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## THESIS

CLASSIFICATION OF N-TYPE CARBON STARS

by

William Val Bollwerk

June 1986

Thesis Advisor:

Cynthia E. Irvine

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## ABSTRACT

Low resolution spectrophotometry has been used to examine the relationship between spectral class and effective temperatures in a sample of eleven cool carbon stars.

Using effective temperatures from lunar occultation observations of Tsuji and Ridgeway et al, CN and C2 features have been examined for their utility as classification criteria. It is found that C2 strength is not a reliable temperature classification parameter, while CN should be useful.

Comparison of the carbon star classification systems of Keenan and Morgan and that of Richer with recently derived temperatures and the results of this study indicates that the Richer classification system more accurately reflects the temperatures of cool carbon stars.

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Classification of N-type Carbon Stars

by

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Submitted in partial fulfillment of the  
requirements for the degree of

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## I. INTRODUCTION

Carbon stars are in an advanced state of evolution and are of interest for understanding the rapid evolutionary processes during late stages of stellar evolution. They are cool ( $T < 4000\text{K}$ ) stars with an atmospheric carbon to oxygen ratio (C/O) greater than one. Most other classes of stars exhibit atmospheric  $\text{C/O} < 1$ . The first evidence that carbon stars were unique came in the mid-nineteenth century when Secchi (1868) classified a wide variety of stars into four spectral types. Secchi's Type-IV consists solely of carbon stars, which could be identified by their blue-degraded bands of  $\text{C}_2$ . During their work on the Henry Draper Catalog, Cannon and Pickering (1918) classified stars with strong  $\text{C}_2$  and CN bands into two sub-groups: R- and N-type. Finally, Keenan and Morgan (1941), developed a 2-dimensional classification system for all carbon stars under one designation, the letter C. The intent of the Henry Draper and Keenan and Morgan systems of classification was to assign the stars to a class in order of decreasing surface temperature and in the latter case according to carbon abundance as well.

### A. CARBON STAR EVOLUTION

Carbon stars occupy the red giant branch of the Hertzsprung-Russell (HR) diagram, having evolved to that

position from the main sequence. The evolutionary track of a carbon star is depicted on Fig. 1.

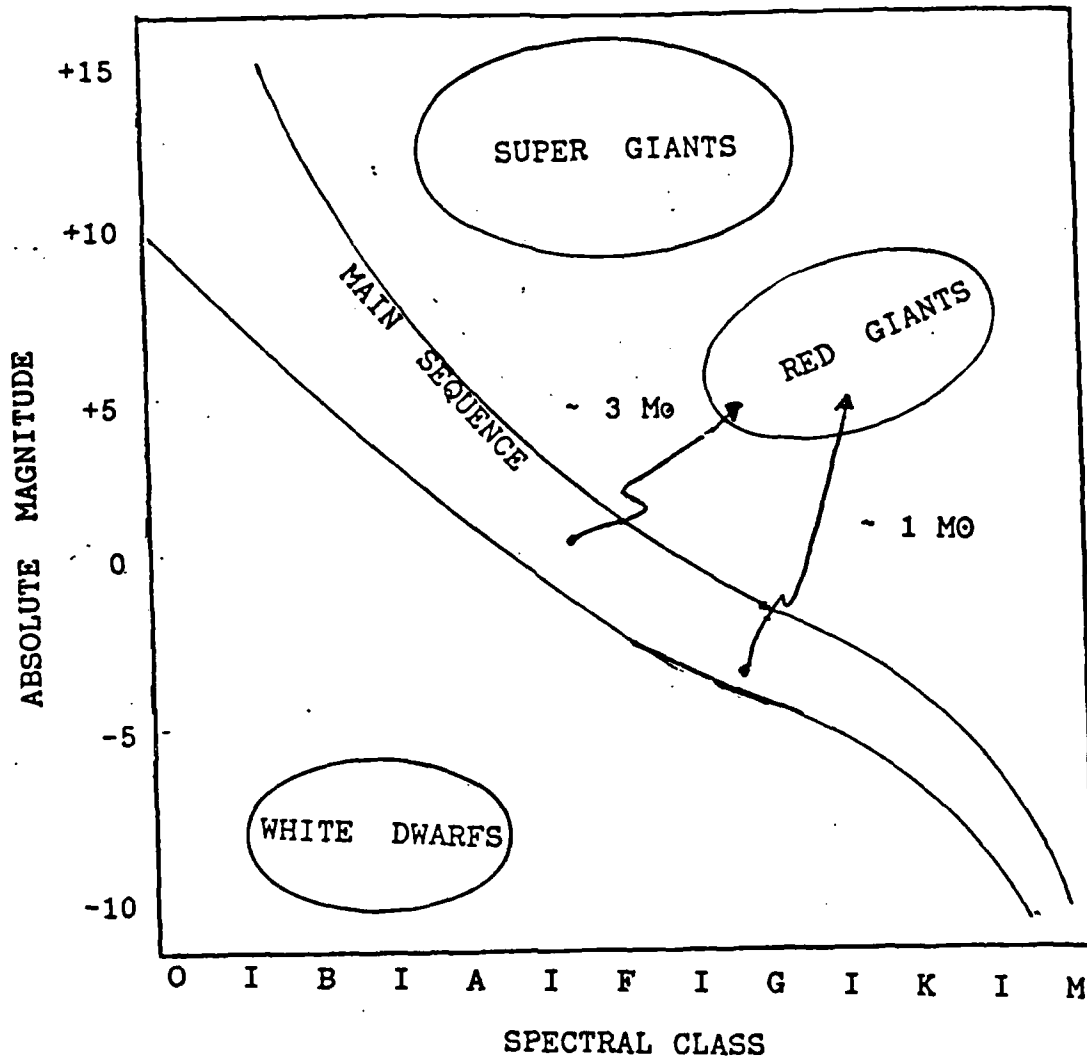


Figure 1

Hertzsprung-Russell Diagram for Carbon Stars

The star progresses onto the asymptotic giant branch (AGB) undergoing significant changes in its internal composition,

and due to mixing, exhibits a rise in the C/O ratio at its surface (McClure, 1985).

In his review paper, McClure cites three possible reasons for changes in composition: (1) helium-shell flashing on the AGB (2) a helium core flash at the tip of the first ascent to the giant branch or (3) the CNO process. All of these processes require convection within the stellar atmosphere to bring carbon rich elements to the surface from the core region.

Of these three processes, the first is often favored, based upon observations and computer models conducted by Schwarzschild and Harm (1965) and Weigert (1966). Helium-shell flashing would only occur for stars greater than 3 solar masses whereas the helium core flash is most likely for less massive stars. In the helium core flash, a difficulty exists in explaining the carbon abundance seen at the surface, due to the triple- $\alpha$  reaction. For this to occur, an artificial constraint is required in the theoretical models. A drawback of the CNO process is that although it increases the C/O ratios, the theoretical oxygen abundances do not match those observed. The model predicts a decrease in the oxygen abundance with a resulting increase in the C/O, whereas observations indicate that the oxygen abundance in carbon stars is near normal or only slightly depressed.

## B. CARBON STAR CLASSIFICATION

Shane(1928) discovered that the spectra of N-type carbon stars were depressed in the ultra-violet region, a characteristic distinguishing them from the R-type carbon stars. This feature of the carbon stars has been termed the ultra-violet (U-V) depression and is characterized by reduced intensity of a stars spectra in the 3500-5000A region. This easily recognizable feature is a dominant feature in the spectra of N-type carbon stars.

N-type carbon stars are significant in that they may represent a key position in stellar evolution, just prior to a stage of extreme mass loss exhibited by OH/IR stars followed by rapid evolution into a planetary nebula, for which the central star is a pre-white dwarf. To date, approximately 3,000, N-type carbon stars have been found (Alksne and Ikaunieks,1981).

There are two theories to explain their U-V depression: (a) absorption within the photosphere by the tri-atomic molecule  $C_3$ , (McKellar and Richardson,1954) or (b) absorption by the SiC dust envelope surrounding the star. (Gilra,1973). The SiC is the solid condensate of gaseous  $SiC_2$ . To date, the source of the U-V depression has not been resolved.

### 1. Keenan and Morgan System

Keenan and Morgan(1941) were the first to regroup the spectral classes R and N into a coherent classification

system based upon a definite temperature sequence. All carbon stars were grouped into a general spectral class, C, which was followed by decimal numbers indicating temperature and carbon abundance. Four criteria were used for their classification:

1. Atomic line ratios: The ratio of the relative strengths of the absorption bands in the spectra were used to compare stars. The absolute strengths were ignored since the continuum for determining these values is unknown in a majority of the stars due to the U-V depression. The intensity ratios used for comparison were:  $I(\text{Fe}4045)/I(\text{Mn}4032)$ ,  $I(\text{Cr}4245)/I(\text{Fe}4250)$  and  $I(\text{Cr}4245)/I(\text{Fe}4260)$ . The Cr4245 ratios proved to be the most accurate indicator of temperature due to the proximity of the iron lines. Since only a few stars were bright enough to be observed in this region, these stars were used as standards for the new C classification.
2. Color: Estimates of the continuum were used in the region 5190A to 6150A to derive the approximate black body curve and associated temperature. Errors in this method could result due to either strong line blanketing or circumstellar dust. When the continuum is depressed due to these effects, the resulting continuum will not yield the true blackbody curve for the star's temperature.
3. Intensity of the Na D-lines: For the later classes (C4 to C9), the absolute intensity of the Na5890,5896 lines was used. In the R-type stars, (C0 to C3) these Na lines were blanketed by broad bands of absorption primarily from C2 and CN, reducing their usefulness in classification. Subsequent studies by Tsuji(1981b) have shown that the intensity of the Na D-lines is independent of temperature and should not be used to classify C4 - C9 stars either.
4. Band intensity gradients: For symmetrical molecules, such as C2 and CN, Wurm(1932) showed that the relative intensities of the vibrational bands may be correlated to temperature. Keenan and Morgan relied on the relative intensities of C2 5636/C2 5585 to aid in the determination of temperature, based upon Wurm's previous work, where it was found that the temperature decreased as the relative intensities increased.

The strength of the Swan bands were also used to classify stars according to their relative carbon abundance. A subscript (1 to 5) following the decimal number was used for this purpose. Subscript 1 corresponds to intensities 0-2 while subscript 5 corresponds to intensities 8-10. Rather than reflecting temperatures, these values are dominated by the carbon abundance in the stellar atmosphere. So, a C<sub>5,3</sub> would be an N-type star with an effective temperature of 3450K and Swan band intensity of 5-6.

## 2. Classification System Review

Improved observational techniques in the 1960's led to a reevaluation of the C classification system. Fujita, Yamashita, Kamijo, Tsuji, and Utsumi(1965) studied the intensity of the Swan and the Merrill-Sanford (M-S) bands, attributed to the ring molecule SiC<sub>2</sub>, in 25 carbon stars. Their study found poor agreement with the Keenan and Morgan system, indicating these bands should not be used as a means of classification. Yamashita(1967) classified over 80 carbon stars using the intensities of atomic lines and molecular bands. This review correlated well with those stars previously classified by Keenan and Morgan. Fujita(1970) did a comparative study of 72 carbon stars as they related to the R-N and C-classifications. The following six distinctive features were used for this comparison: C<sub>2</sub>4737, C<sub>2</sub>5165, CN5239, C<sub>2</sub>5635, CN5730 and

Na5890/5896 doublet. The stars were placed into eight groups, based upon the strength of these features, and compared to the previous classifications. He found a better correlation to the C- system versus the R-N system, with the bands of CN more sensitive to the C- system than the bands of C<sub>2</sub>.

### 3. Richer System

Richer(1971) revised the Keenan and Morgan C-system of classification based on temperatures and luminosity using near infra-red (7500A-8900A) spectra. He used photometric data from Mendoza and Johnson(1965) and Mendoza(1967) to derive the effective temperatures of the stars. A comparison of the effective temperature with the C- system of Keenan and Morgan showed no correlation for the C<sub>4</sub>-C<sub>9</sub> stars, Fig 3. Richer's system uses C letters and decimal numbers but it is not the same system as that of Keenan and Morgan. In his 1971 paper, Richer describes the classification of late carbon stars as follows:

C4 - At C4 the CaII line at 8498A is just barely visible above the CN blend, while the line at 8582A remains conspicuous. From this type onward the best criterion is the ratio of the CaII line at 8662A to the nearby line at 8648A (probably due to CN) which remains relatively constant. At C4 this ratio is about 5.

C5 - the ratio of CaII at 8662A to 8648A is about 3 at this class. The CaII line at 8498A has ceased to be visible above the CN blend, and the line at 8582A disappears at this type and never reappears at later classes.

C6 - At this type CaII8662/8648 is slightly greater than unity. The CaII line at 8543A is completely blended here with CN features.

C7 - At C7 the spectra undergo a marked change from the previous class. The ratio of CaII8662/8648 is about unity, but some of the continuum features have changed. In classes C3-C6 all the features have remained relatively constant in strength, but at C7 the feature at 8462A has completely disappeared while the one at 8508A has greatly weakened relative to the ones at 8452A and 8474A.

C8 - At C8 the weakened continuum features persist. The one at 8452A becomes weaker than at C7. All CaII lines have totally disappeared. In fact, the entire spectrum has a veiled appearance. The CN throughout this spectral region has decreased in intensity to the extent that this type resembles classes C0-C2 except for the CaII lines. The KI line at 7699A becomes weakly apparent at this type.

C9 - At this type the KI doublet (7665A, 7699A) appears very strongly, easily separating this type from the others. The CaII line at 8662A is very weak, if present at all.

The approximate temperature for Richer's C classes are given in Table 1 (Richer, 1971).

Table 1  
APPROXIMATE EFFECTIVE TEMPERATURES  
OF C CLASSES

C type	T <sub>EFF</sub> (K)	C type	T <sub>EFF</sub> (K)
C0	4400	C5	2450
C1	3800	C6	2300
C2	3200	C7	2200
C3	2700	C8	2000
C4	2600	C9	1800

The two systems of carbon star classification in use today are Keenan and Morgan and Richer. The Keenan and Morgan system is more often used and referenced.

Tsuji(1981a) determined the effective temperature of 31 N-type stars using the infra-red flux method developed by Blackwell, Petford, and Shallis(1980). The accuracies of these temperatures varied from 3% at high temperatures (around 2800k) to 8% at temperatures less than 2600K. The effective temperature for 5 of the stars studied by Tsuji were calculated using lunar occultations. Since this method uses a measured radius of each star, these temperatures are considered to be very accurate. Tsuji's temperatures for the same 5 stars, used in the lunar occultation study, were in agreement with the lunar occultation method, thus supporting his calculated results.

Based on the temperatures calculated above for the 31 stars, Tsuji concluded that the Keenan and Morgan system does not represent a temperature scale for N-type stars. In addition, Tsuji(1981b) discovered that the SiC<sub>2</sub> and C<sub>2</sub> bands could not be correlated to the effective temperatures. This supported the proposal by Richer, that a new C- system was needed to replace that established by Keenan and Morgan.

### C. PROGRAM STARS

The focus of the present study is centered around 11 N-type carbon stars observed over a three month period in spring of 1985. The observing log for the stars is located in Appendix A. Since these stars are variables, their

fluxes will change with time. The stars were selected based upon their position and visual magnitudes and represent a varied grouping within the C- type designation.

#### D. OBJECTIVES

The primary objective of this thesis is to examine the classification schemes currently in use and to determine if additional criteria should be incorporated in the classification process.

## II. OBSERVATIONAL TECHNIQUES

This chapter will explain the methods, means and assumptions employed in obtaining the stellar spectra and quantitative data. Observations were obtained on the 36-inch f/10 Cassegrain telescope located on Chews Ridge in the Los Padres National Forest. The telescope, owned and operated by the Monterey Institute for Research in Astronomy (MIRA), is configured to allow for visual, photographic and electronic stellar studies. Chews Ridge is a dark-sky site at 5000-feet located approximately 12 miles east of the Pacific Ocean.

### A. OBSERVATORY

The telescope consists of a 36" mirror housed in an equatorial mount with an electronic-pneumatic drive controlled by dedicated Z-80 microprocessors. Backup systems are available in the event of a failure in the primary system.

The observatory uses a slide-on roof versus the usual dome characteristic of many major observatories. This arrangement allows for faster and greater sky coverage since only the telescope needs to be moved. The site's excellent seeing is maintained since there is no dome slit through which heat generated by the electronics must flow. A disadvantage of the roll-off roof is the effect of high

winds (>20 kts). When a star is set on the slit, which has a gap of 4" of arc, a high gusty wind can load the telescope making guiding extremely difficult.

The stars selected for this study were N-type stars with minimum magnitude of 13 or greater which were accessible to the telescope ( $\delta > -35^\circ$ ). Nine of the 11 stars studied are variable in brightness.

## B. RETICON

The Reticon Detector system is a liquid nitrogen-cooled, linear array of 512 photoconductive silicon diodes. MIRA uses the EG and G Reticon, device type RL1024 S with an active area of 65 mm<sup>2</sup>, full well capacity greater than  $2 \times 10^7$  electrons and peak quantum efficiencies in excess of 70% at 6000A (Timothy, 1983). The photodiodes operate by initially having a reverse bias in the p-n junction creating a region, between the interface, devoid of charge. As radiation strikes the diode it causes charge to accumulate at the interface and at predetermined integration times the junction is again reversed biased to clear the interface of this charge. The amount of charge required to reset each diode to its original level is a measure of the energy incident on the detector.

This level is influenced by thermal leakage within the interface, which is referred to as the dark current. The measured drop in level for each diode is recorded onto

memory within the computer and subsequently transferred to the floppy disc for hard storage at the end of the night. To determine the dark current of the detector, a series of dark scans are obtained for which no stray light reaches the diodes. Any charge accumulated at this point is attributed to thermal leakage. The dark scans also allow clock noise to be subtracted from the spectrum.

The primary reason for cooling the Reticon with liquid nitrogen is to maximize the signal-to-noise ratio. This Reticon has a signal to noise ratio of about  $2 \times 10^4$  which makes it ideal for observing extremely bright stars in short times. For this study the average time per observation was on the order of 30-35 minutes with the longest integration being 50 minutes.

### C. GRATINGS

Various gratings are available ranging from 150 to 1200 lines/MM. The dispersion was also a function of the lens used between the grating and the detector and for MIRA's system ranged between approximately 30 to about 3 A/diode. This study used the 150 line/MM grating with the 55MM lens giving a dispersion of approximately 28 A/diode.

The grating tilt within the spectrograph was set to center the spectrum on the Reticon diodes and to set the grating at the appropriate order. Modern gratings are blazed to provide greater efficiency in certain wavelength

regions. The 150-line grating was blazed for 5500A. In these observations the 150-line grating was set at  $3^{\circ} 0'$ . Slight variations in resetting the grating tilt vernier lead to minor variances in the quadratic dispersion constants from night to night. These deviations were accounted for in the reduction process.

#### D. RETICON PROGRAM

"Reticon" is the computer program designed to facilitate data collection from the Reticon. It interfaces with the spectrograph microprocessor and transfers data directly from the Reticon to a disk for later reduction. The user specifies the number of clearing scans, observing time in seconds, and gain to be used during the collection process.

During readout, the data from the Reticon is displayed on an oscilloscope, thus enabling the observer to take a quick look at the spectrum to see, for example, if any of the diodes were saturated. If necessary, the observer can obtain another spectrogram at a different gain or exposure time. The Reticon program saves the data along with a log entry supplied by the observer stating the star's name and any applicable information, i.e. Hour Angle or weather conditions.

#### E. GUIDANCE ACQUISITION PACKAGE (GAP)

The GAP is a unique piece of instrumentation designed to increase observing efficiency and is specifically designed for use on the MIRA telescope. It consists of a control paddle and a multi-port extension at the cassegrain focus of the telescope. There are five ports which are accessible at any given time to which instrumentation or eyepieces may be attached. Controlled by a Z-80 microprocessor, the GAP enables the observer to rapidly switch electro-mechanically between the five ports without altering the telescope or removing the eyepiece. It has proven to be a significant time-saver since few, if any, re-calibration adjustments are required.

### III. REDUCTION TECHNIQUES

Reticent is a menu oriented program which takes the raw data from the Reticon diodes and converts them into meaningful spectra. In this study, the strong U-V depression in the 3000-5000A region, along with the gross molecular features, confirmed stars as an N-type carbon stars. The assumptions used in the application of Reticent will be discussed in the description of various steps in the reduction sequence.

Data reduction involves the following steps: (a) dark scan subtraction, (b) flat lamp correction, (c) sensitivity correction, (d) atmospheric correction, (e) standard star fit, (f) standard star correction, (g) spectrum analysis, and (h) equivalent width measurements. The dispersion of the grating and initial diode wavelength value are required to calculate the sensitivity correction and standard star fit. The dispersion and initial diode value are determined through identification of atomic lines (Balmer series) and atmospheric extinction bands in the spectrum of a standard star.

#### A. DARK SCANS

First, the median of three or more dark scans, taken at the same gain as the program star, is calculated. The dark scan is used to remove the clock and electronic switching

noise generated by the computer during the collection of stellar radiation onto the diodes. For the MIRA system, the effects of dark current have been assumed to be invariant with exposure time. This is accomplished by subtracting the dark scan from the stars scan, diode by diode.

$$\text{Scan}(I)_D = \text{Scan}(I)_O - \text{Dark}(I)$$

The median of the dark scans gives a statistically valid reading for the noise removal.

#### B. FLAT SCAN CORRECTION

Diode-to-diode variations in the Reticon are calibrated using a standard light source, the flat lamp. The output gives the response curve for the detector or flat scan. Three or more flat scans are taken each night; all are used for the correction. Each flat scan is corrected for electronic noise by subtracting the dark scan. The flat lamp was applied to the stellar scan as follows:

$$\text{Scan}(I)_F = \text{Scan}(I)_D / \text{Flat}(I)$$

If  $\text{Flat}(I) = 0$ , then  $\text{Scan}(I)_F = 0$ .

#### C. SENSITIVITY CORRECTION

The next step is to correct the scan for the temperature ( $T=3150\text{K}$ ) of the flat lamp. A 3150K blackbody curve is derived using Planck's function. Because the derived dispersion constants are required at this point, this is

the first source of subjective errors. The sensitivity correction was applied to the program star as follows:

$$\text{Scan}(I)_B = \text{Scan}(I)_F * \text{S.C.}(I)$$

Variations of the dispersion constants by 3% resulted in significant changes in the output, ranging from 2% at 7500A up to 45% at 9500A. Therefore, high accuracy in the determination of the dispersion constants is required.

#### D. ATMOSPHERIC CORRECTIONS

An extinction correction is made to remove atmospheric effects resulting from the variation of air mass as a function of zenith distance. Observations are corrected to bring them to values that would have been obtained at the zenith. The standard formula developed by Hayes and Latham was used in correcting for air mass changes, using the H.A. and  $\delta$  of the star at the time of observation as the variable parameters. The result is  $\text{Scan}(I)_A$ .

#### E. STANDARD STAR FIT

Each night's observations included the spectrum of a standard star for which spectro-photometry was available in the literature. The standard star is used to calibrate the program star in flux units ( $\text{ph sec}^{-1} \text{ cm}^{-2} \text{ A}^{-1}$ ) per diode. The next source of subjective error occurs in this step since the fit is a function of the wavelength, therefore the proper dispersion and wavelength scale is essential.

The range of diodes for which the standard star fit is applicable depends on: (a) reference fluxes for the standard star within the desired wavelength region and (b) a good spectrum of the proposed standard star. The lower limit for the diode range was established at 3000A due to the opacity of the atmosphere while the upper range was specified at 1 $\mu$ m due to the rapid decrease in Reticon sensitivity at longer wavelengths. The standard star correction is in the form of a global parabola and further refined using a diode-to-diode linear fit.

#### F. STANDARD STAR CORRECTION

The scan is normalized using a correction function,  $Corr(I)$  obtained in the above section, with two types of functions available for use: (a) Global parabola or (b) Diode-to-Diode spline (DDS). By applying both corrections separately to the standard star and comparing flux units to those from the reference star, the DDS proved to be more accurate and was used for the reductions. This correction was applied to the scan in the following manner:

$$Scan(I)x = Scan(I)A \div Corr(I)$$

$Scan(I)x$  is the spectrum of a given star as it would appear outside the earth's atmosphere with the abscissa in units of flux and the ordinate in angstroms.

## G. SPECTRUM ANALYSIS

The resultant stellar spectrum is analyzed visually to determine which atomic and molecular constituents are present. This was accomplished through the use of line lists from Merrill(1958), Alksne and Ikaunieks(1981), Fujita et al.(1965) and Keenan and Morgan(1941). In order to determine whether a line was in emission or absorption, the continuum needed to be approximated and superimposed on the spectrum. This is estimated based upon the temperature of the star and matching this to a corresponding black body curve. The continuum used to approximate the black body was readily recognizable for the standard star. However, for the N-type stars this was not the case since the maximum of the black body curve was longward of  $1\mu\text{m}$  and the spectra covered only to  $1\mu\text{m}$ . A pseudo-continuum was drawn between 4000A and 8000A, using the relative maxima in this region. This method is justified by the analysis of Y CVn by Fujita and Tsuji(1964).

## H. EQUIVALENT WIDTH (EW)

Equivalent widths may be used to determine the relative abundances of elements present in the spectrum. The continuum on both sides of an absorption line are established and the area under this continuum is measured in units of Angstroms. As discussed previously, finding the true continuum in the U-V and blue-green portion of the

spectrum is difficult due to the abundance and intensity of the molecular bands. In particular, the CN, Swan (C<sub>2</sub>) and Merrill-Sanford (SiC<sub>2</sub>) bands create significant blending of the spectra in the vicinity of their band heads. Blending restricts the ability of the observer to discern distinct atomic lines and prohibits the measurements of equivalent widths for the atomic lines. However there were discernable maxima, albeit a few, which were used for comparison of the spectra.

#### IV. RESULTS AND CONCLUSIONS

A qualitative and quantitative analysis of the 11 stellar spectra was conducted to identify distinguishing characteristics. These features were used for the comparative study of the Keenan and Morgan and Richer classification systems.

##### A. SPECTRA REVIEW

The qualitative analysis of the spectra, Appendix B, showed both distinct differences and similarities between the stars. The similarities of the U-V depression and the profile of the continuum verified the program stars were N-type carbon stars. Strong CN was evident in all stars with CN band heads at: 8272(4,2), 8067(3,1), 7915(2,0), 7435(6,3), 7259(5,2), 7091(4,1) and 6954(3,0) (Pearse and Gaydon, 1963). Three "continuum points" were visible at 5660A, 6785A and 7780A through which a pseudo-continuum was drawn for equivalent width analysis.

The differences in the spectra were as follows:

1. U Hya, Y CVn and RY Dra had the Swan band C<sub>2</sub>5165 (0,0) clearly visible with distinctive bandheads to 4300A. All other stars were more depressed in the blue-violet but exhibited significant flux at 5100A with increased intensity redward of the C<sub>2</sub>5636 (0,1) bandhead.
2. A blanketing effect of the spectra to the violet of 6785A, possibly due to the circumstellar material, was present in 7 of the 11 stars. This blanketing

did not manifest itself in the spectra of U Hya, V CrB, Y CVn and U Lyr.

3. Only V CrB exhibited an emission line at 5577A which is attributed to a "forbidden" line of OI (Merrill, 1958). This suggests the presence of a gaseous, or planetary, nebulae surrounding the star. No other emission lines were present in any of the other stars studied.
4. The Na5890/5896 doublet, present in all the spectra, had three characteristics:
  - a. deep and narrow (V CrB, V Oph, U Hya)
  - b. deep and wide (Y CVn, RY Dra, T Lyr)
  - c. shallow and wide (U Lyr, V Aql, V Hya, SS Vir, TW Oph).

#### B. EFFECTIVE TEMPERATURES

As stated in chapter I, the classification of stars is primarily an attempt to estimate their effective temperatures. The unique nature of carbon stars with extensive circumstellar material and abundant molecular species presents a significant problem in determining temperature. Because their distances are not known and none are in eclipsing binary systems, the radii of carbon stars cannot be determined by direct or simple techniques. A precise radius of the star is required for accurate effective temperature calculations once the stellar flux is known.

Recent lunar occultations have allowed the radii of 5 N-type stars to be accurately determined (Tsuji, 1981a). Using these five stars as standards, Tsuji(1981a) successfully completed a comparative analysis of temperatures he calculated using the IR flux method. Therefore, his

effective temperatures will be used for classification, as shown in Table 2. Of the 11 program stars, only 5 had temperatures calculated by Tsuji, and are marked with an asterisk in Table 2. Temperatures of the remaining 7 stars, given by Berget, et al(1976), Baumert(1971) and Bouigue(1954), were converted to Tsuji's temperature scale, with the exception of TW Oph.  $T_{\text{EFF}}$  for TW Oph was determined by the occultation method (Ridgeway, et al. 1983).

Table 2  
EFFECTIVE TEMPERATURES OF  
PROGRAM STARS

Star	$T_{\text{EFF}}$	Star	$T_{\text{EFF}}$
U Hya	2825*	TW Oph	2890
Y CVn	2730*	T Lyr	2380
V Aql	2610*	U Lyr	2300
RY Dra	2500*	V CrB	2175
V Oph	2410	V Hya	1750
SS Vir	2400		

A plot of Richer's spectral type versus  $T_{\text{EFF}}$ , Fig. 2, supports the system proposed by Richer(1971) with the following modifications assumed; a) TW Oph is reclassified as type C8 based upon its spectra similarities to T Lyr and known  $T_{\text{EFF}}$  (Ridgeway, et al, 1983) and b) V CrB is classified as C6I based on  $T_{\text{EFF}}$ , since no previous classification is given. The two parallel lines on Fig. 2 show a proportional decrease in  $T_{\text{EFF}}$  with increasing spectral type as expected for any classification system.

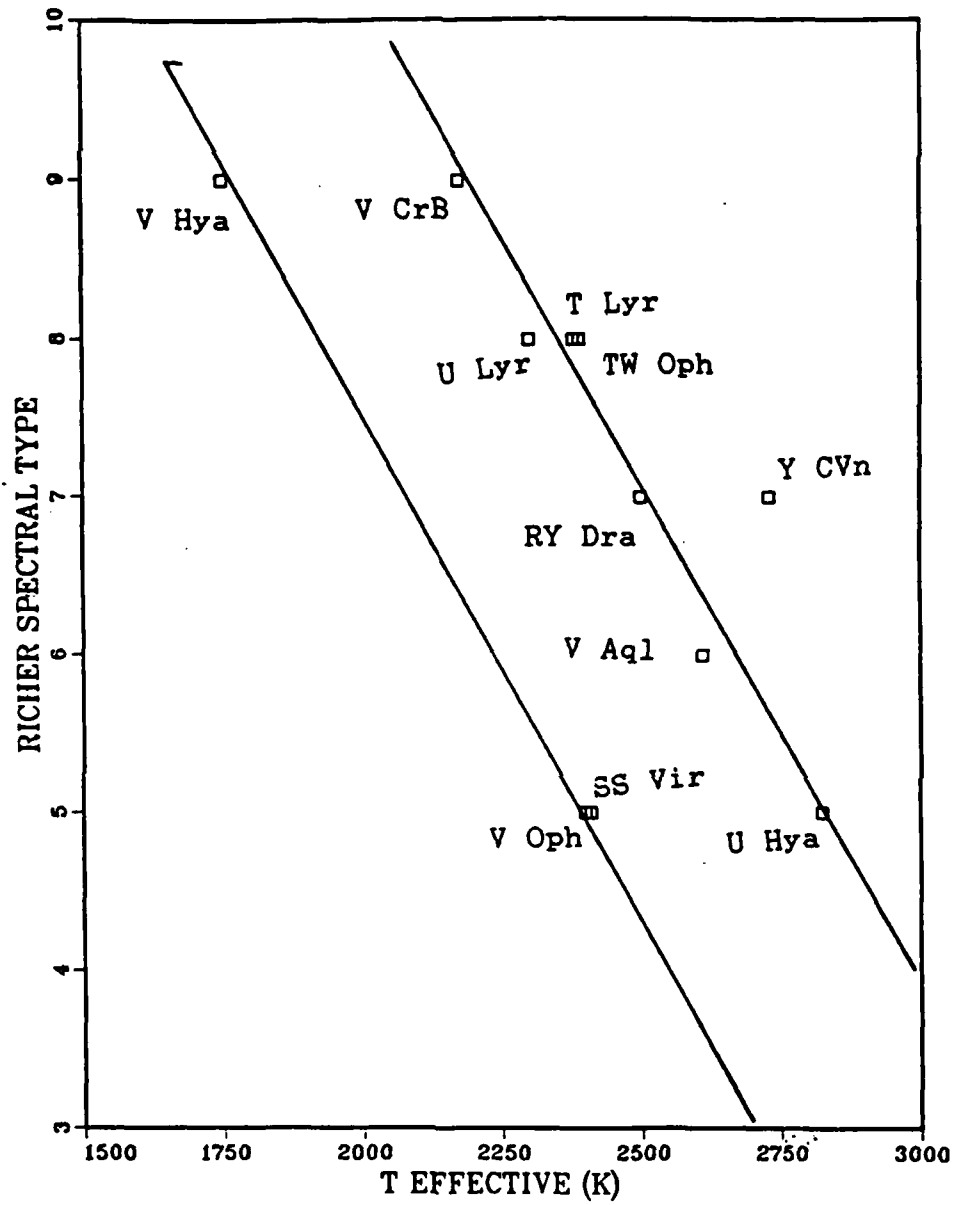


Figure 2

Richer Spectral Type versus Effective Temperature

The same plot using Keenan and Morgan's system shows no correspondence between temperature and spectral type, Fig. 3. Additionally U Hya and V Hya, both classified as C7 on the Keenan and Morgan system, represent the extremes of N-type stars and should be at opposite ends of the spectral types (U Hya as C4 and V Hya as C8 or C9). Thus, the Keenan and Morgan system does not represent a sequence of N-type stars by temperature.

#### C. C<sub>2</sub> AND CN BAND MEASUREMENTS

The relative intensities of C<sub>2</sub>5636 (Swan), CN7435, CN7259 and CN7091 band heads as they compare with the maximum flux at 7780A is given in Table 3. The CN7435 band head correlated well with both Richer spectral class and effective temperature. A minimum was present at spectral type C7, Fig. 4, in the plot of CN7435 versus Richer spectral type. Correspondingly in Fig. 5, a linear relationship exists between the relative intensity of CN7435 and T<sub>EFF</sub>. It is interesting to note that in both Fig. 2 and Fig. 5, SS Vir and V Oph form a separate grouping parallel to the remaining 8 stars. This may be lead to another means of sub-dividing the stars within a spectral class based on their CN dependance.

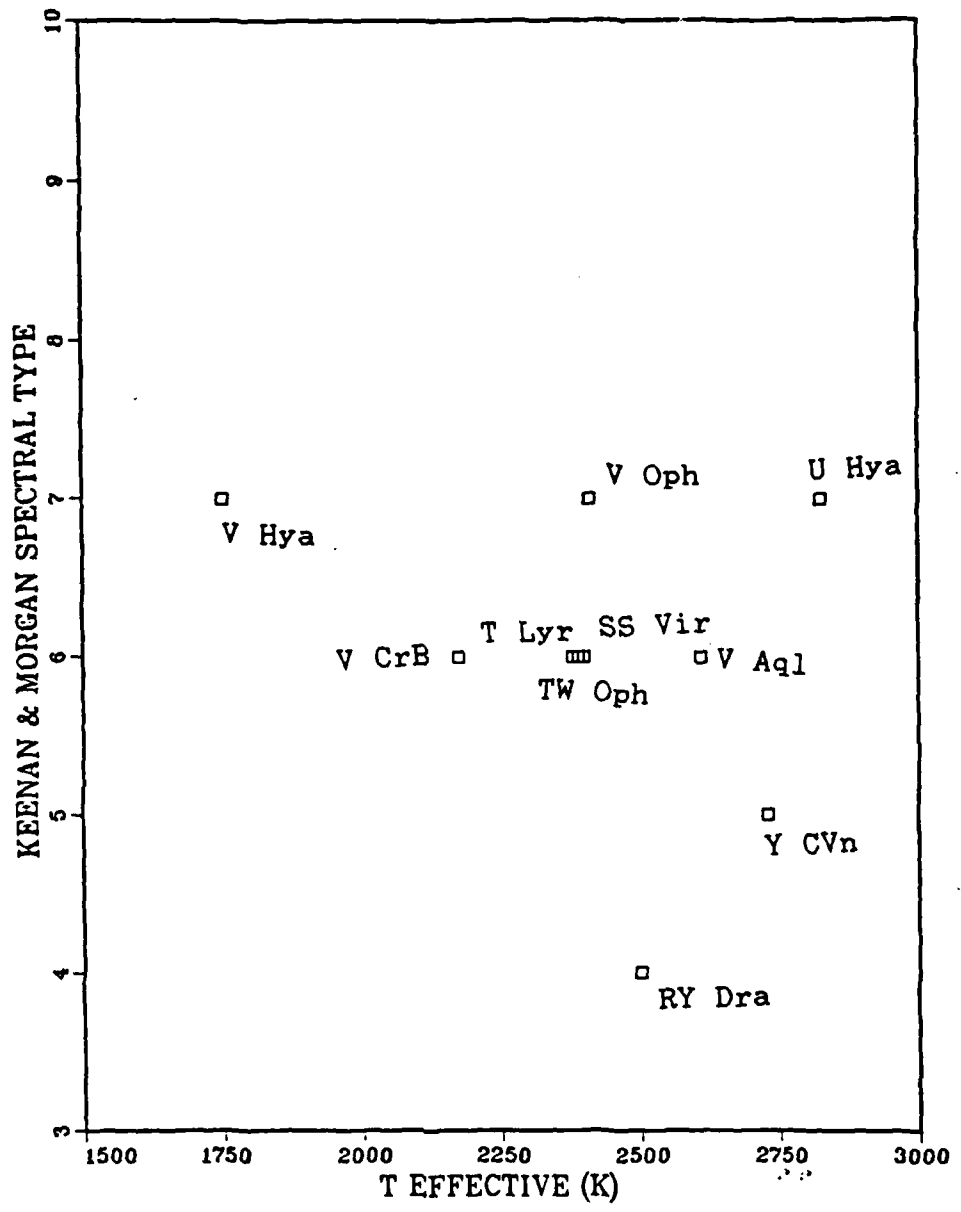


Figure 3

Keenan and Morgan Spectral Type versus Effective Temperature

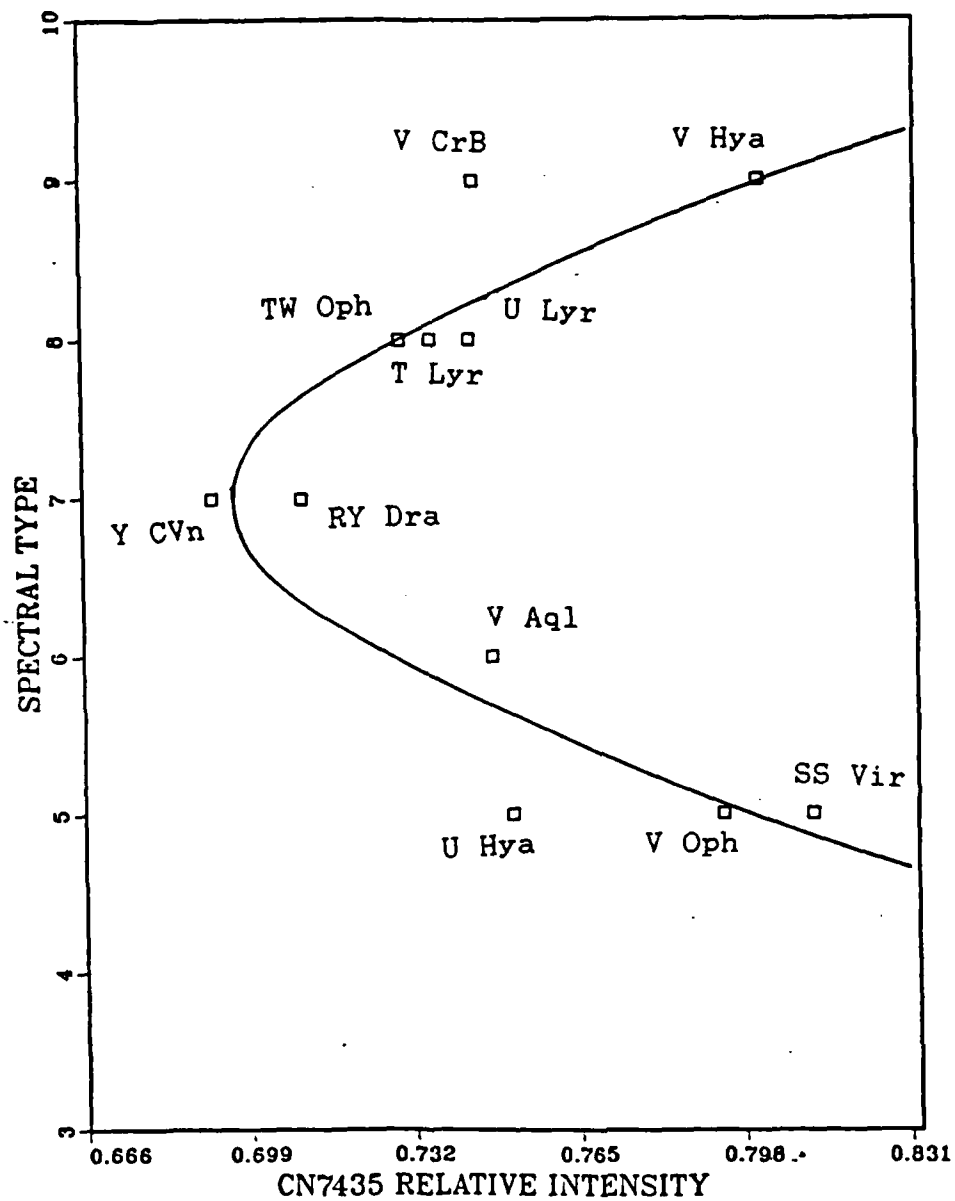


Figure 4

Richer Spectral Type versus Relative Intensity  
of the CN7435 Band Head

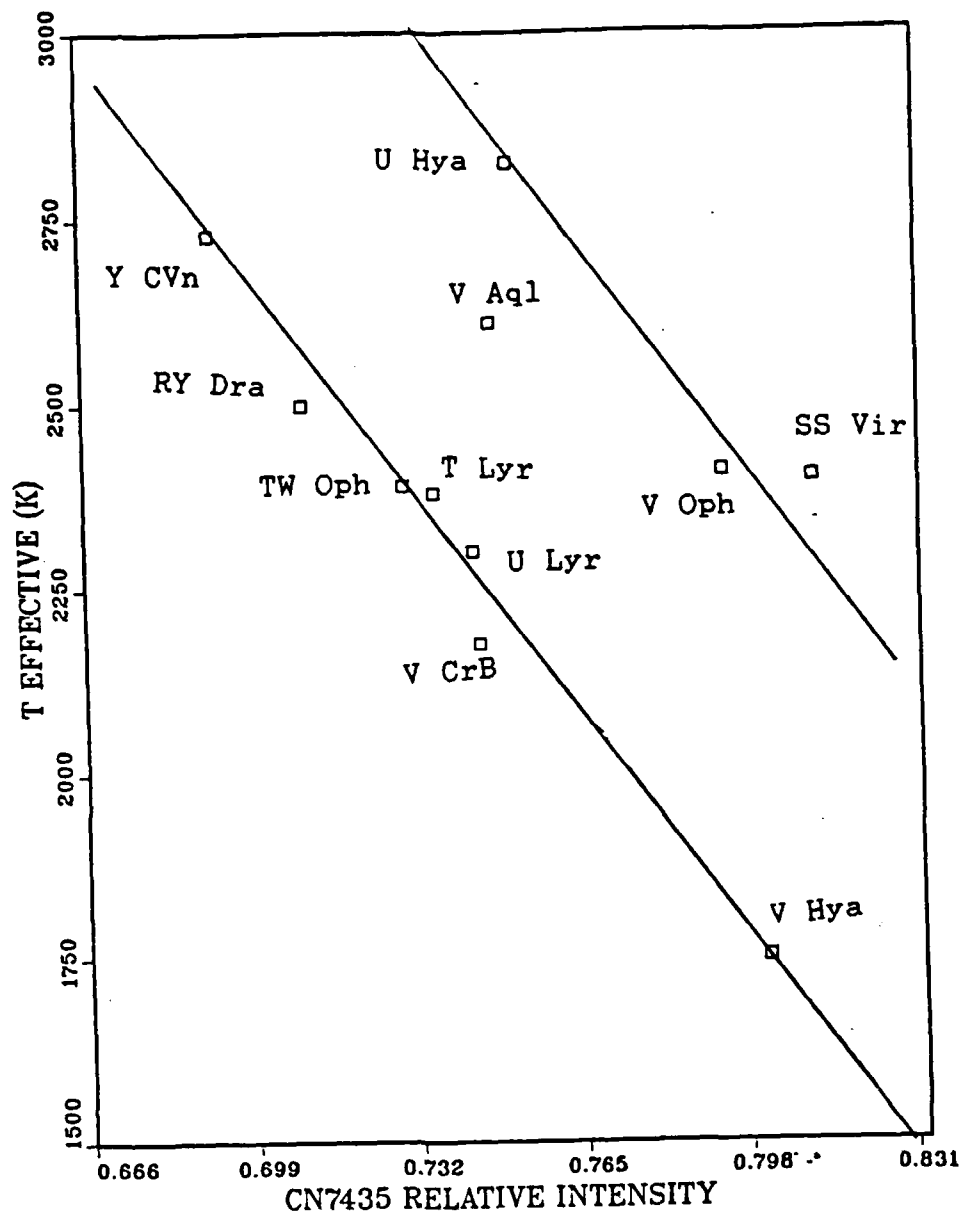


Figure 5

Effective Temperature versus Relative Intensity  
of CN7435 Band Head

Table 3  
 RELATIVE INTENSITY OF C<sub>2</sub> AND CN BAND HEADS  
 WITH RESPECT TO THE MAXIMUM FLUX AT 7780A

<u>Star</u>	<u>Band Head</u>			
	<u>C2 5636</u>	<u>CN7091</u>	<u>CN7259</u>	<u>CN7435</u>
U Hya	.181	.447	.522	.752
Y CVn	.098	.337	.437	.692
V Aql	.065	.432	.516	.748
RY Dra	.074	.368	.468	.710
V Oph	.071	.474	.563	.794
SS Vir	.060	.490	.571	.812
TW Oph	.050	.400	.498	.730
T Lyr	.045	.400	.501	.736
U Lyr	.085	.439	.549	.744
V CrB	.146	.460	.555	.745
V Hya	.056	.471	.580	.802

As shown in Figure 6, no correlation exists between the C<sub>2</sub> band and Richer's spectral type. However, there is an apparent linear correlation of the C<sub>2</sub> band to T<sub>EFF</sub> for the majority of the stars studied in this thesis, Fig. 7. Further investigation with a broader selection of stars should be conducted to confirm these results. Neither the C<sub>2</sub> nor CN bands correlated with the Keenan and Morgan system, Fig. 8 and Fig 9.

A comparison of the relative intensities of C<sub>2</sub>5636 versus CN7435 showed no correlation between the two molecules, Fig. 10. This lack of correlation is indicative of the independence of CN and C<sub>2</sub> abundance and provided no classification criteria. The classification of carbon

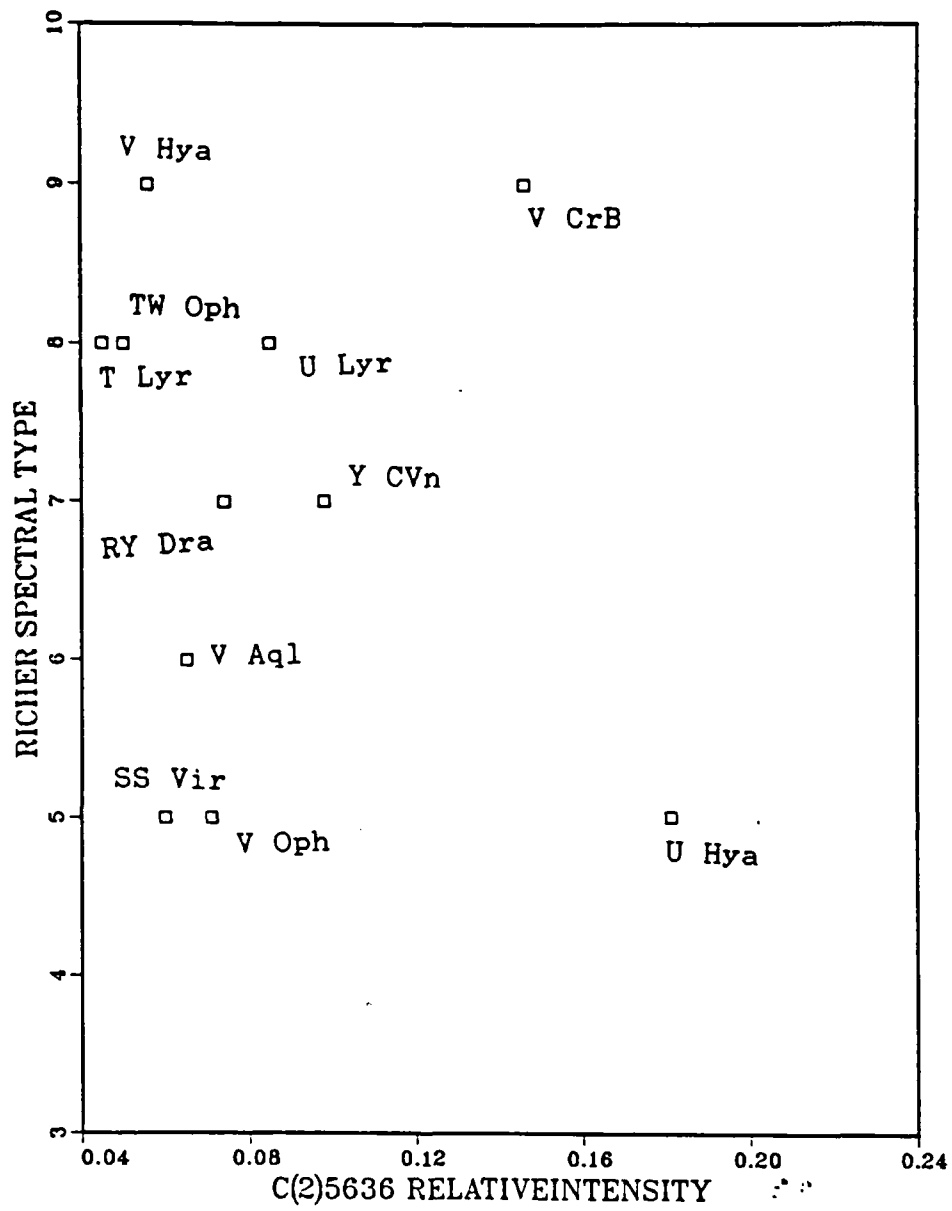


Figure 6

Richer Spectral Type versus Relative Intensity  
of the C25636 Band Head

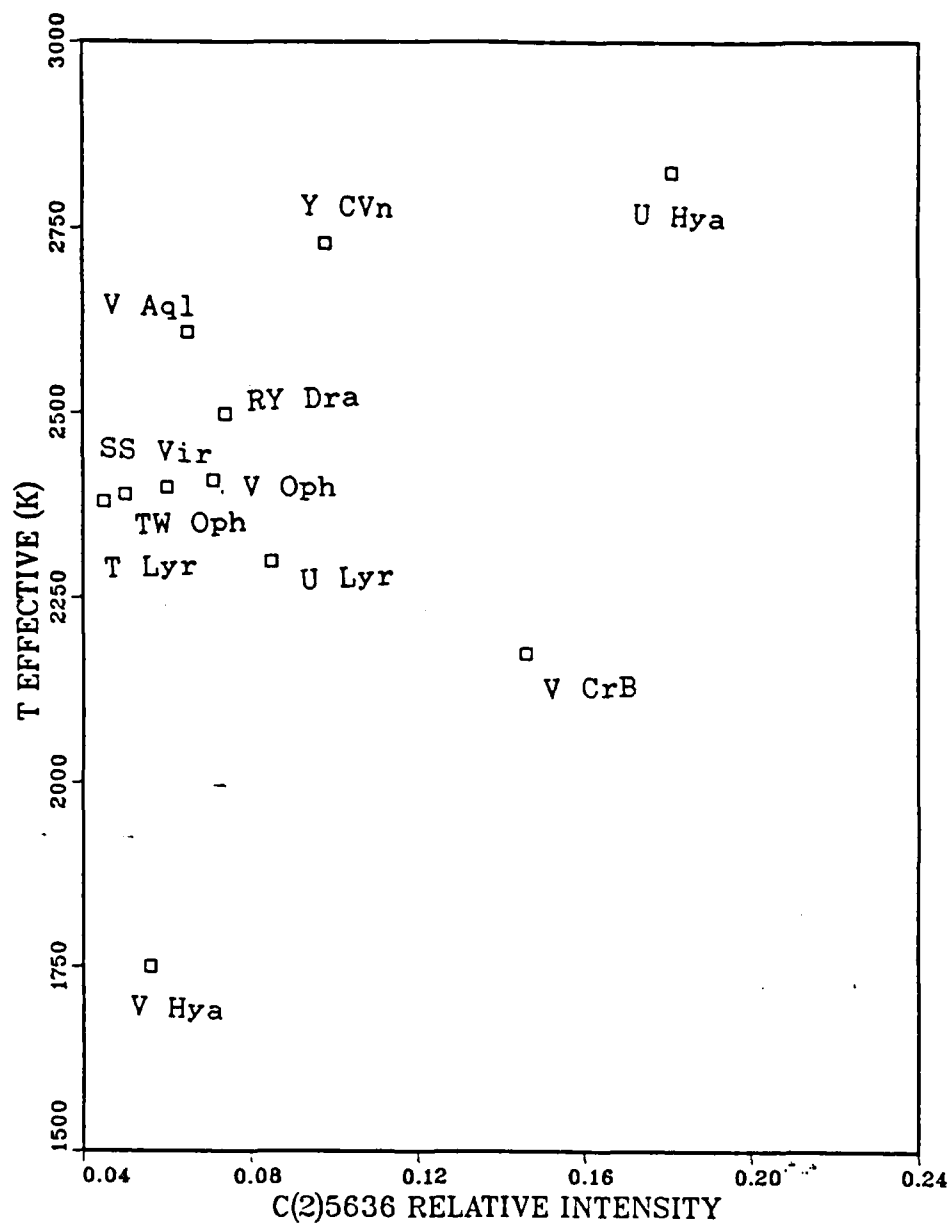


Figure 7

Effective Temperature versus Relative Intensity  
of the C25636 Band Head

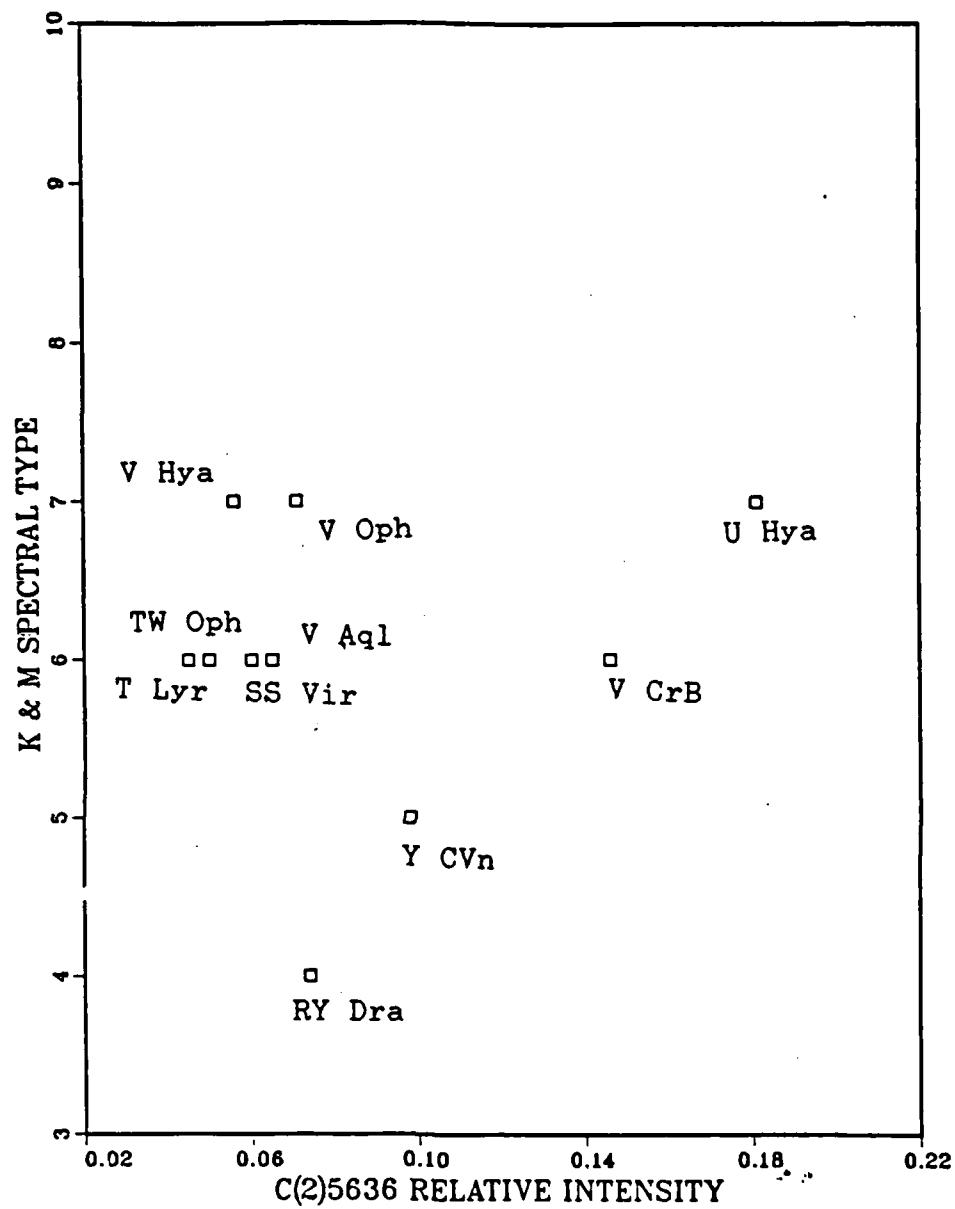


Figure 8

Keenan and Morgan Spectral Type versus Relative Intensity  
of the C25636 Band Head

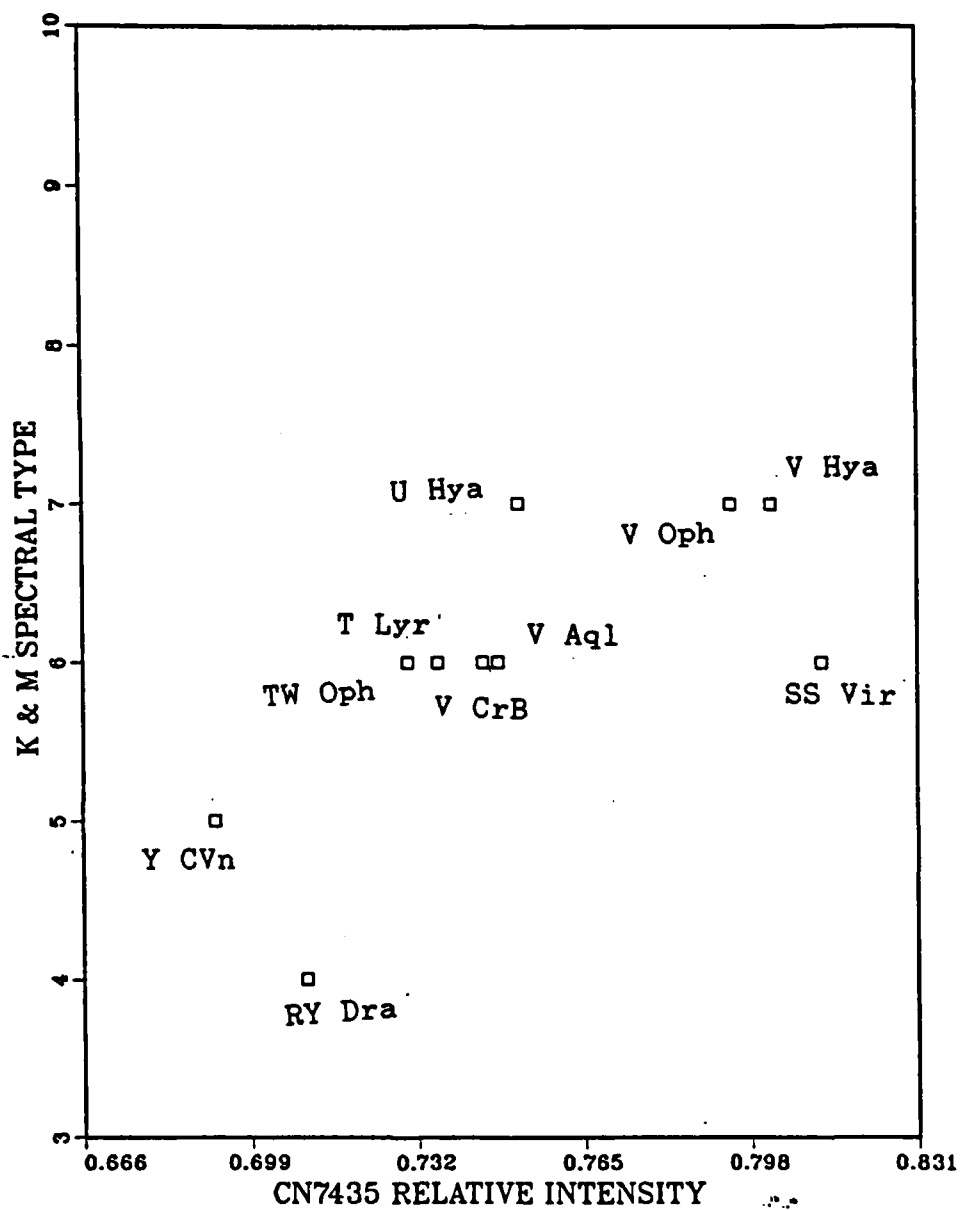


Figure 9

Keenan and Morgan Spectral Type versus Relative Intensity  
of the CN7435 Band Head

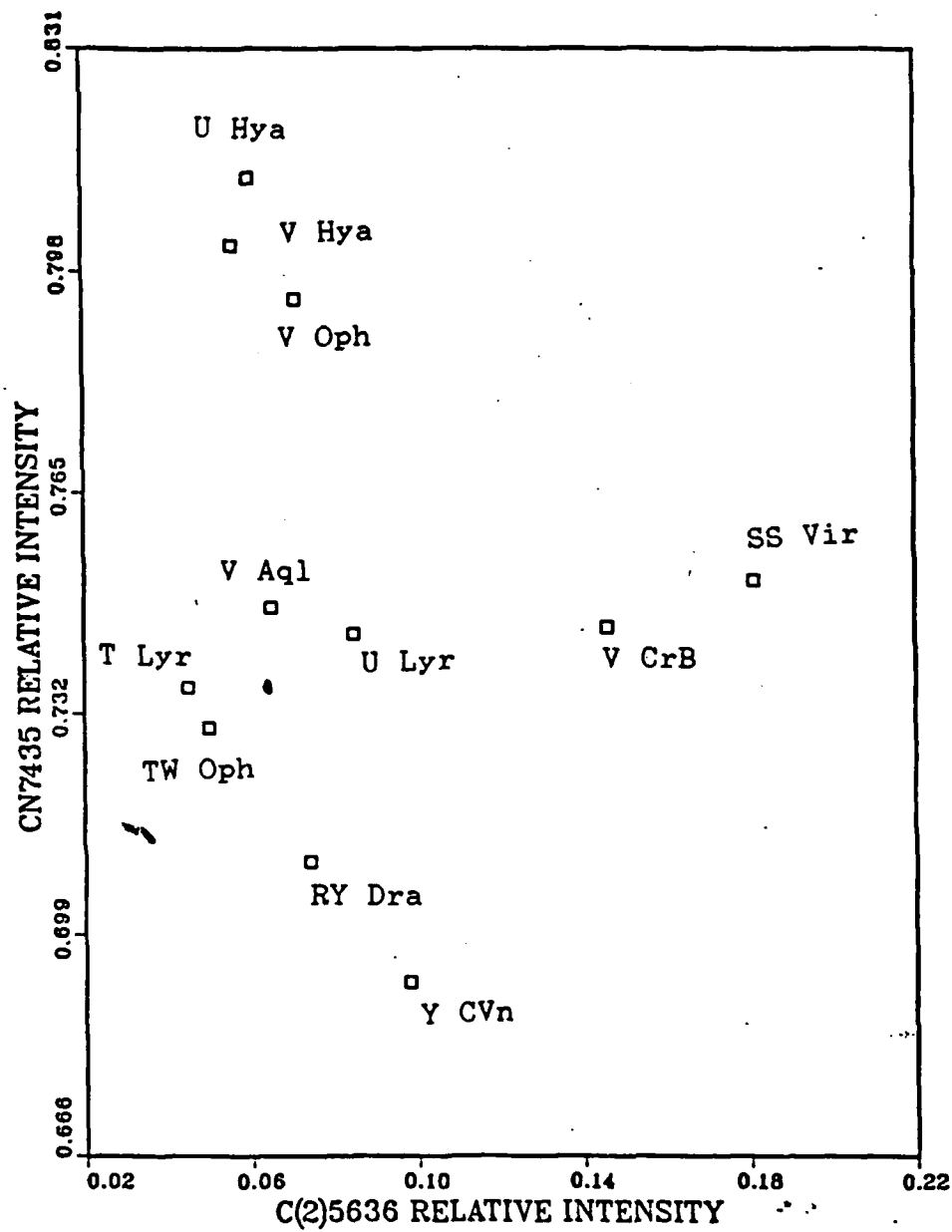


Figure 10

Relative Intensity of the Cn7435 Band Head versus  
Relative Intensity of the C25636 Band Head

stars is independent of the abundance of C<sub>2</sub> based upon Figures 6 and 8. This supports the theory of Fujita (Fujita, et. al., 1965 and Fujita, 1970) which questions Keenan and Morgan's criteria based on the intensity of the Swan bands. Figure 7 shows no relationship between C<sub>2</sub> and temperature.

A comparison of the relative intensities of CN7435 versus Cn7259 and CN7091, using the maxima at 7780A as a yardstick, showed a distinct linear relationship, Fig. 11. This indicates that both CN7259 and Cn 7091 should have the same sort of relationship as found in Fig. 2 for CN7435.

#### D. EQUIVALENT WIDTH MEASUREMENTS

Equivalent width (EW) measurements were made with the psuedo-continuum defined by the points in section A above. A plot of T<sub>EFF</sub> versus EW ratios of EW8520/EW6960 showed a possible new classification tool for these stars, Fig. 12. Knowing the EW ratio, T<sub>EFF</sub> can be found and used on Fig. 2 to obtain the spectral type. With the exception of the 2 stars at the temperature extremes (U Hya and V Hya), a straight line plot allows T<sub>EFF</sub> to be determined given the EW ratio.

Since there is significant broad line blanketing in these and other carbon stars, this method must be approached with caution. Careful consideration must be given to the following points:

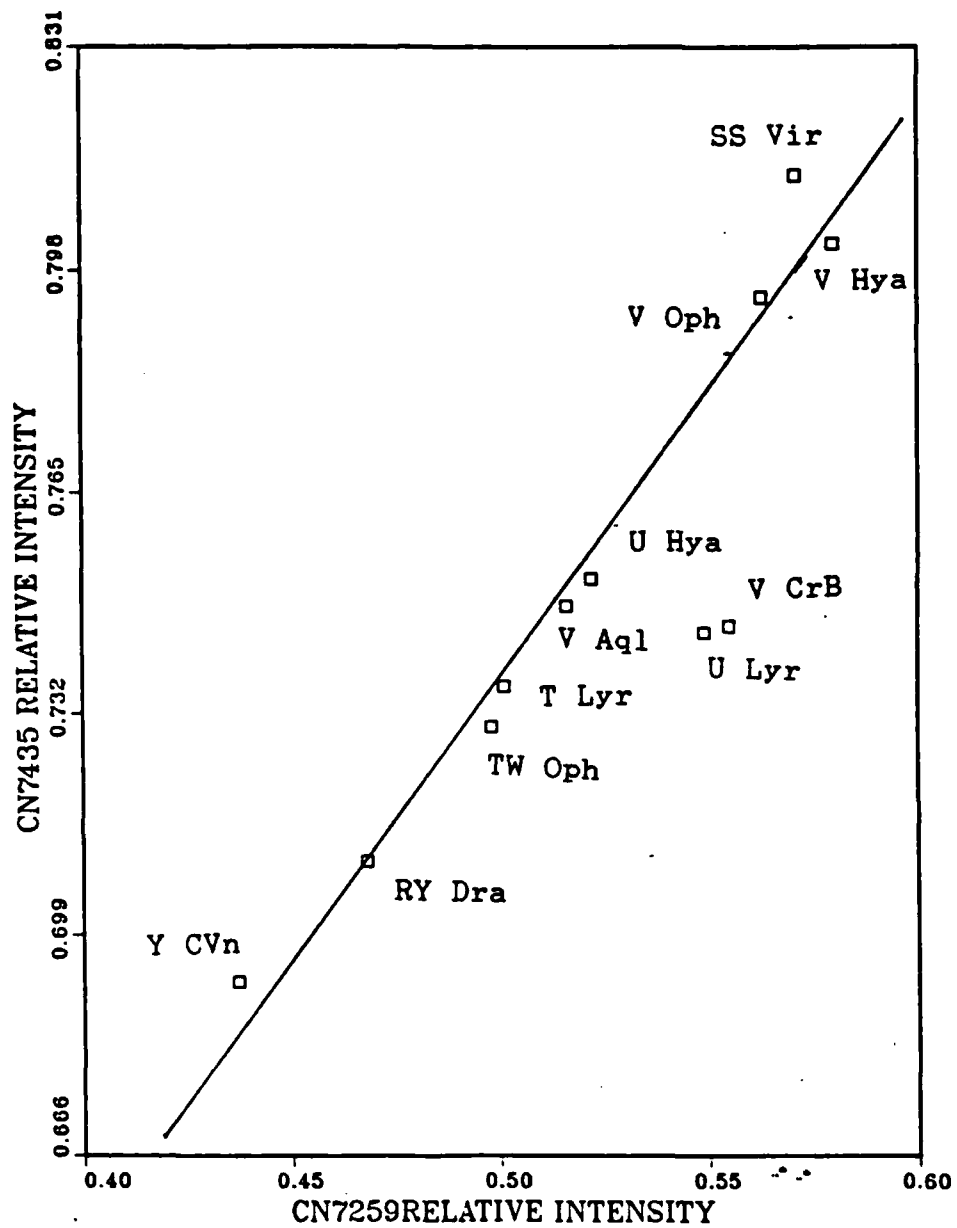


Figure 11

Relative Intensity of the Cn7435 Band Head versus  
Relative Intensity of the CN7259 Band Head

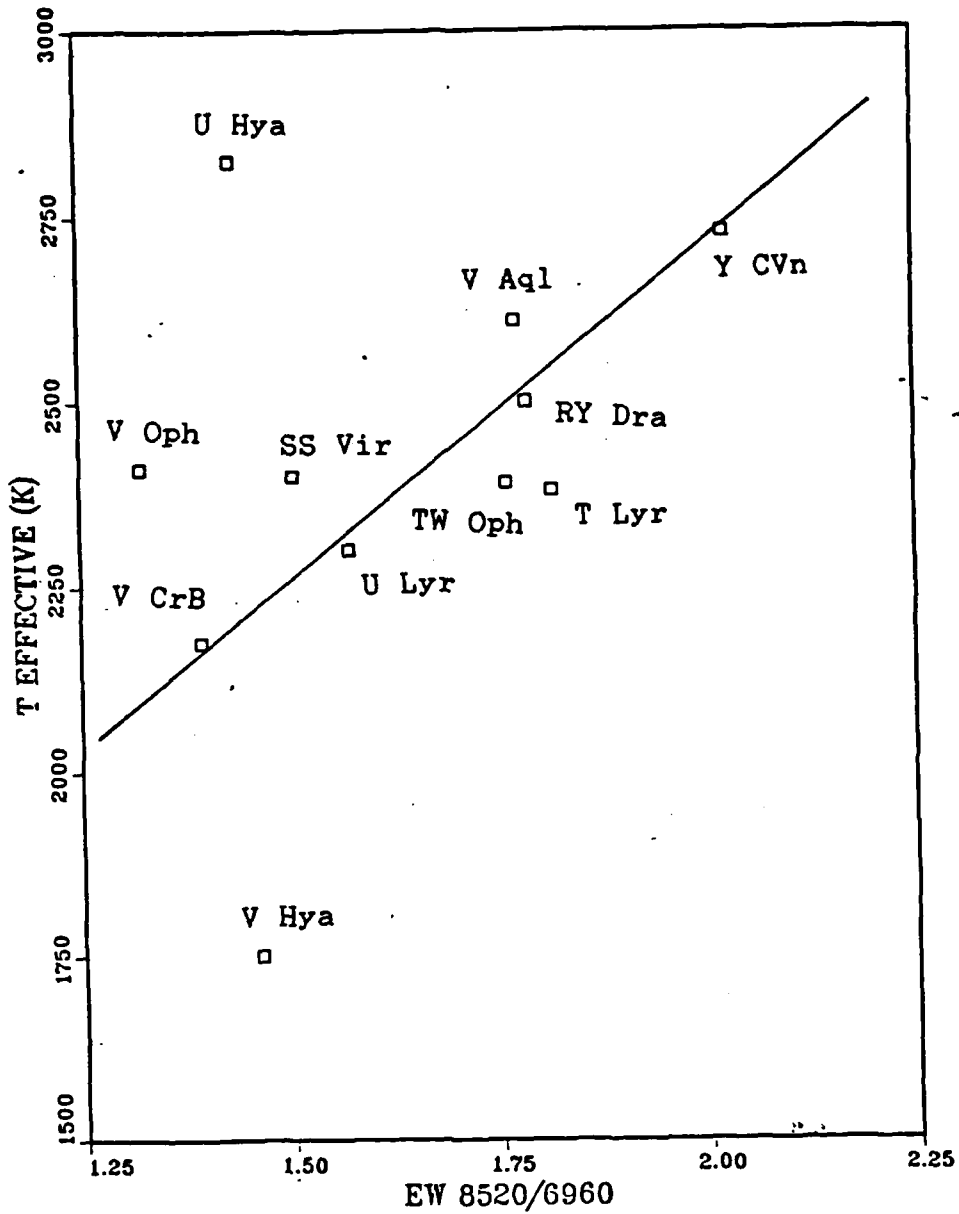


Figure 12

Effective Temperature versus Relative Equivalent Width Ratio of 8520A/6960A

1. The true continuum is equal to or above the pseudo-continuum. This lower pseudo-continuum yields lower EW's and the amount of reduction is dependent upon the location and breadth of the region considered.
2. The reduction program for this analysis used a straight line to approximate the continuum for any equivalent width. Due to the extremely large size of the intervals in this study, on the order of 100 or more Angstroms, this led to large EW values with errors approaching 20%.

Therefore, the ratio of the equivalent widths as a means of classification requires further investigation and should be calculated using known stars, i.e. standard stars, and with a data base of more than these stars.

#### E. CONCLUSIONS AND RECOMMENDATIONS

The evaluation of the two classification systems indicates agreement with Tsuji(1981) and Fujita(1970) that the Keenan and Morgan system requires substantial revision. Good agreement with the system proposed by Richer (Richer, 1971) was found for a majority of stars. However, a revision of the entire carbon star classification system is recommended as a result of improvements in the accuracies of the effective temperature measurements. Using the method proposed by Tsuji(1981), temperatures need to be recalculated for those stars with measured IR fluxes.

The correlation between CN strength and  $T_{\text{eff}}$  needs to be analyzed in greater detail using a much larger data base (50 to 100 stars). In addition, since 80% of the N-type stars are variables, an in-depth study of a few stars over

their entire cycle needs to be conducted to determine the effect of variability on this correlation.

The equivalent width measurements need to be verified using stellar models of varying abundances and black body functions. Until this is done, it would be premature to use this method of classification.

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APPENDIX A

OBSERVATION LOG

<u>Star</u>	<u>Date</u>	<u>Time(sec)</u>	<u>Hour Angle</u>
Y CVn	2-22-85	180	00h 32m
U Hya	4-19-85	60	00h 35m
V CrB	5-12-85	600	02h 25m
	5-15-85	1200	00h 50m
	5-28-85	300	01h 50m
RY Dra	5-12-85	120	04h 29m
SS Vir	5-12-85	500	03h 04m
TW Oph	5-15-85	300	01h 24m
T Lyr	5-15-85	600	00h 37m
V Oph	5-15-85	600	01h 54m
V Hya	5-15-85	900	02h 43m
V Aql	5-28-85	200	00h 15m
U Lyr	5-28-85	300	00h 31m

<u>Standard Star</u>	<u>Date</u>	<u>Time(sec)</u>	<u>Hour Angle</u>
$\alpha$ Leo	2-22-85	5	03h 45m
$\alpha$ Leo	4-19-85	10	01h 36m
$\alpha$ Leo	5-12-85	7	02h 30m
$\alpha$ Leo	5-15-85	20	02h 02m
Vega	5-28-85	2	00h 13m

Grating used: 150 line/MM blazed for 5500A.

Grating tilt set at 3° for all observations.

STELLAR DATA

<u>Star</u>	<u>HD</u>	<u>DM</u>	<u>IRC</u>	<u>GCCCS</u>
U Hya	92055	-12 3218	-10242	1714
V Hya	*	-20 3283	-20213	1766
SS Vir	108105	+01 2694	+00217	1999
Y CVn	110914	+46 1817	+50219	2030
RY Dra	112559	+66 780	+70116	2047
V CrB	148182	+40 2929	+40273	2293
V Oph	148182	-12 4510	-10339	2334
TW Oph	158377	-19 4644	-20364	2449
T Lyr	*	+36 3168	+40321	2608
V Aql	177336	-05 4858	-10486	2695
U Lyr	*	+37 3418	+40345	2724

\* Data not given.

HR Henry Draper Catalogue Number  
 DM Durchmusterung Number  
 IRC Infra-Red Number  
 GCCCS General Catalog of Cool Carbon Stars

Data from Hirshfield and Sinnott(1982, 1985) and  
 Stephenson(1973).

STELLAR DATA (contd)

<u>Star</u>	<u><math>\alpha</math></u>	<u><math>\delta</math></u>	<u>l</u>	<u>b</u>	<u>VR</u>
U Hya	10H37M33	-13° 23' 04	259.97	+38.07	-25
V Hya	10H51M37	-21° 51' 00	268.96	+33.60	-15
SS Vir	12H25M19	00° 47' 44	288.46	+62.93	+3
Y CVn	12H45M08	45° 26' 25	126.47	+71.64	+12
RY Dra	12H56M26	65° 59' 37	122.13	+51.12	-20
V CrB	15H49M	39° 34'	63.28	+51.23	-115
V Oph	16H26M	-12° 26'	2.97	+24.52	-48
TW Oph#	17H23M50	-19° 23' 36	6.11	+ 8.11	*
T Lyr	18H32M	37° 00	63.34	+19.49	-21
V Aql	19H04M24	-05° 41' 06	29.33	- 5.47	+37
U Lyr	19H20M	37° 53'	69.99	+11.08	*

\* Data not given.

# . 1900 epoch for  $\alpha$  and  $\delta$ .

$\alpha$  Right Ascension for epoch 2000

$\delta$  Declination for epoch 2000

l Galactic longitude (°)

b Galactic latitude (°)

VR Rotational velocity

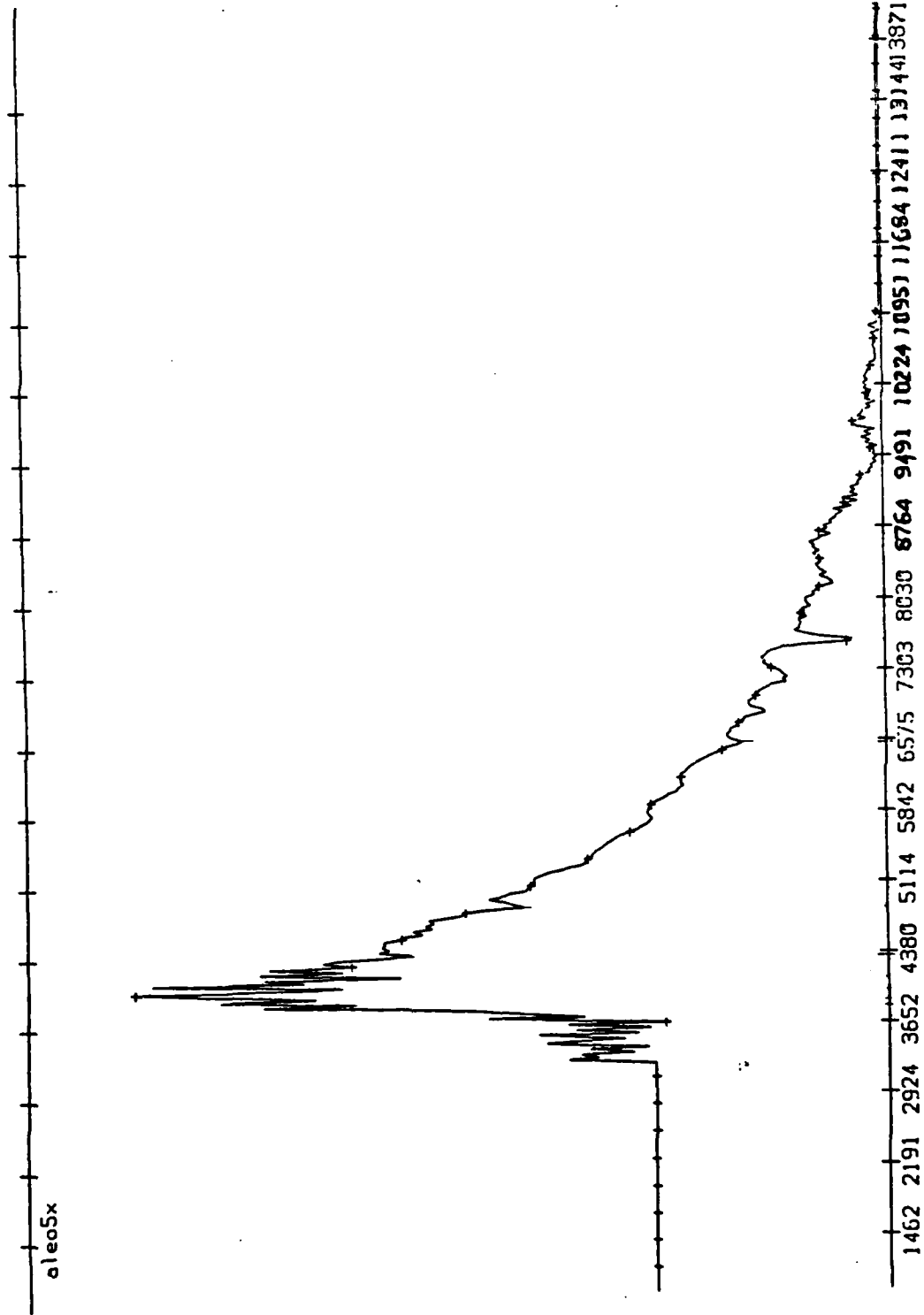
## Spectral Type Table

<u>Star</u>	<u>System</u> <u>Keenan &amp; Morgan</u>	<u>Richer</u>
U Hya	C7,3	C5,II
Y CVn	C5,4	C7,I
V Aql	C6,4	C6,II
RY Dra	C4,4	C7,I
V Oph	C7,4	C5,II
SS Vir	C6,3	C5,II
TW Oph	C6,5	C6,II
T Lyr	C6,5	C8
U Lyr	*	C8
V CrB	C6,3	*
V Hya	C7,5	C9,I

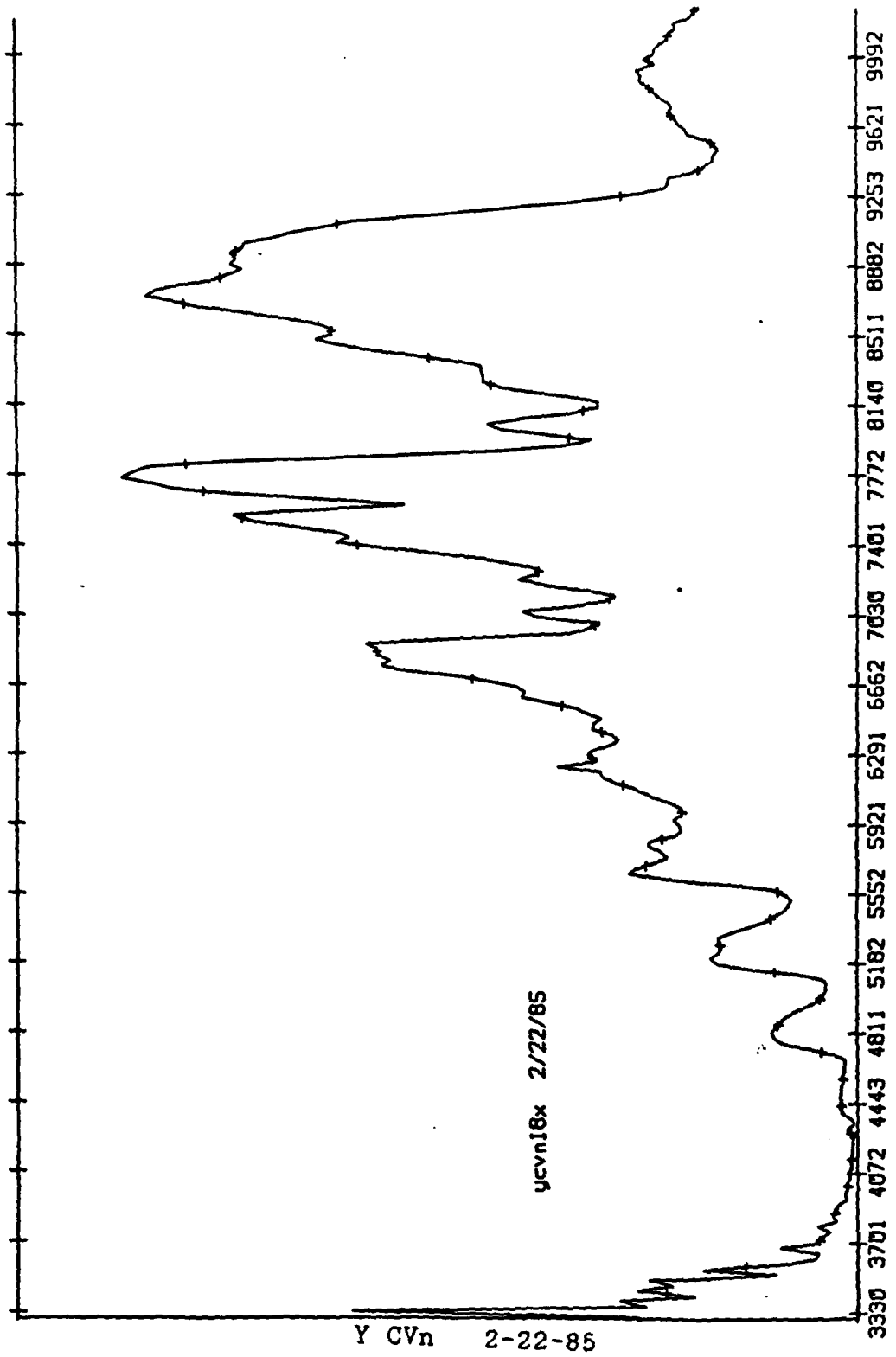
\* No designation given.

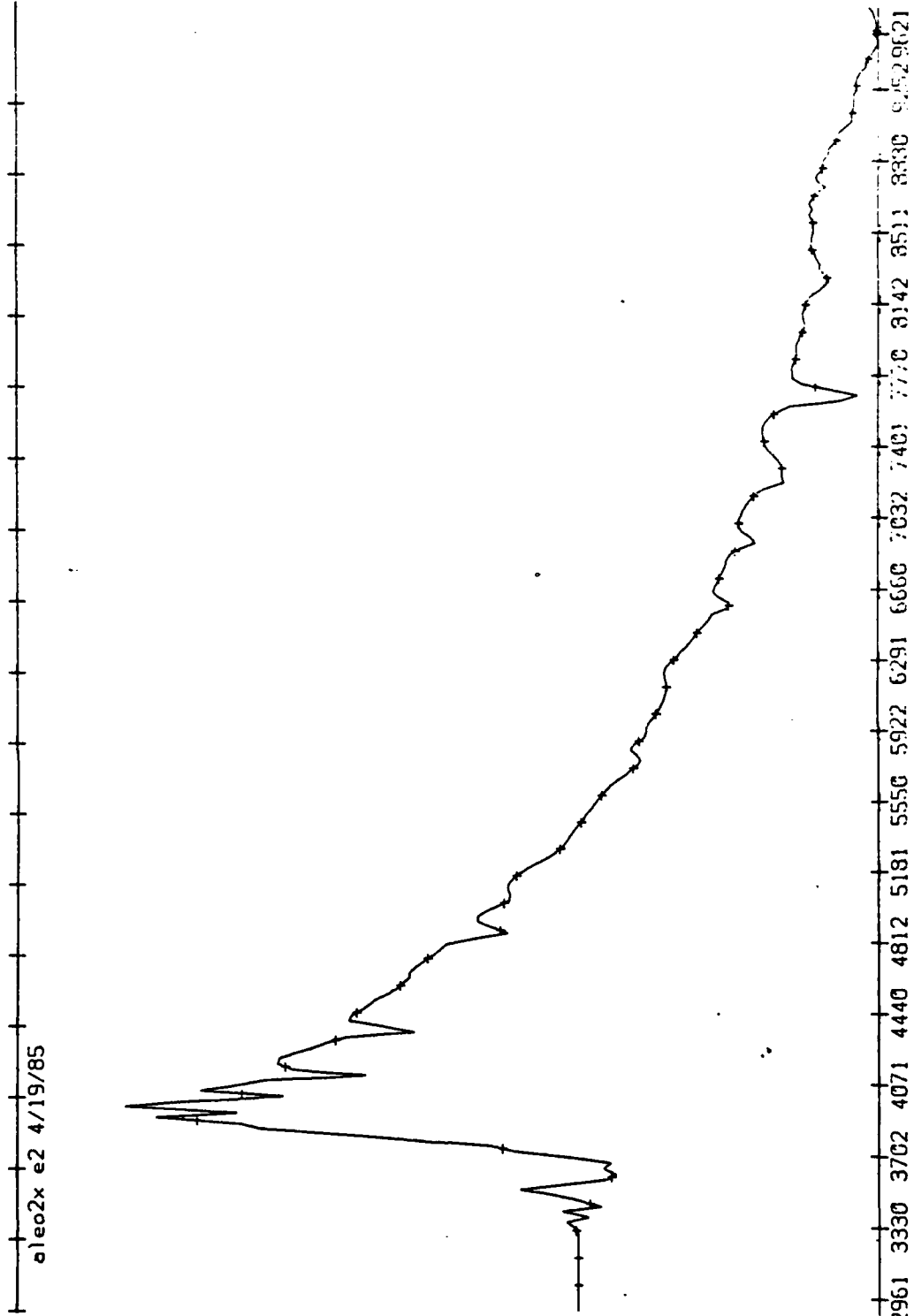
## APPENDIX B

Appendix B contains the stellar spectra arranged according to observation date. The standard star is listed prior to the program stars spectra. The spectra of V CrB (5-15 85) includes the location of the primary band heads noted in this thesis. All spectra are listed with the star name and date. The ordinate axis gives the wavelength in Angstroms, with the abscissa representing the flux.

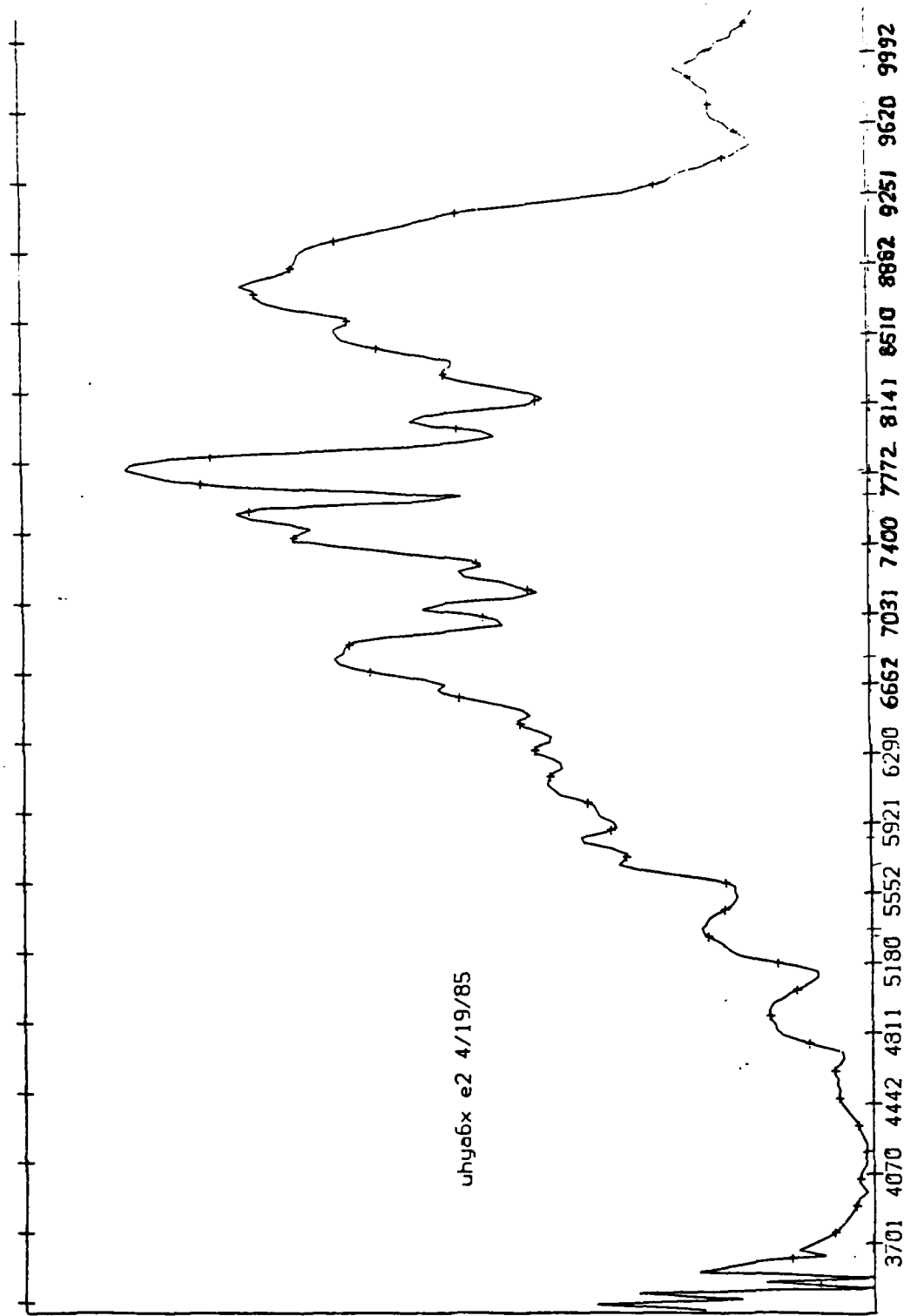


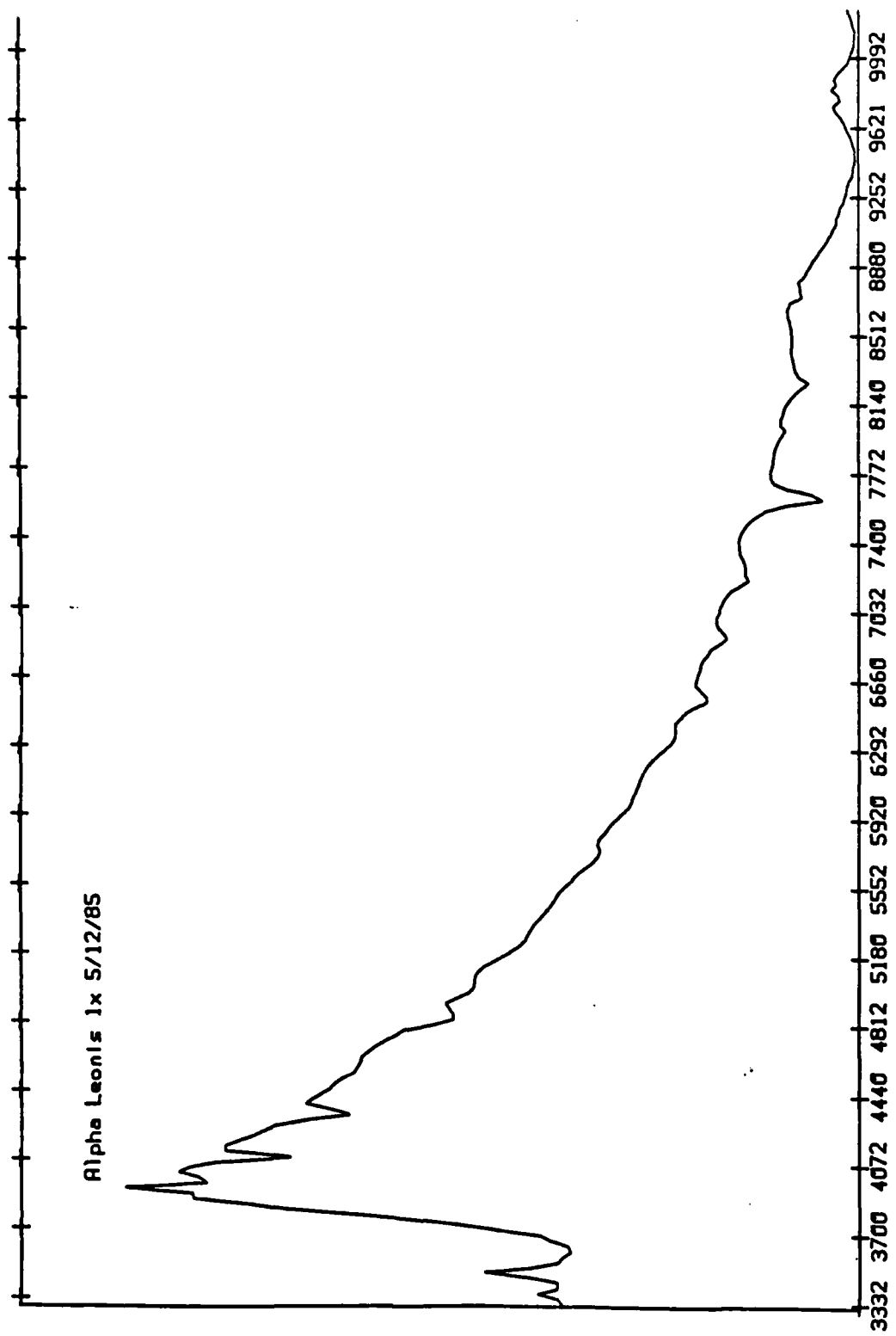
$\alpha$  Leo 2-22-85



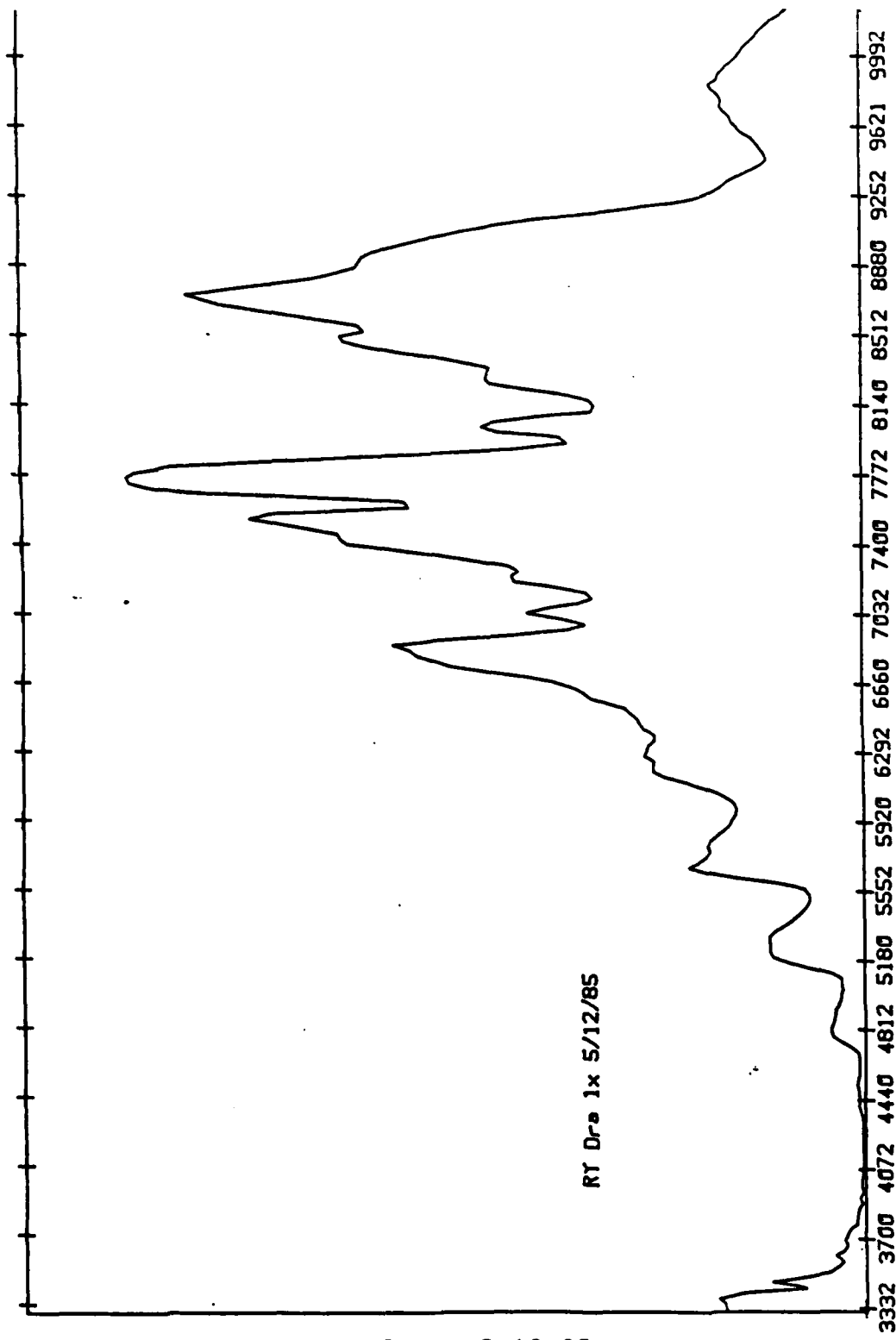


$\alpha$  Leo 4-19-85

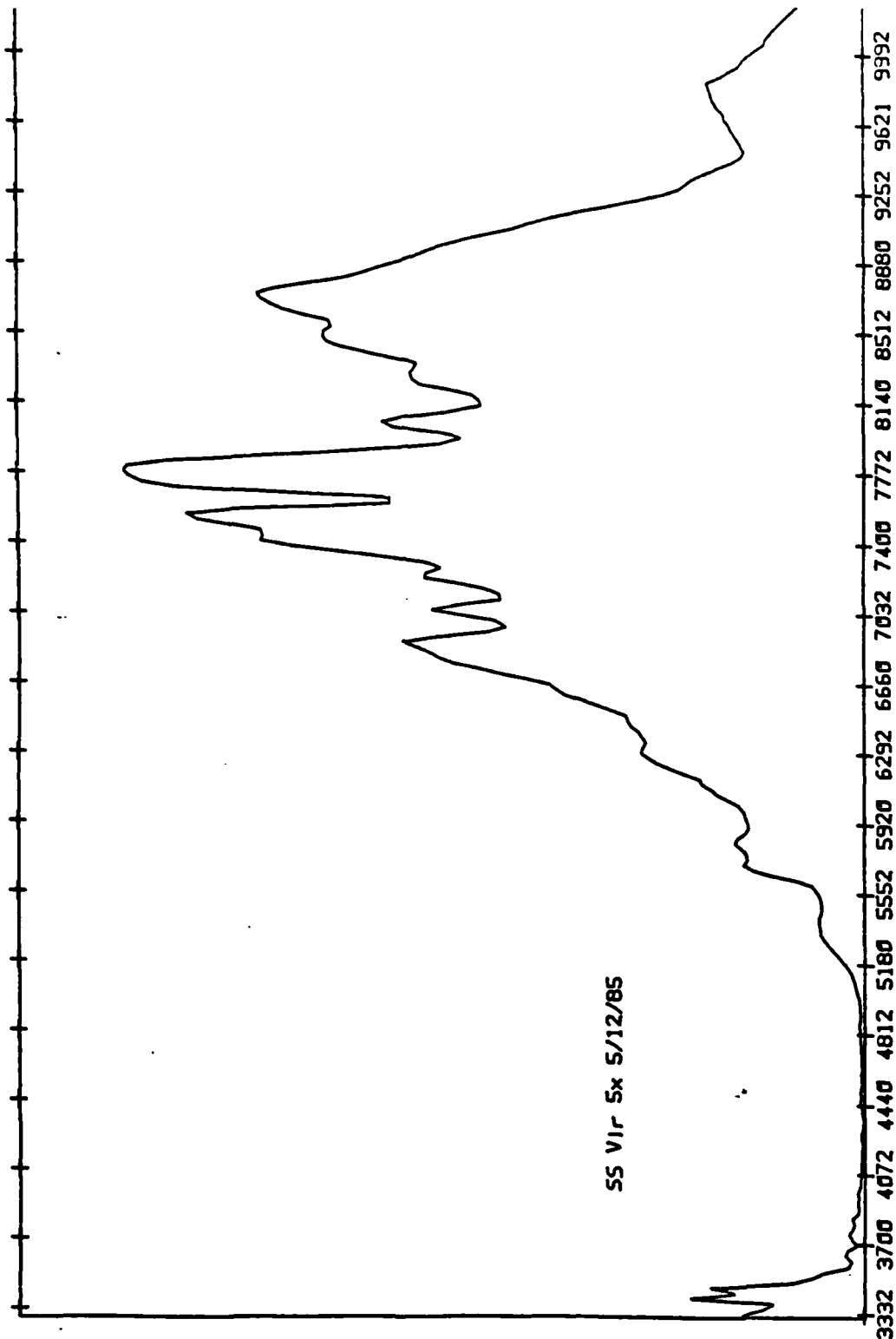




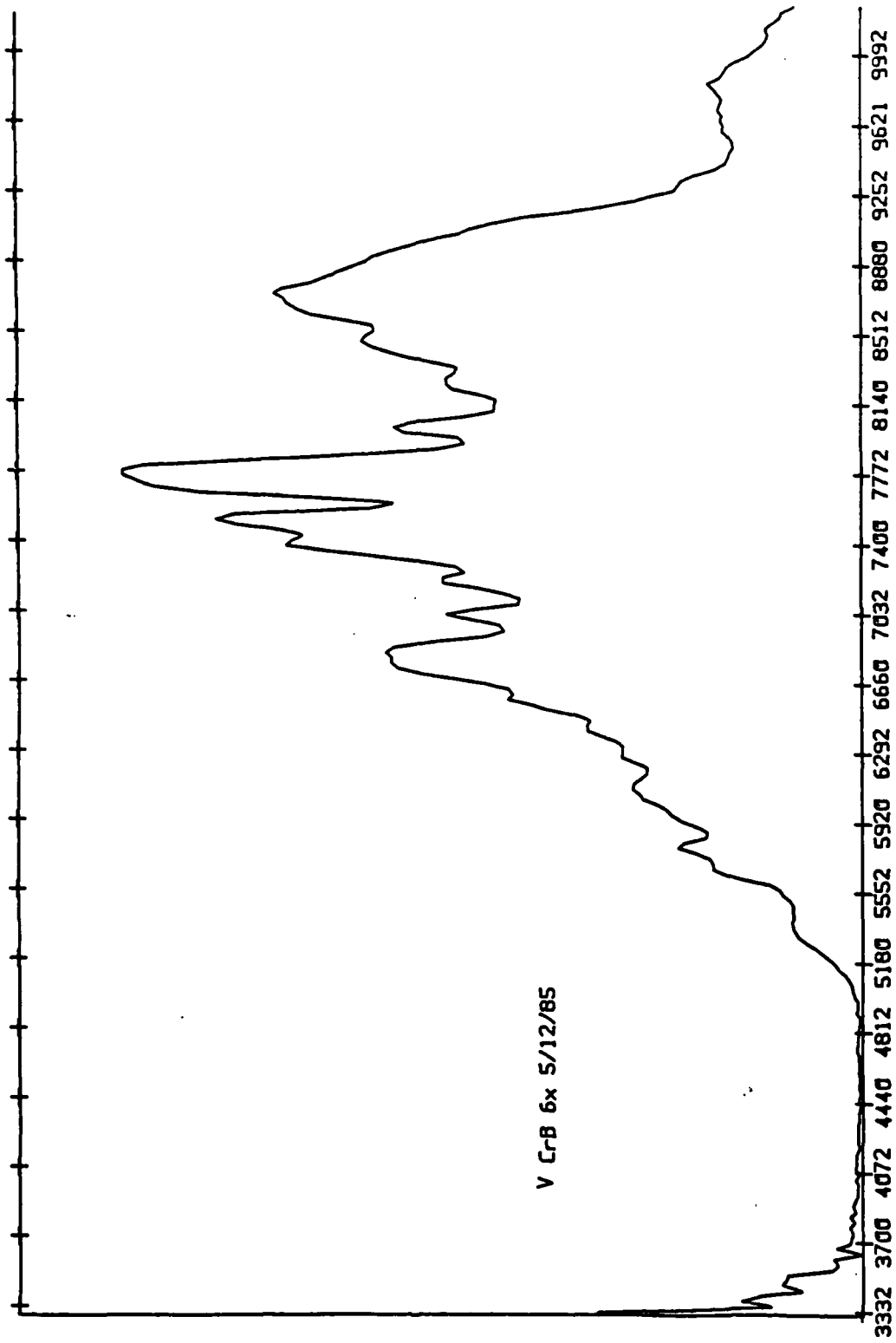
$\alpha$  Leo 5-12-85



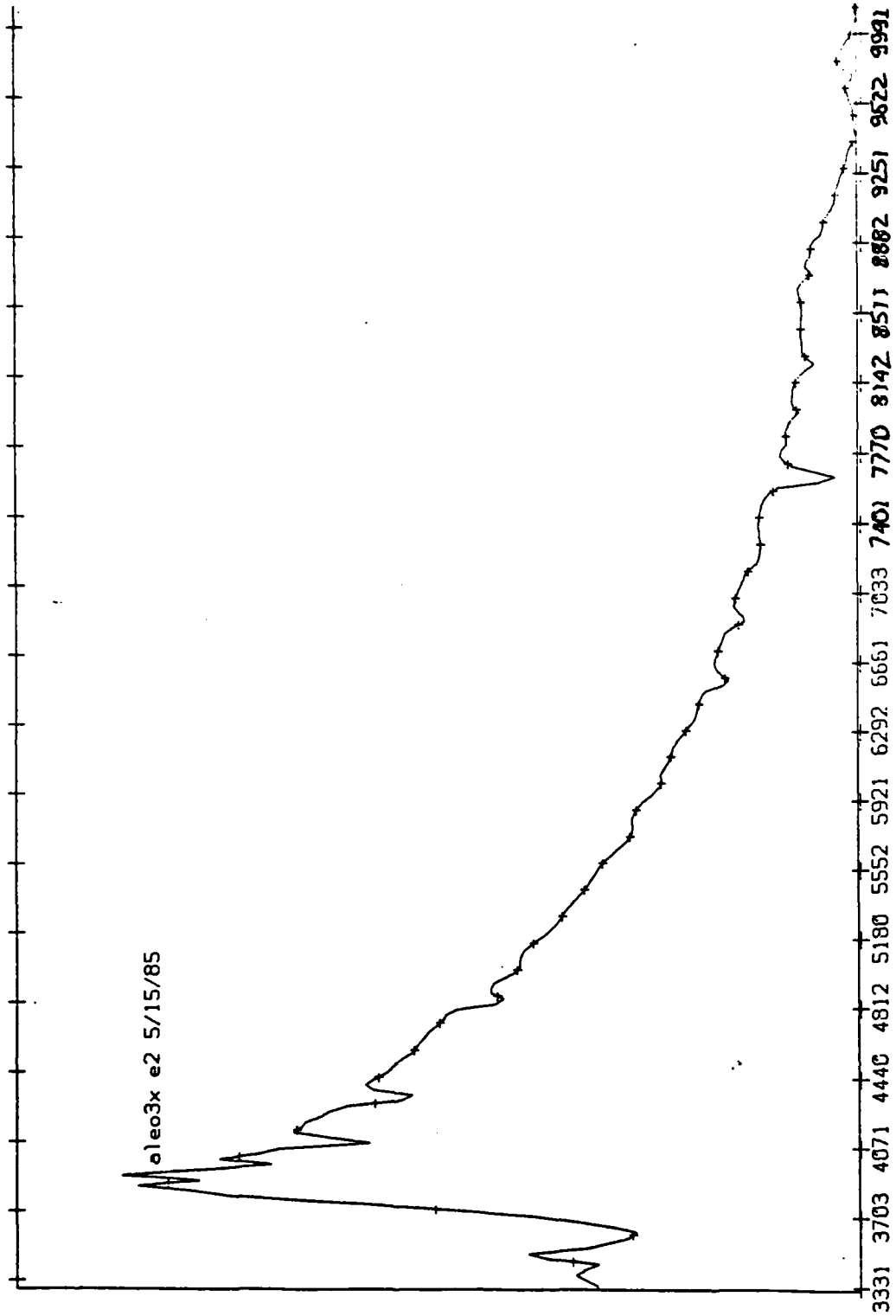
RY Dra 5-12-85



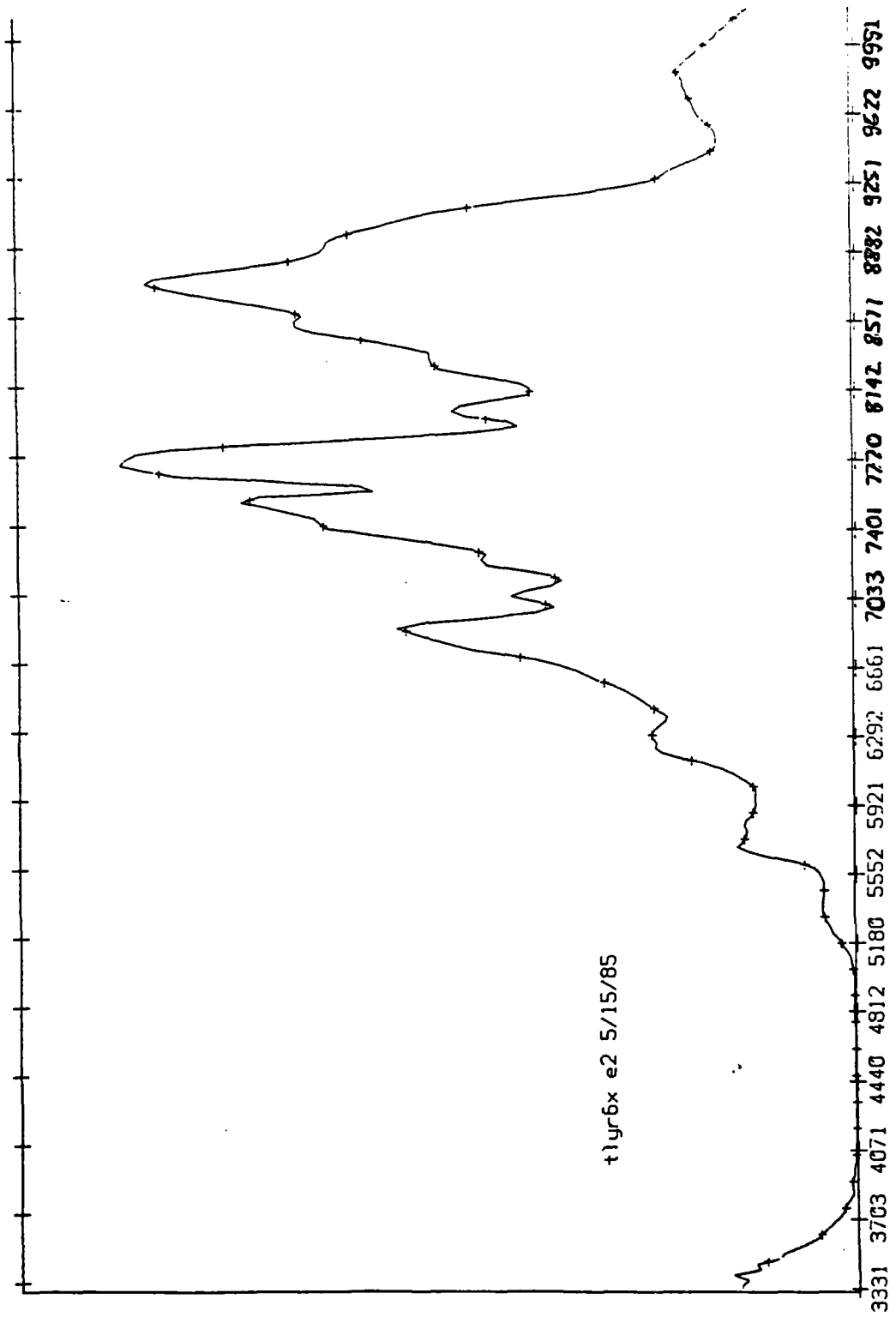
SS Vir 5-12-85



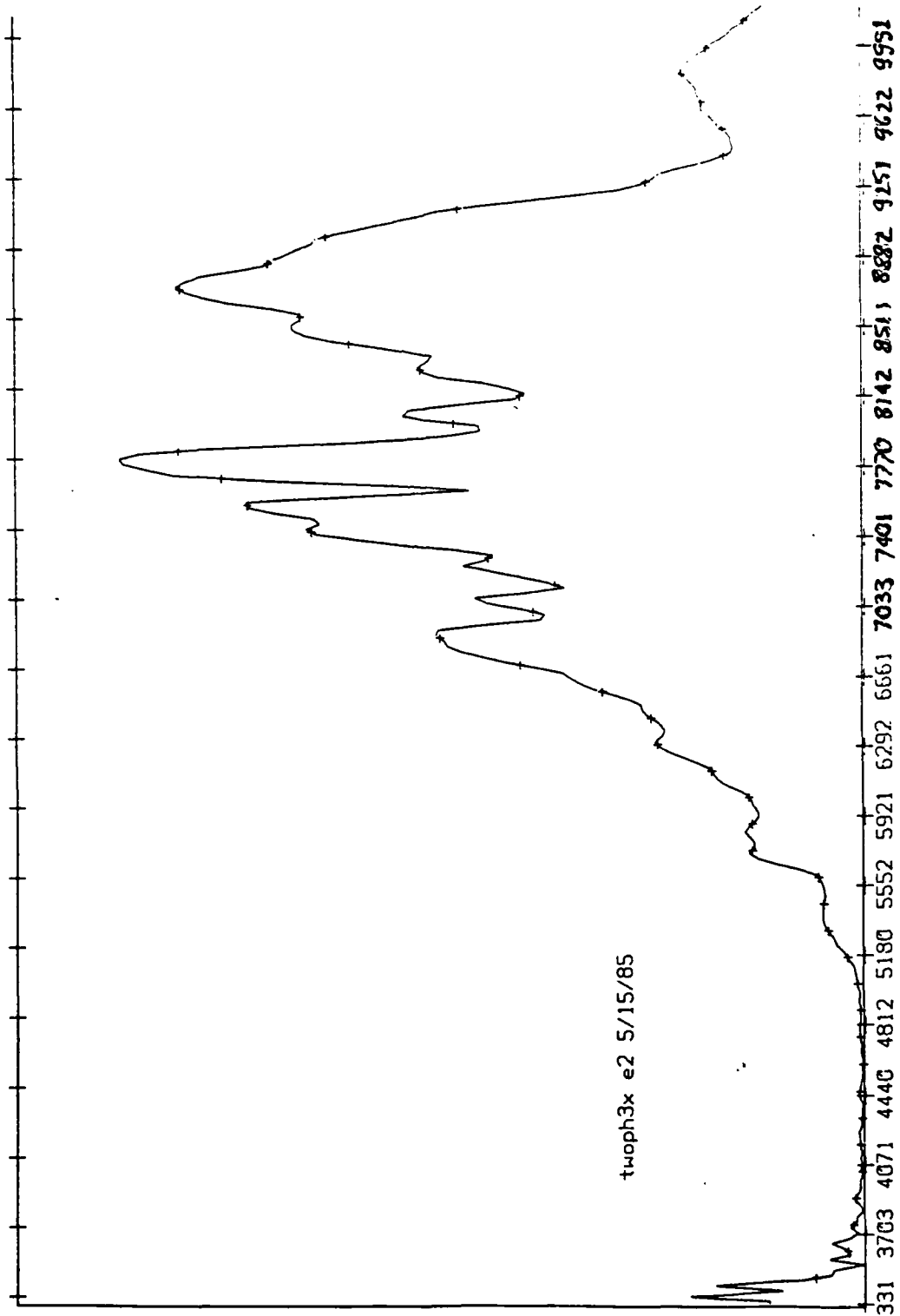
V CrB 5-12-85



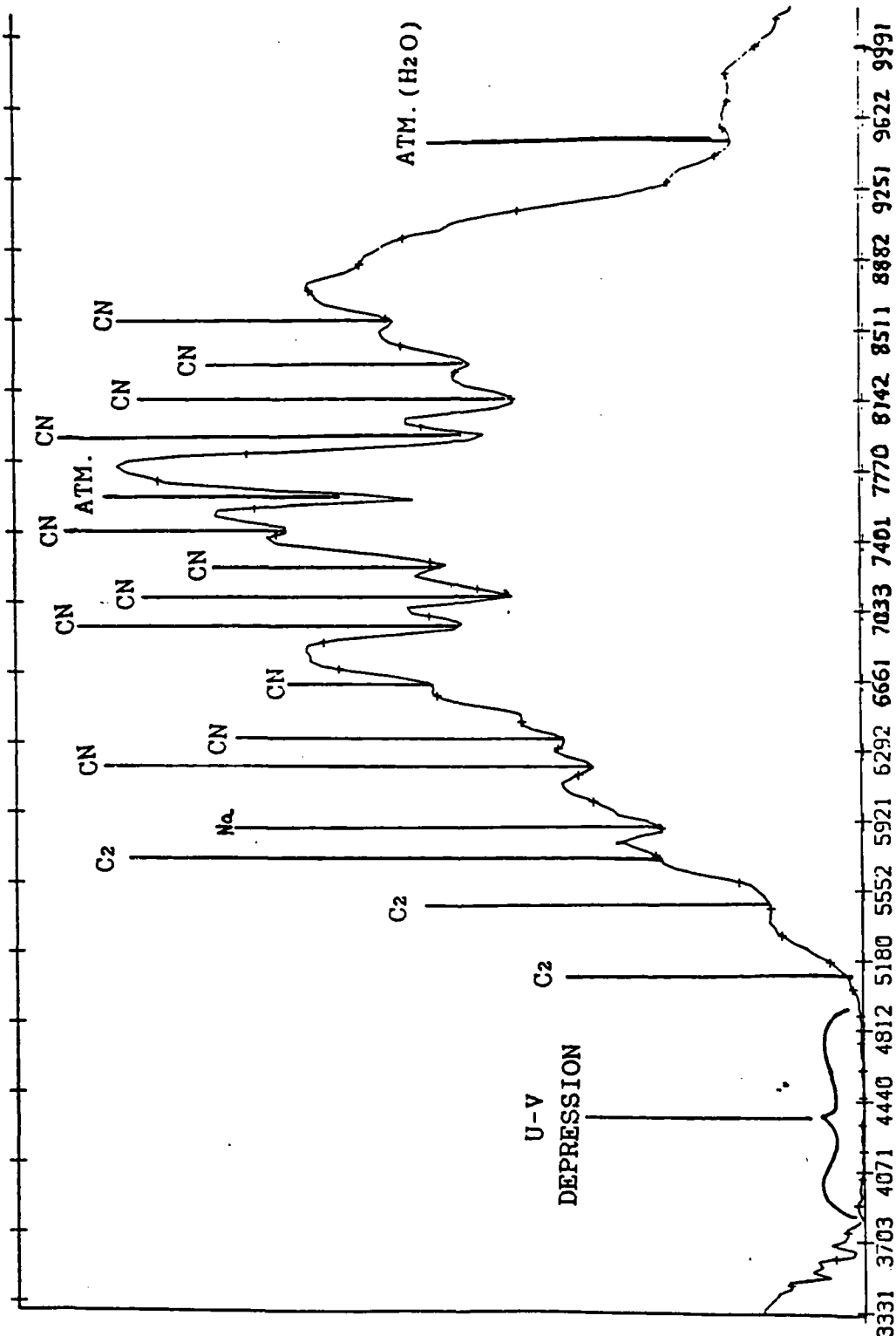
α Leo 5-15-85



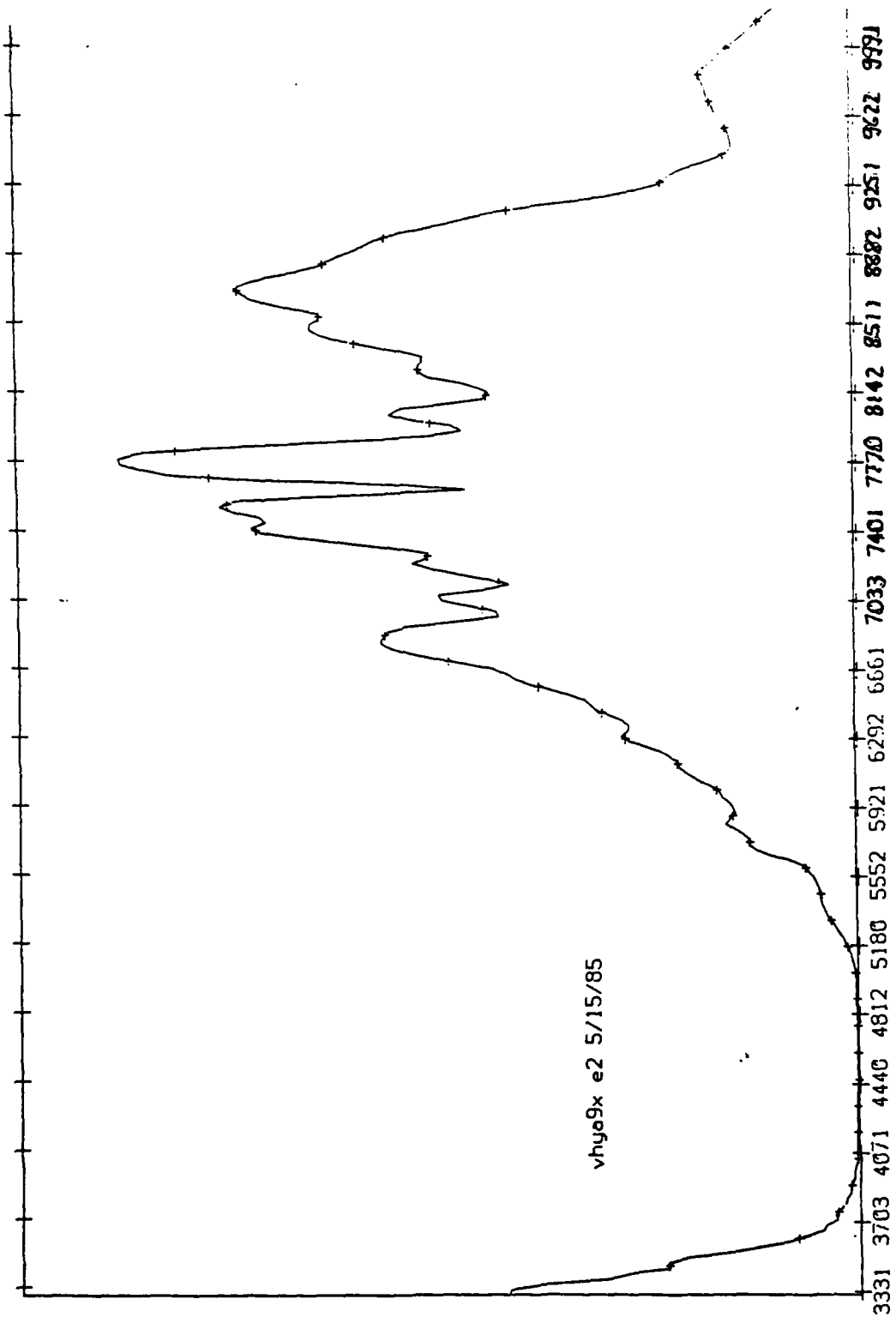
T LYR 5-15-85

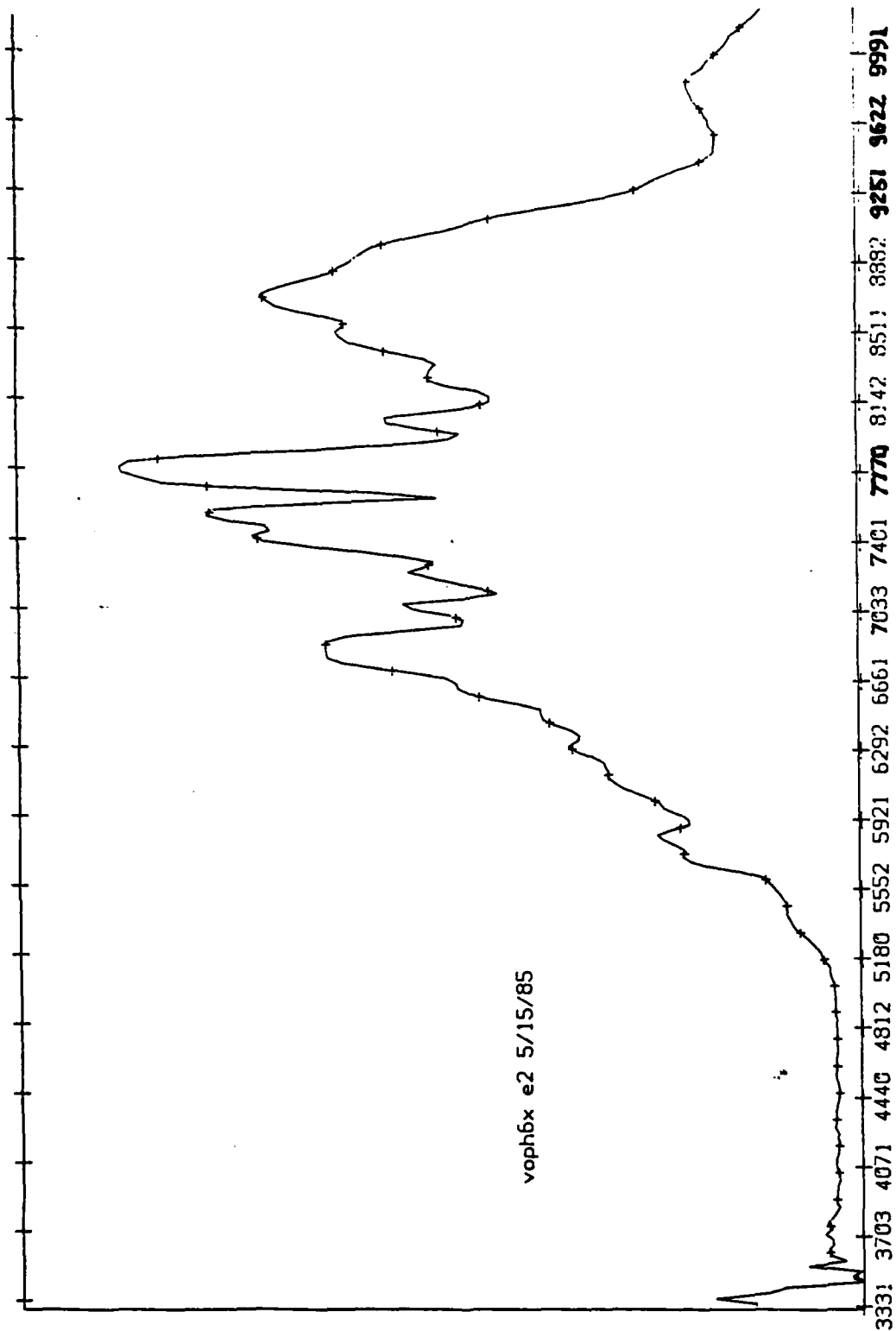


TW OPH 5-15-85

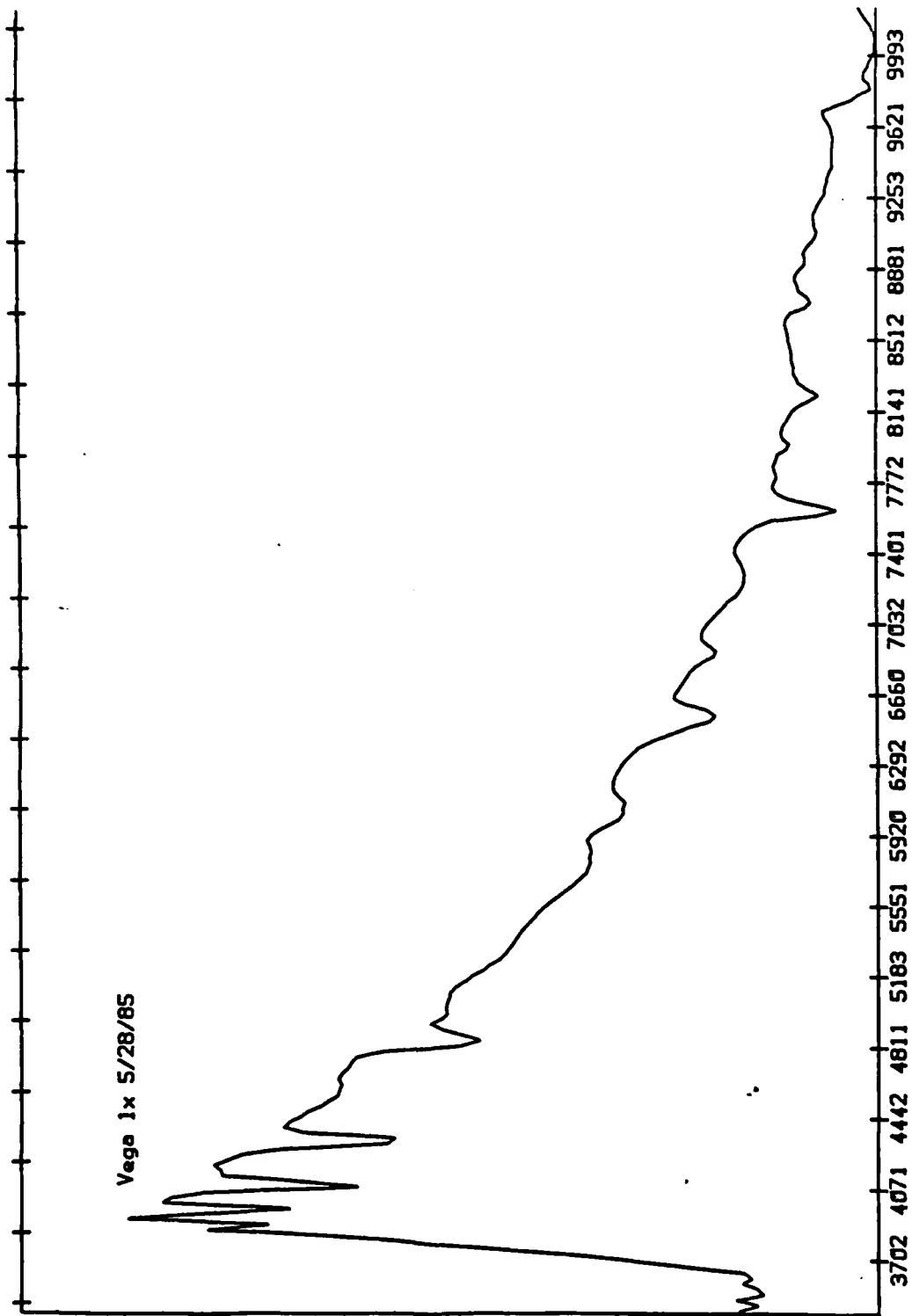


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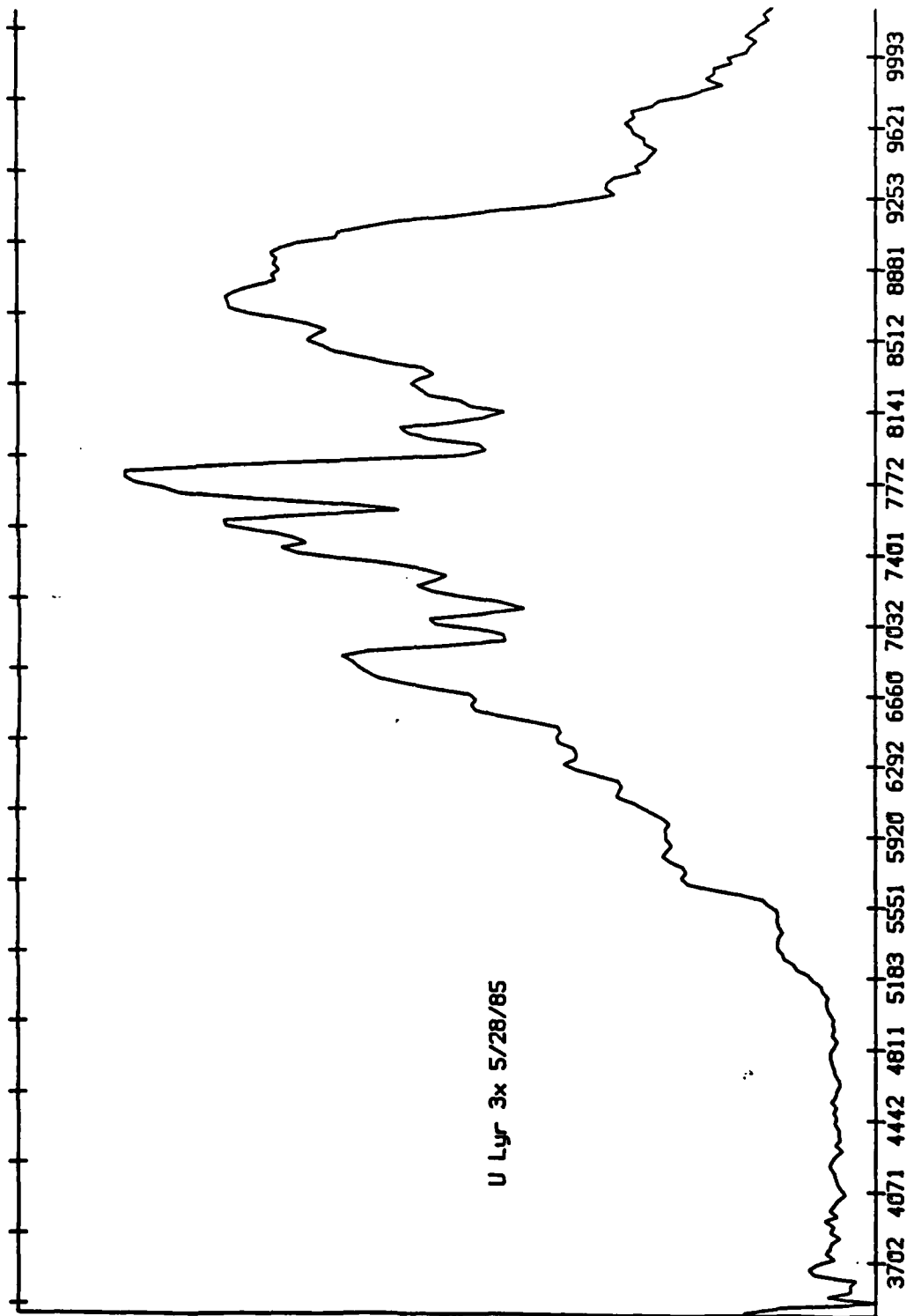




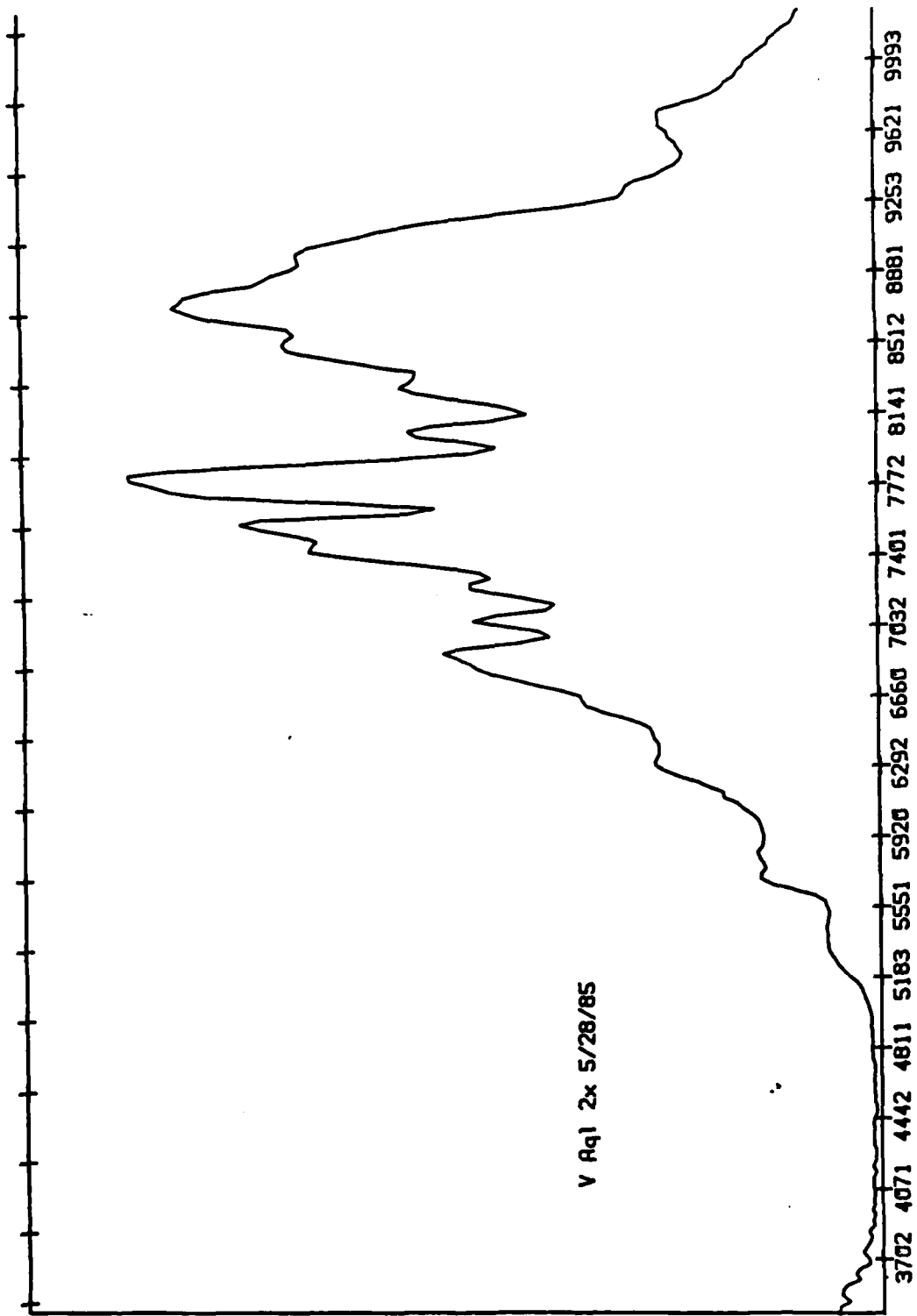
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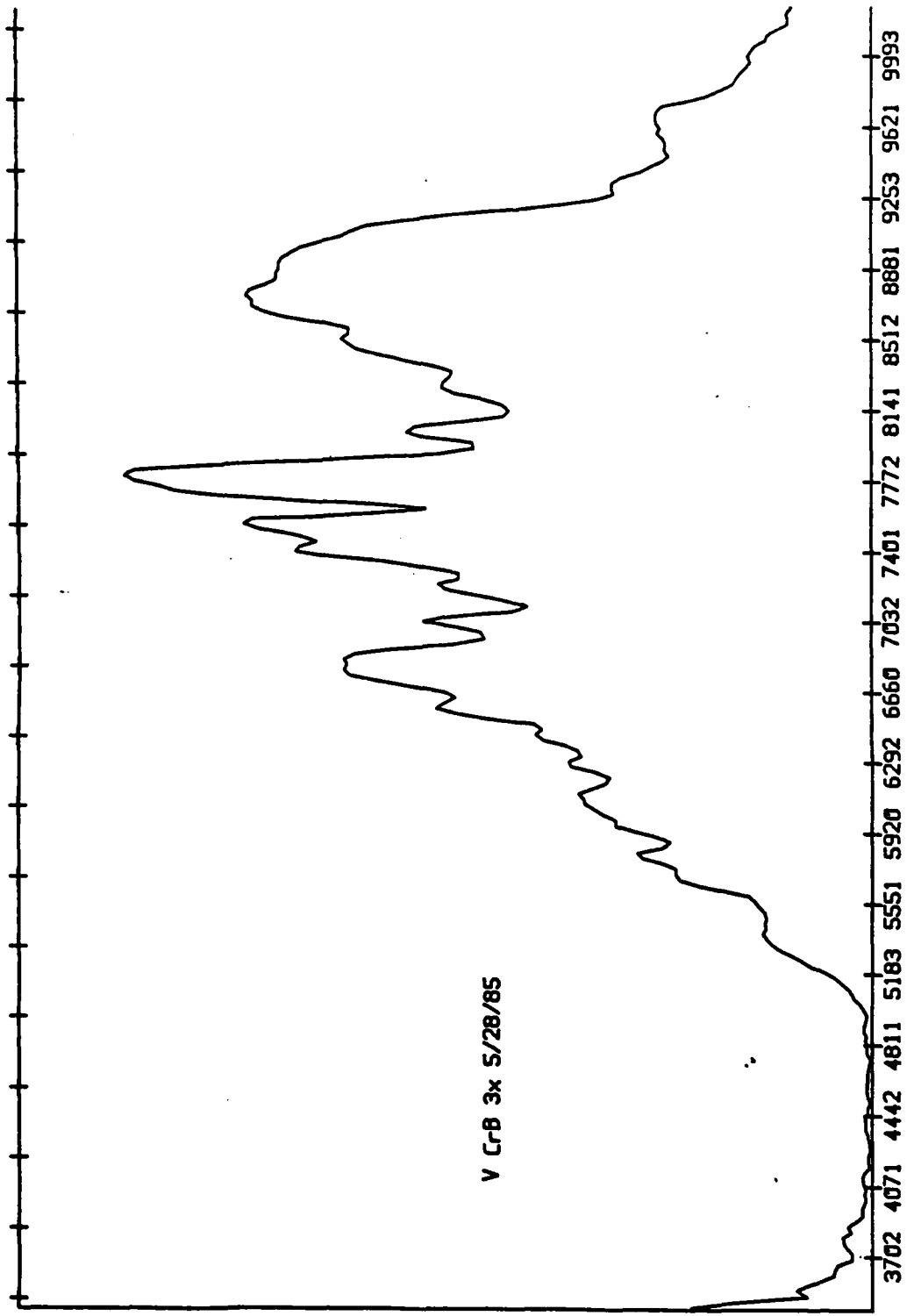
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