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AN ATLAS OF OPTICAL SPECTROPHOTOMETRY OF SOUTHERN WOLF-RAYET CARBON STARS

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RESUMEN. Se presentan observaciones espectrofotométricas en la región del visible (3360 - 7350 A) y a resolución moderada (~10 A) de las estrellas Wolf-Rayet, serie del carbono (WC), en el hemisferio sur, incluyendo las estrellas WC en la Gran Nube de Magallanes. El Atlas presenta los flujos observados en unidades de magnitud, sin corregir por el enrojecimiento interestelar. Las estrellas han sido agrupadas por tipo espectral y tambien se incluye un montaje de las estrellas prototipo de cada clase espectral. Se da la identificación de las líneas espectrales.

ABSTRACT. We present a homogeneous set of optical spectrophotometric observations (3360-7350 A) at moderate resolution (~10 A) of almost all southern WC stars in the Galaxy and the LMC. The data are presented in the form of spectral tracings (in magnitude units) arranged by subtype, with no correction for interstellar reddening. A montage of the prototype stars of each spectral class is also shown. Line identifications are given.

Key words: SPECTROPHOTOMETRY -- STARS-WOLF-RAYET

I. INTRODUCTION

Several atlases of Wolf-Rayet (W-R) stars have been published in various spectral bands during the past five years. To mention a few, a new atlas of ultraviolet (UV) spectra has been done by Willis et al. (1986). Because of its high resolution it is the most appropriate for studies of line transfer of W-R atmospheres, along with the optical work by Smith and Kuhi (1981) which discusses line profiles of the nitrogen sequence (WN). Vreux, Dennefeld and Andrillat (1983) have a catalogue of near infrared spectra of southern galactic W-R stars. In addition, Smith and Willis (1983) have done UV and visible spectrophotometry of some W-R stars in the Large Magellanic Cloud (LMC). All these studies are complemented by the Sixth Catalogue of Galactic W-R stars (van der Hucht et al. 1981, hereafter the Catalogue).

Most of the above studies involve only prototype stars of a given subtype, or a few stars of the same subtype. Because of the well-known heterogeneity of spectral properties within a given subtype (Conti 1982), we have decided to compile a homogeneous set of spectrophotometric observations at moderate resolution (~10 A) of WC stars. The full atlas covers all WC subtypes and almost all known WC stars in the Galaxy and the LMC, including the WO stars. Here we present a preliminary report that contains only the southern hemisphere WC and WO stars. Due to lack of space only sample plots are shown.

Completeness and homogeneity in the observations are not the only needs for this compilation. From an evolutionary point of view, it is indispensable to know the chemical composition of the stars, which can be done only once the spectral lines have been identified. The observations in this atlas can also be used for studies of interstellar extinction towards W-R stars. Once the observations have been properly dereddened, they serve as a test of models of stellar atmospheres.

II. OBSERVATIONS AND REDUCTION

The stars were observed by P.M. at Cerro Tololo Inter-American Observatory (CTIO) between November 1981 and February 1985. The SIT-Vidicon detector was used on the Cassegrain spectrograph of the 1.5 m telescope. It is a two dimensional detector consisting of 512 x 512 pixels, of which only 512 x 70 are used for spectrophotometry. The system has a linear response to light and photometric accuracies may be achieved at the 3% level. The SIT target has a saturation level of about 1000 photons per pixel. Since WC stars have very strong emission lines, each observation consisted of two exposures: one to get good continuum fluxes, with the strongest emission lines usually saturated, and another to get unsaturated lines.

Several combinations of gratings and filters were used, giving resolutions of about 10 to 15 A (FWHM of a spectral line in the comparison arc). The slit was opened to 6-10" to allow absolute fluxes to be measured. The wavelength coverage was ~3360-4780 A (blue region) and ~3900-7350 A (yellow-red region). The flux calibrations were done by observing several standard stars each night. The wavelength scale was calibrated by taking exposures of a He-Ar and a Hg lamp. The observations were done at air masses $<$ 1.5 in typical seeings of 1.2". Exposure times were selected to yield signal-to-noise ratios of about 20:1.

Table 1 lists all the stars that are included in this presentation. The majority of the stars were observed more than five times in the blue and red spectral regions. Not all observations were done under photometric conditions, although in almost all cases there are at least three photometric exposures. The photometric observations of a given star agree with each other to about 4% in flux units (0.04 mag). The agreement at $\lambda < 3600$ A is only about 6% in flux units (0.06 mag).

The non-photometric observations are obviously less accurate. When the correction for atmospheric extinction is done in the presence of clouds, it is assumed that the clouds are grey. This assumption introduces an error whose effect is to change the shape of the continuum; the shortest wavelengths of the spectrum are affected the most. Sometimes the slope of the continuum may be different from that of photometric observations by as much as 12% in flux units at $\lambda < 3600$ A. When the slope varied more than 8% the observation was dicarded. The non-photometric observations were scaled to the flux level of the photometric observations and all observations that gave the best signal-to-noise ratio were averaged. The unsaturated lines were inserted in the final reduction. The few stars that do not have photometric observations have a note in Table 1. The error assigned to them is at least 0.08 mag at $\lambda < 3600$ A.

III. THE ATLAS

The fluxes were converted to magnitude units using the calibration of Vega by Hayes and Latham (1975), that is $m=-2.5\log(f_\nu)-48.59$ mag, where $f_\nu=(\lambda^2/c)f_\lambda$. By plotting the data in magnitude units instead of flux units the relative strengths of the lines can be readily compared from the plots, and approximate colors at any given wavelength can be read directly. We have chosen not to normalize the plots, nor to give any equivalent widths, line widths or intensities above the continuum in order to avoid any errors that can be introduced by picking the continuum level. All these quantities can be found in Torres (1985). The fluxes have not been corrected for interstellar reddening because the interstellar extinction is known to vary across the sky (e.g. Massa, Savage and Fitzpatrick 1983); thus assuming the average galactic extinction law would give the wrong absolute fluxes. Furthermore, many W-R stars are associated with H II regions, which makes their reddening deviate even more from the galactic average. The correction can only be done if the reddening law is known over the region in which the W-R star is located, and if it is known to be constant.

Figure 1 is a plot of one "prototype" star of each subtype. The numbers in parentheses are the number of magnitudes by which the spectrum has been shifted. For reference, the lines that are used to classify WC stars are indicated. The criterion for classification is based an ionization/excitation sequence and it consists on taking ratios of

TABLE 1

SOUTHERN WC STARS

(a) Class	(b) Star	Notes	(a) Class	(b) Star	Notes
WC 4	BR 7, HD 32125		WC 7	WR 42, HD 97152	
	BR 8, HD 32257			WR 56, LS 8	(1)
	BR 10, HD 32402			WR 57, HD 119078	
	BR 28, HD 36156			WR 68, BS 4	
	BR 31, HD 36402			WR 86, HD 156327	
	BR 32, HD 36521			WR 93, HD 157504	
	BR 43, HD 37026				
	BR 50, HD 37248		WC 8	WR 53, HD 117297	
	BR 74, HDE 269898			WR 60, HD 121194	
	WR 19, LS 3			WR 70, HD 137603	
	WR 38, MS 8	(1)		WR 77, MR 62	
WC 5	WR 9, HD 63099		WC 9	WR 59, LSS 3164	
	WR 17, HD 88500			WR 65, WRA 1297	
	WR 33, HD 95435			WR 69, HD 136488	
	WR 52, HD 115473			WR 73, NS 3	
				WR 80, WRA 1581	
WC 6	BR 22, WS 16			WR 81, MR 66	
	WR 13, MR 15			WR 88, MR 70	
	WR 14, HD 76536			WR 92, HD 157451	
	WR 15, HD 79573			WR 95, MR 74	
	WR 23, HD 92809			WR 96, LSS 4265	
	WR 27, LS 4			WR103, HD 164270	(1)
	WR 30, HD 94305	(2)		WR104, MR 80	
	WR 39, MS 9				
	WR 50, MR 44	(2)	WO	BR 93, Sand 2, FD 73	
				WR 72, Sand 3, NS 1	(PN)

(a) From Torres, Conti and Massey (1986). Stars with absorption lines in their spectrum are included in the same class as stars without absorption lines.
(b) WR number from the Catalogue. BR number from Breysacher (1981, LMC stars).
Notes: PN=central star of a planetary nebula, (1)=blue observation is non-photometric, (2)=red observation is non-photometric

line strengths: (C IV λ5801-12/C III λ5696) and (C III λ5696/O V λ5590). The line ratios have been recently quantified in Torres, Conti and Massey (1986). The FWHM of the λ4650 line is a complementary classification criterion. Earlier subtypes (WC4 to WC6) show higher ionizations than later subtypes (WC7 to WC10), as is evidenced in Figure 1 by the relative strengths of the C III λ5696 and the C IV λ5801-12 lines. Note also that the width of the lines increases towards earlier subtypes. WO stars show the oxygen lines greatly enhanced, hence their name. This is clearly seen in Figure 1 at λλ3811,34 (O VI) and λ5590 (O V).

The next part of the atlas consists of montages of the stars belonging to a given WC class. This is shown in Figure 2 for the WC 6 subtype. The number next to the star name indicates the magnitudes added in order to shift the spectrum. Montages like this one will be given for each spectral class (WO to WC 9) in the final form of the atlas.

IV. LINE IDENTIFICATION

Most of the lines in WC stars are very broad and blended. In many instances the

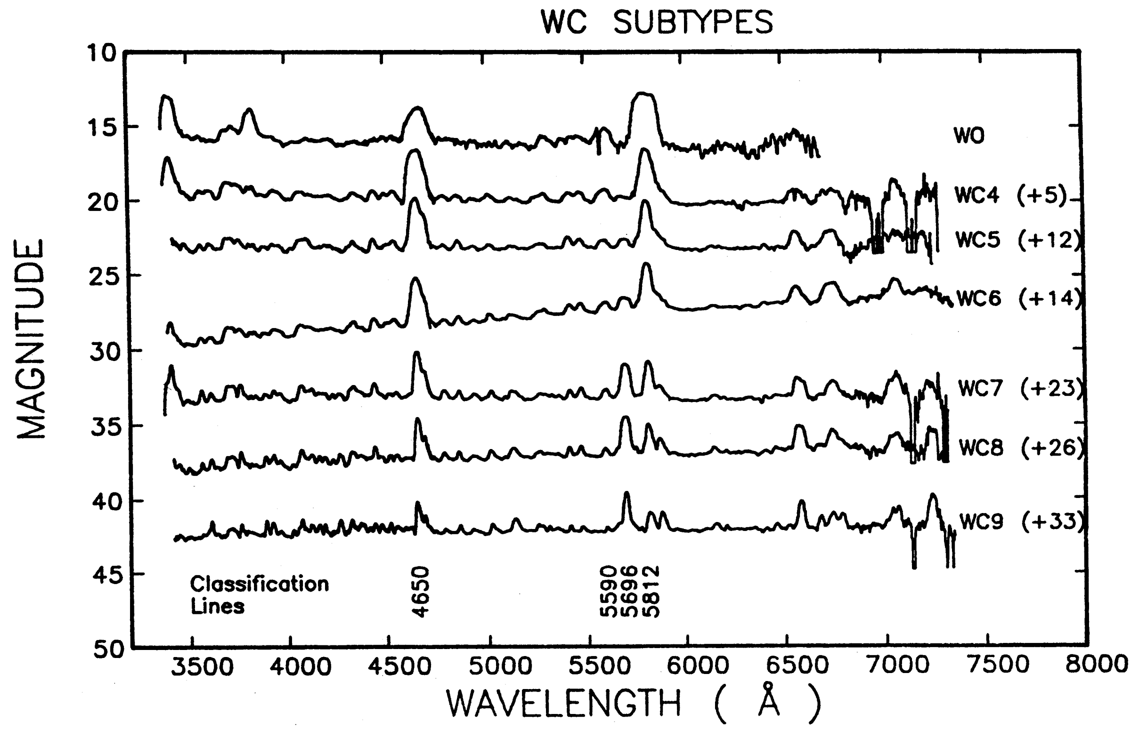

Fig. 1. Prototype stars of each WC class. The flux of the star is obtained from the relation m_ν = (MAGNITUDE - number in parentheses), where MAGNITUDE is read directly from the plot. Early types (WO-WC6) show broader lines and higher ionizations than late types (WC7-WC9).

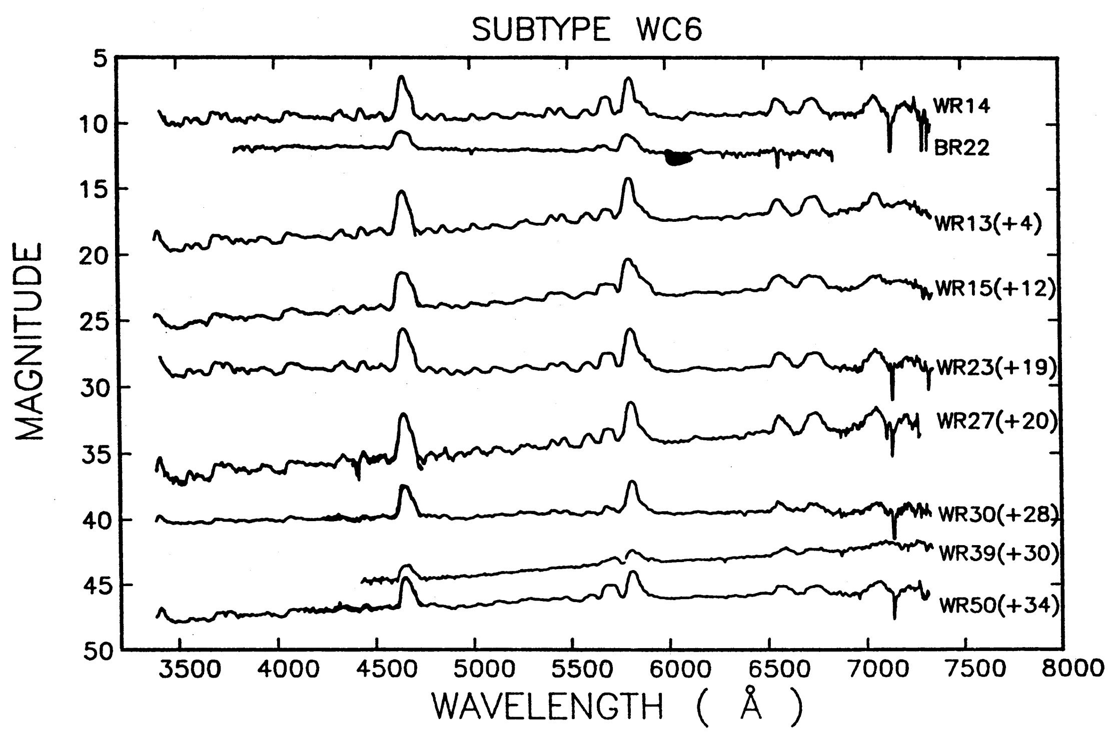

Fig. 2. Montage of the Southern hemisphere WC6 stars. The flux of the star is obtained from the relation m_ν = (MAGNITUDE - number in parentheses), where MAGNITUDE is read directly from the plot.

contributions from individual ions cannot be resolved, they can only be inferred by looking at all the lines that belong to the same atomic series or to the same atomic multiplet. The resolution of the spectra in this atlas is not high enough to separate all the blends in weak lines. For this we have looked at tracings of spectrograms taken by Dr. P. S. Conti at a resolution of 1 A and 2 A in the blue and red regions, respectively. For a description of these observations see Torres, Conti and Massey (1986).

The line identifications are based on the tables by Moore (1945, 1965, 1970) and the papers by Smith and Aller (1971) and by Edlen (1956), who was the first one to successfully identify the hydrogenic transitions arising from high quantum levels in C IV. We have also looked at the infrared (Vreux, Dennefeld and Andrillat 1983) and ultraviolet lines (Willis et al. 1986) to make sure that our identifications are compatible with the lines present in other spectral bands. It must be noticed that a few lines still remain unidentified.

Figure 3 shows the line identifications in a WC 9 star. Similar figures are available for all other subtypes. Table 2 shows how the spectral lines will be tabulated in the final version of the atlas. Tables of the same format, grouped by element, have been done for the transitions present in the optical spectra WC stars. They include the following ions: He I, He II, C II, C III, C IV, Si III, Si IV, O II, O III, O IV, O V, and O VI.

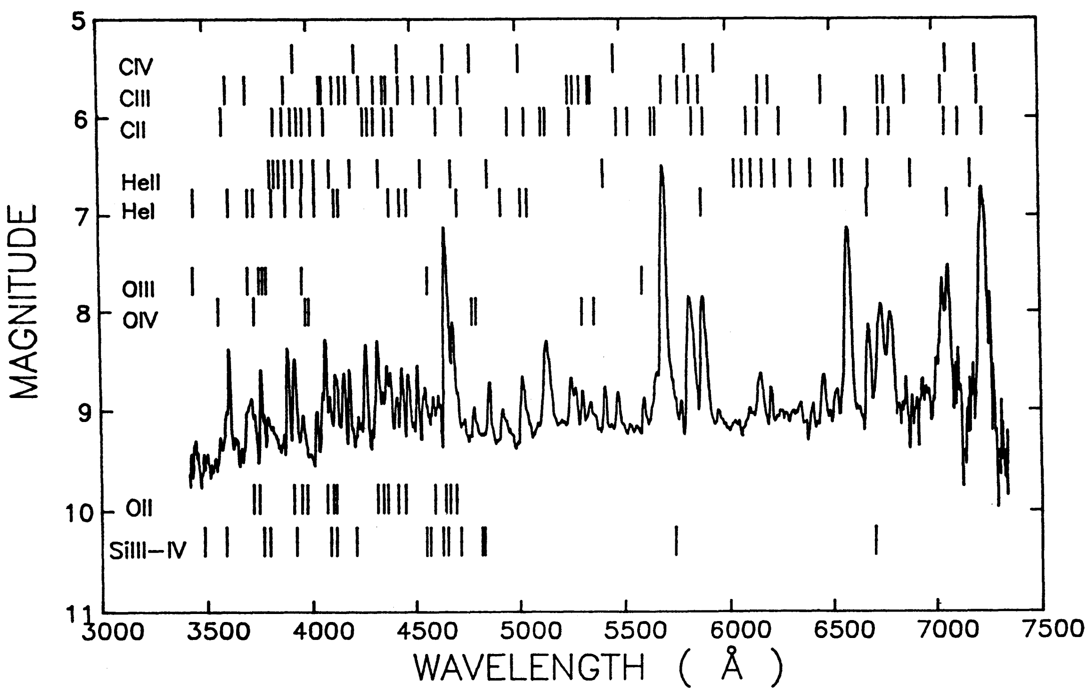

Fig. 3. Ions present in the optical spectrum of WC9 stars. Shown here is HD 164270 (WR103). The positions of the laboratory wavelength of contributing lines are marked as vertical ones.

Along with the final version of the atlas a magnetic tape will be available containing the observed fluxes (f_λ) and magnitudes as a function of wavelength for almost all WC stars in the Galaxy and the LMC.

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Table 2

Some Contributing Lines in the Spectrum of WC Stars

He I				He II				
λ_{lab}[a]	I_{lab}[b]	M[c]	transition	λ_{lab}	M[c]	transition	Notes	Blends With Other Ions
				3203.1	1	$5\ ^2F^0-3\ ^2D$		
3447.6	(2)	7	$6\ ^1P^0-2\ ^1S$	....			np in WC7	O III
3613.6	(3)	6	$5\ ^1P^0-2\ ^1S$	....			np in WC7	O III λ3609 d
3705.1	(3)	25	$7\ ^3D-2\ ^3P^0$	....			vw or np in WC8, np in WC7	O III, C III
3732.9	(1)	24	$7\ ^3S-2\ ^3P^0$	....			vw or np in WC8, np in WC7	O II, O IV
				3781.7	5	$21\ ^2G-4\ ^2F^0$	b or m in all subtypes	O III, Si IV
				3796.3	5	$20\ ^2G-4\ ^2F^0$	b or m in all subtypes	O III, Si III
				3813.5	4	$19\ ^2G-4\ ^2F^0$	b or m in all subtypes	Si III, O VI
3819.6	(4)	22	$6\ ^3D-2\ ^3P^0$	....			np in WC7	
				3833.8	4	$18\ ^2G-4\ ^2F^0$	b or m in all subtypes	C II, O VI
				3858.1	4	$17\ ^2G-4\ ^2F^0$	vw in all subtypes	
				3887.4	4	$16\ ^2G-4\ ^2F^0$	b or m in all subtypes	C III
3888.6	(10)	2	$3\ ^3P^0-2\ ^3S$	....			d, P Cygni	C III
				3923.5	4	$15\ ^2G-4\ ^2F^0$	b or m in all subtypes	CII, OII; CIV in WCE

[a]The average wavelength weighted by the intensity is given if the multiplet consists of two or more lines.
[b]The intensity of the strongest line is given if the multiplet consists of two of more lines.
[c]M = multiplet number.
[d]Key to notes: b = blended, d = major contributor, m = masked, np = not present, vw = very weak, w = weak.

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