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ULTRAVIOLET PROPERTIES OF IRAS-SELECTED Be STARS

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ABSTRACT

We present preliminary results of a study of IRAS-selected Be stars using data from IUE. We have obtained new IUE observations of 35 Be stars from a list of stars which show excess infrared fluxes in the IRAS data. We find that IRAS-selected Be stars show larger C IV and Si IV equivalent widths than other Be stars. We also find that the excess C IV and Si IV absorption seems to be independent of spectral type for IRAS-selected Be stars later than spectral type B4. We interpret this as evidence for a possible second mechanism acting in conjunction with radiation pressure for producing the winds in Be stars. No clear correlation of IR excess or $v \sin i$ with C IV or Si IV equivalent widths is seen, although a threshold for the occurrence of excess C IV and Si IV absorption appears at a $v \sin i$ of about 150 $km\ s^{-1}$. These results are preliminary, as this project is ongoing research, and more stars will be included as data become available.

Keywords: Be stars, ultraviolet spectra, infrared excesses, C IV equivalent widths

1 INTRODUCTION

Be stars have been the subject of intense study with IUE since its launch 10 years ago. Snow and Marlborough (Ref. 1) first pointed out the presence of asymmetric line profiles in the spectra of Be stars on the basis of ultraviolet data from the *Copernicus* satellite. Since then, a number of studies have been done with IUE to investigate the ultraviolet characteristics of Be stars (Ref. 2-5). Results of these studies indicate that strong, high velocity, highly ionized winds are a common characteristic of Be stars; variability and the presence of narrow components in the resonance lines of C IV are also important features.

Near-IR observations of Be stars have also been carried out by a number of observers. Gehrz, Hackwell, and Jones (Ref. 6) undertook a large survey of Be stars at near-IR wavelengths. They reported near-IR excesses for the Be stars in their sample, which they showed were due to free-free emission from the circumstellar material. They did not find evidence for a correlation of IR excess with $v \sin i$.

With the completion of the IRAS mission in 1983, far-IR data became available for the first time for a large number of Be stars. Coté and Waters (Ref. 7) analyzed the IRAS data and found that 101 Be stars showed significant IR excesses in at least one IRAS band. In other analyses of the IRAS data, Waters (Ref. 8) found no direct correlation of the 12 μm excess with either $v \sin i$ or spectral type, although some thresholds did seem to be present. He found that stars of early spectral type (B0-4e) showed larger excesses than stars of later spectral type (B5-9e). He also found that large 12 μm excesses only tended to occur in stars with $v \sin i$ larger than about 200 $km\ s^{-1}$.

A number of *ad hoc* models have been proposed to try and explain various Be star characteristics. Good reviews of the current state of modeling can be found in Slettebak and Snow (Ref. 9). Many researchers now believe that the basic geometry of Be stars consists of an axisymmetric concentration of cool material in the equatorial region combined with hot, high velocity polar regions. A study using both infrared and ultraviolet data may provide some useful insights into the true nature of the Be phenomenon. Accordingly, we have begun a program to obtain IUE data (both archive and new observations) for Be stars which show infrared excesses in the IRAS data. In this paper, we present some preliminary results from the study, including only those *new* observations which we have obtained. The archive data will be included in the complete paper to be published elsewhere.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Selection criteria

For this study we have observed Be stars which showed infrared excesses in at least one of the IRAS bands. Hereafter these stars will be referred to as IRAS Be stars. We used the results of Coté and Waters (Ref. 7) to select these stars. From their list, we have chosen stars for which there are no (or in some cases only one or two) high dispersion IUE spectra available. We have attempted to obtain a good cross-section of spectral types and luminosity classes, although at this point in the study there remain some gaps, noticeably at very early spectral types (B0-1e). The archive data, combined with future observations, will remedy most of these deficiencies.

2.2. Observations and data extraction

The sample of new observations which we will discuss here consists of 35 Be stars. For each star, at least one high dispersion SWP spectrum was obtained with IUE. In some cases, more than one spectrum was obtained. Because we have found that a number of these stars show interesting characteristics at Mg II, we have also begun obtaining high dispersion LWP spectra of the stars as well, but at present only 13 of our sample stars have LWP spectra available.

Standard IUESIPS reduction (Ref. 10) was used to convert the spectral data to the form of extracted data. Echelle blaze function corrections were made using the algorithm of Ake (Ref. 11), and the variation of detector sensitivity with wavelength was included using the data of Cassatella, *et al.*(Ref. 12, 13). The line profiles of Si IV ($\lambda\lambda$ 1393.73, 1402.73 Å) and C IV ($\lambda\lambda$ 1548.195, 1550.768 Å) were extracted using the HIGH program at the Colorado IUE RDAF. For the LWP spectra, the profiles of Mg II ($\lambda\lambda$ 2795.523, 2802.648 Å) were extracted. The profiles were smoothed using a five-point running filter. Overexposed spectral regions have not been analyzed further.

3. RESULTS

3.1. C IV and Si IV

We have measured the equivalent widths of the C IV and Si IV line profiles in each of our spectra. Uncertainties in individual equivalent widths are estimated to be 0.3 to 0.5 Å, and are due to uncertainties in the placement of the continuum and of the point at which the absorption feature returns to the continuum. For those stars which have more than one observation, we have taken the mean value of all the observations as the equivalent width for purposes of this study. This approach minimizes the effects of variability.

When the C IV equivalent widths are plotted against those for Si IV, a reasonably good correlation is found (see Fig. 1). This is not an unexpected result, since both lines are formed in similar regions of the wind. However, it does show that the Si IV arises mostly in the wind, which is not obvious from the shapes of the line profiles alone in many cases. The result is a useful one, since it means that the correlations with other parameters will be similar for both C IV and Si IV. Although we have examined the data for both lines, we will present only the results for C IV from here on, since the results are the same in both cases.

3.1.1. Comparison with normal B and Be stars. In order to compare the IRAS-selected Be stars with normal B stars and with non-IRAS Be stars, we have chosen to average together the equivalent widths of all stars in each spectral class. Averaging helps to minimize the effects of the well-known time variability in the ultraviolet spectra of Be stars, thus producing a better indication of overall trends than would be seen in individual stars. By averaging, we have assumed that all stars of a given spectral type within each data set are similar. This is not completely correct, since obviously there are different luminosity classes as well as a range of other stellar parameters included within each type. Nevertheless, the stellar photospheric temperatures are approximately the same.

We have used the data from Grady, Bjorkman, and Snow (Ref. 5) and Grady *et al.*(Ref. 14) for our normal B star sample. We have taken the Be star results from these same papers and removed those stars which appear in the list of IRAS Be stars to produce our non-IRAS Be sample. There is therefore no overlap of stars between the three data sets.

We plot the mean equivalent widths *vs.* spectral type for all three data sets in Fig. 2. The error bars represent the standard deviations of the mean equivalent widths. This is a measure of the intrinsic variation within each spectral type. We will take the curve shown for the normal B stars to define a standard mean equivalent width for each spectral type. We will use this value to define an excess C IV equivalent width for Be stars which will be discussed later. A similar process has been followed for the Si IV data.

The data show a definite difference in mean C IV equivalent widths for the three data sets. Be stars in general show a larger C IV equivalent width than do normal B stars. This agrees with the findings of Grady, *et al.*(Ref. 5, 14). In addition, it is clear that the IRAS Be stars show even larger C IV (and Si IV) equivalent widths than do the non-IRAS Be stars.

3.1.2. Dependence on spectral type. From Fig. 2, we notice that the equivalent width for the Be stars remains approximately constant later than spectral type B5. For spectral types earlier than B5, the equivalent widths increase with luminosity, as is expected for radiation driven winds; however, the excess mean equivalent widths, defined by $W_{ex} = W - W_{std}$, are at most only a weak function of spectral type earlier than B5, and remain approximately constant later than B5

3.1.3. Correlation with $v \sin i$. The excess C IV equivalent widths for the IRAS Be stars are plotted *vs.* $v \sin i$ in Fig. 3. Note that in this case the data points represent values for individual stars, and not mean values, since wide ranges of $v \sin i$ occur within each spectral type. There is no clear correlation of C IV excess equivalent width with $v \sin i$, although there does appear to be a threshold in $v \sin i$ (at around 150 $km\ s^{-1}$) at which excesses begin to occur. Above this $v \sin i$ value there is a wide range of excesses. One might think that this could be a selection effect due to the inclusion of only the IRAS Be stars, which have preferentially larger values of $v \sin i$. However, we have examined this more carefully by including the non-IRAS Be stars and the normal B stars, and we find that the threshold is not just a selection effect. It also occurs in the Si IV data. This result is interesting in light of thresholds found at similar $v \sin i$ values for the occurrence of IR excess (Waters, Ref. 8), and for the UV, polarization, and Hα (Grady, *et al.*, Ref. 5).

3.1.4. Correlation with IR excess. Since the IRAS Be stars show noticeably higher C IV mean equivalent widths than the other stars, we might expect a possible correlation of C IV equivalent width with 12 μm excess. However, as we see in Fig. 4, this is not the case. The C IV equivalent widths do not correlate with the 12 μm excess defined by Coté and Waters (Ref. 7). The Si IV data also show no correlation.

3.2. Mg II

At this point in the study, our sample of stars with LWP spectra is limited. However, several interesting results are apparent from these spectra. Of the 13 stars for which Mg II profiles have been examined, 4 show evidence for emission wings and 1 star (HD 50123) shows prominent P Cygni profiles at Mg II (shown in Fig. 5). The remaining stars show only normal Mg II absorption. These results can be better examined as soon as we have completed our upcoming observations.

3.3. HD 50123

In addition to the P Cygni profiles at Mg II, HD 50123 shows several other interesting characteristics in the IUE data. It shows absorption features at N V ($\lambda\lambda$ 1238, 1242 Å), which is very unusual for a star of its spectral type (*B 6 IV npe*). It also has strong lines of Si IV and C IV, as well as lower ionization lines of Si II and S II. It shows a remarkable range of ionization, as well as large time variability in the line strength. We are continuing to observe HD 50123. A paper detailing the results of these observations is in preparation.

4. INTERPRETATION

Although the data presented in this paper are preliminary, some interesting results are beginning to emerge. We consider some possible interpretations of these data in terms of models for Be stars. Since C IV and Si IV are superionized states in stars later than about B2 (or earlier for C IV), we assume that these lines are produced in the wind of the stars and are not photospheric. This is not new, and has been known about Be stars for some time. However, the fact that stars with large IRAS IR excesses also tend to exhibit excess C IV and Si IV equivalent widths suggests that there is an enhanced density in both the IR and UV producing regions of the circumstellar envelope. Perhaps this can be interpreted as evidence that the same underlying physical mechanism is responsible for enhancement in both regions.

Higher luminosity will result in larger mass loss rates if a radiatively driven wind is responsible for the mass loss. The results in Fig. 2 seem to bear this out for the normal B stars, but the excess C IV and Si IV mean equivalent widths seen most notably in the IRAS Be stars cannot be explained by radiation driven winds alone, since they do not appear to be luminosity dependent for later spectral types. One possible interpretation is that this is direct evidence of a second mechanism acting in conjunction with radiation pressure to produce the winds in Be stars This same mechanism would also have to produce the IR excess, since the effect in the UV is seen most strongly in those stars with IR excesses.

The well-known link of Be stars to high values of $v \sin i$ shows that rotation must clearly play an important role Observations using many wavelengths and techniques have shown thresholds at similar values of $v \sin i$ for the onset of different aspects of the Be phenomena, including polarization, IR excess, narrow components, Hα characteristics, and now UV excess absorption at C IV and Si IV. These other observations also show no correlation with $v \sin i$ other than the threshold. One might interpret this as evidence for the onset of an instability which initiates the mechanism responsible for these effects

From the result that the relationship between IR excesses and excess C IV equivalent widths is merely a threshold, rather than a direct correlation, we must conclude that the densities, and hence the mass loss rates, in the IR and UV producing regions may be different What does this imply for models of Be stars?

In the spherically symmetric model of Doazan (Ref 15), the UV and IR producing regions are assumed to be at different radii in the wind If this is the case, then the behavior of the superionized UV producing region and the cooler IR producing region must be linked, simply because of the requirement that mass be conserved as it flows out through the wind Hence a change in one region would produce a change in the other region, perhaps offset slightly in time. The observations presented here do not support this requirement One might argue that this is due to the lack of simultaneous observations in the IR and UV, but we do not believe this can necessarily explain the problem.

First, there is no clear evidence for large variability of Be stars in the IR. In fact, Gehrz, *et al.*(Ref. 6) find no evidence of variability in the near-IR over a timescale of about one year. The IRAS Point Source Catalog provides some information about the probability that its sources have varied over the lifetime of the IRAS mission (about one year). The IRAS Be stars in general do not show large probabilities of having varied. Second, if a large sample of stars is used, and multiple observations of individual stars are averaged together, then even the effects of UV variability, which are well established, can be eliminated by statistical means

In the case of an axisymmetric model in which the IR producing region is assumed to equatorially concentrated (not necessarily in a thin disk) and the UV producing region is assumed to exist at higher latitudes, one can perhaps explain the results of this study more easily. An axisymmetric geometry permits different mass loss rates in the UV and IR producing regions, since they are not radially linked. This geometry allows uncoupled behavior to occur in the two regions even if the underlying driving mechanism is the same for both regions. This picture is also consistent with polarization measurements, which provide strong evidence for non-spherical symmetry (Coyne and McLean, Ref. 16).

More recently, evidence has been presented for non-radial pulsations (NRP) in Be stars. Baade (Ref. 17) provides a good overview of this evidence. The properties of NRP are such that they fit rather nicely with the axisymmetric model, as well as with the idea of instabilities and underlying, temperature independent driving mechanisms for the Be phenomena. NRP might also explain much of the scatter observed in the data, since different modes might well occur in different stars, changing the relative mass loss rates in the polar and equatorial regions from star to star. All of these ideas are of course speculative, and much work remains to be done before Be stars are well understood.

5. FUTURE PLANS

We have observations scheduled for this study in the coming year, and additional stars will be added to the results as the data become available. We will also include the appropriate IUE archive data. The complete results will be published elsewhere

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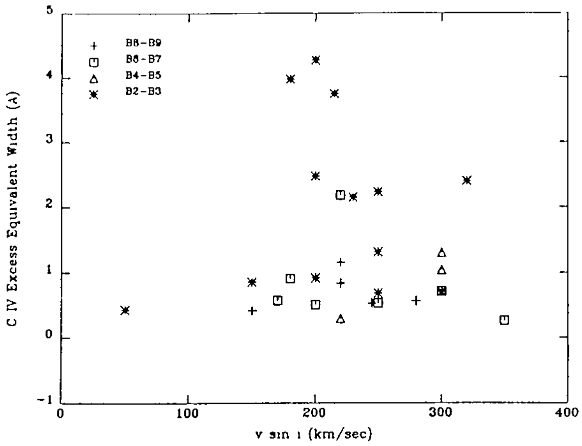

Figure 3. Excess C IV equivalent widths *vs.* $v \sin i$ for IRAS Be stars

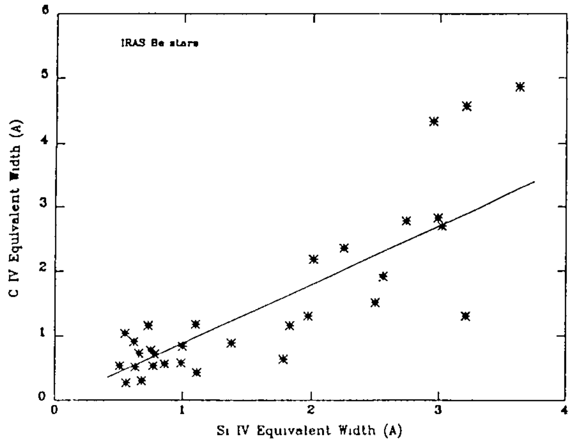

Figure 1. C IV equivalent widths *vs.* Si IV equivalent widths for IRAS Be stars

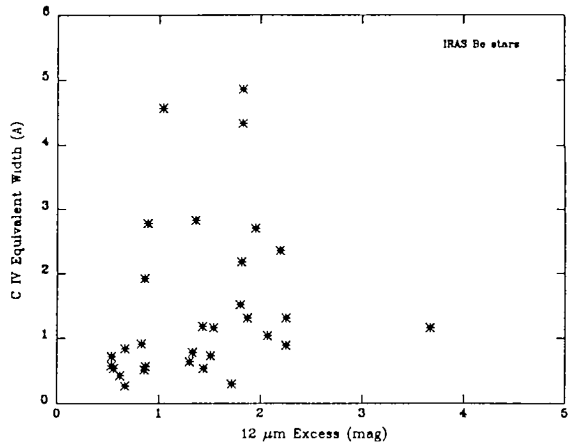

Figure 4 C IV mean equivalent widths *vs.* 12 μm excess for IRAS Be stars (broken out by spectral type)

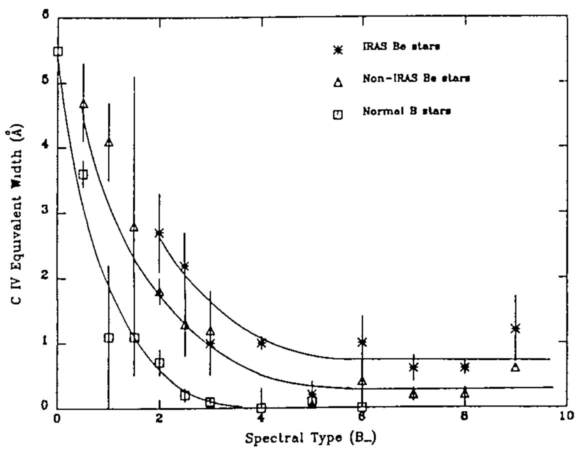

Figure 2. C IV mean equivalent widths *vs.* spectral type

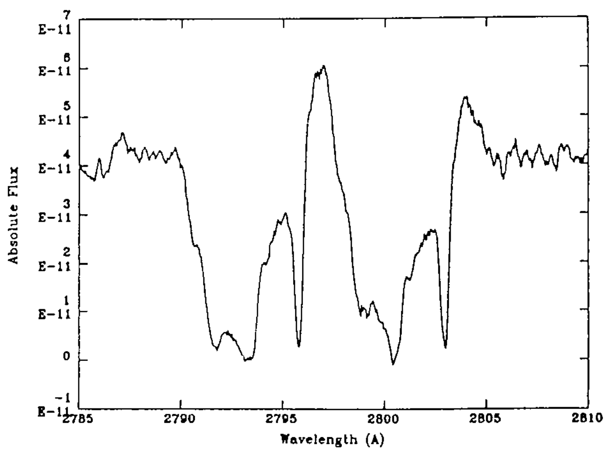

Figure 5. Representative Mg II profiles seen in HD 50123