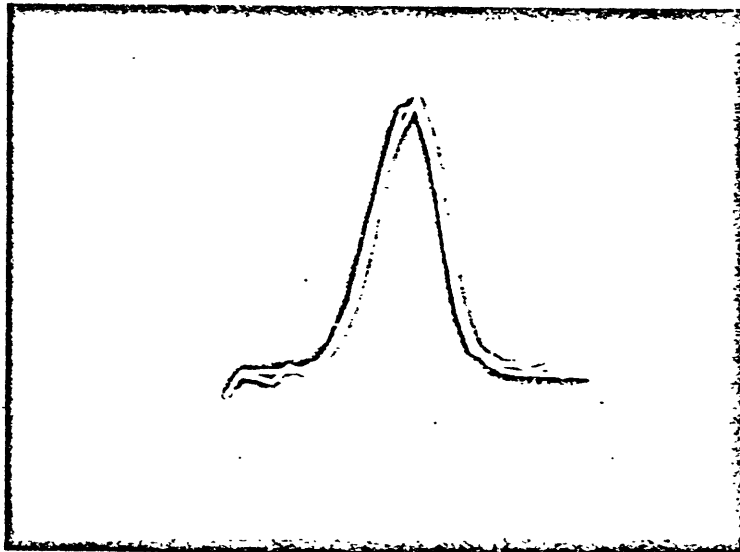
∝ Boo 1 Min. Exposure
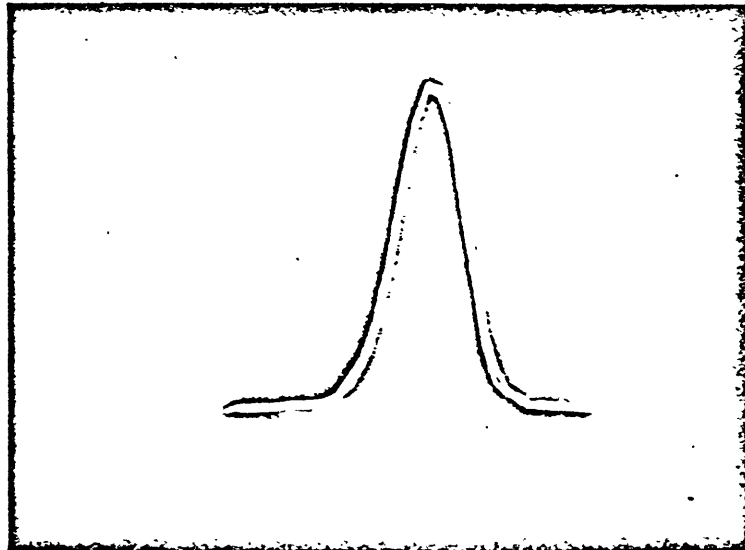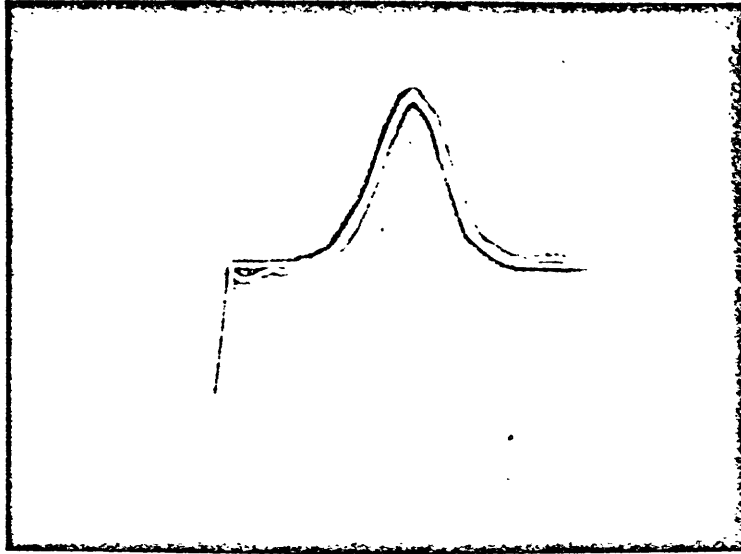

∝ Lyr 2 Min.

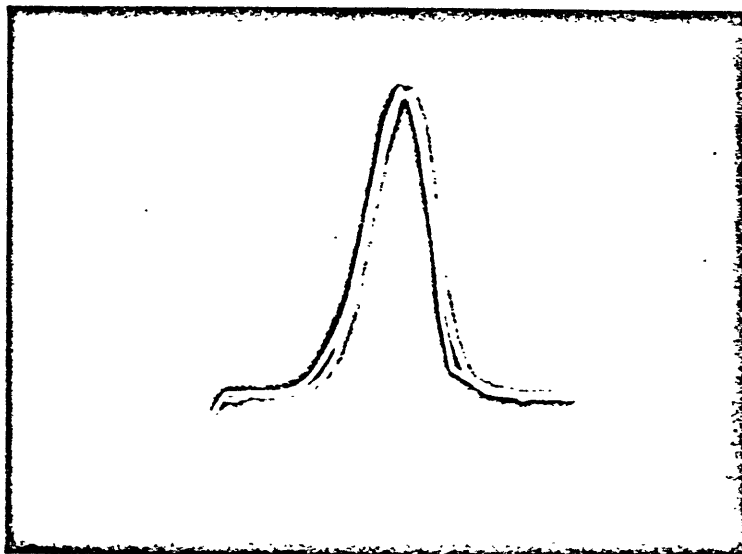FIGURE 4: GAUSSIAN FITS Part 1

α Lyr .5 Min.

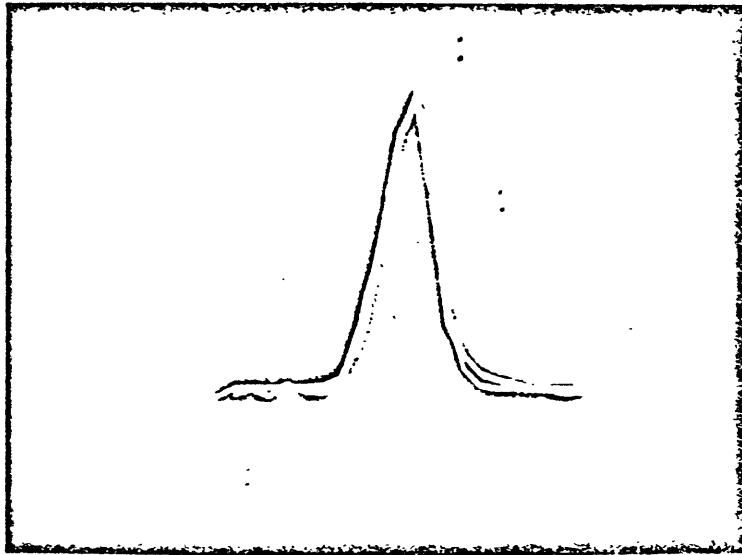
β Boo 5 Min.

FIGURE 4: Part 2

δ Leo 6 Min.

η Boo 10 Min.

FIGURE 4: Part 3

α Boo 7 Sec.

FIGURE 4: Part 4

assumed to be of the form $e^{-k_\lambda M}$ where k_λ is a wavelength-dependent coefficient and M is the air mass. Thus the measured intensity was modelled as

$$I_\lambda^N = I_\lambda^O \, e^{-(k_\lambda - k_\lambda^O)M}$$

where I_λ^N is the normalized measured intensity, I_λ^O is the intrinsic normalized intensity, and k_λ^O is the atmospheric coefficient at the wavelength of normalization. The program allows 3 choices in averaging the spectra: a) solution for I_λ^O and $(k_\lambda - k_\lambda^O)$ at each wavelength; b) solution for I_λ^O without air mass corrections; c) solution for I_λ^O with a priori air mass corrections. The third option was the one used most often in practice since the data contained too much error in general to obtain reasonable air mass corrections. The values used were those obtained by Hayes (4) for Lick Observatory. Although these are certainly wrong for Wallace Observatory, the corrections are nevertheless small, especially in star ratio measurements, and are dominated by other errors in the data. In all cases fits were made by least squares. Parts of a spectrum that were saturated were deleted.

5) Star ratios were normally made to α Lyra, since this star is the primary standard. In some cases, however, a star was ratioed to itself in order to make consistency tests of the vidicon-spectrometer system.

V. Results

The data from the first night proved to be relatively useless for several reasons: a) the moon was up and provided a large amount of background; b) previous standard stars other than α Lyra were not observed, and thus no comparison with known results could be made; c) too few observations of each star were made.

On the second night the useful observations obtained included 2 sequences of spectra of α Lyra at air masses of 1.4 and 1.0 (12 spectra total) and 1 sequence each of 109 Vir (2 spectra total) and ζ Oph (3 spectra total). A sequence of observations means a number of spectra taken consecutively with various exposure times. All spectra included here were either close to saturation or saturated in parts. Other observations of α Leo and α Boo proved to be useless due to uncertainties in their reference calibration.

Figures 5 to 7 are sample individual spectra of α Lyra, 109 Vir, and ζ Oph respectively. These are spectra that have been averaged spatially but otherwise reflect the raw data. For comparison Figure 8 is a theoretical spectrum of α Lyra based on the model spectrum of (3) with approximately the same dispersion function, but without the vidicon response function included. Several important aspects should be noted in comparing the observed and theoretical α Lyra spectra. The non-linearity of the dispersion function is clearly apparent, with the blue part of the spectrum being
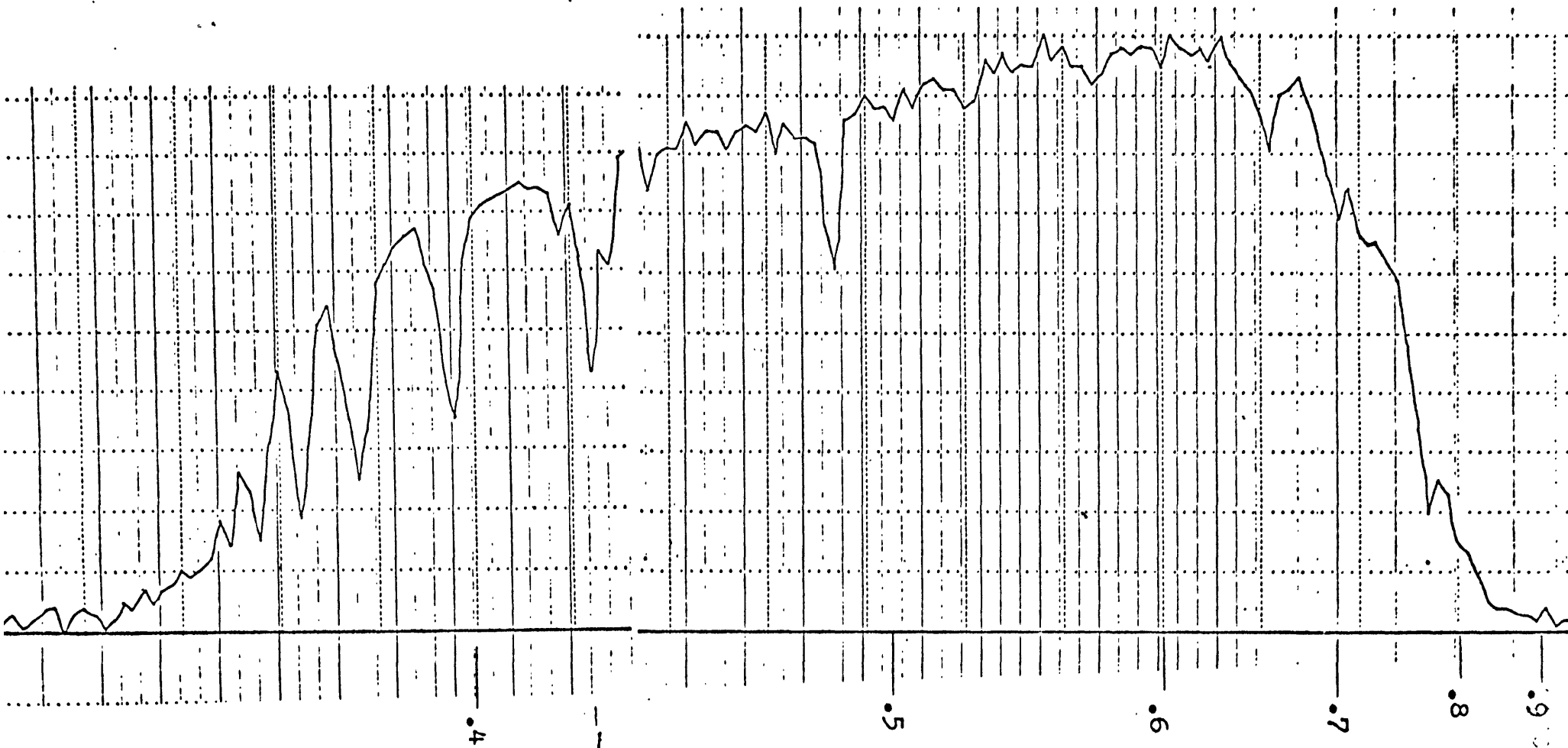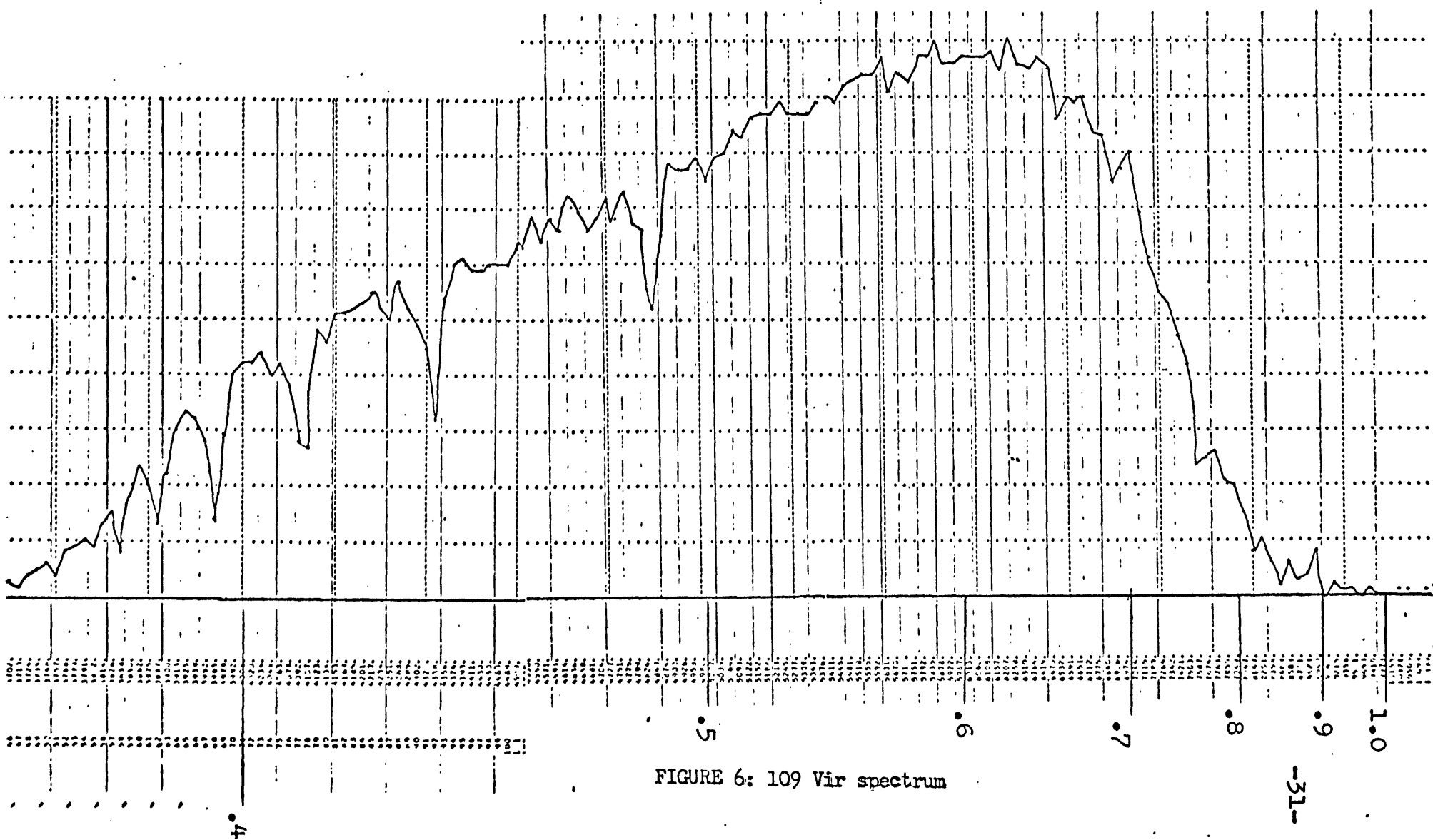
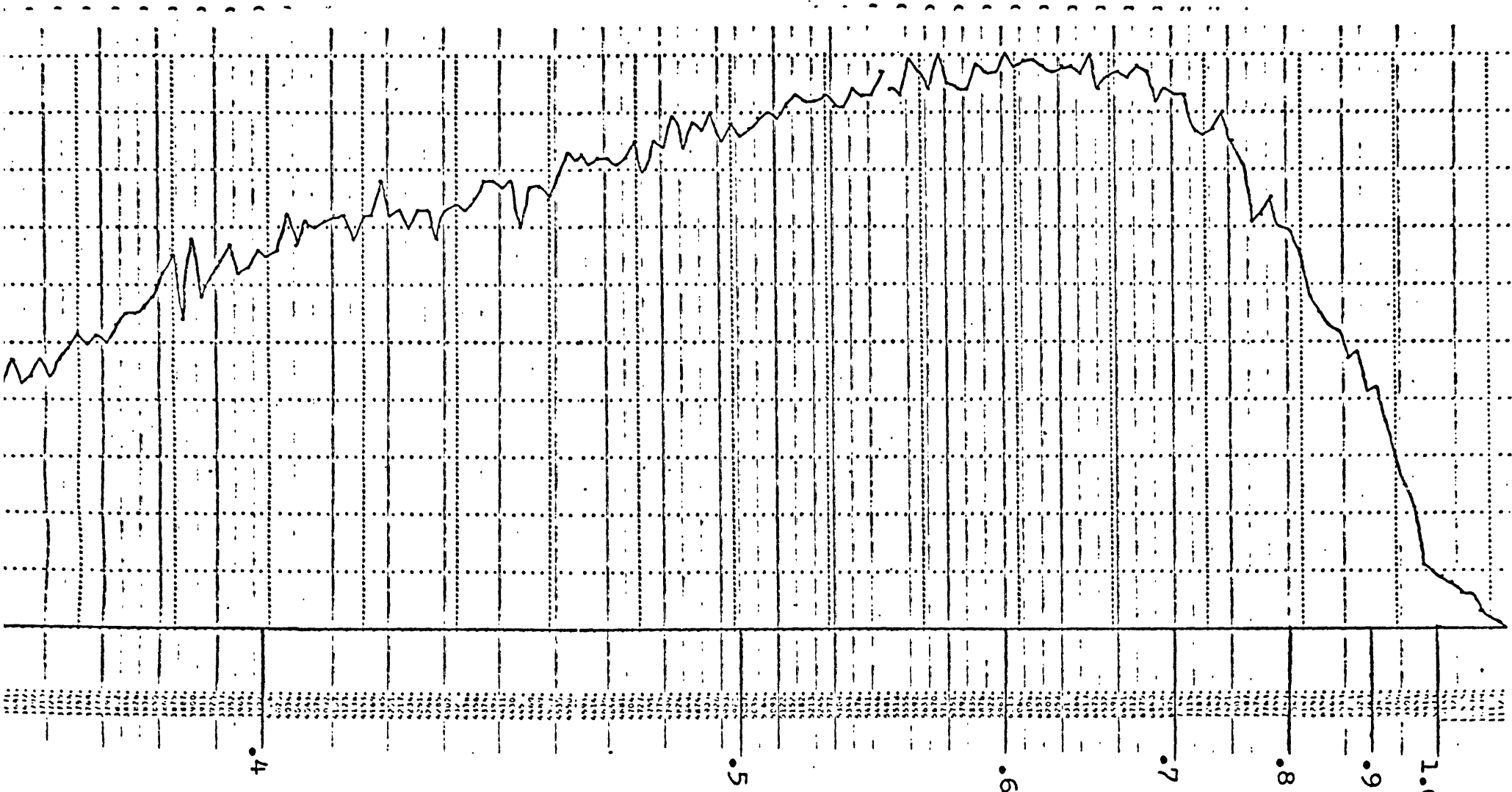FIGURE 5 : α Lyra Spectrum

FIGURE 6: 109 Vir spectrum
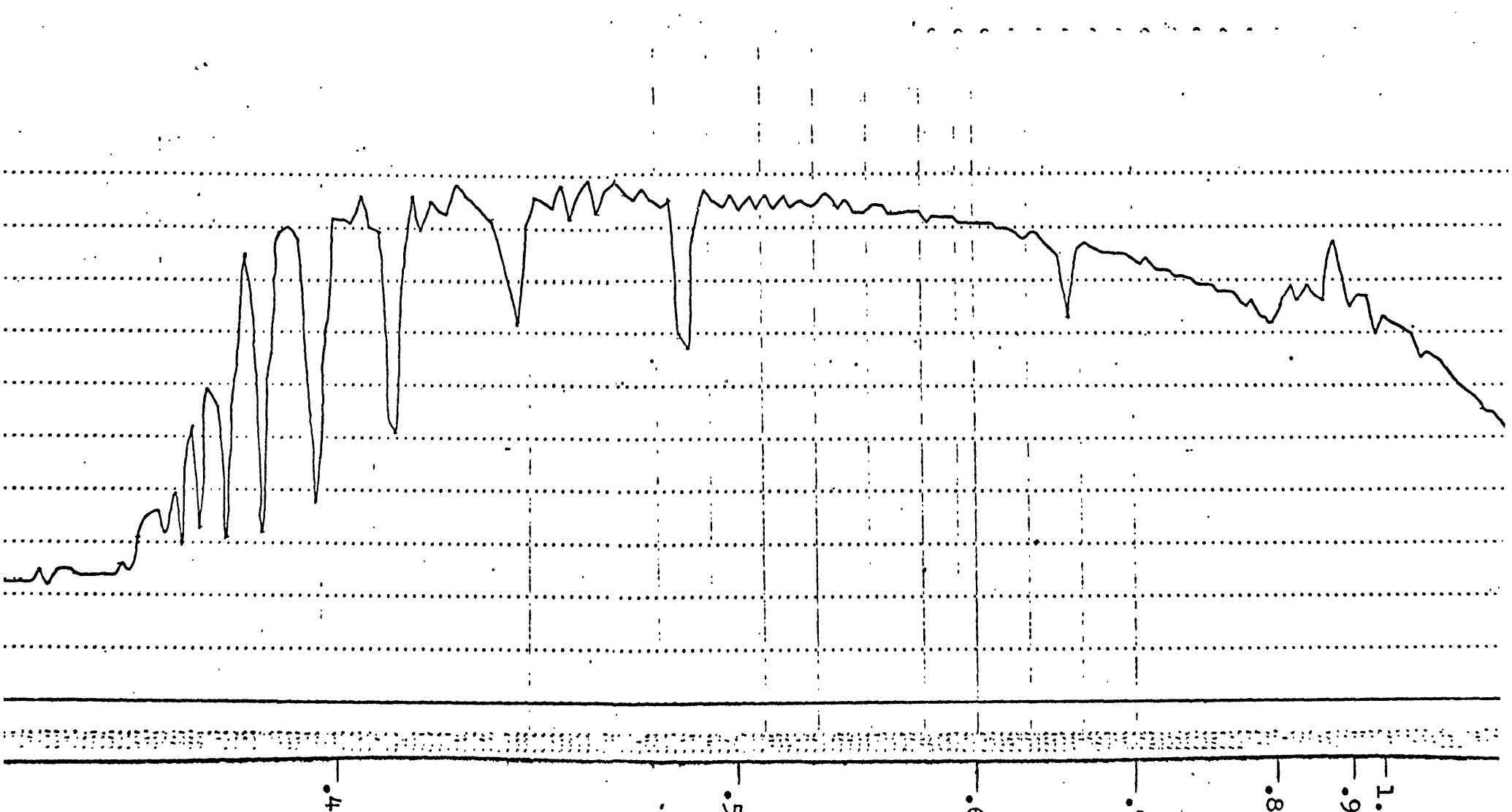
FIGURE 7: 5 Oph Spectrum

FIGURE 8: α Lyra Spectrum (Theoretical)

quite dispersed while the red part is greatly compressed.
The vidicon response function can also be seen, and combined
with the non-linear dispersion function leads to a sharp cut-
off in the red part of the spectrum. The cut-off in the blue
from the vidicon response function is much less apparent be-
cause of the high dispersion. By comparing the absorption
lines of the observed and theoretical α Lyra spectra, the in-
trinsic resolution of the spectrometer of about 2 elements is
apparent, as the observed line depths are shallower than the
theoretical depths.

As a preliminary check of the data, different spectra
of the same star were ratioed to determine their self-consis-
tency. Figure 9 is the ratio of 2 spectra of 109 Vir. Fig-
ure 10 is the ratio of 2 spectra of ς Oph to a third. Fig-
ure 11 is the ratio between 2 sets of 3 spectra each of α
Lyra, all within the second sequence. Figure 12 is the ratio
between all the spectra of the 2 sequences of α Lyra. In
all cases a 50 Å resolution was used, and the ratios were
normalized to unity at 5550 Å. The vertical scale in the
graphs is 0 to 2.

Clearly problems can be seen in all cases. The first is
the intrinsic noisiness of the ratios, being on the order of
3-4%. Occassional points that stick out are due to the spike
noise in the data not being properly removed. The remaining
noise could be removed by using a larger resolution interval.
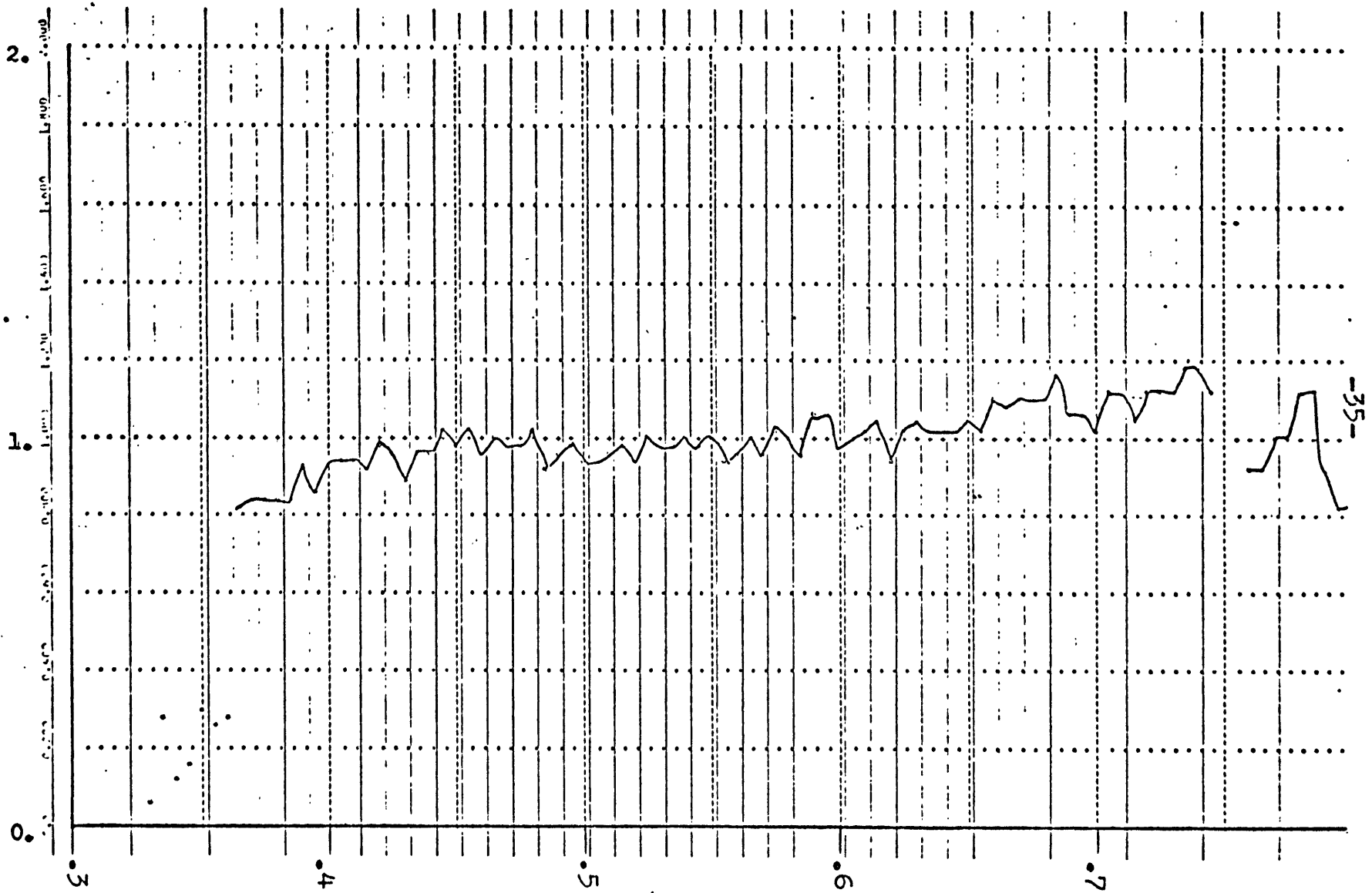The second problem is the systematic trends that appear in
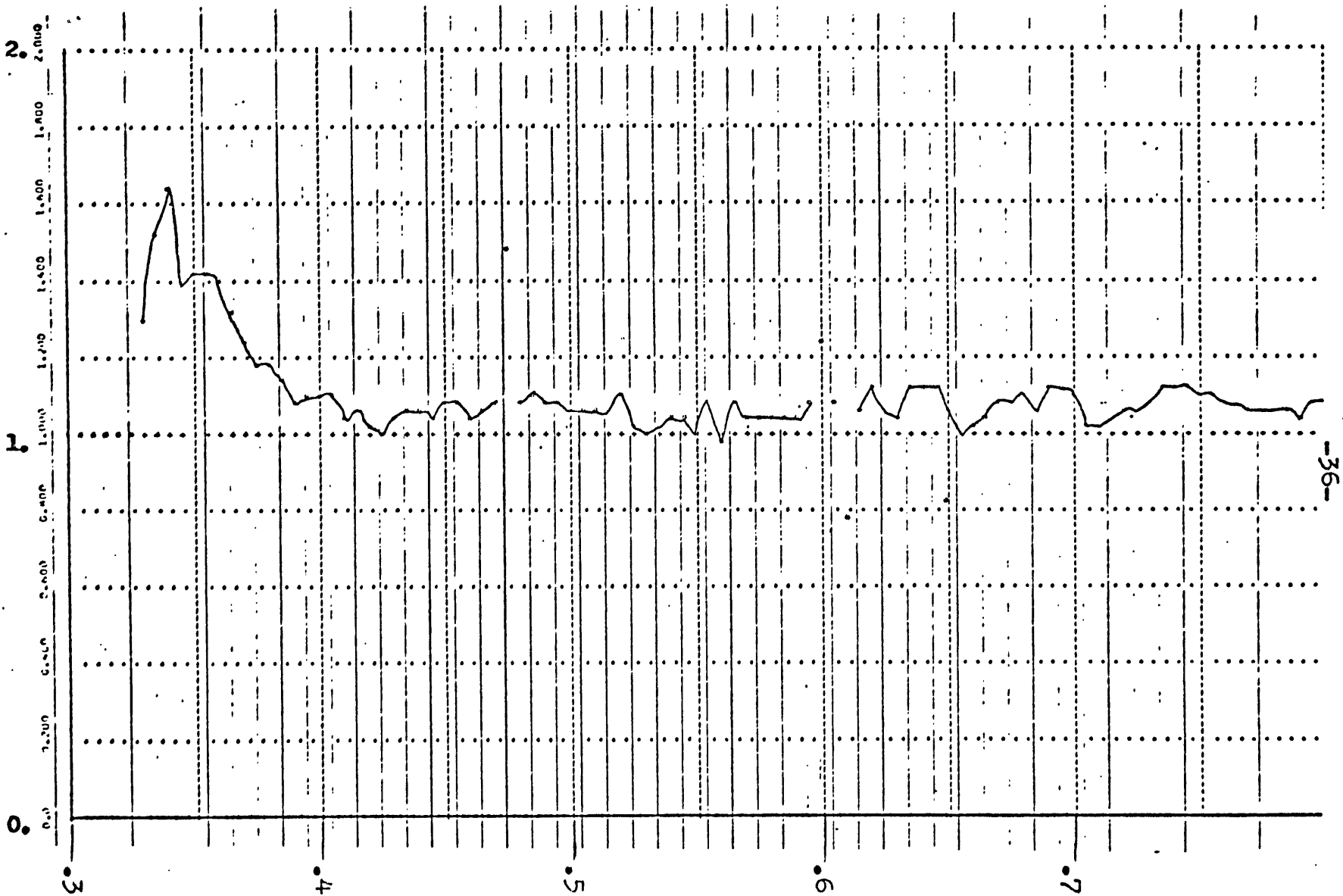
FIGURE 9: 109 Vir/109 Vir
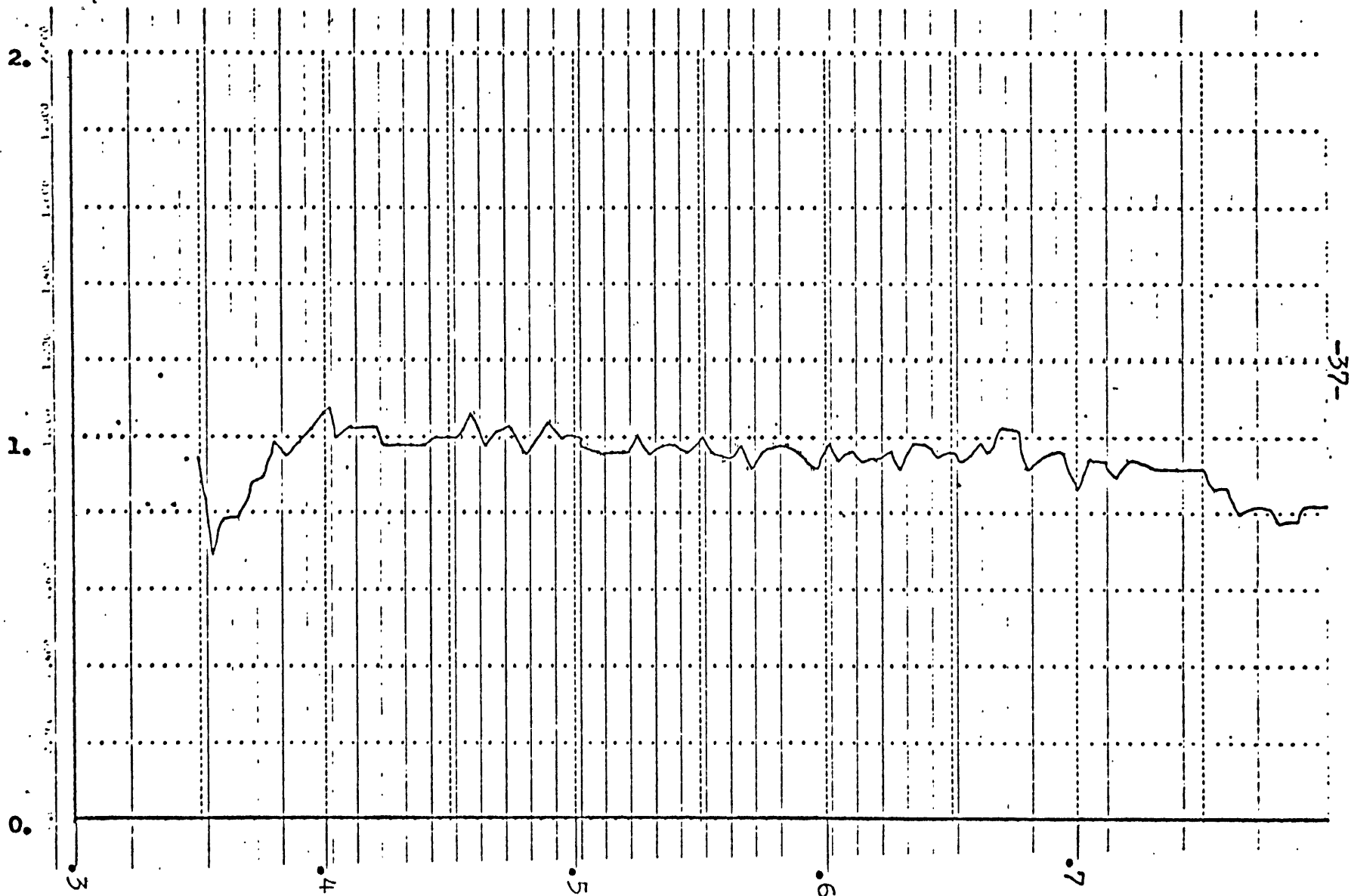
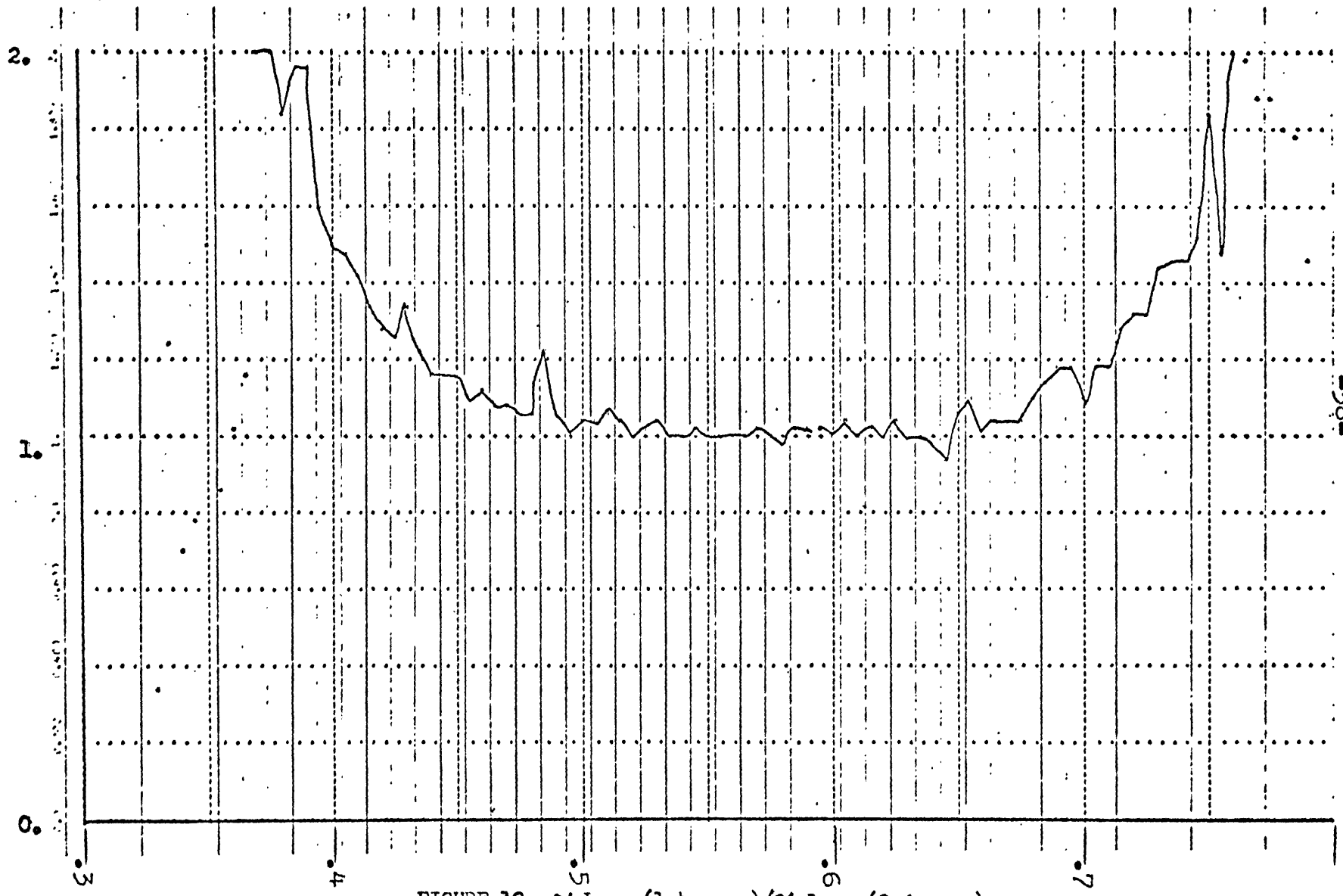FIGURE 10: ζ Oph/ ζ Oph

FIGURE 11: α Lyra/α Lyra (Second sequence)

FIGURE 12: ∝ Lyra (1st seq.)/∝ Lyra (2nd seq.)

all cases, particularly in the blue and red. The drift in
the blue is due to the relatively low intensities of the spec-
tra there. The drift in the red is due to compression of
the dispersion function combined with the sharp drop-off in
intensity; a slight drift in the dispersion function be-
tween the two spectra would significantly alter their ratio
in the red. The second set of ratios of α Lyra spectra may
be so poor due to improper air mass corrections, although
the discrepancies are so large that this seems unlikely. It
might possibly be due to the lack of proper flat field cor-
rections, although this cause seems unlikely also.

Overall, the usable range of the spectrometer for making
accurate ratios appears to be .4 - .8 μ at best.

The second check of the data was to make ratios of 109
Vir and ζ Oph with α Lyra. Since the α Lyra sequences
are not self-consistent, the ratios will be a function of
which sequence is used. Therefore, 4 sets of ratios were
made. The first set, Figures 13 and 14, are 109 Vir and
ζ Oph ratioed to the average of the first sequence of
Lyra data; Figures 15 and 16 are ratios with the second se-
quence of α Lyra; Figures 17 and 18 are ratios with all the
α Lyra data combined. The last set, Figures 19 and 20 are
ratios   to all the α Lyra data with atmospheric absorption
coefficients solved for. In all graphs, the ratios of Oke
(7) are marked with X's.

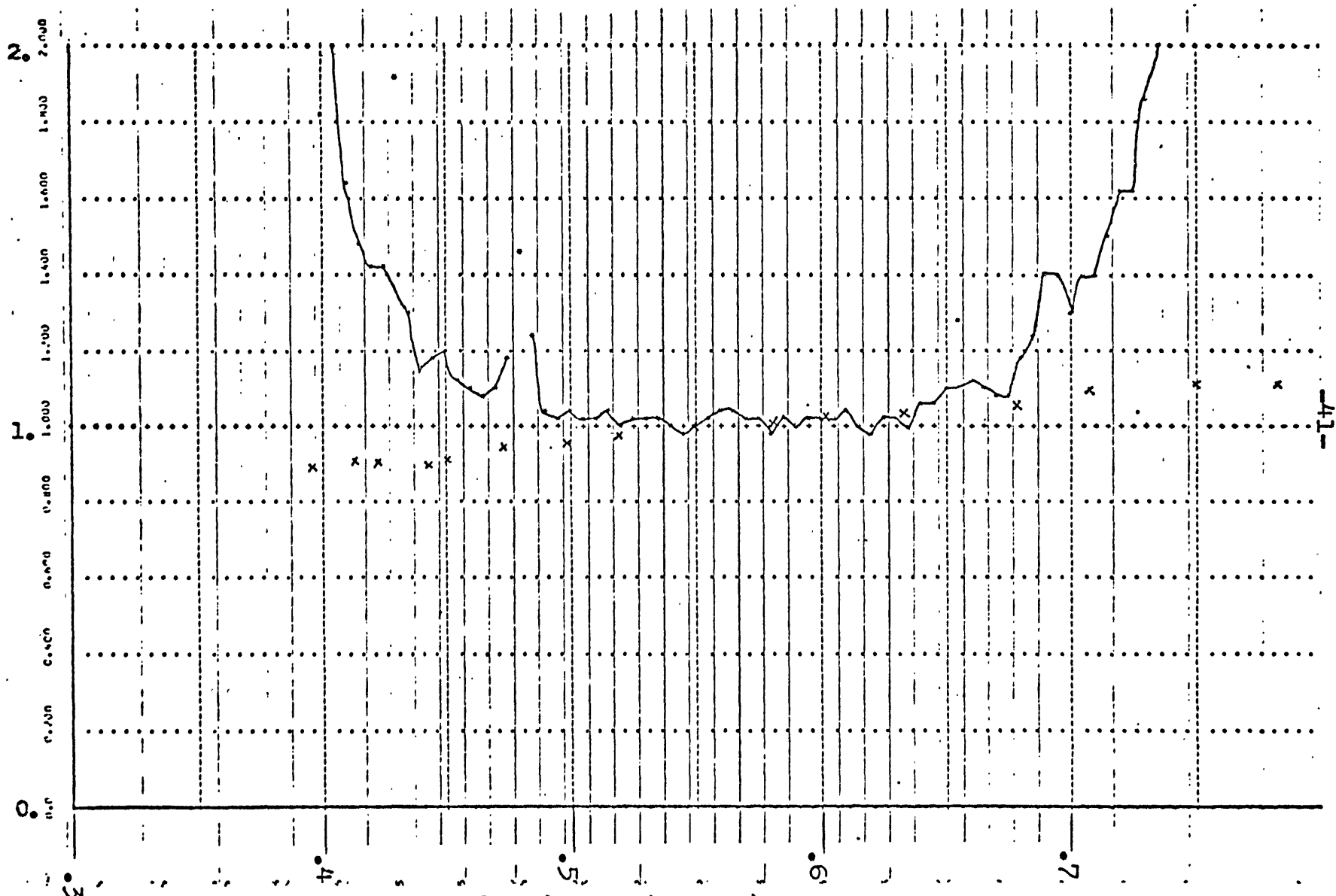In general these graphs confirm the conjectures made
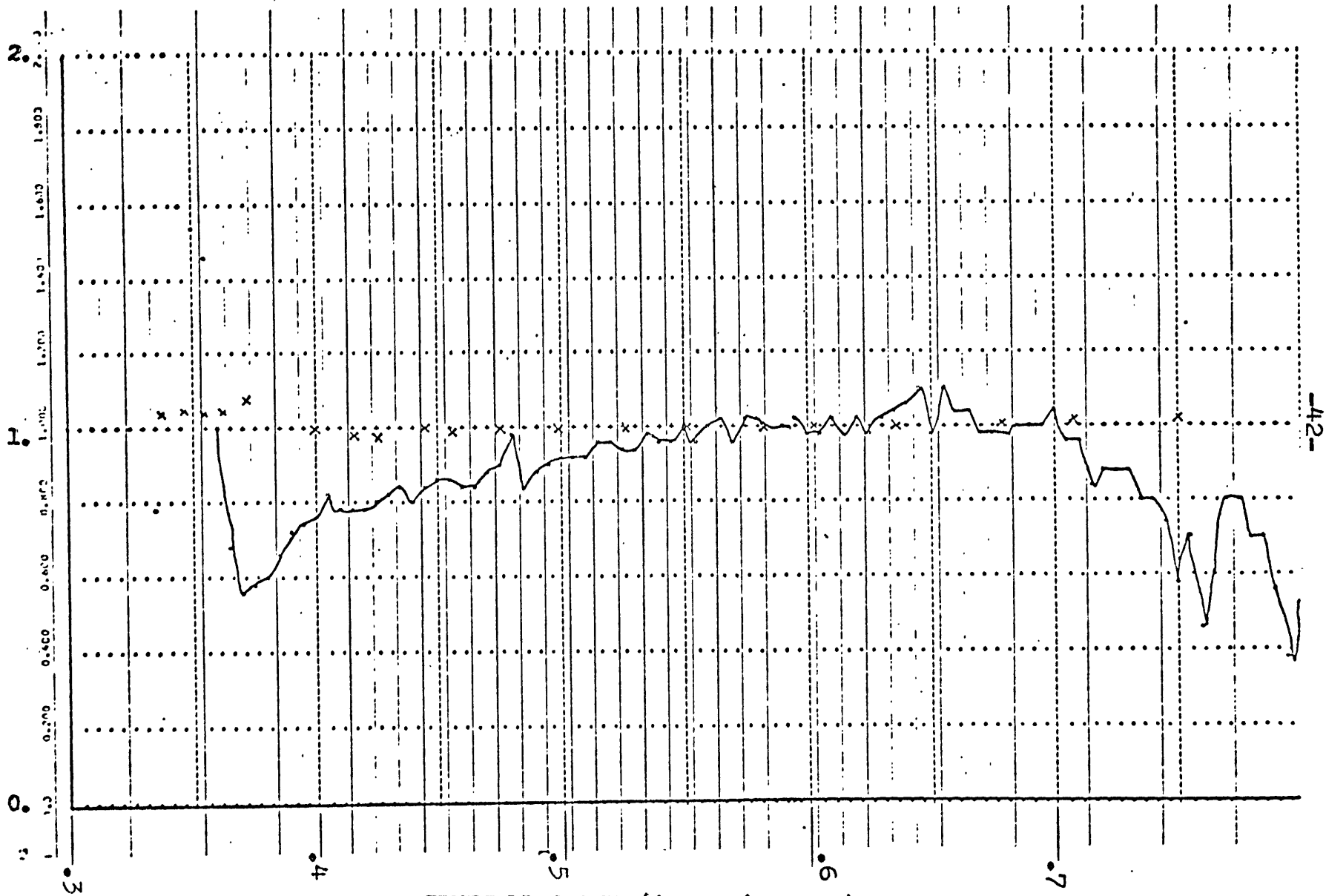
FIGURE 13: 109 Vir/α Lyra (1st seq.)

FIGURE 14: 5 Oph/α Lyra (1st seq.)
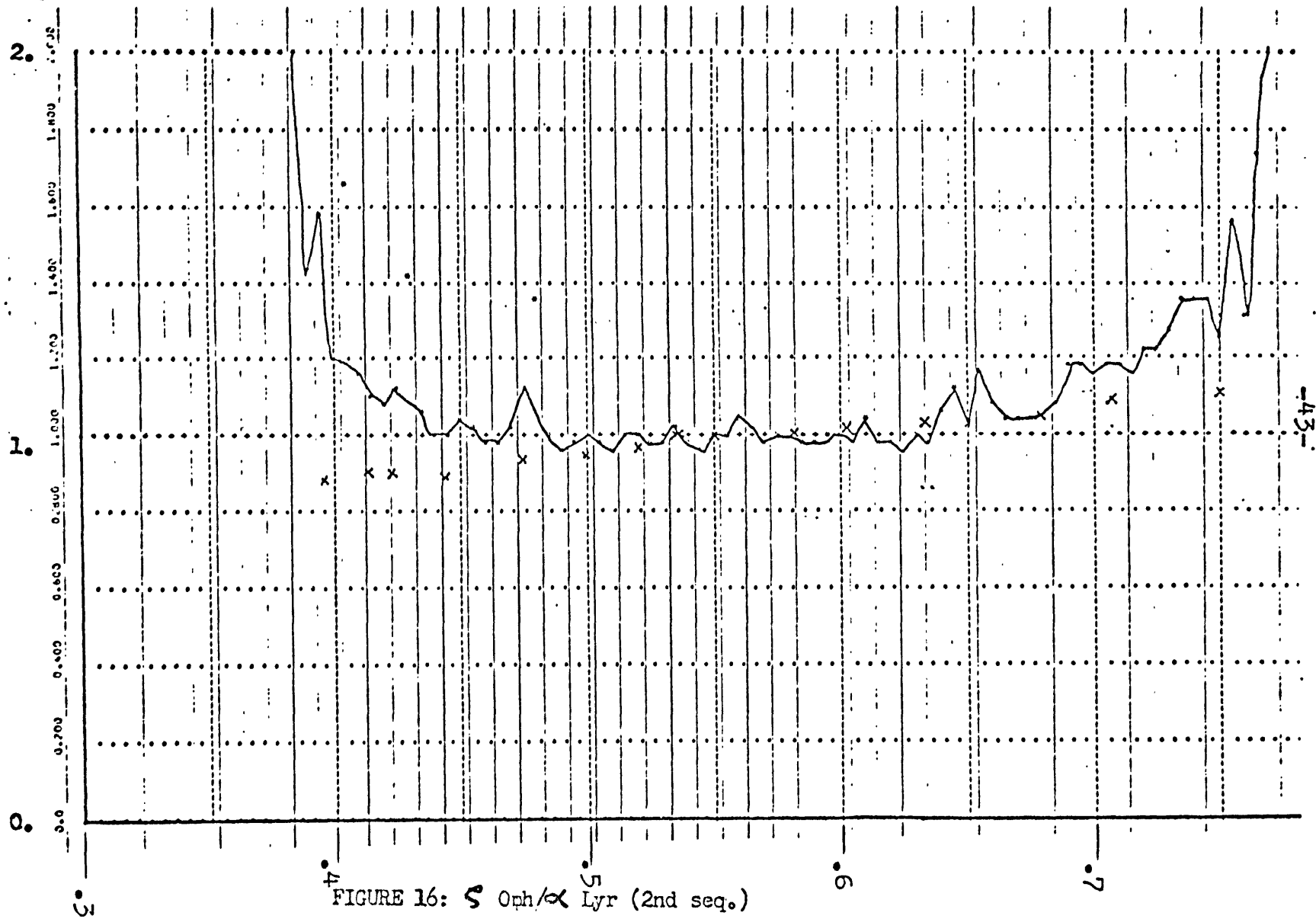
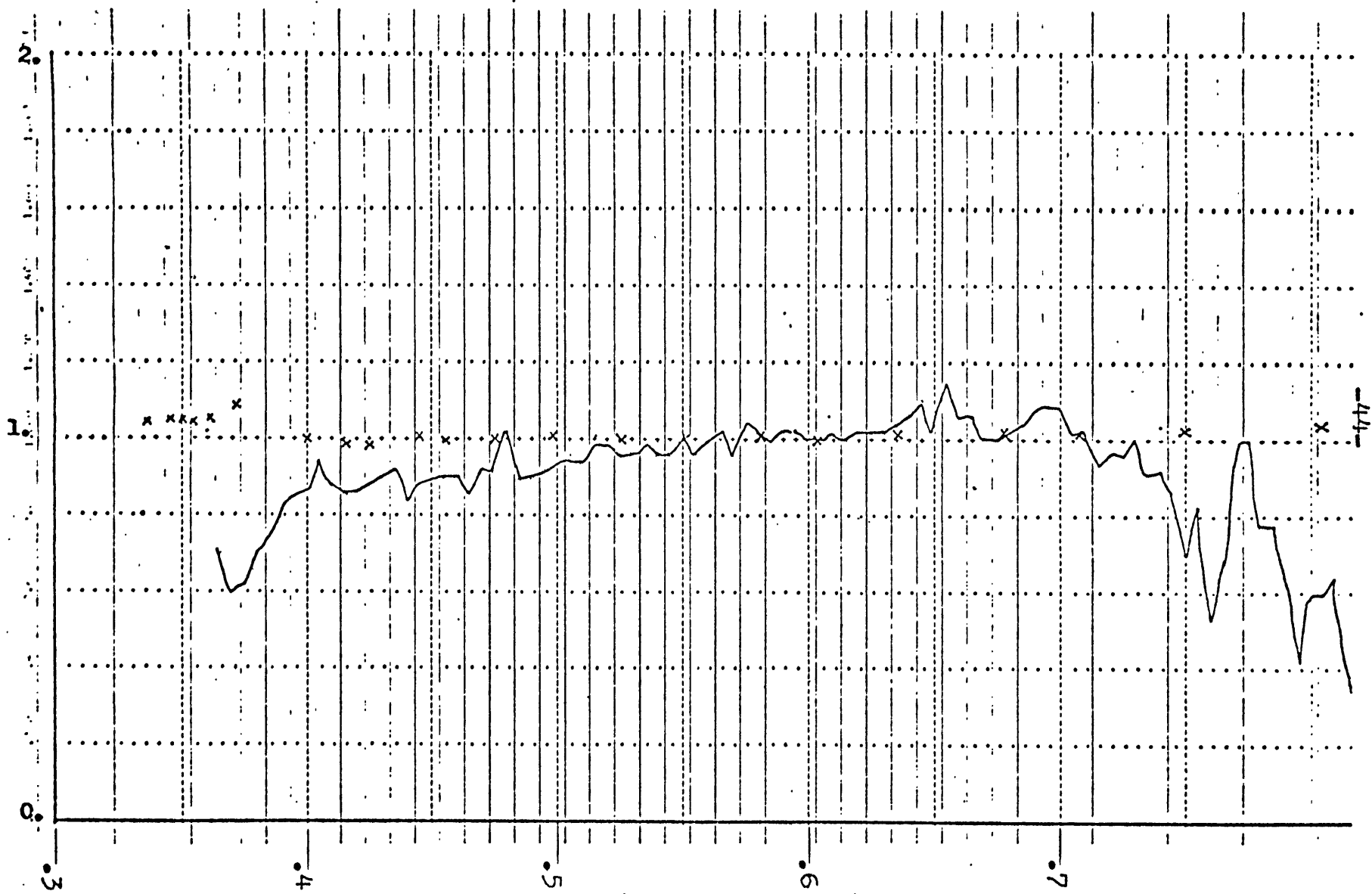FIGURE 15: 109 Vir/α Lyra (2nd seq.)

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FIGURE 16: ς Oph/α Lyr (2nd seq.)

FIGURE 17: 109 Vir/α Lyra (all points)
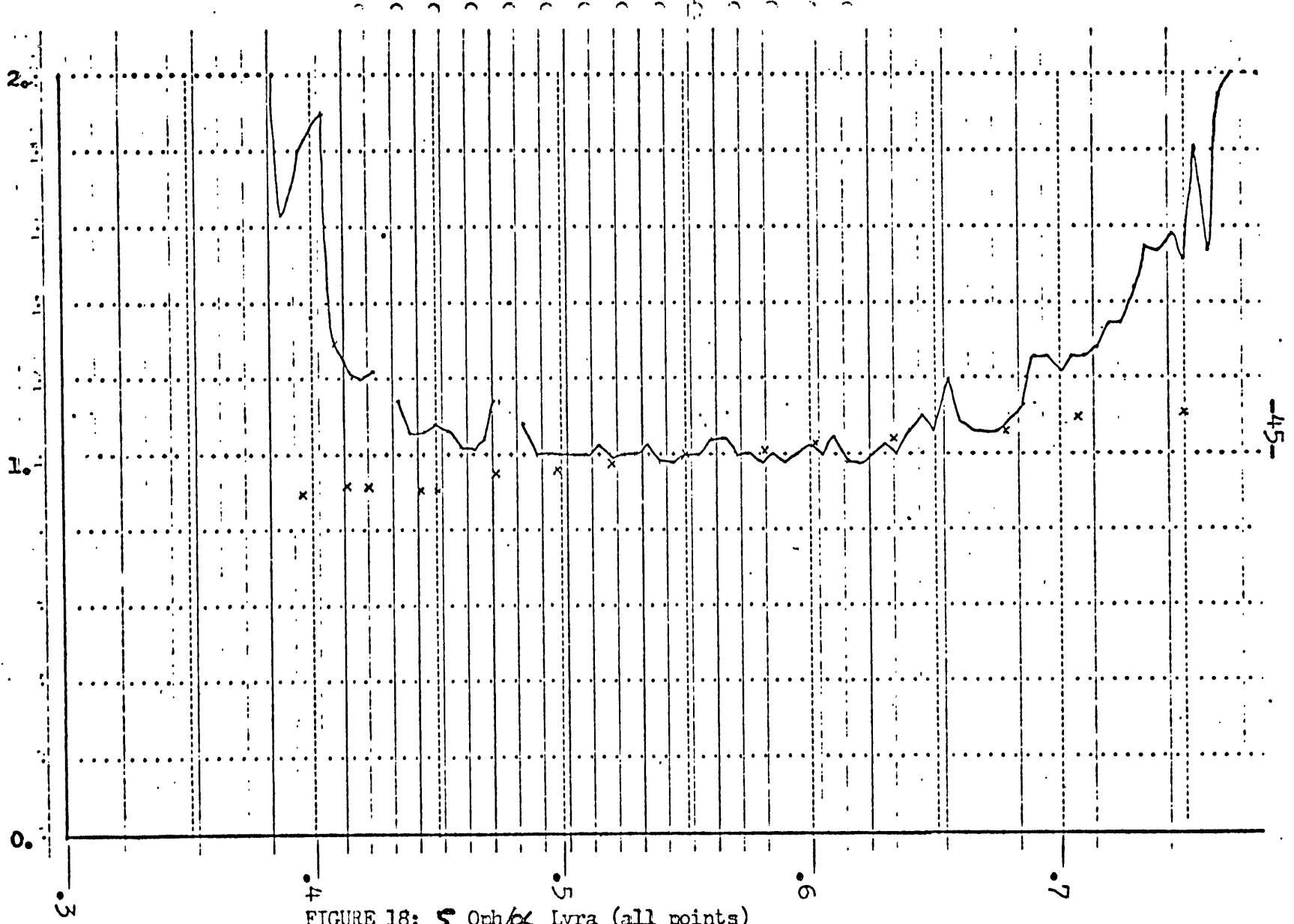
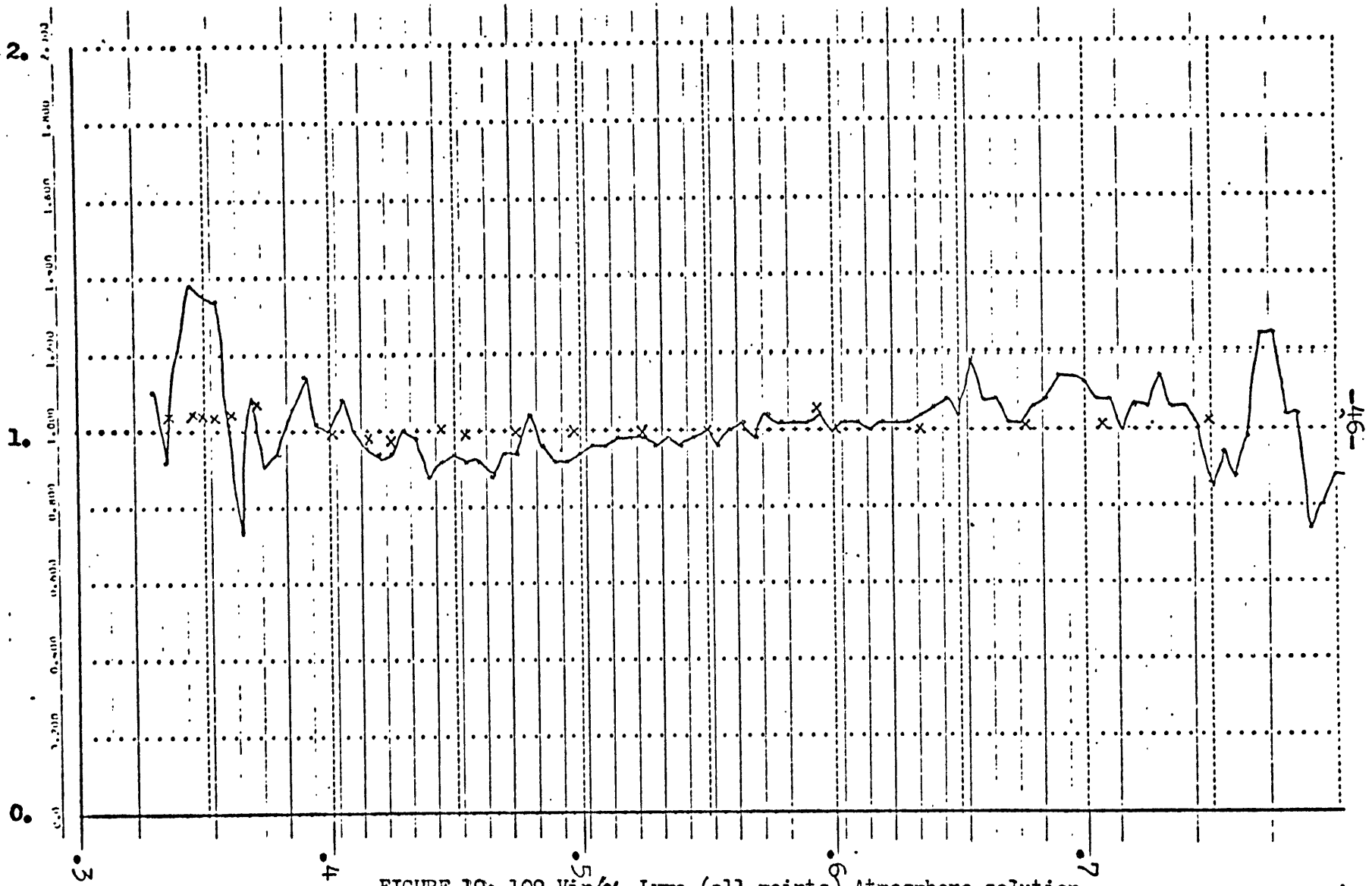FIGURE 18: ς Oph/α Lyra (all points)

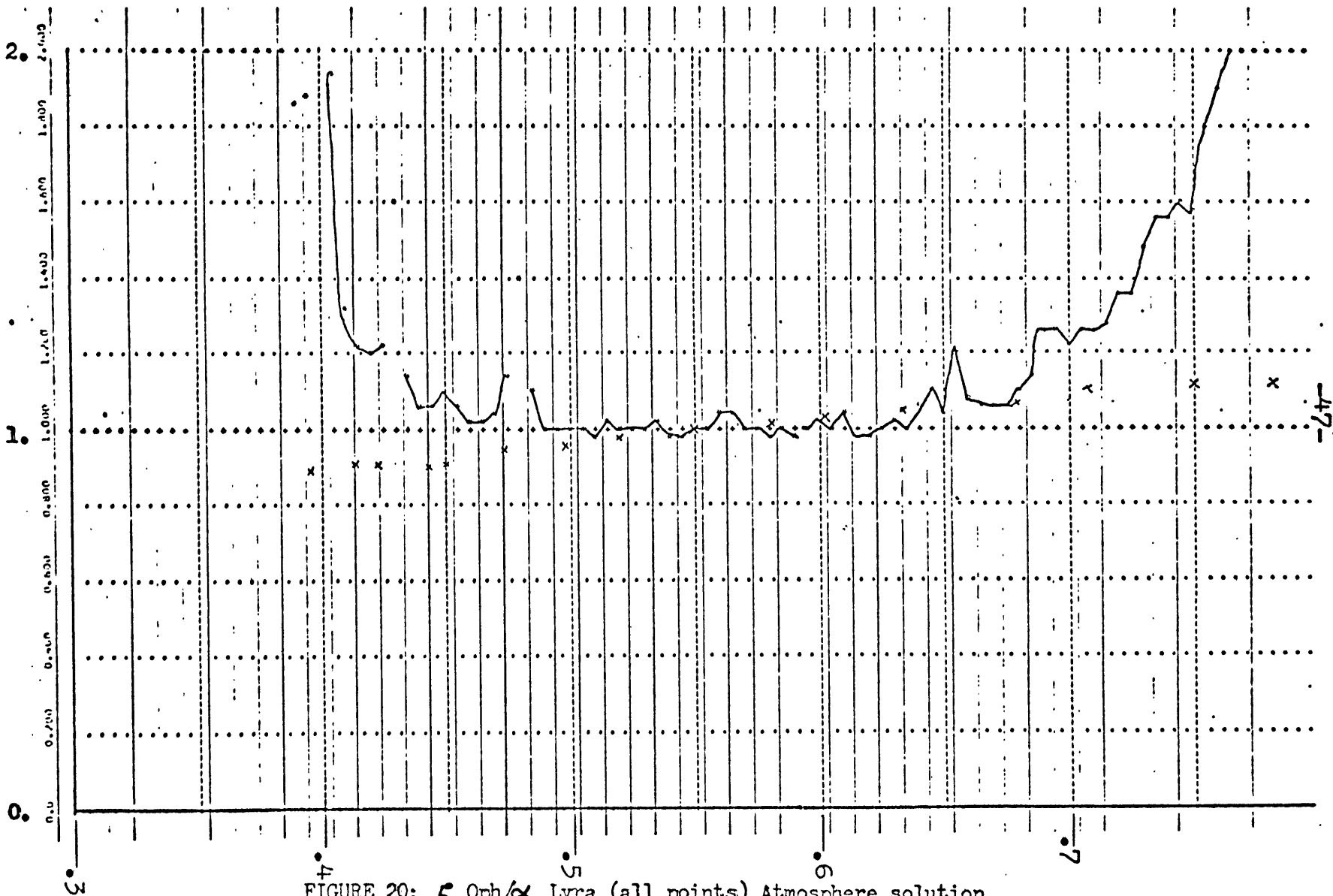FIGURE 19: 109 Vir/α Lyra (all points) Atmosphere solution

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FIGURE 20: ζ Oph/α Lyra (all points) Atmosphere solution

-47-

above. The ratios agree reasonably well (10%) in the region .4 or .5 to .7μ. Quite strange is the fact that the best match for 109 Vir occurs when the atmospheric coefficients are solved for. These numbers are listed in table IV along with the values used by Hayes; the large discrepancies are obvious. As noted above, points before .4μ and past .7μ have large errors and disagree greatly with Oke's data. The agreement for ζ Oph is not as good as for 109 Vir. The ratios past .7μ are all high as the spectra for ζ Oph are much more intense in the red than one would expect for an O-type star. The best set of ratios occurs with the second sequence of α Lyra data, although differences between different sets of α Lyra data are not as remarkable as for 109 Vir. Again, an explanation for the discrepancy in these ratios is an uncalibrated drift in the dispersion function of ζ Oph.

TABLE IV

Atmospheric coefficient solutions

$$k_\lambda - k^o_\lambda$$

Wavelength	Hayes	This Work
3200	.835	—
3250	.710	—
3300	.627	—
3350	.568	—
3400	.523	—
3450	.484	—
3500	.449	—
3571	.405	—
3636	.367	—
3704	.327	2.66
3862	.261	1.93
4036	.202	1.22
4167	.161	.92
4255	.136	.71
4464	.094	.47
4566	.076	.31
4785	.053	.20
5000	.024	.14
5263	.010	.090
5556	.0	.0
5840	-.010	-.05
6056	-.016	.12
6436	-.060	-.05
6790	-.070	.06
7100	-.076	.37
7550	-.089	.89
7780	-.093	1.48
8090	-.089	1.86

VI. Conclusions and suggestions for improvement.

The main conclusion to be drawn is that the vidicon-spectrometer system has considerable room for improvement. The star ratios presented here are not usable for reference calibrations but do indicate that the system has the capability of making reliable calibrations, at least for certain wavelengths. Of the numerous suggestions that can be made for improving the system and making measurements, the following seem to be of great importance:

Instrumental

1) New spectrometer. The non-linear dispersion function is probably the single most important problem encountered. It rendered useless measurements in the red part of the spectrum, while the red part is of great interest for planetary work. As a new spectrometer is in the making, this problem should hopefully soon be resolved.

2) Better calibration of the calibration source.

3) Improvements to the vidicon. Recent test with the vidicon system (3) demonstrate that the dewar holding the vidicon tube does not maintain it as cool as it should. Packing the dewar in dry ice can reduce system noise considerably. An improved cooling system is therefore desirable.

4) Slit width. Another possible source of error not mentioned above is the differential refraction of the atmosphere. When a star image is focused on the slit at one wavelength it may be off the slit at another. The cure is an increase in

slit width at the cost of decreased resolution. An additional gain is a decrease in the length of exposure times necessary.

5) Flat fields. A desirable addition to the system would be the capability of making flat field measurements. As such an addition would be difficult to make, however, as an alternative one would like to have an average flat field to be used in correcting intensity measurements.

6) Calibration of atmospheric absorption at Wallace Observatory. Such a calibration would be useful not only for the present work but also for any other photometric work done at Wallace.

Observational

7) Calibration spectra should be taken more frequently, preferably before observations on each new star begin.

8) A star should be observed as much as possible, preferably at a number of different air masses. Each time several exposures at various lengths should be taken. To ensure repeatability of results, a star should be observed on two or more nights.

9) As flat field corrections are in general not available, all spectra should be make as close as possible to the same spot on the vidicon tube.

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