ABSOLUTE SPECTROPHOTOMETRY OF WOLF-RAYET STARS: ARE THE COLORS THE SAME?

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Until now, all that we've known about the magnitudes and colors of Wolf-Rayet stars has been based on photoelectric photometry made with 50-150 A wide interference filters, selected to exclude as far as possible the stronger emission lines (Westerlund 1966; Smith 1968; Lundstrom and Stenholm 1979). This was clearly an improvement on the pioneering efforts of Pyper (1966), who obtained broad band photometry and attempted to correct for the presence of emission; nevertheless, with modern detectors it is possible to go one step further.

For the past year I have been collecting data on all the northern hemisphere WR stars brighter than v $\sim$ 15 with the Intensified Reticon Scanner (IRS) on the Kitt Peak No. 1 - 36" (0.9-m) telescope. The instrument consists of the regular cassegrain spectrograph followed by a three stage image tube coupled to a 920x2 Reticon via a microchannel plate. Measurements were made with simultaneous sky subtraction, with coverage obtained from λλ 3300 - 7100 A. The resolution is 3 A in the blue and 6 A in the red. Counts were converted to absolute flux by observations of standard stars tied into the Hayes and Latham (1975) calibration of Vega.

The data can be used for determining absolute fluxes and continuum energy distributions. As a subset of the latter, one can extract line-free, monochromatic magnitude at the effective wavelengths of the u, b, v and r filter system of Westerlund (1966) and Smith (1968), e.g., λλ 3650, 4270, 5160, 6000. This should reveal how badly the filter measurements were contaminated by emission lines. In order to measure monochromatic magnitudes, the spectra were examined uisng an interactive graphics terminal. If a line appeared to be present near the u, b, v, or r wavelengths, the continuum to either side of the line was extrapolated to these wavelengths. In order to check for systematic errors, I multiplied the IRS data by an approximation to the filter bandpasses to produce "filter" scanner measurements. The colors found

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from these measurements show no systematic differences with the published (actual) filter measurements, once the latter have been fudged to the system of Smith using the corrections listed in van der Hucht et al's catalog, and then transformed from the old Oke (1964) calibration of Vega to that of Hayes and Latham (1975). Thus it is legitimate to compare these "filter" scanner measurements with the "monochromatic" scanner measurements to see the result of emission line contamination.

The results are illustrated in Figure 1, which shows the difference between the narrow and "broad" (e.g. Smith bandpass) u-b colors. Most of the WN stars show only small (< .03) differences, but many of the WC stars show large differences - some as great as 0.3 mag (The difference between the "filter" and "monochromatic" magnitudes of HD 16523 is 0.5 mag in u and 0.2 mag in b).

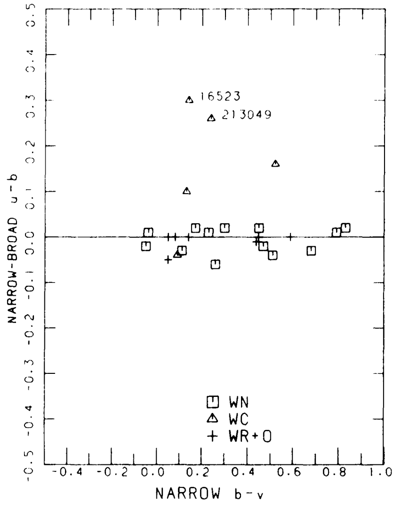

Figure 1. The differences in the u-b colors found from "monochromatic" (narrow) and "filter" (broad) are as great as 0.3 for some WC stars.

Figure 2 graphically demonstrates the contamination of the filter bandpass with various emission lines. The 50% filter response is shown by the heavy bar; the 10% limits are shown by the thinner lines. One should recall Smith's (1973) warning that her system "effectively avoids emission lines in the spectra of WN stars...this is not the case for WC stars." In fact, the errors in using the filter magnitudes to represent continuum magnitudes can be as great as 0.5 mag.

If the data from Smith (1968) is plotted in a two-color diagram one quickly finds that WR stars do not lie along a single reddening line. Do the monochromatic colors reduce this scatter? The surprising answer is no, as shown in Figure 3. This suggests that not all WR stars have the same intrinsic colors. One must then ask if stars of the same subtype have the same colors.

By adopting a reddening law, one can define reddening free parameters, analogous to Smith's (1968) Δ parameter. Using the reddening

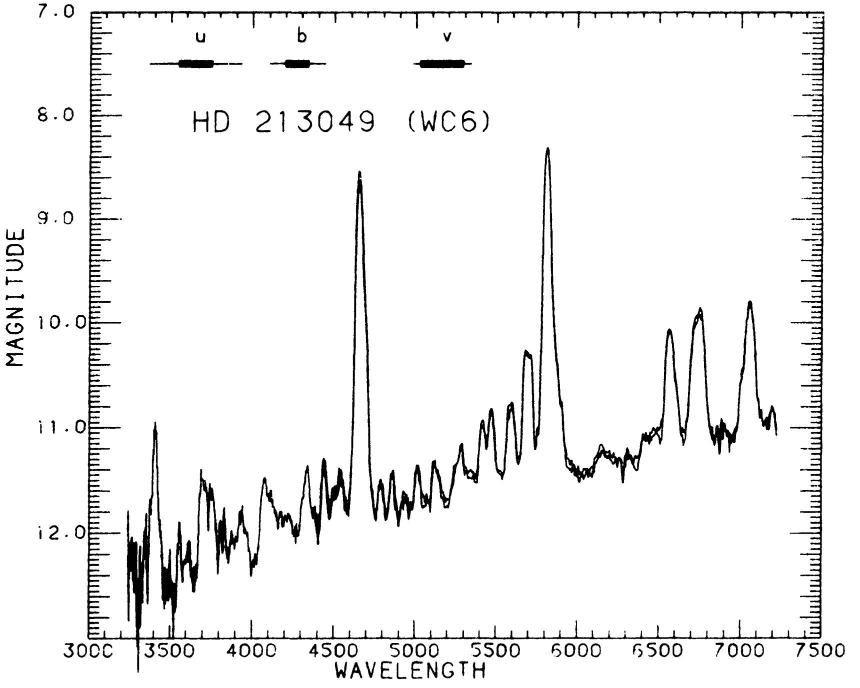

Figure 2. The absolute flux of HD 213049 is shown in magnitudes ($-2.5 \log F_\nu - 48.64$). The location of the u, b, v band-passes of Smith (1968) are indicated.

law of Schild (1977) and the effective wavelengths of the filters, one would expect the parameters

$$\text{Delta } (u-b) = (u-b) - 0.85\ (b-v)$$
$$\text{and} \quad \text{Delta } (v-r) = (v-r) - 0.88\ (b-v)$$

to be free of any reddening. Each delta quantity essentially measures the departure from linearity of the log F_ν distribution plotted in $1/\lambda$ space.

These two parameters are plotted in Figure 4, as a function of spectral subtype. It is immediately apparent that not all stars of a given subtype have the same value, and hence can not have the same intrinsic colors. The sign convention is such that a smaller delta (u-b) value corresponds to additional UV flux (e.g. Kuhi's 1966 finding that WN stars have a larger UV excess than WC stars, but see van Blerkom 1973). The delta (v-r) show much less scatter.

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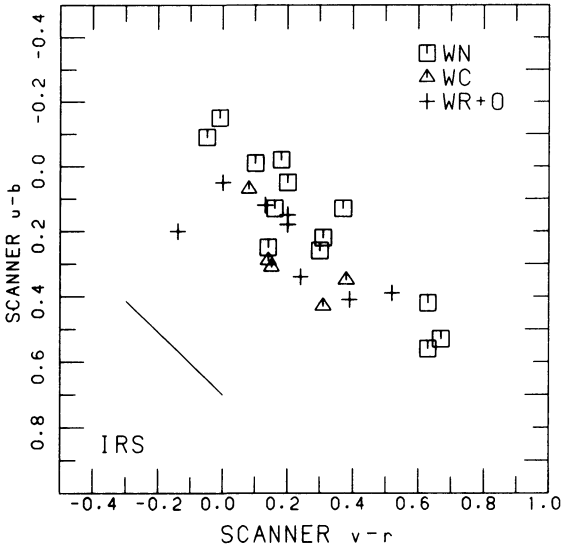

Figure 3. A two-color plot based on line-free magnitudes reveals that neither the WN's nor WC's fall on a single reddening line.

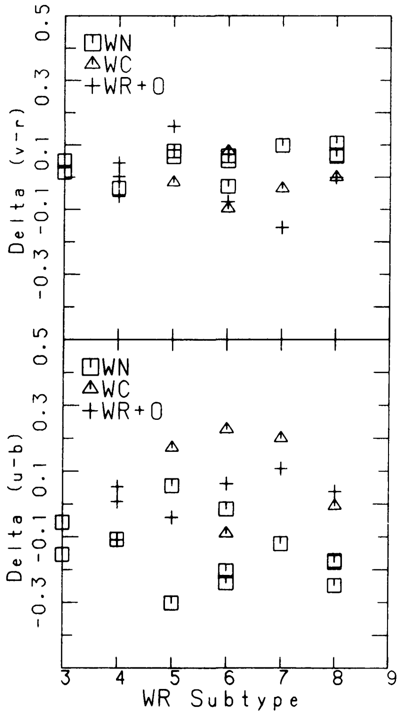

Figure 4. Reddening free parameters differ for stars of the same sub-type.

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DISCUSSION

Williams: How much of the scatter in the colour diagrams can be ascribed to different emission line strengths ? From studies of the visual-infrared colours of WR stars, I find that the difference in intrinsic (b-v) of WN and WC stars is greater than those tabulated by Lyndsey Smith and generally used in the sense that the WC stars have bluer (b-v).

Massey: The point of using scanner data is that you get essentially monochromatic, line-free magnitudes and colours. I do not believe you can correct filter colours for the emission lines, except star by star, since the line strengths are different in stars of the same subclass.

Garmany: We have been dereddening the UV spectra of WN stars through the removal of the λ2200 bumps in the LWR spectra taken with IUE. When we compare the dereddened flux in line-free regions, we find large flux ratio variations within a given spectral type, just as you do. This assumes the standard interstellar extinction law.