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FOURIER TRANSFORM SPECTROSCOPY OF SIX STARS

(Invited Paper)

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RESUMEN

Este trabajo bosqueja resultados obtenidos a partir de un análisis digital de espectros de seis estrellas: ϵ Aur, β Ori, α Lyr, ζ Aql, α Aql y α Cyg que se observaron con un espectrofotómetro del tipo Fourier-Michelson. Cerca de 1200 líneas han sido identificadas en estos seis espectros, en el rango espectral 4800-10200 A, en el cual los espectros son de muy alta calidad, ya que el porcentaje del error probable del ruido de la señal versus longitud de onda, es menor que uno. Las estrellas α Lyr y α Cyg muestran variaciones en el perfil e intensidad de algunas de sus líneas espectrales, las cuales son visibles fácilmente en sus espectros.

ABSTRACT

This paper outlines results from a digital analysis of the Fourier transform spectroscopy of six stars: ϵ Aur, β Ori, α Lyr, ζ Aql, α Aql and α Cyg. Nearly 1200 different spectral lines have been identified in the spectra of these six stars in the wavelength interval 4800-10200 A where the spectra are of very high quality, less than the one per cent level of noise versus signal. α Lyr and α Cyg show spectral line and profile variations easily seen in their spectra.

Key words: **INFRARED-SPECTRA – SPECTROPHOTOMETRY – STARS-Be**

I. INTRODUCTION

I have been very fortunate to collaborate with Dr. H.L. Johnson †, now and then, during the last seventeen years. He always agreeably surprised me with new instrumental developments and brilliant ideas to gather astronomical information.

Dr. Johnson became full professor at the University of Mexico in December 1978. Very soon after that his equipment arrived from Tucson. He immediately started to put things together: a Nova computer system and a Michelson-Fourier spectrophotometer. We started to work together a few months later. Our first task was to investigate if the stars published in his Atlas of Stellar Spectra (Johnson 1977*a*, 1978) have the resolution and observational technique most adequate to our purposes. Unfortunately, Dr. Johnson passed away unexpectedly on April 2, 1980, just at the beginning of our work.

I was able last year (cf. Johnson and Mendoza 1980) to report preliminary results on two stars. In this occasion I am going to do the same with six stars (see below) published in his Atlas of Stellar Spectra II (Johnson 1978). I would like to dedicate this talk to his memory in recognition of his outstanding contributions in this field, and because he also was an exceptional good friend.

Johnson (1977*b*) has described his Michelson-Fourier spectrophotometric system. Here it will suffice to mention only a few words. He preferred analog recording at the telescope with later digitization and reductions; mainly because the analog recording is simpler and more reliable than digital systems, and moreover, analog tapes can be replayed to the digital analyser so that the reductions can be redone or a new method of reduction can be tried with the same raw-observational data. The reduction of the analog-recorded data from the telescope at the observatory proceeds in several stages:

a) *Digitalization and co-adding of the interferograms.* The digital data are obtained by taking four samples per cycle (twice the minimum required) of the highest frequency present in the interferogram of the HeNe reference laser.

b) *Fourier transformation to produce the observed spectra.* The combination of the detector, an EG + G UV100B photodiode, with a quartz beam splitter coated with a layer of AnSe one-quarter wavelength thick at 4500 A produces spectra between 4000 and 10300 A. The probable error of noise ripple in per cent of signal versus wavelength are below the one per cent level in the wavelength range 480-1020 nm(see Johnson and Mendoza 1980).

c) *Correction for atmospheric extinction and absorption, and to the standard photometric system.* The output of an FTS consists of a set of statistically independent data points, i.e., the spectra may accurately be described as multicolor photometry (4096 colors) using square, flat-topped filters which have no significant tails. Therefore, the corrections are made in the same fashion as in standard photometry. They have the same

TABLE 1

OBSERVATIONAL DATA FOR SIX STARS

Star	MK	*V*	*52*	*40-52*	*45-52*	*52-58*	*52-63*	*52-72*	*52-80*	*52-86*	*52-99*	Remar
ϵ Aur	F0 Iap	2.99	3.137	0.524	0.330	0.293	0.495	0.668	0.817	1.014	1.118	2
β Ori	B8 Ia	0.13	0.172	– 0.110	0.046	0.021	0.047	0.080	0.073	0.100	0.004	1
α Lyr	A0 V	0.03	0.039	0.013	0.001	0.001	– 0.011	0.008	0.010	– 0.004	0.011	1, 2
ζ Aql	A0 V: nn	2.99	2.981	0.007	0.008	– 0.007	0.008	0.022	0.028	0.020	0.037	
α Aql	A7 IV, V	0.76	0.799	0.255	0.098	0.120	0.182	0.236	0.304	0.328	0.339	
α Cyg	A2 Ia	1.25	1.309	0.035	0.102	0.063	0.118	0.185	0.218	0.317	0.284	1, 2

1) Fundamental MK standard (Morgan and Keenan 1973).
2) Variable star (see text).

characteristics, namely, that more accurate corrections can be derived when more data are available.

d) *Analysis of the spectra.* The writing of computer programs for the analysis of the Fourier transform spectra also has proceeded in two stages:

1. Those written by H.L. Johnson, mostly in BASIC and FORTRAN.
2. Those written by myself, only in APL.

II. DISCUSSION

The six stars discussed herein are listed in Table 1. The photometric data given in this table is the visual magnitude in Johnson's *UBV*-system and the magnitude and colors of the 13-color intermediate band photometry (Johnson and Mitchell 1975). Three stars listed in Table 1 are variable stars, ϵ Aurigae is a well known variable star. The *UBV* photometry (Johnson and Morgan 1953) of α Lyrae and α Cygni during the last three decades indicates that α Lyr varies ± 0.03 magnitudes (see also Johnson 1980). Several authors have reported small light variations for α Cygni (see, for instance Johnson *et al.* 1966; Johnson and Mendoza 1980).

The dates in which these stars have been observed are given in Table 2 (see also Johnson 1977*a* and 1978). It should be pointed out that α Cygni has been observed extensively (often, more than once during the same night –see Johnson and Mendoza 1980).

TABLE 2

JOURNAL OF OBSERVATIONS

Star	Date
ϵ Aur	1975: Nov 18
β Ori	1976: Oct 9
α Lyr	1975: Jun 22; 1976: Jun 14
ζ Aql	1976: Jun 15, Oct 10
α Aql	1976: Jun 13, Oct 9
α Cyg*	1975: Nov 16-18; 1976: Jun 13-16, Oct 9-12

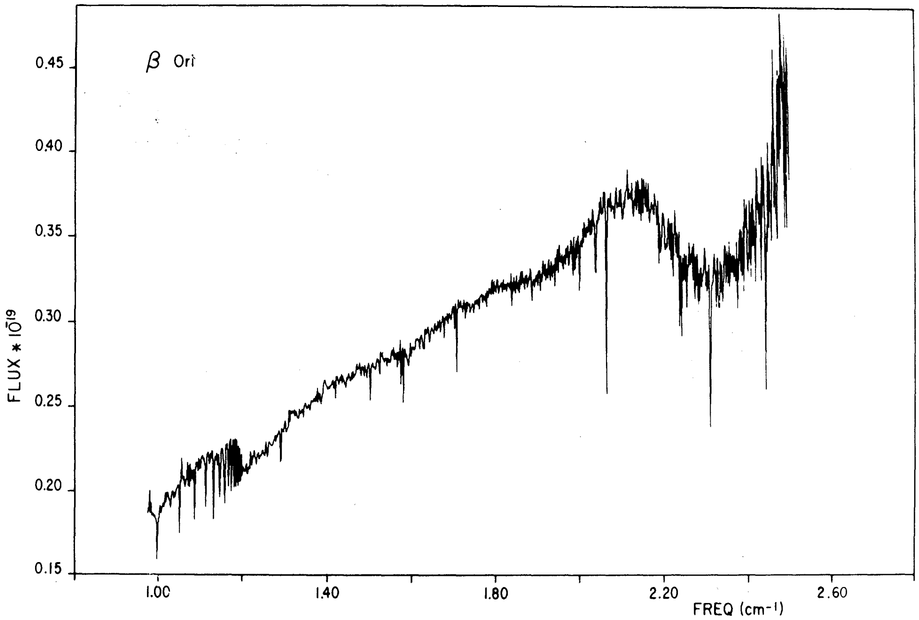
* Nov. 16-18, 1975; Jun 13-16, 1976; Oct 9-12, 1976; analized as three spectra: Nov 75, Jun 76 and Oct 76 (see text).

A preliminary study of α Cygni's spectra indicates n noticeable changes in periods of four or less consecuti nights; therefore, we decided to sum up these spectra t have only three, each one corresponding to an observir season, i.e., one for November 1975, another for Jur 1976, and finally one for the October 1976 run.

Johnson (1980) has also outlined a method t calibrate his stellar spectrophotometry. This calibratio is based upon the 13-color photometry (Johnson an Mitchell 1975) and sixteen stars divided in two group those that their magnitude have remained constar (± 0.01 mag) since the definition of the UBV system: Del, β Lib, γ Cru, γ Oph, ξ^2 Cet, ζ Aql, BS 875 and B 3314 with spectral types near A0 V. The second li: includes also two non variable stars, υ Ori and 10 La with spectral types near B0; ζ Peg (B8 V) may also b nearly constant. Other five stars for which definit statements can be made are α CMa (it has becom steadily fainter by 0.05 mag since 1950), 109 Vir (brightened by 0.03 mag during this time), α Peg and Leo (they may be variable by ± 0.02 mag), and α Lyr (is variable by ± 0.03 mag, at least). Johnson's absolut calibration covers the entire spectral range from 4000 t 10300 A. It appears to be quite firm.

The stars listed in Table 1 have computed absolut spectra with a resolution of 3.858 cm^{-1}. It is prohibitiv to publish such data here (nearly 2500 points), instea we show these spectra in Figures 1-6. They should b compared with the numbers given by Johnson (1980).

Two types of measurements were made from thes spectra: 1) wavelength measures for the purpose of lin identification, and 2) equivalent width measures of al the lines stronger than three times the probable erro (see Johnson and Mendoza 1980). In both cases, th accuracy of the measurement is limited by line blending part of this blending is due to instrumental blending an part to blending of the stellar line themselves. In addition for equivalent width measurements the accu racy may be affected by profile and line intensit variability. Again, it is also prohibitive to publish suc measurements here (800 lines, on the average, per star) A special catalogue of wavelength measures and equiva



ʼig. 1. The compressed spectrum of β Orionis. The spectral wavelength interval is from 10300 (left) to 4000 A (right). The abscissae .re in frequency units, and the ordinates are in absolute fluxes.

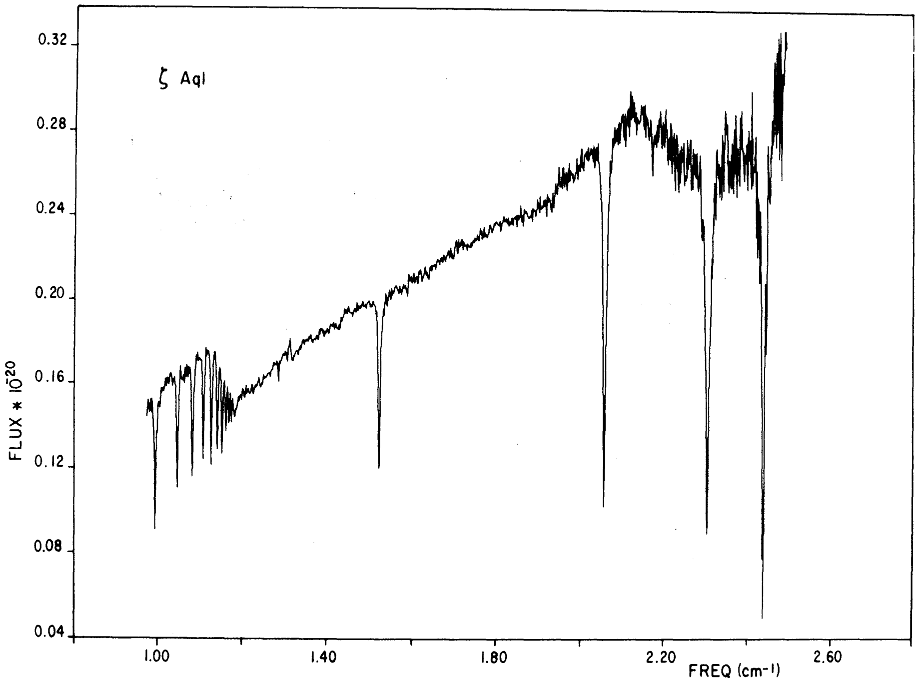


Fig. 2. The compressed spectrum of ζ Aquilae (see Figure 1).

nt widths determinations is being prepared by Mendoza ıd Gómez, which cover the spectral interval ꞩ00-10200 A, only, for the six stars listed in Table 1. his work indicates that nearly 1200 different lines are ·esent in the six stars, among them, 25% in round figures, belong to all the stars, other 25% to five, also 25% to four stars, and the remaining 25% to less than four stars. The supergiant stars have more measured spectral lines than the dwarfs, 10%, on the average, in rough figures. Over 90% of the lines have been identi-

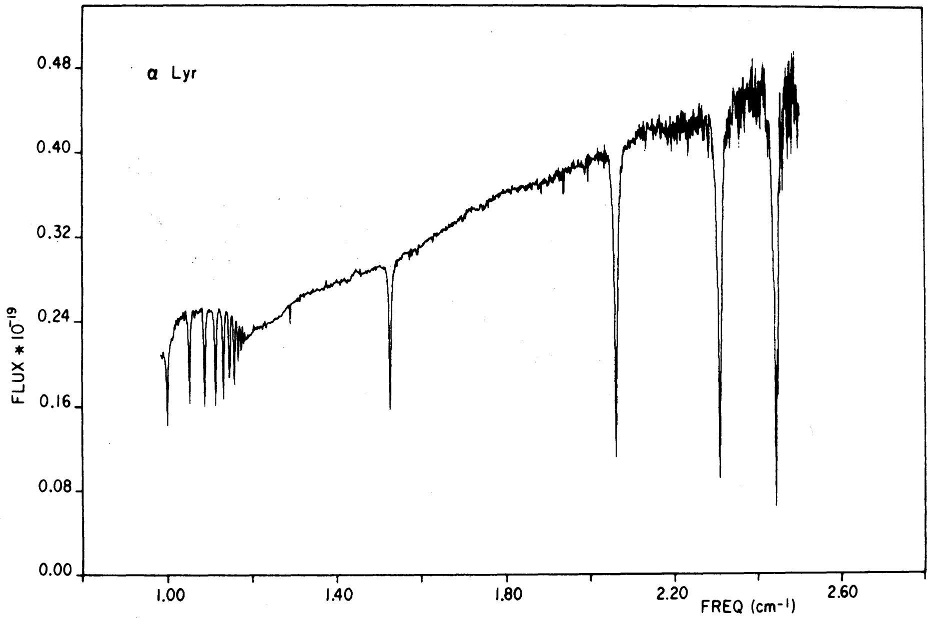


Fig. 3. The compressed spectrum of α Lyrae (see Figure 1).

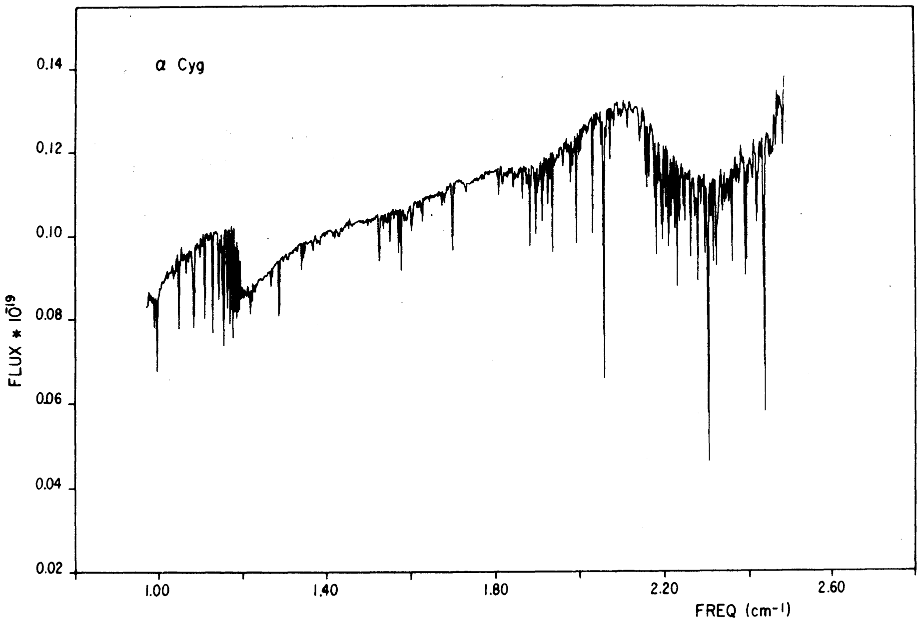


Fig. 4. The compressed spectrum of α Cygni (see Figure 1).

fied. Approximately 27 ions are responsible for these lines (see Johnson and Mendoza 1980). α Cygni and α Lyrae have been observed more than once. Their spectra show profile and line intensity variations. Preliminary reports already have been made (Wisniewski and Johnson 1979; Johnson and Mendoza 1980).

It is also interesting to show the behavior of a fe\ selected lines. For instance the interstellar sodium line D1 and D2 are illustrated graphically in Figure 7 for th three supergiant stars listed in Table 1. This figure als shows the sodium lines in the three individual spectra o α Cygni. There is no doubt in our minds that these line

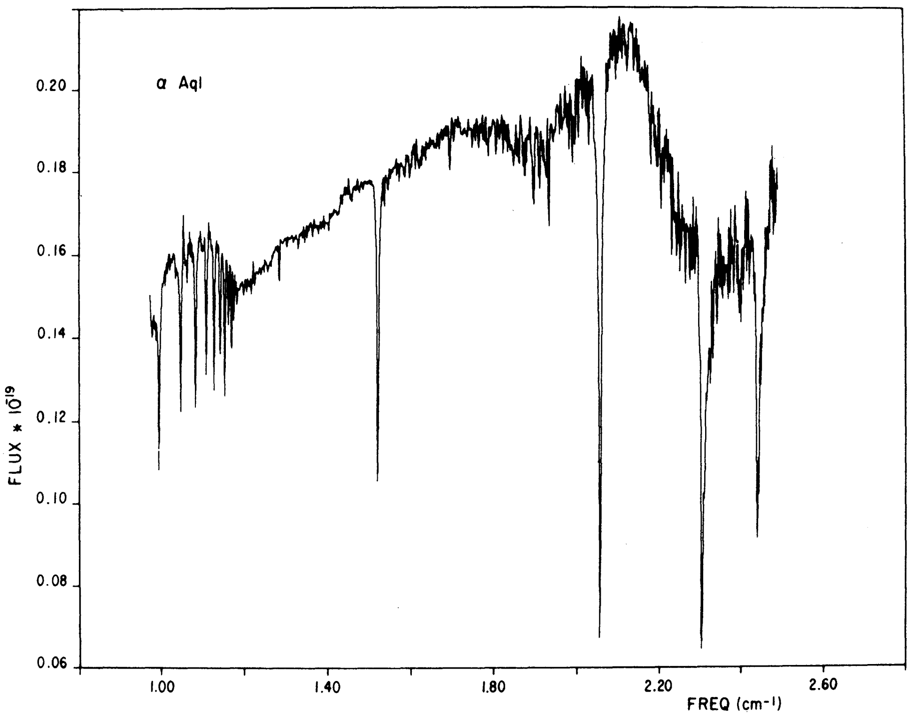


Fig. 5. The compressed spectrum of α Aquilae (see Figure 1).

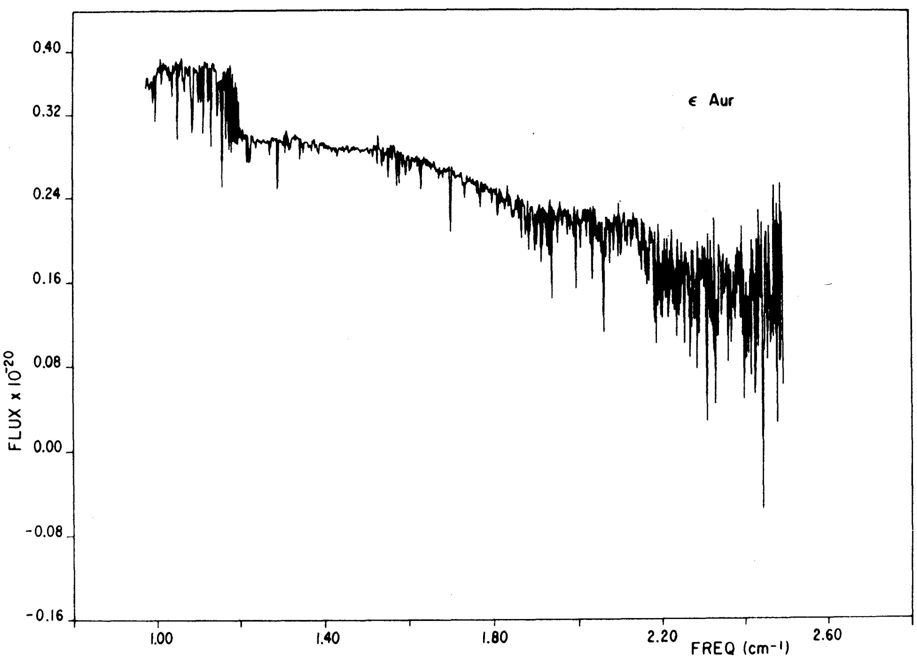


Fig. 6. The compressed spectrum of ϵ Aurigae (see Figure 2).

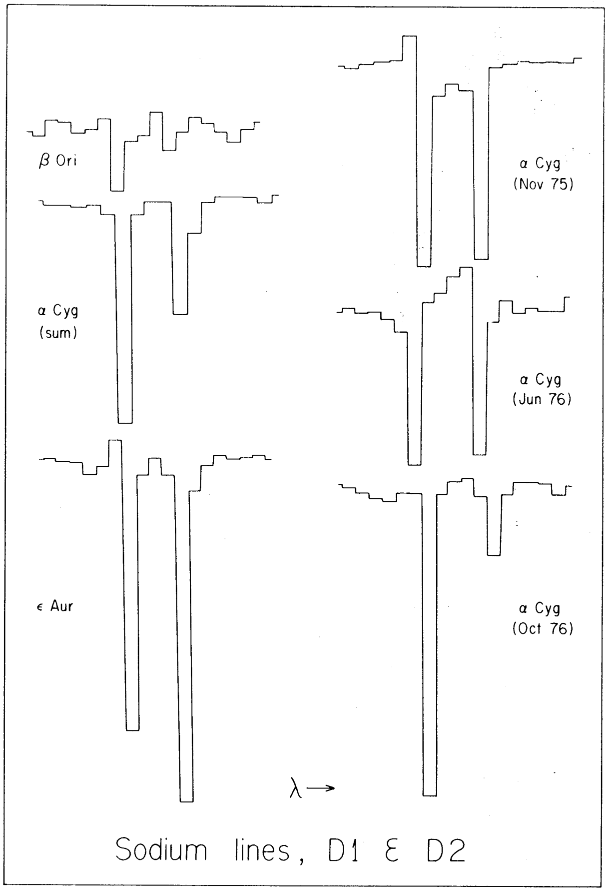


Fig. 7. The behavior of the sodium lines (D1 and D2) in the spectra of three supergiants (see also text).

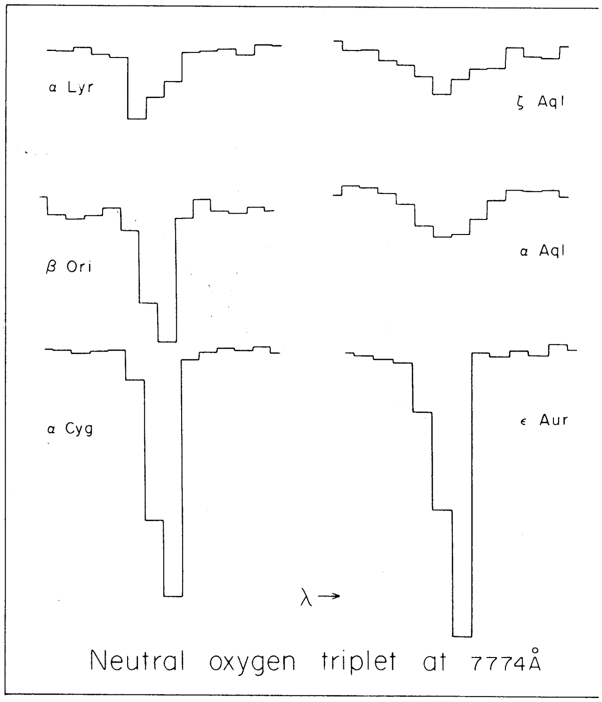


Fig. 8. The behavior of the neutral oxygen triplet line at λ7774 A in the six stars discussed in the text.

are variable. In two occasions they show the known appearance (see, for instance, Blades *et al.* 1980); however, the run of October 1976 shows quite a different story. This spectrum actually consists of eleven different spectra obtained during four consecutive nights, each one of them shows exactly the same behavior. Moreover, other stellar spectra observed during these four nights show no anomalies. Anyway, it would be important to confirm this observation.

Another interesting line is the neutral oxygen triplet at λ7774 A, since it is perhaps the most sensitive single criterium to indicate the stellar luminosity of supergiant stars. It can be seen in Figure 8 how much the strength of the O I-lines increases with stellar luminosity. Spectra of α Lyrae and α Cygni, with twice the present resolution, separate the components of this triplet (not shown here). The presence of more than one line, mainly because of the non-symmetric appearance, is easily noticed in Figure 8. Last we show in Figure 9 the neutral nitrogen lines between the Paschen lines P13 and P12. These lines are weaker and masked by the wings of the hydrogen lines in the dwarf stars listed in Table 1. They are clearly seen in the supergiant stars also listed in Table 1. These lines show dramatic changes in the spectra of α Cygni (see Johnson and Mendoza 1980).

III. SUMMARY AND CONCLUSION

A new and optically very simple Michelson Fourier Transform spectrophotometer was developed by H.L. Johnson (1977*b*). The first results have been published also by Johnson (1977*a* and 1978) as Atlas of Stellar Spectra (Parts I and II). The spectral resolution is 3.858 cm^{-1} which corresponds to 3.85 A at 10000 A and to 0.96 A at 5000 A. The quality is very high, less than the one percent level of noise versus signal over the wavelength region 4800-10200 A. The spectra are excellent for line identifications, equivalent width measures of strong and faint lines, and to analize the changes of line profile and line strength with time, if any.

Six stars has been studied, two of them show definitely spectral line variability, in profile as well as in intensity. Differences in spectral type and luminosity class are very easily observed among the six stars. The results shown above are only the beginning. More work on these stars and others are under way. The discoveries presented here and others to be reported elsewhere indicate that Fourier transform techniques in the field of

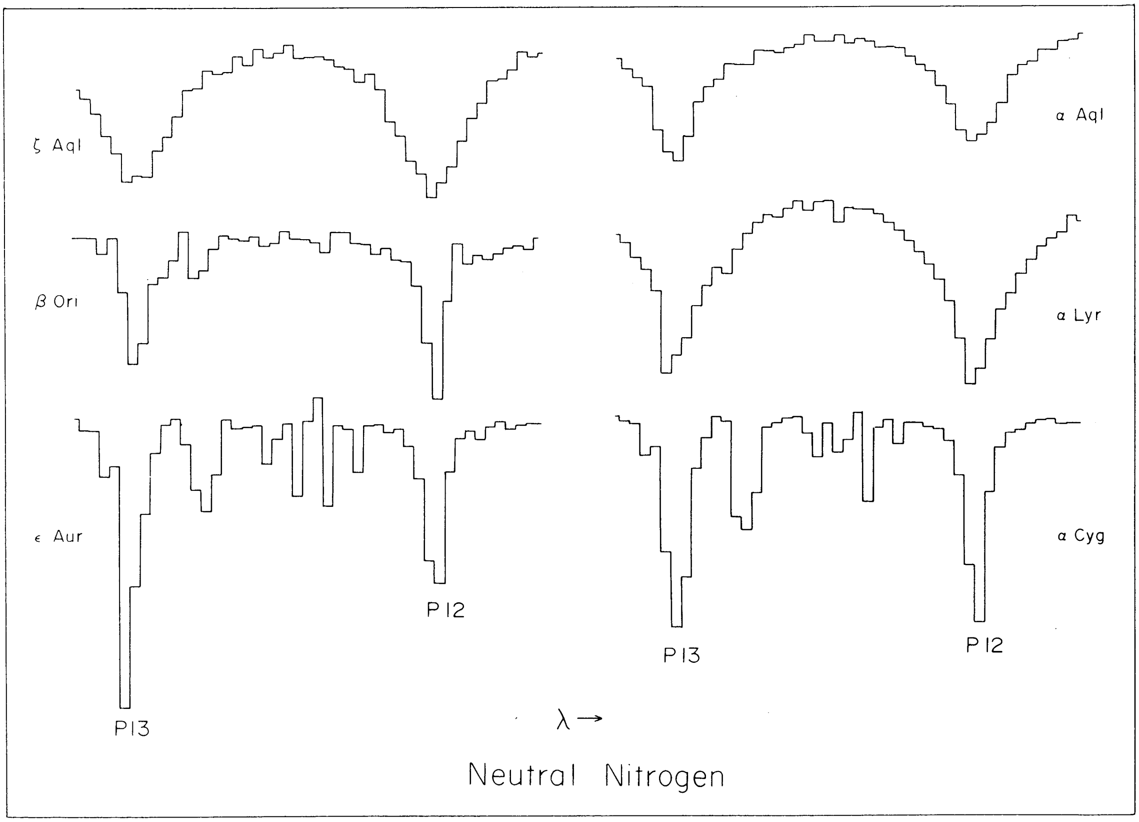


Fig. 9. The behavior of the neutral nitrogen lines in the near infrared (around λ8700 A).

ear infrared spectroscopy are very important to learn ıore about the celestial bodies.

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DISCUSSION

Peimbert: ¿Podría discutir un poco más el problema de la variación de las líneas de Na I?
Mendoza E.: La variación del sodio neutro interestelar observada en α Cygni durante una noche no es instrumental. La causa la desconozco pero espero observar esta estrella más veces para confirmar este extraño fenómeno.
Pacheco: En los espectros mostrados en que se ve la línea de O I los perfiles son asimétricos. ¿Es éste en efecto real o instrumental?
Mendoza, E.: El efecto no es instrumental, lo que sucede es que las líneas de O I forman un triplete y el centro de gravedad es diferente en algunas estrellas. También existe en algunas estrellas una pequeña contaminación.

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