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FOURIER TRANSFORM SPECTROSCOPY OF FOUR O-B STARS FROM 4800 TO 10200 Å

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RESUMEN

Se han hecho observaciones de las estrellas O-B de líneas de emisión, ζ Ori, P Cyg, ϕ Per and γ Cas usando el espectrofotómetro Michelson el cual nos dio espectrogramas con precisión fotométrica en el intervalo 4800-10200 Å. La resolución espectral es 3.85 cm^{-1}. Las estrellas P Cyg, ϕ Per y γ Cas muestran un fuerte y poco común Mg II (9217, 9243 Å) en emisión, mismo que no había sido reportado previamente. Nuestros espectros muestran 42 líneas que no han sido identificadas y que han aparecido asociadas a espectros de novas y nebulosas planetarias. 33 de estas líneas se observan en P Cyg y sólo 4 de estas líneas se presentan en ζ Ori. Muchas de ellas se deben a Fe II.

ABSTRACT

We have made new observations of the O-B emission line stars ζ Ori, P Cyg, ϕ Per, and γ Cas using a Michelson Spectrophotometer which gave us photometrically precise spectra in the 4800-10200 Å range. The spectral resolution is 3.85 cm^{-1}. The stars P Cyg, ϕ Per, and γ Cas show an unusually strong Mg II doublet (9217, 9243 Å) in emission, which has not been previously reported. Our spectra show forty-two unidentified lines previously associated with nova-like and planetary nebulae spectra. Thirty-three of these lines are observed in P Cyg, and only four of these lines are present in ζ Ori. Many are due to Fe II.

Key Words: **INFRARED SPECTRA — LINE IDENTIFICATIONS — SPECTROPHOTOMETRY — STARS, EARLY TYPE — STARS, EMISSION LINES.**

I. INTRODUCTION

Two excellent reviews of the complex changes in the optical spectra of O-B emission-line stars have been written by Underhill (1960-1966). One of her conclusions is thas it would be very useful to monitor these spectra over long periods of time to obtain a better understanding of the dynamics and physical conditions in their changing envelopes. The 6500 to 8800 Å spectral regions of these stars has been observed at relatively low spectral resolution during the past 40 years by a number of workers, who found that the H I, He I, O I and Ca II lines vary in appearance and strength from star to star, and from time to time, in a most interesting way.

Andrillat and Houziaux (1967) published prints of spectra of Be stars, including P Cyg, ϕ Per and γ

Cas, at wavelengths between 6500 and 8800Å. They gave extensive references to previous work. Slettebak (1951) made observations in 1949-1950 of the 7774 and 8446 Å O I lines of P Cyg and ϕ Per. He found that both stars had intense 8446 Å in emission. The apperance of the 7774 Å line, however, was quite different because P Cyg showed intense 7774 Å absorption, and ϕ Per, only weak 7774 Å emission. Kitchin and Meadows (1970) recently reexamined the spectra of early-type stars, using dispersions of 40 Å/mm or poorer.

The O I lines of P Cyg appear to be variable with time. De Groot (1968) found from spectra taken in 1943, the 7774 Å line to be present both in emission and absorption, but he did not note emission at 8446 Å. He did not identify the lines near 8446 Å and says that they were blended with weak atmospheric H_2O lines. The appearance of the O I lines in 1943 was so different from that observed in 1950 by Slettebak that time variation seems to be the only explanation.

The behaviour of the O I lines of γ Cas may be as bizarre as those of P Cyg; Slettebak (1951) reported no O I lines in 1950, whereas Hiltner observed O I emmission in 1946 (Hiltner 1947). Furthemore γ Cas has been reported as an X-ray source (Jernigan 1976). Polidan (1976) suggested that the 7000-10000 Å spectral region is optimum for a search for spectroscopic Be binaries.

The spectral resolution of many of the infrared spectra of O-B emission stars has been low (poorer than 6-16 Å/mm) and they were used principally for qualitative comments upon the relative changes and differences among the stars. The limits upon interpretation of the data were imposed by the poor sensitivity and the non-linearity of the photographic emulsions used as detectors, combined with their limited wavelength response (shorter than 8800 Å). Burbidge and Burbidge (1955) commented on the lack of equivalent width measurements; they gave equivalent widths for six Paschen lines in P Cyg. Merrill and Wilson (1934) measured relative central intensities (only) for a number of Paschen lines in P Cyg and γ Cas.

Polidan and Peters (1976) recently completed a study of Be star spectra obtained at dispersions of 25-35 Å/mm. Progress in the interpretation of these spectra has been made despite the lack of extensive precision spectrophotometry at Coudé resolution. For example, Bowen (1947) qualitatively interpreted the bizarre O I line behaviour as due to a flourescence of the 8446 Å line by the Lyman beta radiation field. This early work was confirmed by Kitchin and Meadows (1970). This proposed association between the far UV and near IR spectra is of current interest because of the fact that at least two Be stars are now known to be X-ray sources. Keenan and Hynek (1950) discussed the O I line problem in some detail, including the importance of the 7774 Å line as a luminosity indicator in stars of spectral type B5-G0.

Mihalas and Athay (1973) provided a general review of the effects of departures from local thermodynamic equilibrium upon stellar spectra. They concluded that non-LTE effects become very large for lines in the near infrared region, even for infrared helium lines in normal B stars. They also pointed out some of the difficulties in quantitatively demonstrating detailed flourescence mechanisms in very hot stellar atmospheres. These difficulties are compounded if the outer stellar envelope is non-spherical and dynamic. Rapid stellar rotation can cause such effects.

Both quantitative observations and detailed models are needed to understand better the unusually complex spectra of the emission-line O-B stars. We report here a study of the near infrared spectra of two shell-stars, γ Cas and ϕ Per, the B1pe supergiant, P Cyg, and the O9.5 supergiant, ζ Ori. All four stars have at least some spectral lines in emission. These spectra were observed at 3.85 cm^{-1} resolution with a Michelson Spectrophotometer system (Johnson 1977*a*, 1977*b*). These photometrically precise spectra should encourage development of more detailed models.

II. INSTRUMENTATION

The Michelson interferometer that was used to obtain these spectra is the same one described by Johnson *et al.* (1973), considerably modified for the present program. A silicon photo-diode was used as the detector. It has the advantage of a nearly flat response over the wavelength range discussed in this paper, as well as a quantum efficiency of 50 to 90 percent. The scan time of the interferometer was set to 2.8 seconds and it was necessary to add together many interferograms to obtain spectra of the quality we have. The instrument has been described by Johnson (1977*b*). All of these observations were made using the 229 cm telescope of the Steward Observatory, during the month of November 1975.

III. DATA REDUCTION

The procedures used in the reduction of the data are similar to those described by Johnson and Méndez (1970) and Johnson *et al.* (1973). Corrections for the wavelength-dependent atmospheric extinction have been applied to the spectra shown in this paper. The spectra are plotted as linear intensity graphs, versus wave-number in inverse micrometers (lower scale) and nanometers (upper scale).

The linearity of the intensities is guaranteed by the use of a silicon photo-diode as the detector; such diodes are linear over an intensity range of 10^7, or more. The remainder of the equipment has been checked and found to be highly linear (including the analog tape recorder). The corrections for atmospheric extinction were determined by standard photometric techniques; the only differences being that the filters are very narrow, and that there are about 4000 of them. The individual "filters" are not only square-shaped in their bandpasses, but the band edges are maintained as accurately as the HeNe reference laser permits. Therefore, it is possible to assume that the "filters" are fixed in wavelength (and that the wavelength of the center of each "filter" is known) and that extinction coefficients obtained from standard-star observations will accurately represent the extinction for all observed stars. No shifting of the spectra in wavelength is needed to make the filters match.

The width of each square "filter" is 3.85 cm^{-1}, which corresponds to 3.85 Å at 10000 Å and to 0.96 Å at 5000 Å.

The reductions and analyses have been done almost completely by computers. Even the equivalent widths and wavelength measures were made using a special inter-active program which operates on the computer data file; these measures were made, therefore, from the computer data file and were not measured from the plotted tracings. The entire procedure has been described by Johnson (1977*b*).

We have performed a careful analysis of the noise, including point-by-point comparisons of independent spectra of ϕ Per and γ Cas (the sums of the independent spectra are plotted in this paper). Table 1 contains the derived probable errors of our measurements; these errors are given for each star as a function of wavelength and are expressed as a percentage of the stellar flux. Note that the probable errors for all stars are at or near the one percent level over almost all of the wavelength region. These are the probable errors of each individual data point and, because of the method of data reduction, these individual data points are statistically independent.

TABLE 1

PROBABLE ERROR OF NOISE RIPPLE IN PERCENT OF SIGNAL VERSUS WAVELENGTH

Wavelength Å	Star				
	α Cyg (5 Spectra)	ζ Ori	P Cyg	ϕ Per	γ Cas
4 854	0.5	1.6	2.7	1.1	1.1
5 405	0.3	0.9	1.4	0.7	0.7
6 060	0.3	0.8	1.3	0.5	0.5
6 897	0.3	0.8	1.3	0.5	0.5
8 621	0.2	0.7	1.2	0.5	0.5
10 000	0.4	1.3	2.1	0.8	0.8

A comparison of our spectra of α Cyg with that of Hiltner and Williams (1946) is shown in Figures 1 and 2. We have selected two regions of about 100 Å wide for this test: a region around Hα (Fig-

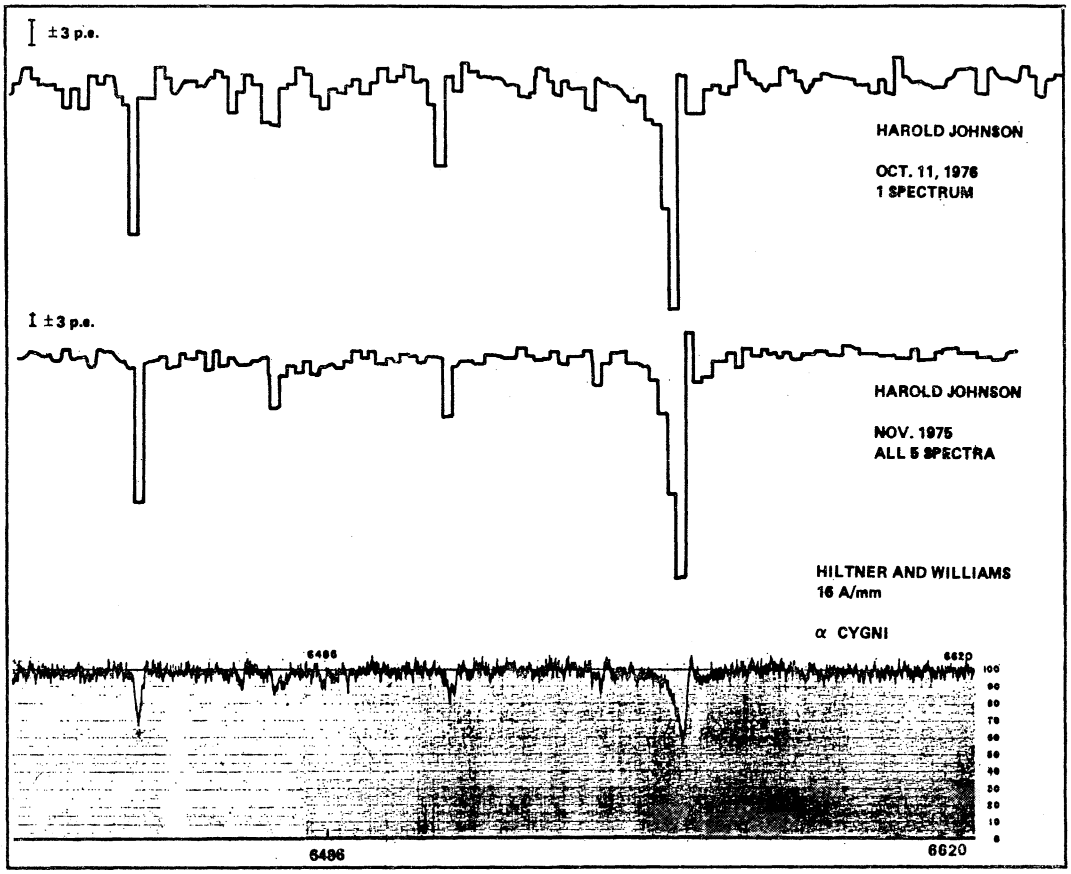

FIG. 1. The Spectrum of α Cyg from 6840-6620Å. The upper two spectra were taken by the Michelson Spectrophotometer System: the lower spectrum is that of Hiltner and Williams, a photographic spectrum at dispersion 16 Å/mm.

ure 1) and one around 5200. Å (Figure 2.) A comparison of spectra at the short wavelength end of our range is more demanding of our data because the response of our spectrophotometer system is poorer at short wavelengths, while the performance of photographic plates is better.

In addition, we compare in Figure 1 a single night's observation of our data with an average of five (other) nights' data to demonstrate how the noise is reduced as we accumulate spectra; the fact that our individual spectral bands are tied to a very accurate laser means that we can add spectra taken many months, or even years, apart without problems. The original dispersion of the spectra of Hiltner and Williams was 16 Å/mm at Hα (Figure 1) and 5 Å/mm at 5200 Å (Figure 2). The spectral features of the Fourier-transform and the photographic spectrophotometry show few differences. (Our spectra are shown as histograms in Figure 1, while a linear interpolation between data points was used in Figure 2.)

A second comparison of data from the Michelson Spectrophotometer is shown in Figure 3. The spectrum of the region of Hβ from the Michelson Spectrophotometer is shown above, while the photographic spectrum of Bohlin (1970) is shown below. The original photographic spectrum had a dispersion of 12 Å/mm. Our spectrum more clearly resolves the double emission peak of Hβ than does the photographic spectrum, and we find that Hβ is narrower at its base than in Bohlin's spectrum. In fact, this wide tail of Hβ on the photographic

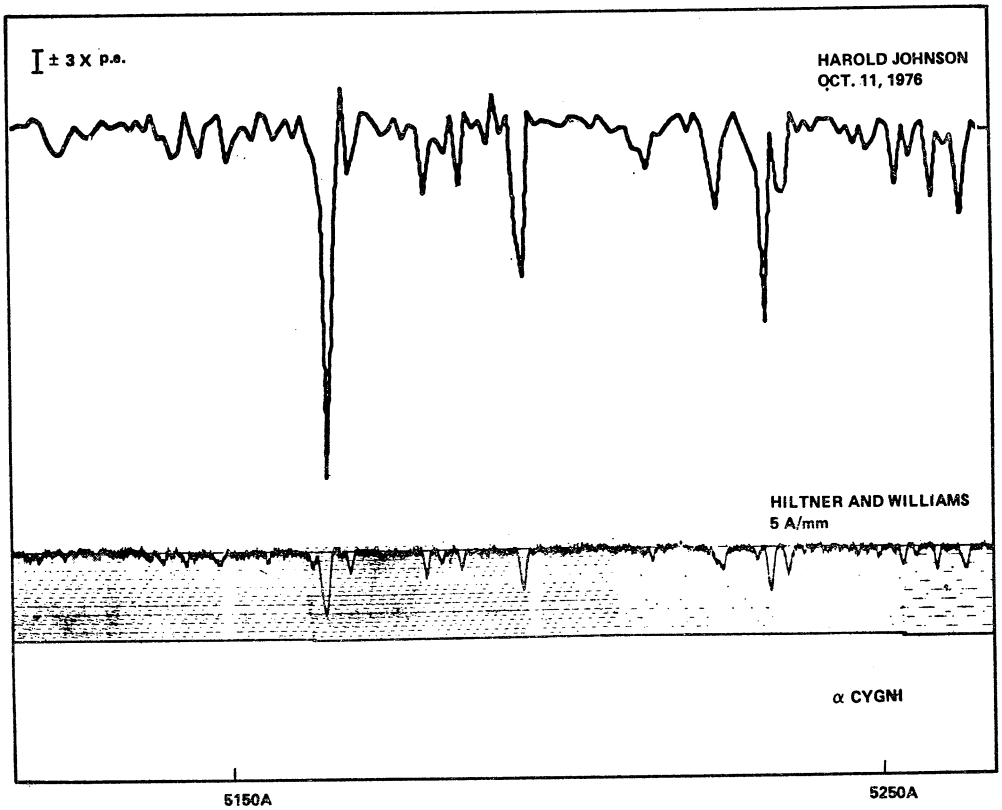

Fig. 2. The spectrum of α Cyg from 5150-5250 Å. The upper spectrum was taken by the Michelson Spectrophotometer System; the lower spectrum is that of Hiltner and Williams, a photographic spectrum at dispersion 5 Å/mm.

tracing obscures the weak, adjacent line of forbidden iron, which is clearly separated from Hβ in our spectrum.

It is clear that the *information content* of our spectra is significantly greater than Bohlin's, at 12 Å/mm, and is comparable with Hiltner and Williams'. Therefore we conclude that our data are comparable to those obtained from coudé spectrographs at resolutions of 6-12 Å/mm.

The reason for the apparent discrepancy between our resolution elements and the commonly quoted resolution of photographic spectra at 12 Å/mm is the improved instrumental profile of the new Spectrophotometer. The long tails of the instrumental profile of a grating spectrograph also are important. Wayte and Ring (1977) state that there is at least a factor of 3 or 4 in favor of the Michelson Spectrophotometer.

IV. MEASUREMENTS

a) *Types of Measurements*

Two types of measurements were made from our spectra: 1) wavelength measures for the purpose of line identifications, and 2) equivalent width measures of selected strong lines (cf. Table 3). In both cases, the accuracy of measurement is limited by line blending; part of this blending is due to instrumental blending and part to blending of the stellar lines themselves. Our stated resolution corresponds to a velocity resolution of 100 km/sec at 10000 Å, and 50 km/sec at 5000 Å. Such a velocity resolution is adequate for identifications, because the rotational velocities of γ Cas and ϕ Per are larger than 300 km/sec.

The spectra of P Cyg, γ Cas and ϕ Per are shown in Figures 5, 6 and 7. All three spectra show com-

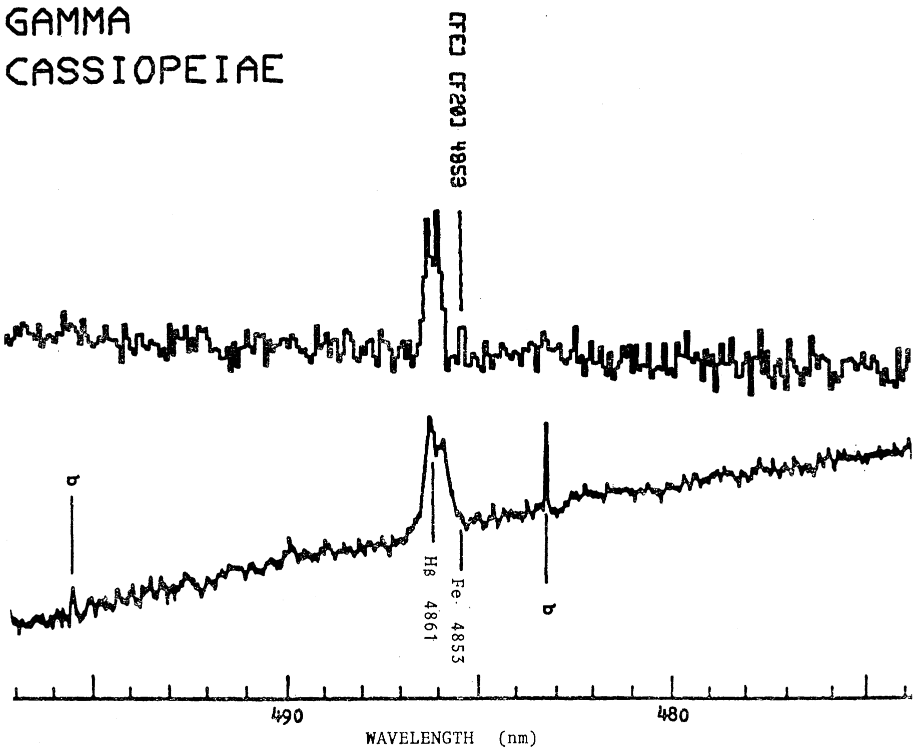

FIG. 3. The spectrum of γ Cas in the region of Hβ. The upper spectrum is the same observation shown in Figure 6; the lower spectrum is a tracing of a photographic spectrum at 12 Å/mm, published by Bohlin (1970). The two lines marked "b" were marked as blemishes by Bohlin.

plicated line profiles having both emission and absorption components. The spectrum of the O9.5 Ib star ζ Ori is shown in Figure 4. Identifications are given on each spectrum in Figures 4-7. These identifications include for each line: 1) the element, 2) the stage of ionization, 3) the multiplet number (Moore 1945), and 4) the wavelength in Angstroms. The pointer lines were drawn by the computer at the positions of the designated wavelengths; they were *not* drawn by eye to correspond with any plotted spectral features. *If the pointer lines and spectral features coincide, this is because there actually is a feature at the specific wavelength.*

b) *Line Identifications*

We show on Figures 4-7 and in Tables 2 and 3, that both types of measurements can be made consistently from our data. For example, we have identified more than 100 spectral lines in P Cyg, including all of the non-zero lines listed by De Groot (1968), as well as many of the lines he listed as having zero intensity. (Lines identified by De Groot are designated by the symbol "<" in Figure 5). His basic data consisted of a heterogeneous collection of coudé spectra, and his wavelength accuracy (1-3 Å) matches our own in the region of overlap (4800-8800 Å). Our measures have an average probable error of ±1.05 Å (Johnson 1977*a*). We extend De Groot's observations nearly to 10300 Å, and measure more than 50 additional lines.

We have also compared our results on ζ Ori with those of Schölz (1972). We have identified all of the lines he lists as present in ζ Ori, and these lines are designated by the symbol "←" on Figure 4. In addition, we have extended the wavelength region to nearly 10300 Å.

As pointed out by Swings (1965), the quantitative study of the spectral region longward of 9000 Å is important to our understanding of the Be stars

TABLE 2

LIST OF CATALOGUED "E" LINES PRESENT ON OUR SPECTRA

Wavelength Å	P Cyg	ϕ Per	γ Cas	ζ Ori	Type of Spectrum
8876				*	
8110	*	*			NL
8050	*				N
7867†		*			
7512†	*	*			NL
7500	*	*			N
7100	*	*	*		NL
6890	*	*			N
6880		*			NL
6835	*				NL
6464	*				PN
6410	*	*		*	PN
6380†	*	*			BE
6292†	*	*			NL
6270	*				
6267	*				GN
6254†	*				NL
6244	*	*			N, BE
6188		*			PN
6173	*				BE
6169	*				PN
6141				*	PN
6118†	*			*	PN, GN
6106	*				N
6079†		*			N
6034	*			*	PN
5988†	*	*			N
5918		*		*	NL
5904†				*	BE
5825†	*				NL
5672	*			*	BE
5623	*	*		*	NL
5613	*				PN
5575†				*	N
5390†	*				NL
5289	*				NL
5261	*				BE
5250	*				N
5153		*			PN
5122	*				PN
5092	*				PN
5040	*				BE

Type of Spectra of Catalogued "E" line:
BE — Be (shell) stars
PN — Planetary Nebulae
N — Novae
NL — Novae like objects
GN — Gaseous Nebulae (H II Regions)
* — Line is present on our spectra.

† We identify these lines with Fe II, in accord with the new list of Fe II identifications given by Johansson (1977). The line which we show on the figures as U 9994 is actually Fe II 9997 Å.

TABLE 3

LIST OF OBSERVED EQUIVALENT WIDTHS
ABSORPTION LINES ( ); EMISSION LINES—

Wavelength Å	Line Identification	Equivalent Width in cm^{-1}			
		ζ Ori	P Cyg	φ Per	γ Cas
10311	He I ($6^3D - 3^3P^0$)	—	−1.3	< 0.2	< 0.2
10210	O II ($^2P^0 - {}^4P$)		(2.8)	(4.0)	(1.9)
10049	H I (7 − 3)	(3.1)	−5.9	−3.5	−1.7
9546	H I (8 − 3)	(1.5)	−5.4	−3.2	−2.7
9516	He I ($7^3D - 3^3P^0$)	—	−0.2	Mg I ?	
9229	H I (9 − 3)	(1.8)	−3.8	−2.8	−2.7
9036	He I ($8^3D - 3^3P^0$)	(0.09)	−0.15	<0.04	<0.04
9015	H I (10 − 3)	(2.0)	(0.6) − 2.1	−2.4	−1.8
8863	H I (11 − 3)	(1.9)	(0.5) − 2.4	−2.3	−1.9
8776	He I ($9^3D - 3^3P^0$)	(0.09)	−0.3	<0.04	<0.04
8750	H I (12 − 3)	—	(0.3) − 1.2	−2.0	−1.9
8665	H I (13 − 3) + Ca II	(1.7)	(0.2) − 1.1	−6.0	−2.0
8598	H I (14 − 3)	(1.4)	(0.1) − 1.2	−2.4	−2.0
8582	He I ($10^3D - 3^3P^0$)	(0.1)	−0.2	<0.04	<0.04
8545	H I (15 − 3) + Ca II	0.73	(0.0) − 0.6	−6.9	−2.0
8502	H I (16 − 3) + Ca II	(0.98)	(0.3) − 0.7	−9.0	−2.6
8467	H I (17 − 3)	(0.69)	(0.2) − 0.4	−2.4	−2.2
8446	H I (18 − 3) + O I	(0.53)	−7.0	−12.0	−4.2
8413	H I (19 − 3)	(0.64)	−0.7	−2.4	−1.6
8392	H I (20 − 3)	—	−0.7	−1.6	−1.9
8371	H I (21 − 3)	—	−0.5	—	−1.2
7774	O I ($^5P - {}^5S^0$)	—	(1.4) − 1.2	−0.8	−0.7
6563	H I (3 − 2)	(1.8) − 2.4	(4.2) − 160	−138	−44.
4861	H I (4 − 2)	(7.9)	(4.9) − 50	−17	−12.
4340	H I (5 − 2)	(9.0)	(8.5) − 39	(2.9)	−4.8

because of the expected presence of many forbidden lines of several elements in this spectral region. We have extended the observed region to 10300 Å in this paper and furthermore, our correction of the atmospheric extinction in the 9000-9800 Å region makes this entire extension available. In the near future, we shall extend the work to 15000 Å and later, to 25000 Å.

In this paper, we do not consider that a line has been positively identified unless it meets both of the following criteria: 1) the measured wavelength must be within one resolution element (3.85 Å at 10000 Å; 1.92 Å at 5000 Å) of the laboratory wavelength and, 2) the central intensity (either emission or absorption) must differ from the mean "continuum" by more than three times the probable error for that star and spectral region as listed in Table 1. Thus, the probability is greater than 0.95 that all are true stellar features. No other lines are considered to be identified, although we have indicated the expected positions (and marked with an "X") other lines which we think should be present, but are not.

A serious problem we encountered in the identification of spectral lines at wavelengths longer than about 8500 Å is the fact that many wavelength lists are not complete, even for elements of high cosmic abundance. This is especially true for Mg I and Mg II; e.g., compare the lists of Moore (1945) with the more complete ones of Striganov and Sventitskii (1968). We have used the wavelengths of Moore (1945) and De Groot (1968, Table 4), supplemented by those of Striganov and Sventitskii (1968) and Harrison (1969), for most lines. For O I, we used data contained in the references cited by Wiese *et al.* (1969) and Moore (1971).

We have found spectral lines of the following elements:

i) For ζ Ori (Figure 4), we found the absorption spectra of H I, He I, He II, C III, C IV, N II, N III, O II, O III, Ne I, Na D*, and Fe III. The lines of C III, N III and Hα are observed in emission in ζ Ori.

ii) For P Cyg (Figure 5), we found in emission and absorption H I, He I, C II, C III, O I, N II, Ne I, Mg II, Si II, Si III, S II, Ar II, Fe II and Fe III. The lines of O II and interstellar Na D are in absorption.

iii) For φ Per (Figure 7), we found in emission H I, He I, C II, C III, O I, Ne I, Mg II, Si II, Si III, S II, Fe II and Fe III. The O II lines and the interstellar Na D lines are in absorption.

iv) For γ Cas (Figure 6), we found in emission H I, He I, C II, C III, O I, Ne I, Fe II and Fe III. The lines of O II are observed in absorption.

We are encouraged by the fact that more than 95 percent of the strong lines in Figures 4-7 can be identified with neutral and ionized spectra of only five elements of high cosmic abundance: H, He, C, O and Fe. The remaining seven elements, N, Ne, Na, Mg, Si, S have high abundance (but are ionized: Ne, Mg) are interstellar (Na, but see footnote about ζ Ori), or have only weak lines (N, Ar, Si, and S). We found the stronger spectral lines of the same neutral and ionic spectra as did De Groot (1968) for P Cyg, except that we also found many additional lines of the same species. For example, De Groot's Table 4 contains only six lines between 6644 Å, and 7112 Å, whereas our Figure 5 lists nearly 50 lines in this same spectral interval. These additional P Cyg features are real because most of the emission peaks coincide (within 4 cm^{-1}) with similar significant peaks on the spectra of φ Per and γ Cas. The weak Ne I spectrum was listed as possibly present in P Cyg by De Groot. Our identification of Ne I lines at wavelengths longer than his limit (8800Å) supports his suggested identifications.

Spectral lines of Fe II and S II were listed as possibly not present by De Groot; nevertheless, he reported Mg II to be present. The ions, Fe II and S II, have ionization potentials and cosmic abundances similar to, or higher than, those of Mg II. Our data indicate that all of these spectra are present in P Cyg and φ Per; we found more than 20 lines of Fe II between 4800 Å and 10200 Å (Figure 5), as well as 20 additional lines of S II. We found no lines of Mg II or S II in either ζ Ori or γ Cas. The presence of Fe II lines in the spectrum of φ Per is well established; a comparison of our P Cyg spectrum (Figure 5) with that of φ Per (Figure 6) demonstrates the reliability of our technique for detecting Fe II in P Cyg.

Gehrz *et al.* (1974) determined from broad-band photometry that the shells of φ Per and γ Cas differ significantly in temperature, being 12000°K and 20000°K, respectively. Therefore, we would expect Fe III/Fe II line ratios to be consistently higher in P Cyg (low-presure supergiant) and γ Cas (Be star, but high-temperature shell) than in φ Per (cooler Be shell star). It may be noted that in Figures 5-7 more than twenty Fe III/Fe II line strength ratios are smaller in φ Per than in either γ Cas or P Cyg, a result consistent with the conclusions of Gehrz *et al.*

c) *Unidentified Lines*

We find many weaker emission lines on our spectra which we cannot identify. These lines are labeled by the symbol "U" on Figures 4-7; they were not listed in any of the papers we reference here. It is evident on our spectra that many of these lines are blends, and their identifications may remain elusive. In all cases, these features are above the noise level (cf. Table 1) and are often found in more than one of the four stars.

The photometric quality of our spectra and the extended wavelength coverage increases the chance of discovering previously unknown lines in these stars. This is demonstrated by the fact that we were able to detect lines to exist in stellar spectra, but which were not noticed on the coudé spectra studied by the other investigators. The lists in Figures 4-7 and Table 2 contain 42 unidentified lines marked "E" on the figures. Each of these lines has been catalogued by Meinel *et al.* (1968), from references to work on Be stars, nova-like and planetary nebula-

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* It is customary to identify these sharp Na D lines in ζ Ori as "interstellar". These is a significant discrepancy here, however, because ζ Ori is nearly unreddenned. Even so, its Na D lines are stronger than those of γ Cas or φ Per, which are more highly reddenned by interstellar material. Because of the high temperature of ζ Ori these lines cannot be stellar. If the lines are actually interstellar, the ratio of Na D absorption/E(B-V) is very much larger for ζ Ori than elsewhere.

type objects. Table 2 lists the wavelengths of the "E" lines we observed, and an asterisk "*" indicates whether a given line was found in the spectrum of one of the stars. The last column contains the type of object for which Meinel *et al.* catalogued the lines. Thirty-three of the 42 "E" lines are in the spectrum of P Cyg, but only four are in ζ Ori. None were noted by De Groot for P Cyg. (The "E" lines in ζ Ori are too few to be significant). The high fraction of lines seen in P Cyg (33 out of 42) indicates that a chance association of the "E" lines with stellar emission features is quite unlikely. The "E" lines may be a link between supergiant, shell-star, and nova-like spectra.

One clue to the identification of these lines may be the fact that they are found in X-ray sources. Chesley (1975) found 18 unidentified "E" lines from the Meinel *et al.* catalogue to be present in the strong X-ray source Sco X-1. We found seven of these "E" lines to be present in the weak X-ray source, γ Cas. The identification of these "E" lines should be an important step toward understanding nova-like and X-ray star spectra.

Certain lines of Mg II that are expected to be present are perhaps filled in with emission and are marked "X" or absent on Figures 4-7. The relative intensity ratio of the Mg II 9243/9633 Å lines is greater than 20, so the 9633 Å line is marked "X" on spectra of P Cyg and ϕ Per. Our unpublished spectrum of α Cyg shows a ratio of 2/3 for Mg II 9243/9633 (absorption). The extreme weakness we observed for the 9633 Å ^{2}D-^{2}F^0 multiplet is supported by the observation of a very weak Mg II ^{2}D-^{2}F^0 multiplet line at 4481 Å, reported by both De Groot (1968) and Struve (1935). We have determined that spectrum of S I does not contribute significantly to the 9240 Å multiplet because of the absence of the 8694 Å S I (marked "X") and all other expected S I lines in this region. Lines of Mg II other than the ^{2}D-^{2}F^0 series lines are present in P Cyg and ϕ Per. We concur with De Groot (1968) that the spectrum of Mg II is present in P Cyg, but the Mg II ^{2}D-^{2}F^0 series problem deserves further study.

d) *Equivalent Widths - (E.W.)*

In this paper, we extend the region of precise equivalent width measurements for these four stars from 8800 Å to 10200 Å. These equivalent width measurements are given in Table 3 for each star listed, along with line identifications. The consistency and accuracy of these measurements are shown by the following discussion.

In P Cyg we measured the equivalent widths of the blended Ca II circumstellar absorptions discovered by the De Groot (1968). We have confirmed the presence of Ca II emission in γ Cas detected by Merrill and Wilson (1934), but not reported by Hiltner (1947). We observed that the O I/Ca II emission line ratio is slightly larger in γ Cas than in ϕ Per. These observation are consistent with the facts that: 1) O I has a higher ionization energy than Ca II (13.6 versus 11.9 eV) and 2) γ Cas has a hotter shell (Gehrz *et al.* 1974). Both O I and Ca II emissions could be weaker in γ Cas due to ionization. These O I and Ca II lines are among the most intense lines in the spectra of P Cyg, ϕ Per and γ Cas, possibly because they are in resonance with Lyman line radiation. There is a possible resonance between the 3^{2}D-continuum levels of Ca II and Lyman alpha, as discussed by Greenstein and Merrill (1946). The O I 8446 Å line radiation field is linked to Lyman beta, as reviewed in our Introduction.

e) *H I Paschen Lines*

We have compared our equivalent width measurements with those of previous workers. For example, Burbidge and Burbidge (1955) measured the equivalent widths (E.W.) for six Paschen lines (P12 through P17) in the spectrum of P Cyg. We have compared our equivalent widths to their published values and they agree within 10%. Merrill and Wilson (1934 reported central lines intensities (*not E.W.*) for 12 Paschen lines in γ Cas (P11 through P23). Their data and ours fall along similar smooth curves when Paschen line intensity (or E.W.) is plotted versus hydrogen level number. Thus there is a correlation between our measurements and those of Merrill and Wilson (1934) despite the fact that a direct comparison of our numbers is not possible. Of course, all of these Paschen lines are in emission in P Cyg and γ Cas.

f) *H I - Balmer Lines*

We have measured the equivalent widths of Hα, Hβ and Hγ in all four stars. These data are in Table 3. Our measurement of the Hγ component is the same that of De Groot (1968, Table 11); our measurements of the Hβ and Hγ emission are both about 25 percent greater than De Groot's (1968). As can be seen in Figures 5-7 and Table 3, these emission lines are very intense. Our detector is linear, whereas the photographic plates used by De Groot (1968) can be saturated by intense emission (see Mitton 1976). Remember that our Paschen line measurements of P Cyg are in agreement with those of Burbidge and Burbidge (1955). We also report new measurements for Hα emission in P Cyg, ζ Ori, ϕ Per and γ Cas.

g) *He I - van Helden Series*

The most significant He I Lines in the near infrared region are the 3^3P^0-n^3D series discovered by van Helden (1972). He observed that two members of this series were luminosity sensitive and that the 3^3P^0 state was overpopulated in B supergiant spectra. We present in Table 3 new observations of the third and fourth members of the series (3^3P^0-7^3D, 9036 Å and 3^3P^0-6^3D, 10311 Å). We found that these lines are present in the supergiants, in emission in P Cyg and in absorption in ζ Ori, but that they are weak or absent in the lower luminosity stars ϕ Per and γ Cas; cf. Table 3 and Figures 4-7. The fact that these features are so weak, but still detected, is further evidence for the quality of our spectra. We observed that the 10830 Å line (2^3S-3^3P^0) is approximately three times higher than the continuum of P Cyg and only twice as high as the continuum of γ Cas (spectra not shown).

The van Helden lines at 11970 and 17000 Å have also been observed in P Cyg and γ Cas by Larson (1976). He reports these lines are several times stronger in P Cyg than in γ Cas.

We found that all members of the van Helden series are present but that the 9516 and 9036 Å lines are blends, as shown in Figure 7. The van Helden lines of He I are weaker than the Paschen lines in P Cyg.

Observations of both infrared He I and O II lines appear to be one of our best means of obtaining information concerning the radiation field at wavelengths shorter than 912 Å. Interstellar absorption from the Lyman continuum blocks this spectral region from our direct observation in all but the nearest stars. Near infrared spectroscopy is, therefore, important as ground-based support of both ultraviolet and soft X-ray observations made from satellites.

h) *Spectral Lines whose Intensities should be Monitored*

Oxygen. The O I spectrum is found to be present in emission at both 8446 Å and at 7774 Å in P Cyg, γ Cas and ϕ Per. The differences between the 8446 Å and 7774 Å lines described by the papers referenced in our Introduction *were not observed* on our spectra of these three stars. Our measured equivalent widths for these O I lines are reported in Table 3, and compare favorably with those measured by Kitchin and Meadows (1970). See also Kitchin (1976). The 8446 Å line in the P Cyg spectrum does not show a normal P Cyg profile, in that there is no short wavelength absorption such as exists for the Paschen lines (see Figure 5).

The spectrum of P Cyg which is shown in this paper was obtained in November 1975. More recently, we obtained a second spectrum of this star (October 1976). The second spectrum is nearly identical to that obtained in November 1975. In particular, the O I lines did not change significantly this eleven-month period.

V. SUMMARY

We have observed the spectrum of two Be stars and the supergiants P Cyg and ζ Ori from 4800-10200 Å. The wavelengths and detailed equivalent widths we measure show differences from one star to the next which are consistent with previous photographic work and extend that work to longer wavelengths. We report the first observations of the Mg II doublet 9213, 9243 Å, and new identifications of Fe II emission lines in P Cyg and ϕ Per.

Two Be stars have already been identified with interesting X-ray sources, and several resonances have been confirmed between far UV and near infrared spectral lines. These discoveries indicate that Fourier transform techniques in the field of near infrared spectroscopy should be given high priority in a ground-based support program for observations of O and B emission line stars that emit X-ray and far UV radiation.

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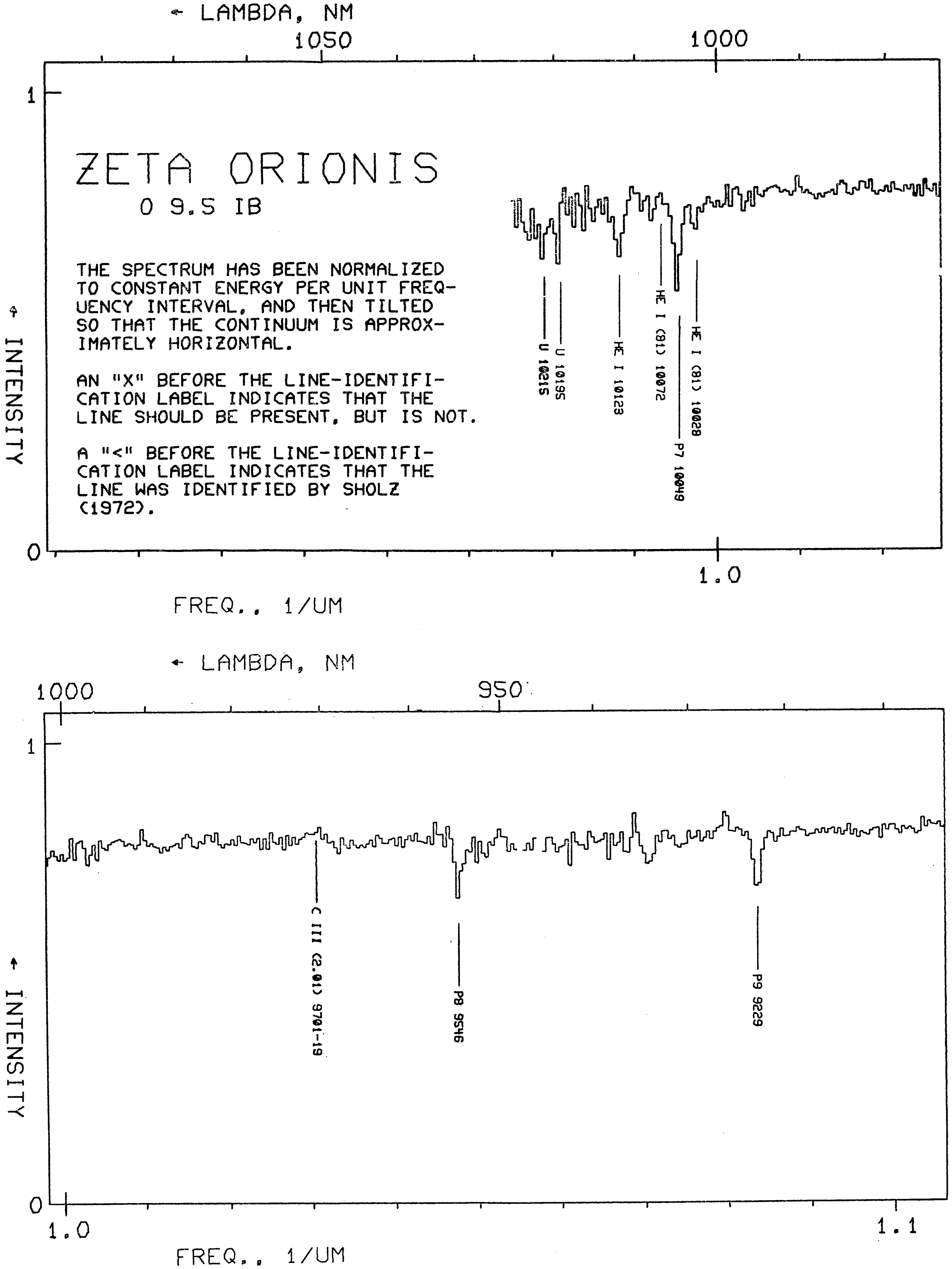
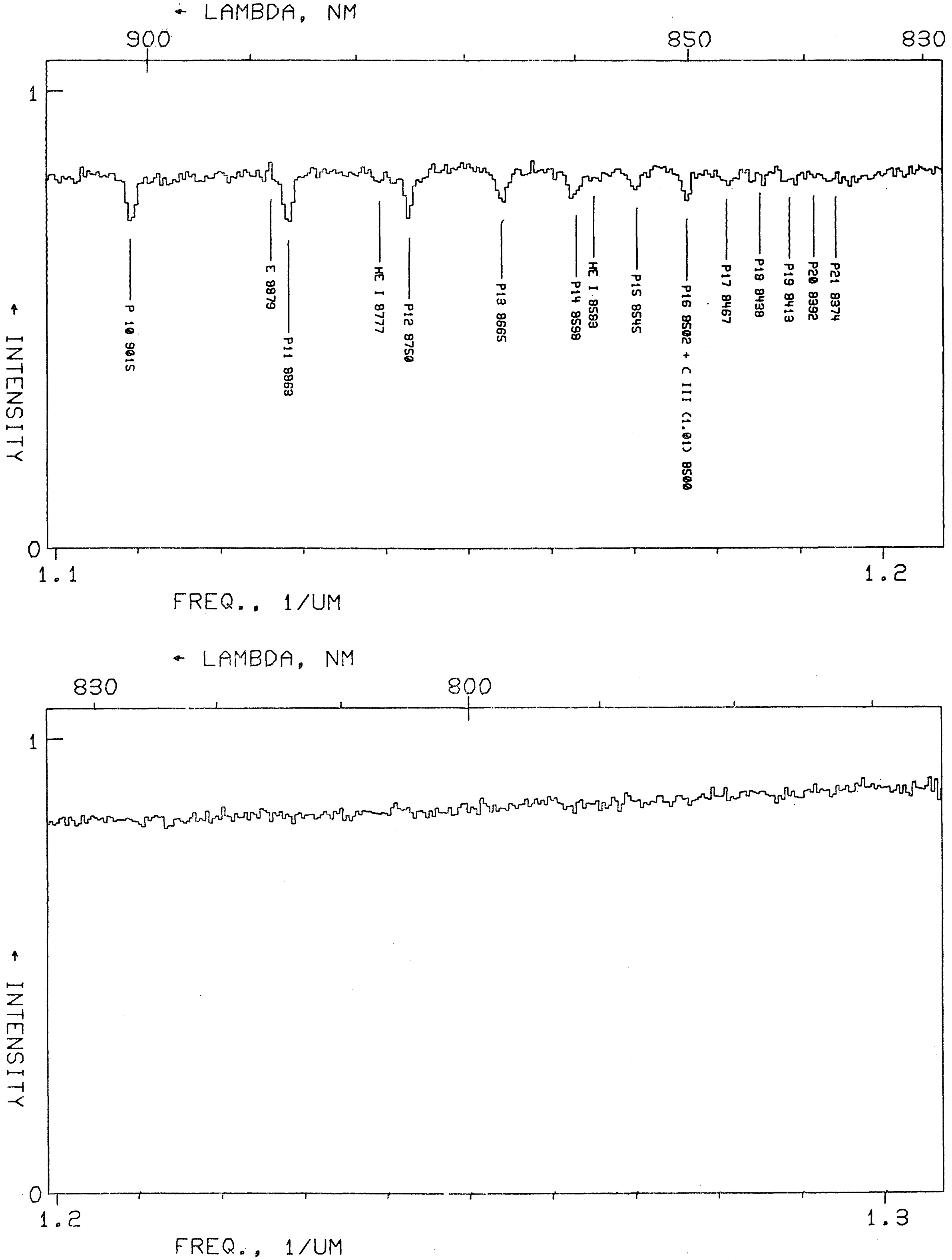


THE SPECTRUM HAS BEEN NORMALIZED TO CONSTANT ENERGY PER UNIT FREQUENCY INTERVAL, AND THEN TILTED SO THAT THE CONTINUUM IS APPROXIMATELY HORIZONTAL.

AN "X" BEFORE THE LINE-IDENTIFICATION LABEL INDICATES THAT THE LINE SHOULD BE PRESENT, BUT IS NOT.

A "<" BEFORE THE LINE-IDENTIFICATION LABEL INDICATES THAT THE LINE WAS IDENTIFIED BY SHOLZ (1972).

FIG. 4. The spectrum of ζ Ori from 4800-10200 Å.



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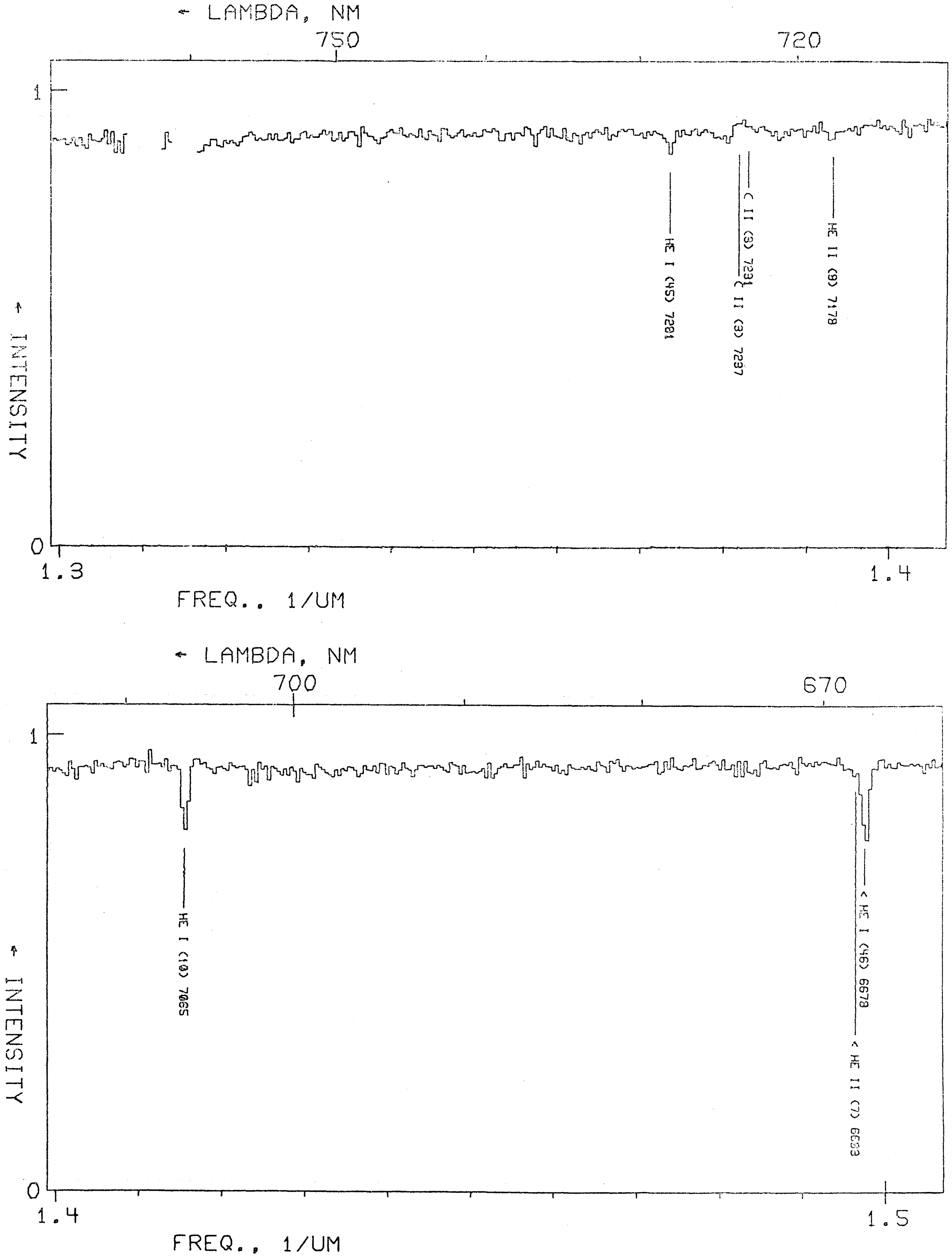

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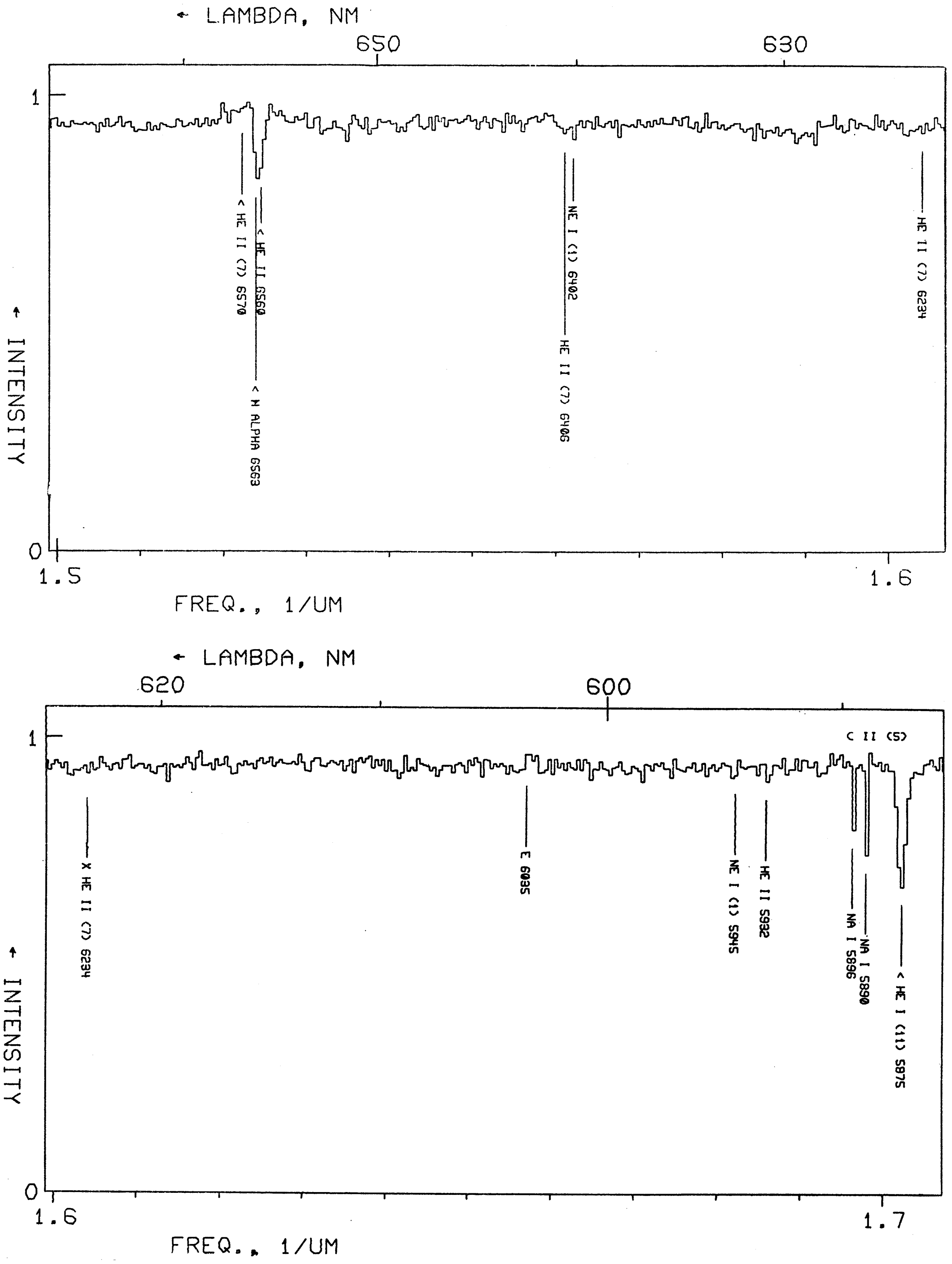

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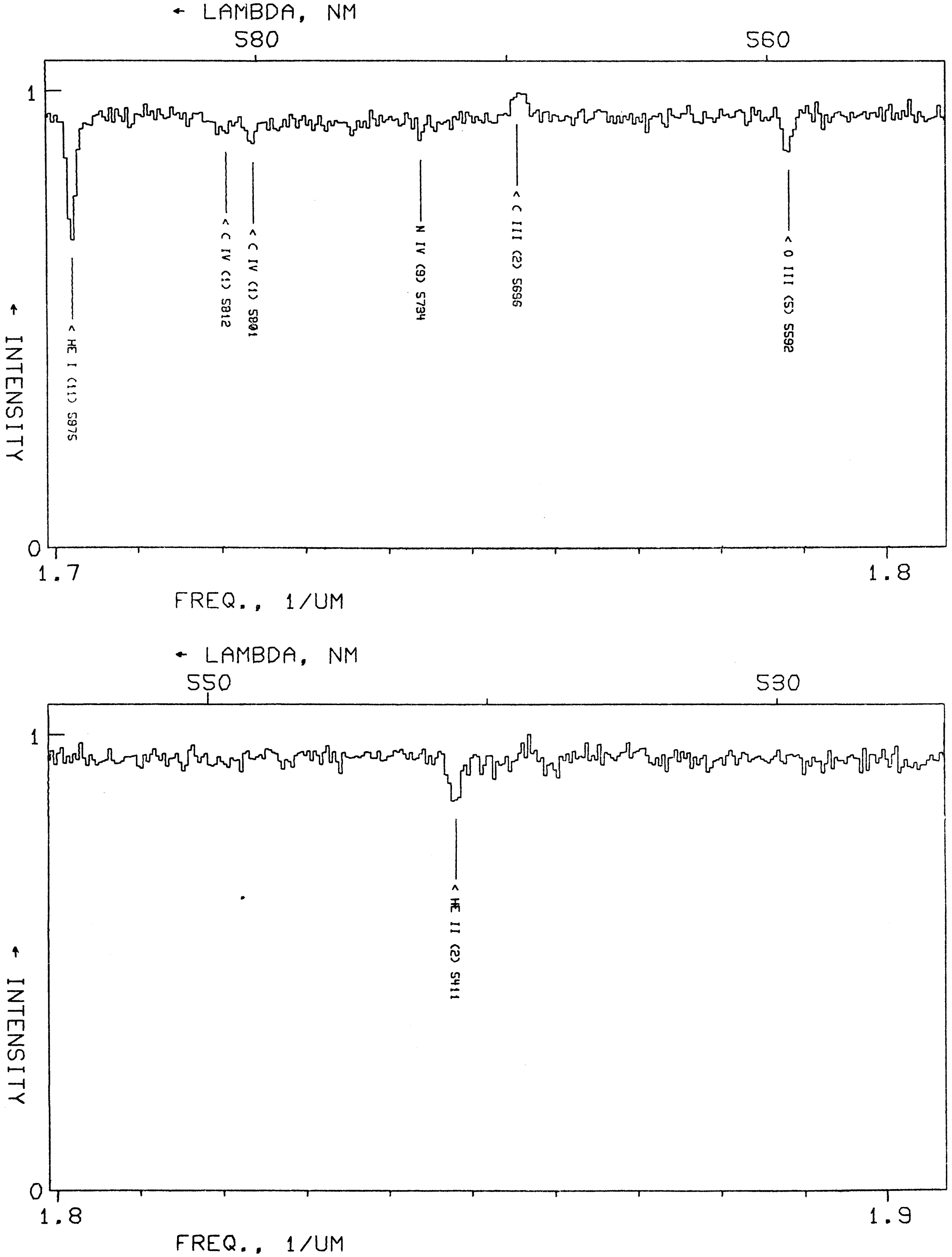

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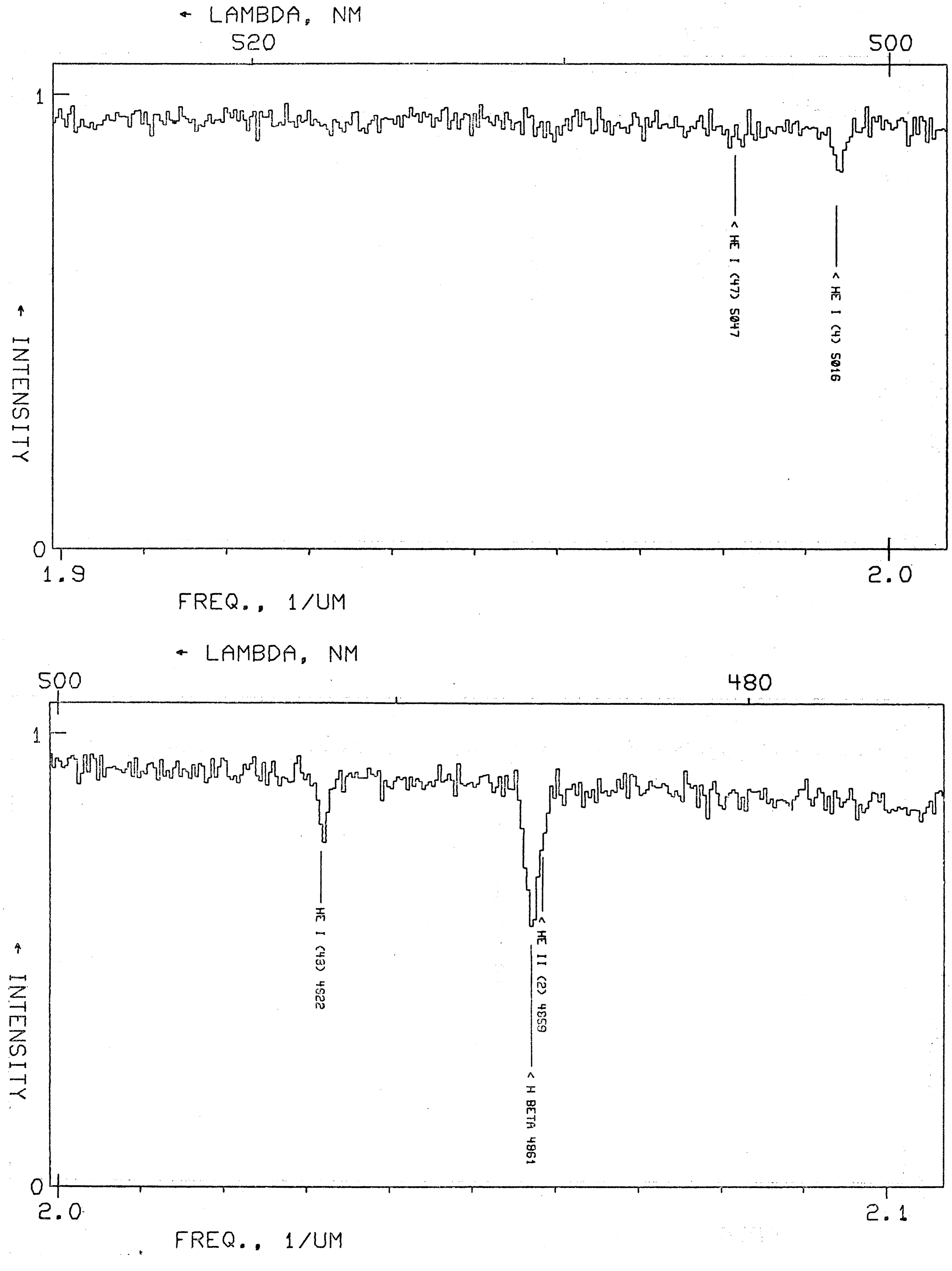

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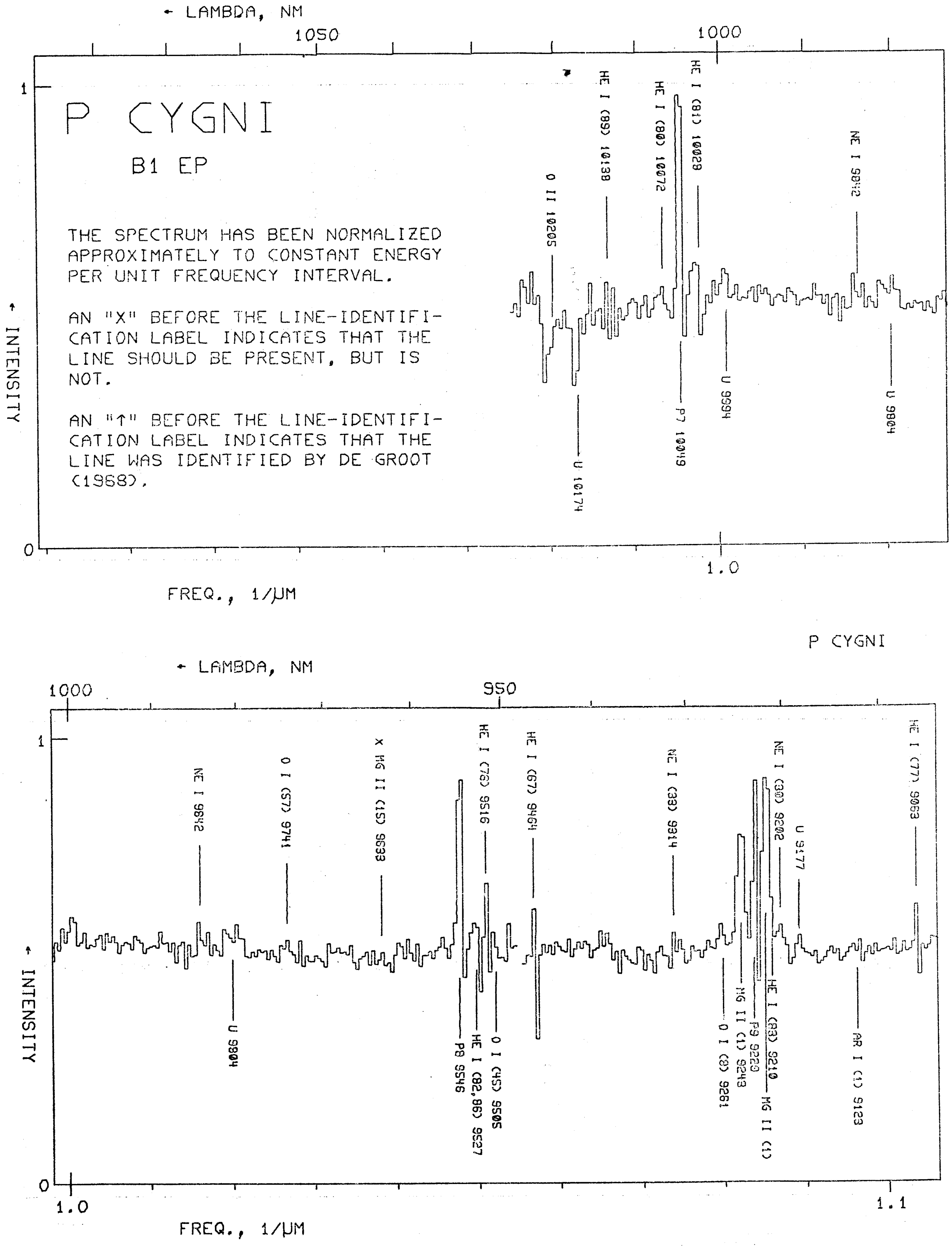

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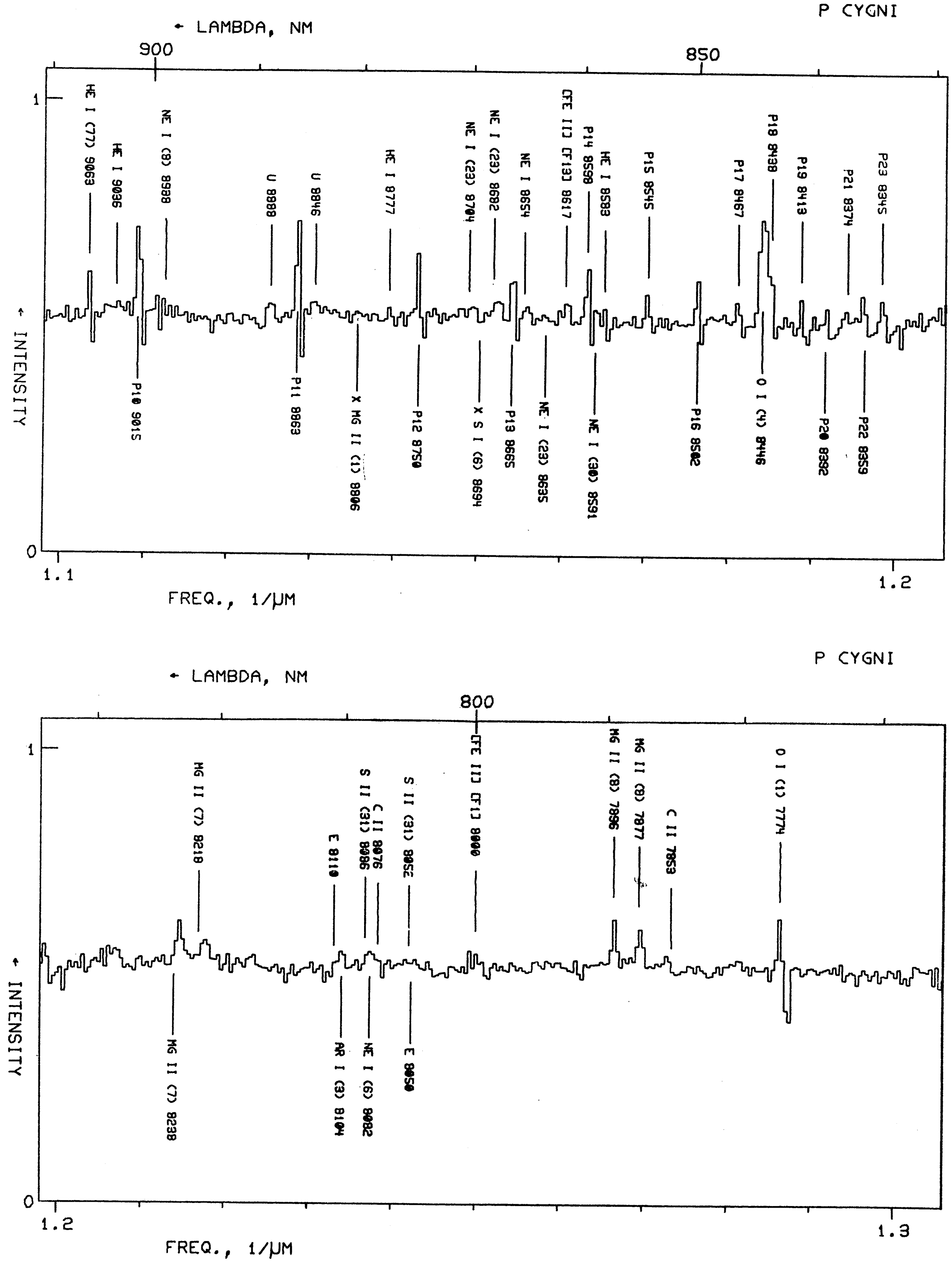
Fig. 5. The spectrum of P Cyg from 4800-10200 Å.



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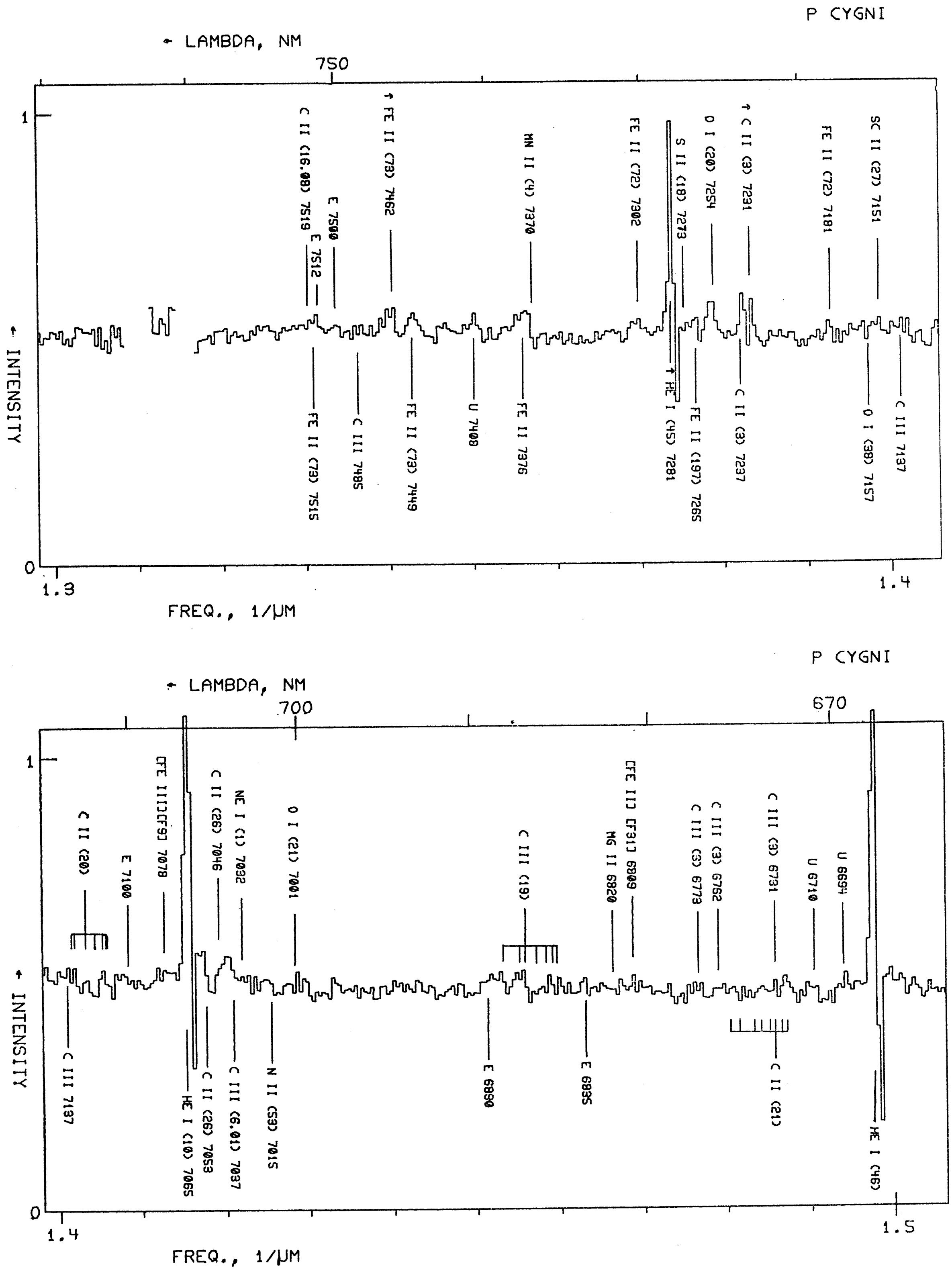

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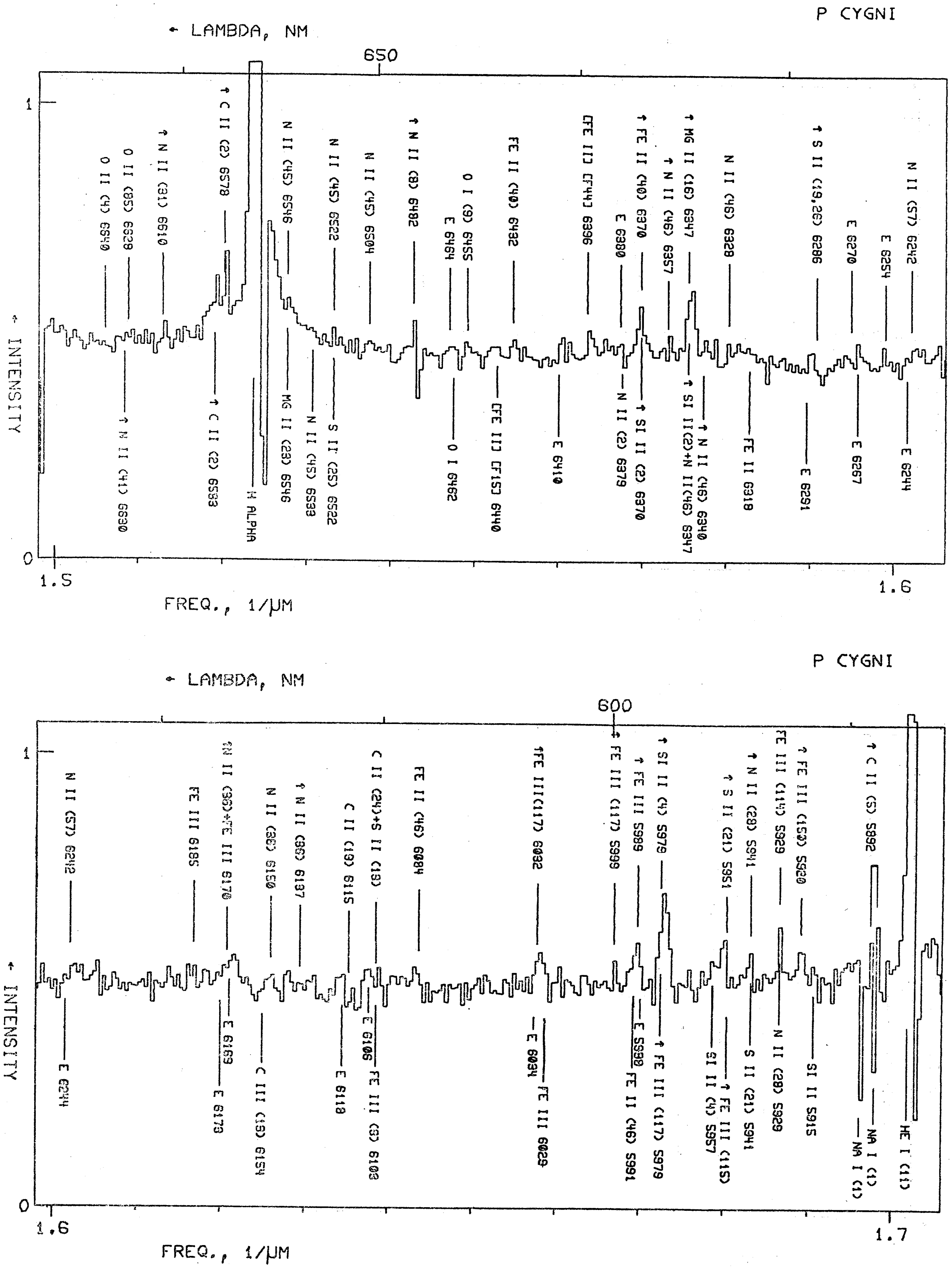

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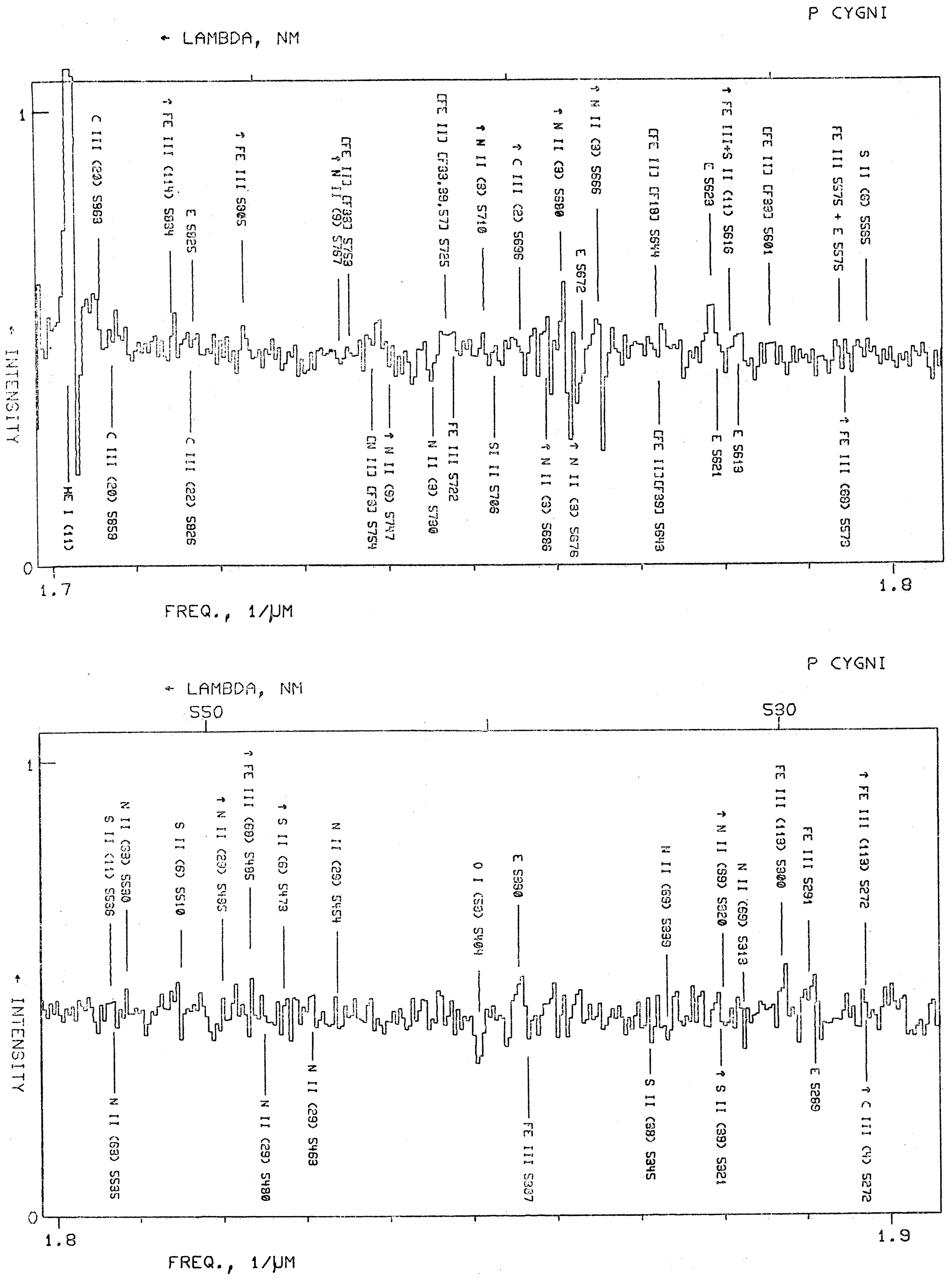

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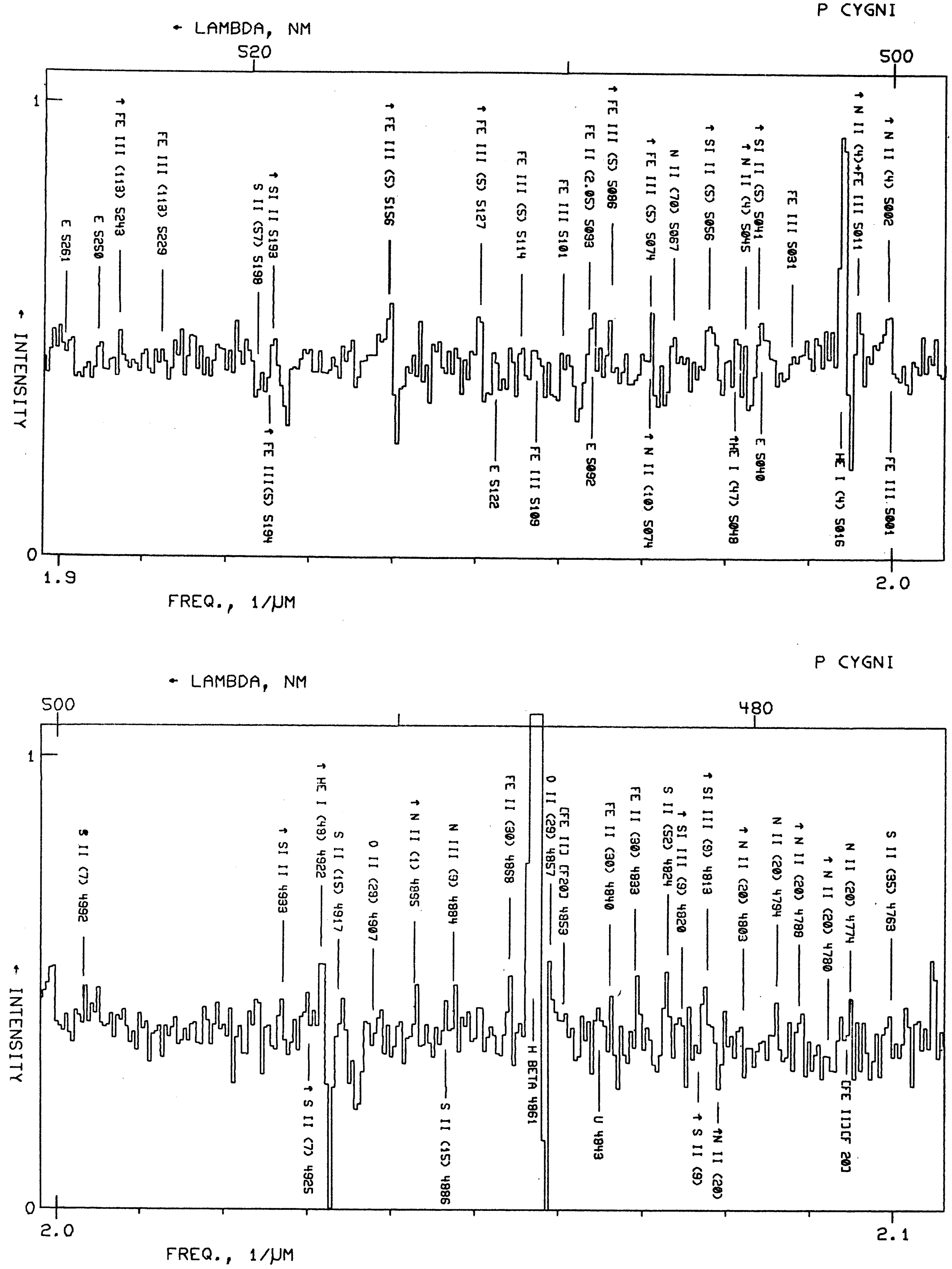

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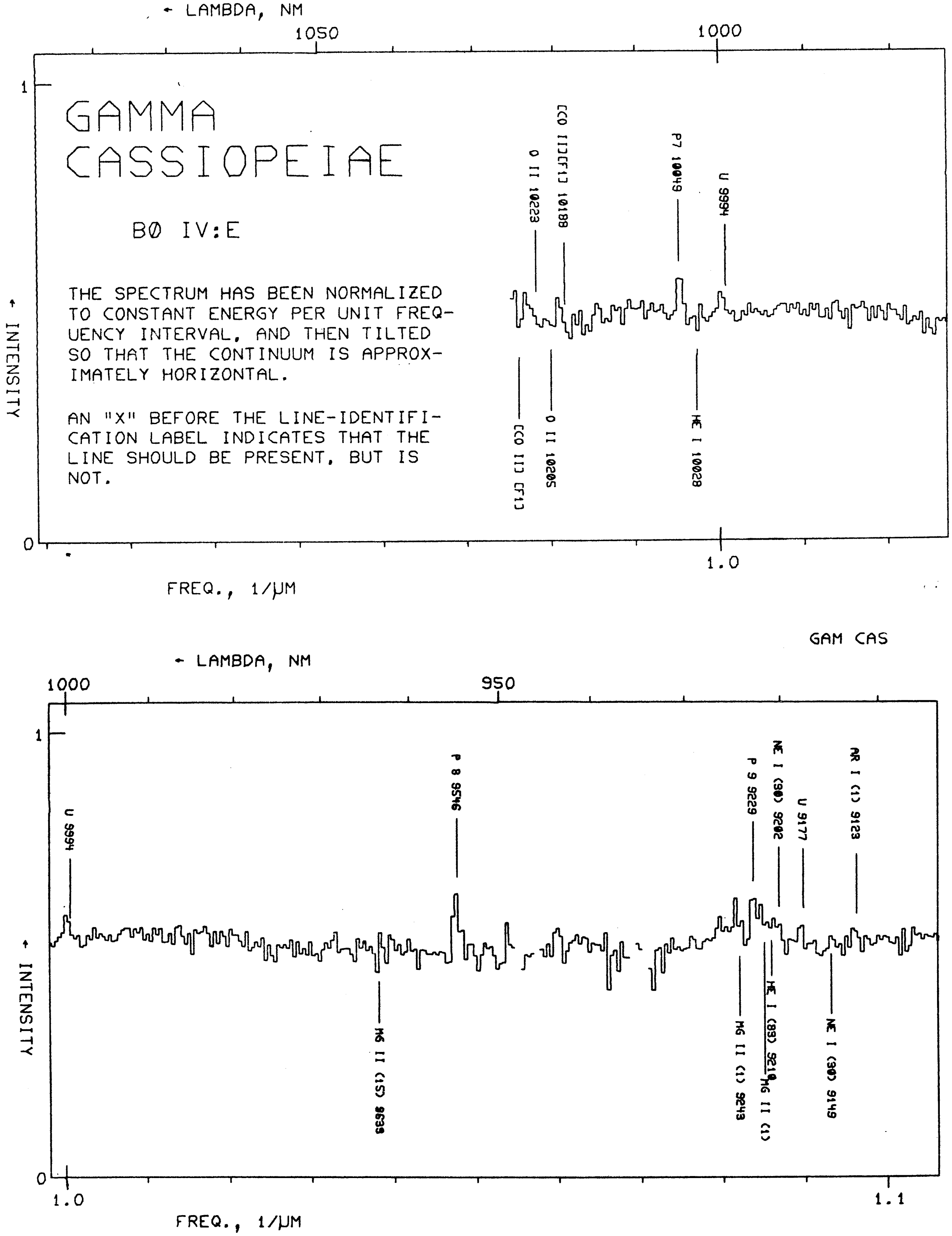

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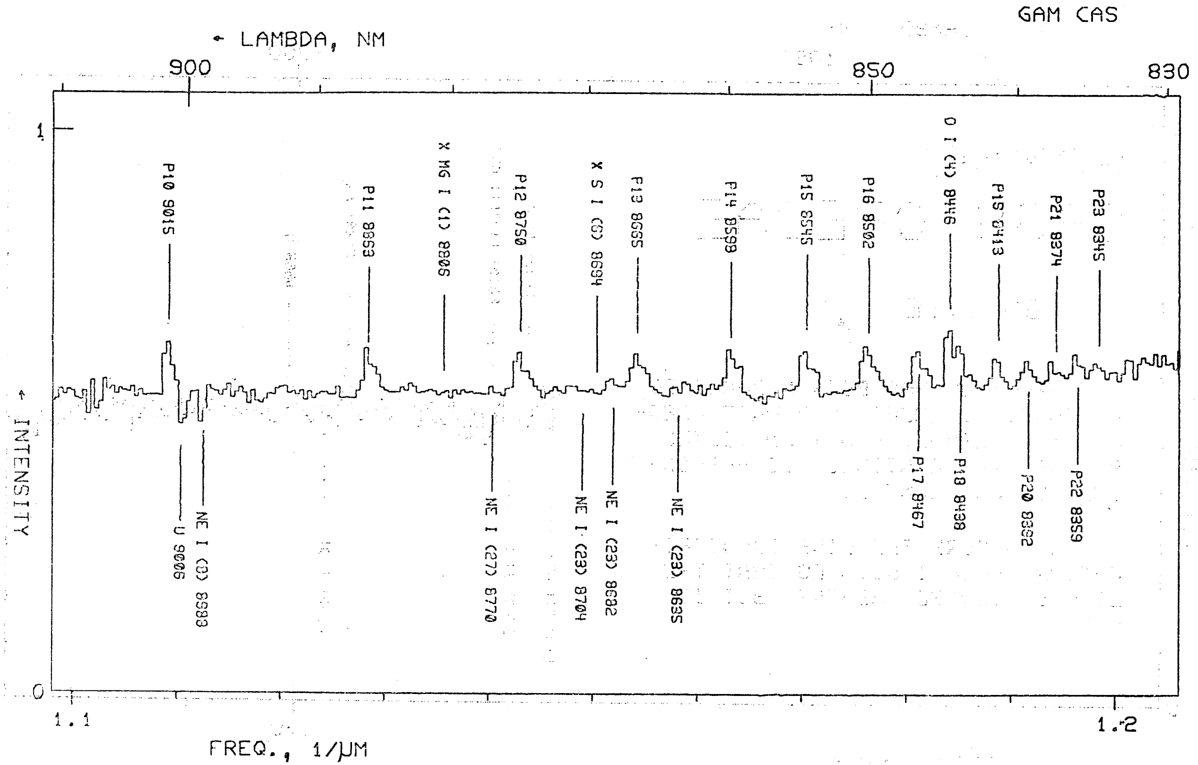
Fig. 6. The spectrum of γ Cas from 4800-10200 Å.



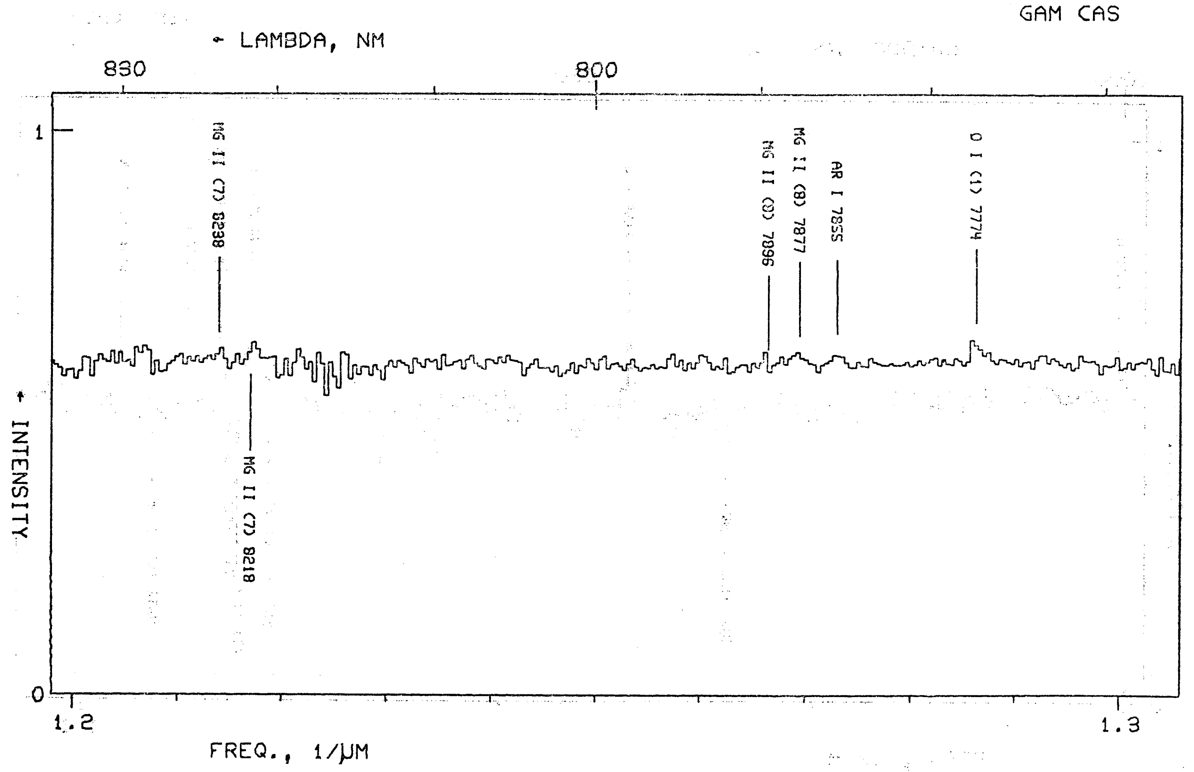


FIG. 6. The spectrum of γ Cas from 4800-10200 Å.

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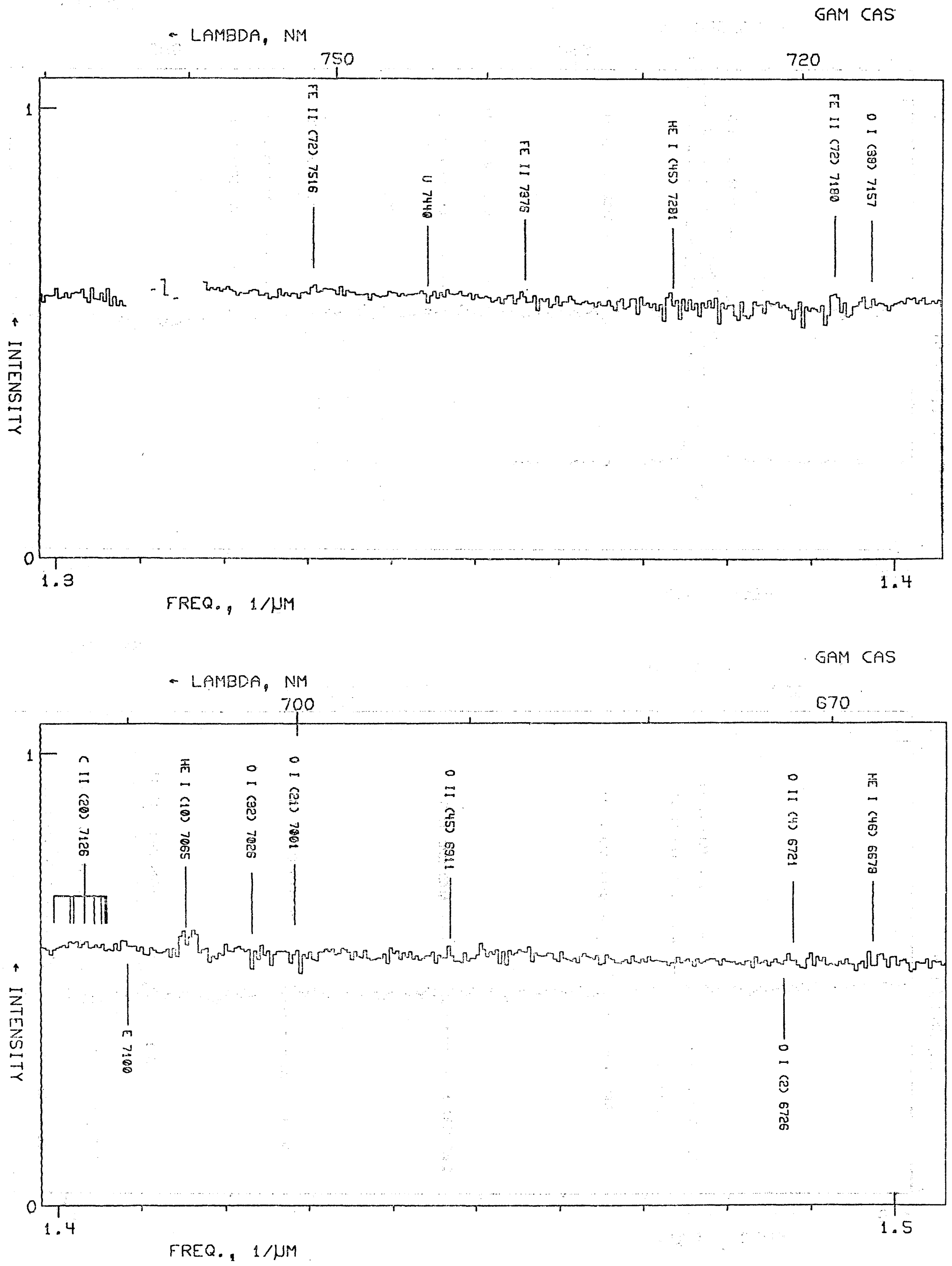

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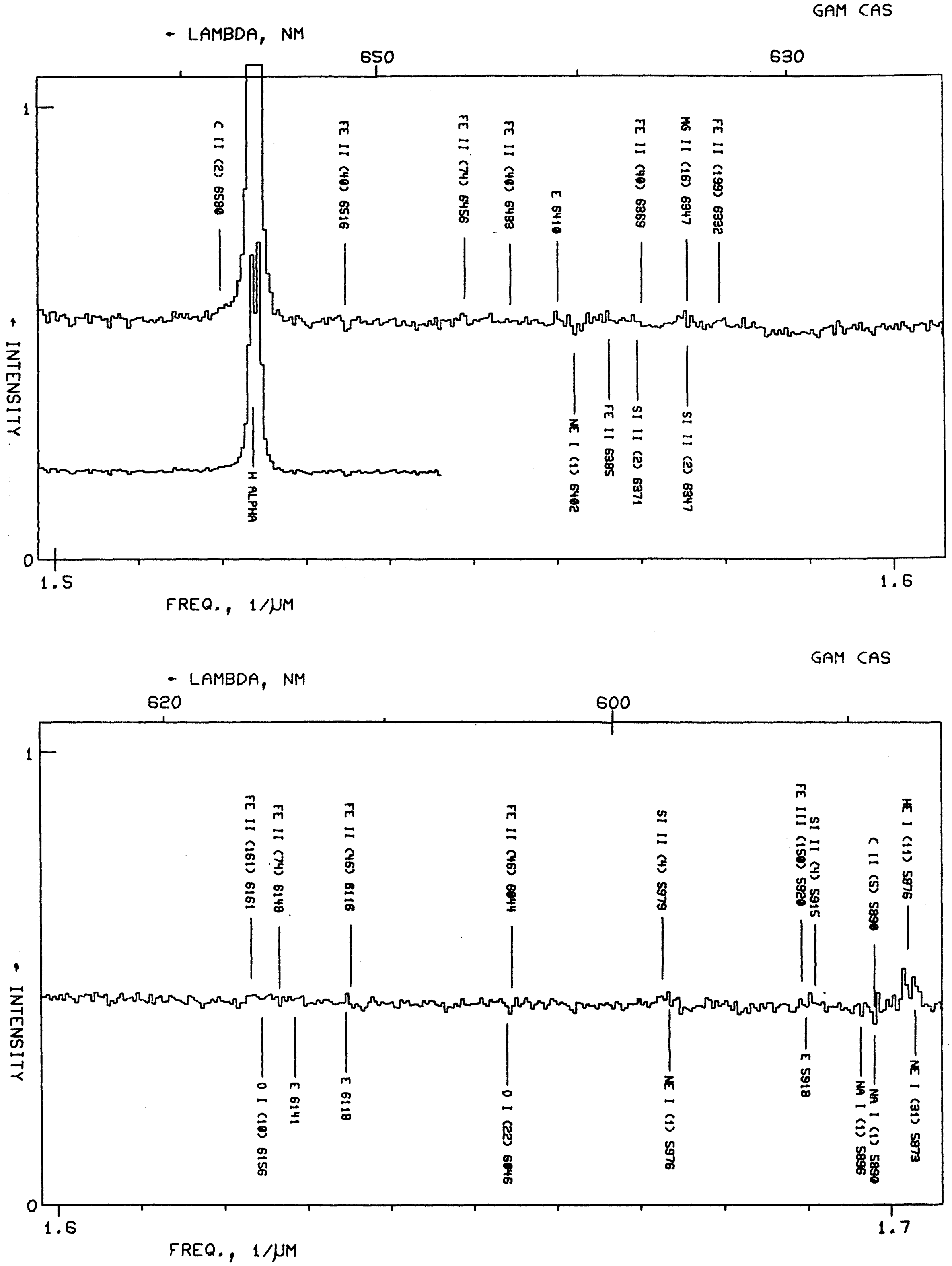

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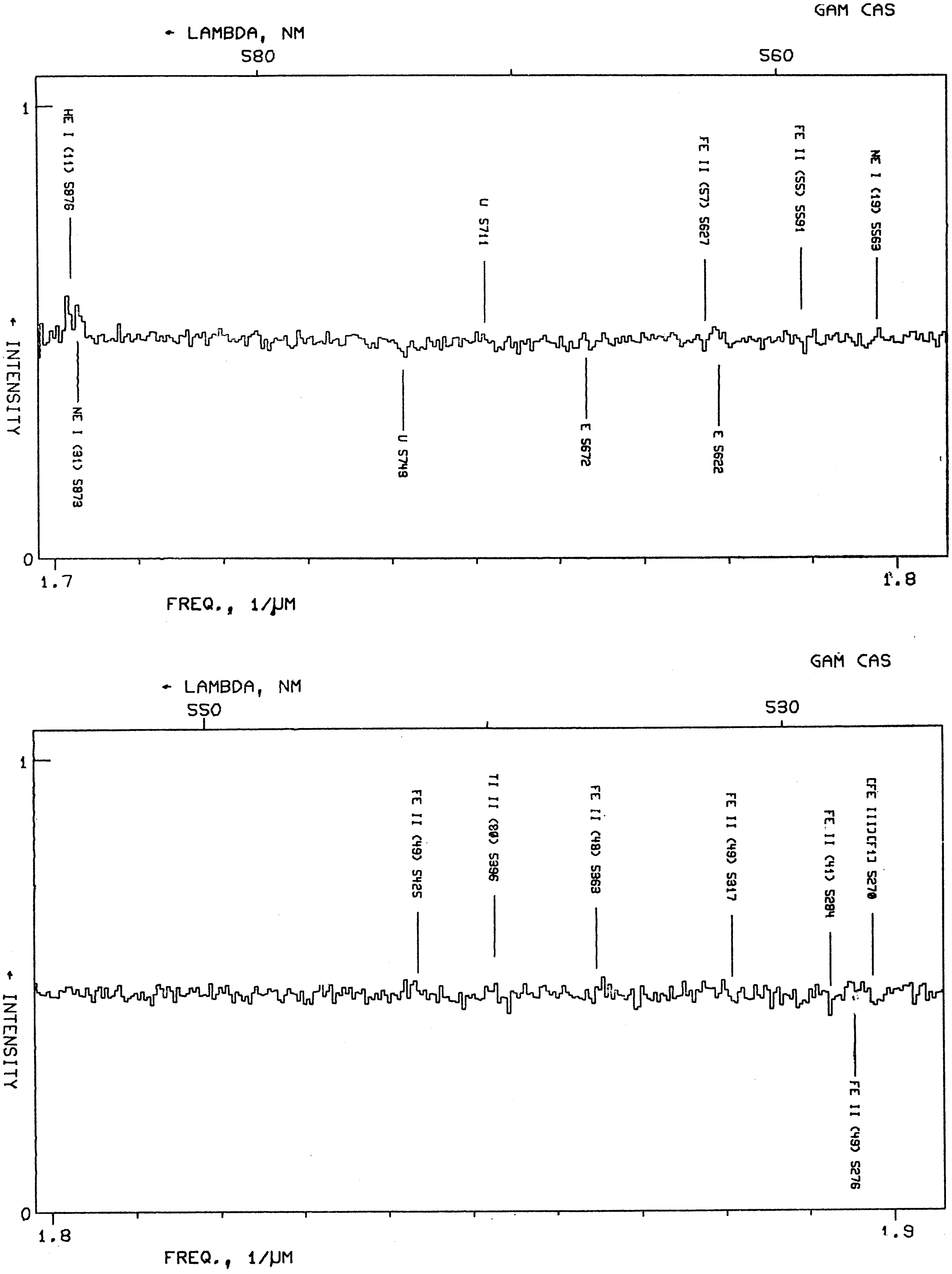

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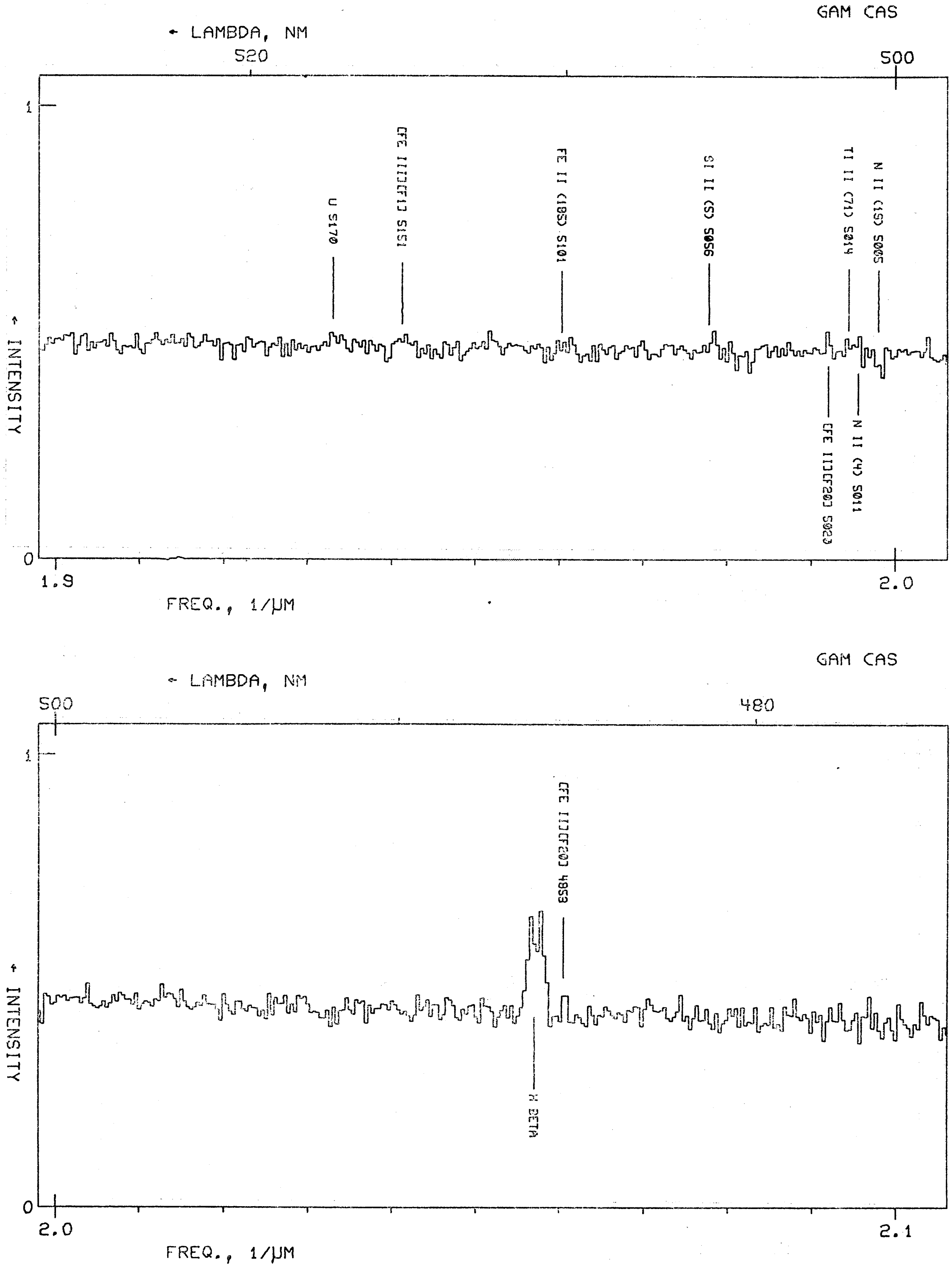

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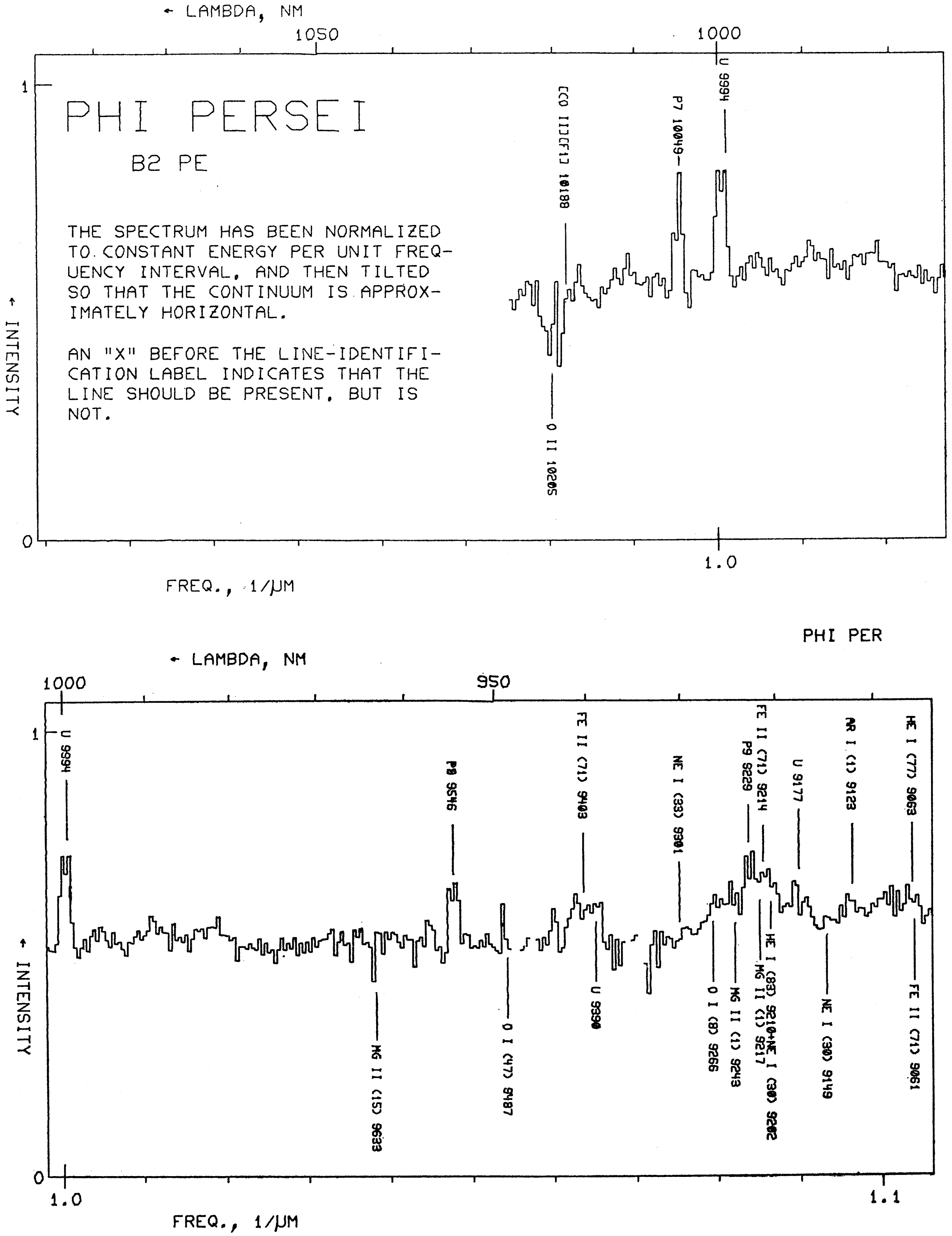

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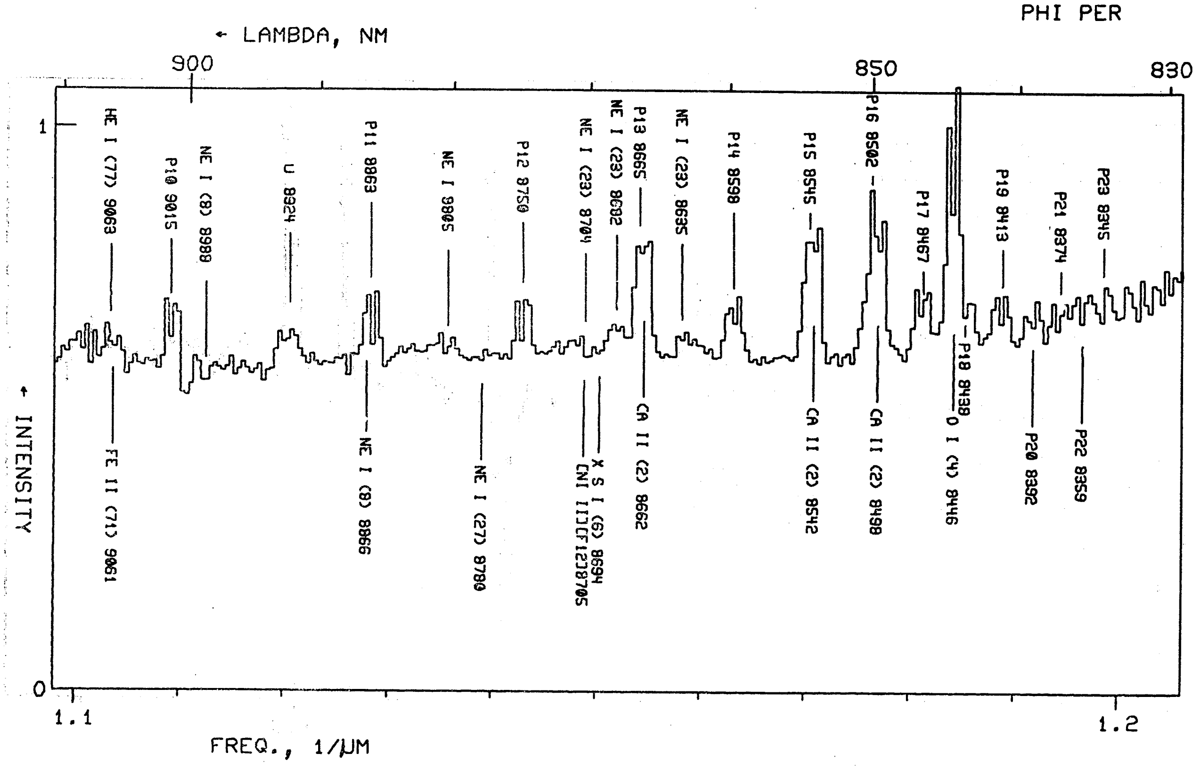
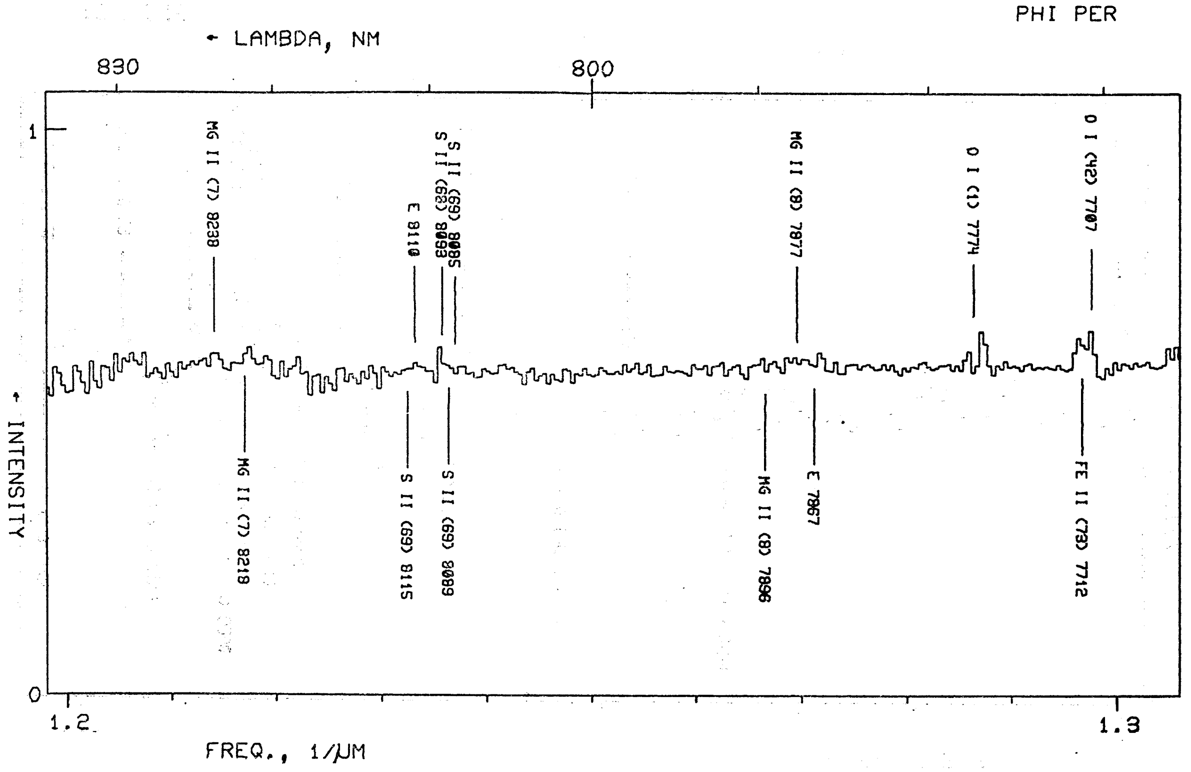
Fig. 7. The spectrum of ϕ Per from 4800-10200 Å.





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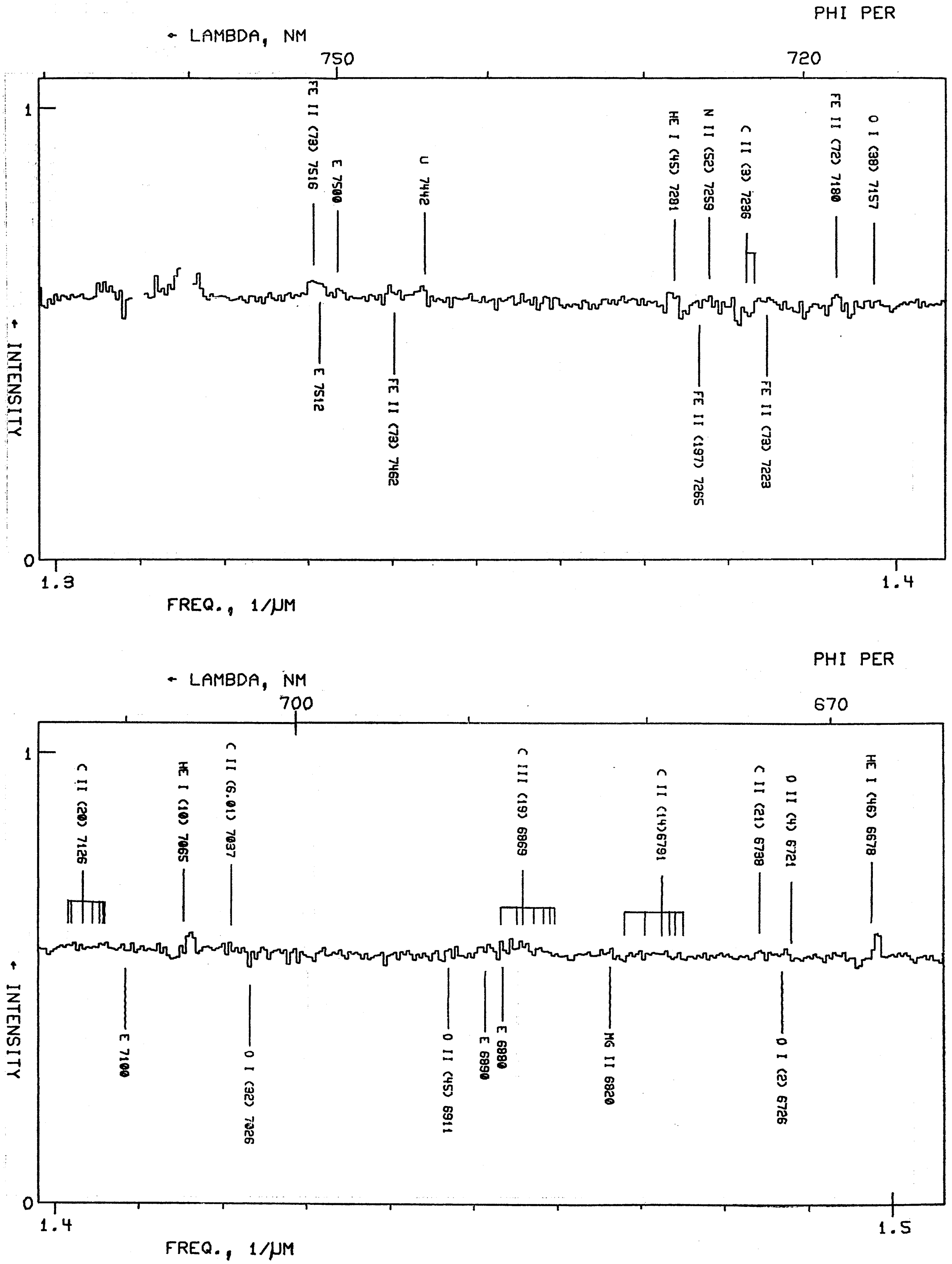

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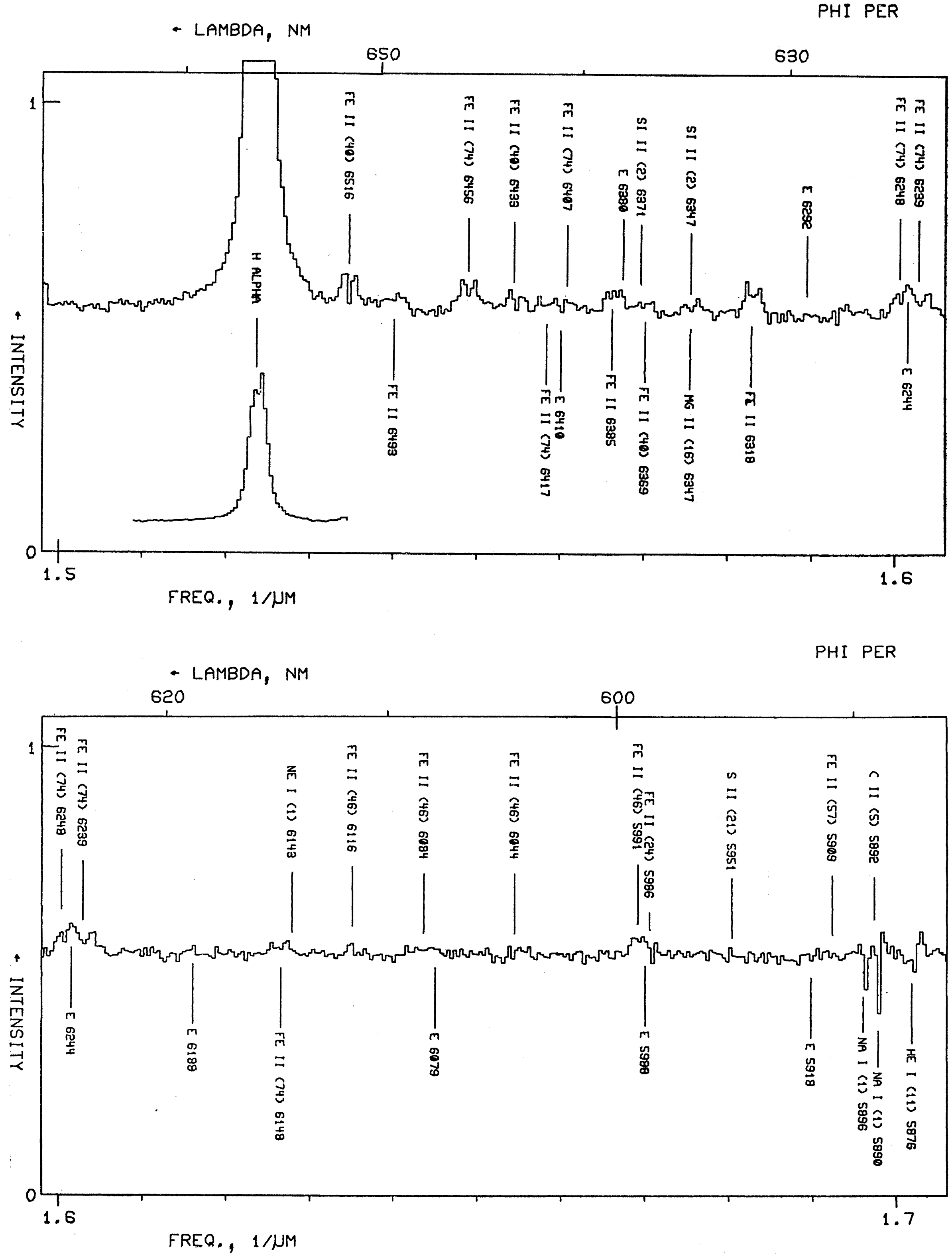


FIG. 7. The spectrum of ϕ Per from 4800-10200 Å.

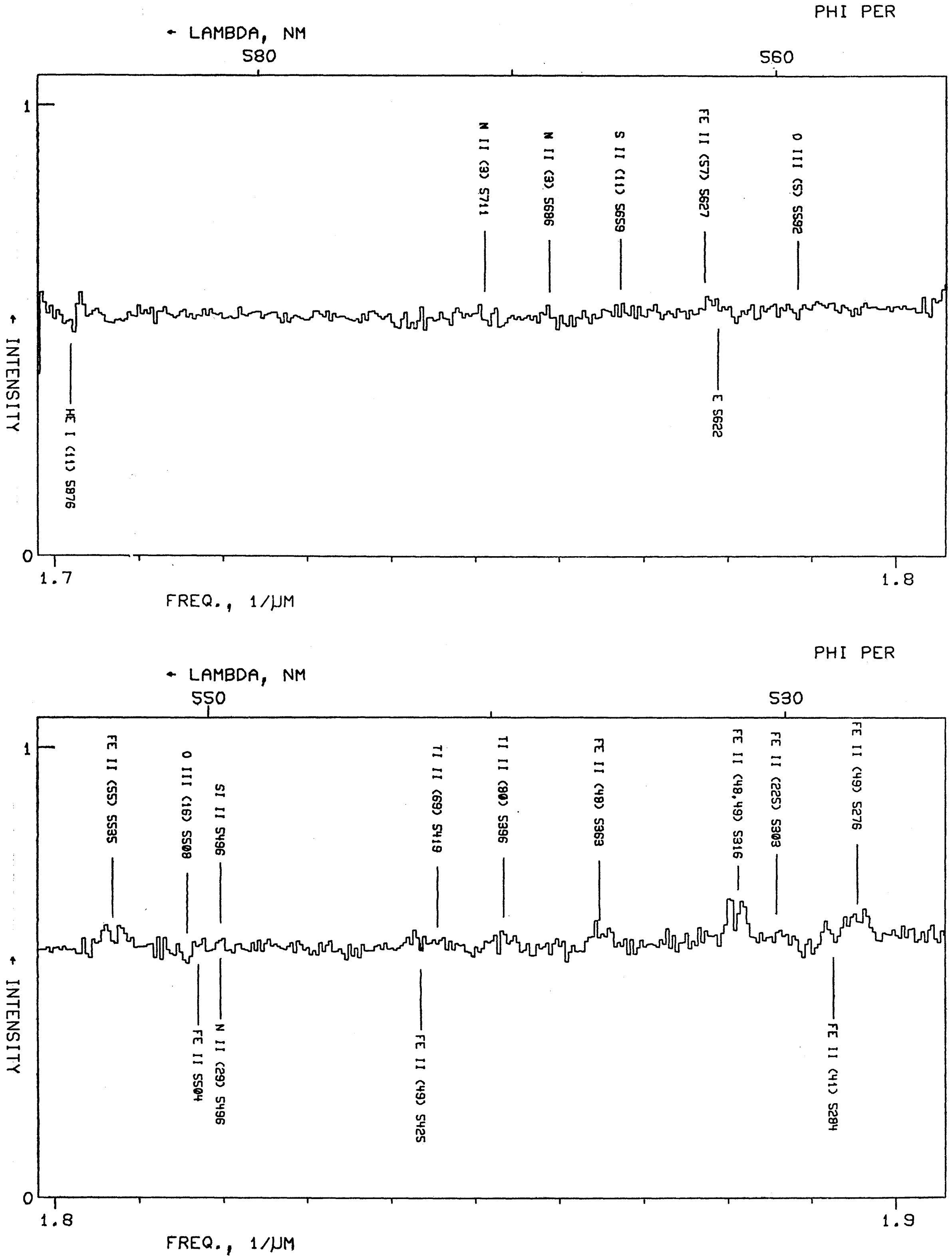
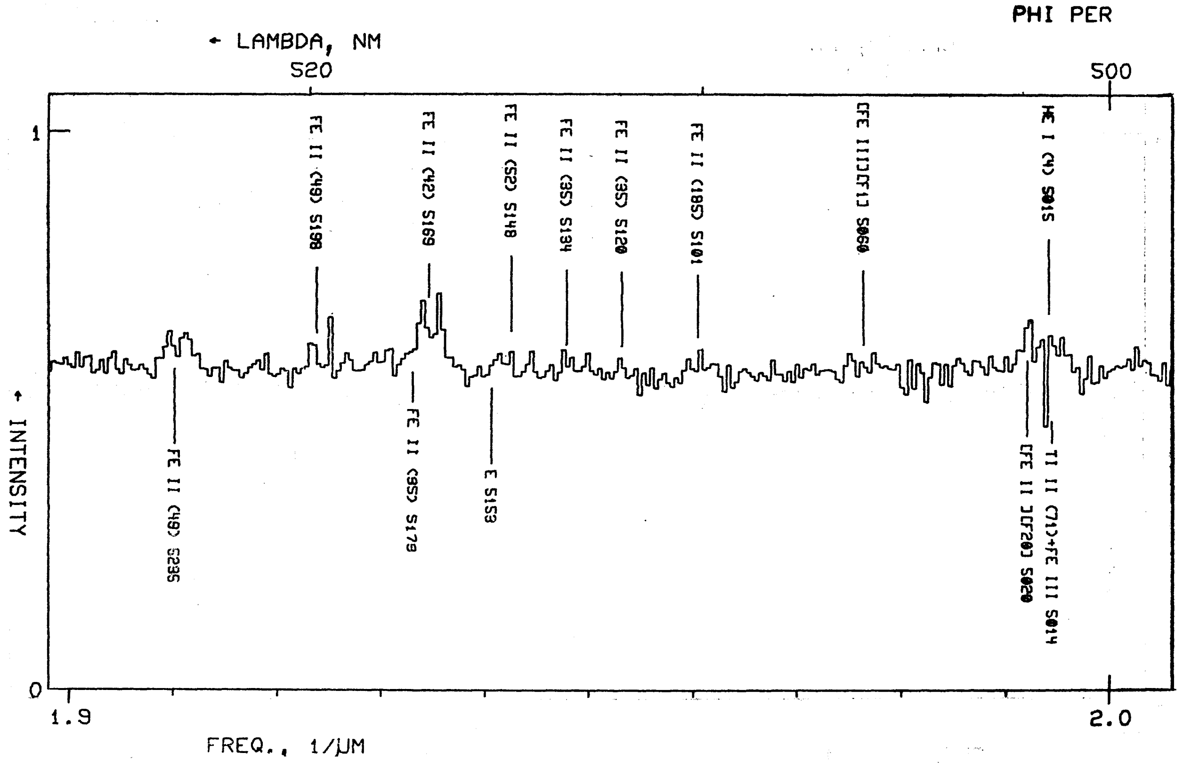
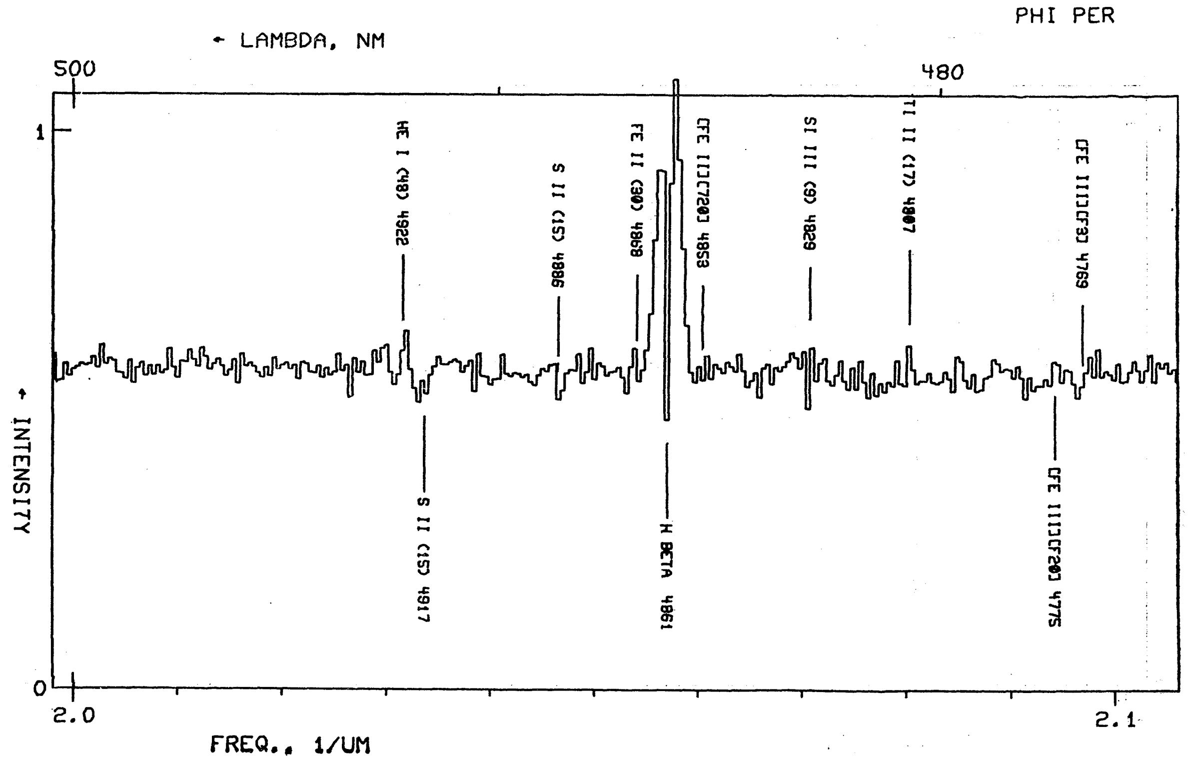


Fig. 7. The spectrum of ϕ Per from 4800-10200 Å.





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