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Final Report on NASA Contract NAG5-78

"SPECTROSCOPIC OBSERVATIONS OF SELECTED STELLAR SYSTEMS"

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I. Introduction

This contract supports work with the IUE satellite, and continues a previous contract NAS 5-22833 for which a final report was submitted in 1982. Our work with the IUE satellite is primarily directed to the study of spectra of very luminous, high temperature stars, the O-type stars with the largest masses among stars, and the Wolf-Rayet (W-R) stars. These stars are characterized by strong stellar winds which produce significant mass loss. We are interested in the nature and evolution of these winds, and to that end we want to learn the densities, velocity structure, ionization balance and composition. The IUE satellite provides the best way to study these phenomena because many of the most important ground state and excited state lines of common highly ionized species are found in the spectral range. In section II we discuss progress made in understanding mass loss from these stars and its implications. Section III covers continuum studies of W-R stars. Section IV outlines progress in the area of line profile variability in the winds of W-R stars. A list of all publications supported by this grant is included at the end.

II. Mass Loss from O-type Stars

Ultraviolet observations of O and B stars invariably reveal the effect of stellar mass loss, seen in the P Cygni profiles of resonance lines. Radio and infrared observations also indicate the presence of stellar winds through the presence of free-free emission. These winds have been studied intensively in recent years, not only for their effect on stellar evolution, but also for their influence on the surrounding interstellar medium. It is now possible to extend our observations to include stars in the Magellanic Clouds, where chemical and kinematical differences are important.

Various techniques have been developed for deriving the mass loss rate from the observations. While radio observations are the most straightforward, only the largest mass loss rates can be detected with the VLA, and only for northern hemisphere stars. Thus IUE has emerged as the workhorse for the determination of mass loss rates. Through the fitting of theoretical line profiles to high dispersion IUE date for P Cygni lines (Castor and Lamers 1979, Garmany, Olson, Conti and Van Steenberg 1981) mass loss rates have been derived for a large sample of stars. The primary factor controlling the mass loss is the stellar luminosity (Fig. 1). Nevertheless, there is sufficient scatter in Fig. 1 to suggest that other effects besides luminosity may contribute to the mass loss rate. (Lamers, 1981, Garmany and Conti 1984).

The functional form of the mass loss rate has important theoretical implications. The most widely accepted explanation for the wind structure is the line radiation pressure model, developed by Castor, Abbott and Klein (1975) and further elaborated upon by Abbott (1982). This model predicts a specific dependence of mass loss on luminosity, mass, metal abundance and temperature:

$$\dot{M} = 1.4 \times 10^{-15} \frac{L^{1.98} Z^{0.94}}{M^{1.03} T^{0.02}} M_{\odot} \ yr^{-1}$$

Although the line radiation model has been very successful in explaining the observations, there are still problems to be solved. In particular, the observed X-ray flux, while explaining the anomalously high ionization stages observed in oxygen and nitrogen, probably originates in shocks throughout the wind. There is also little consensus on the origin of variability in line profiles.

One approach to understanding the mechanism behind mass loss is to correlate the rate with various stellar parameters. The major difficulty here is that the parameters one wants to consider do not vary enough in the observable range. For example, testing for a metallicity dependence in Galactic stars is impractical because there is not a large enough gradient (Garmany and Conti, 1984). As a result, two years ago we began an observing program with IUE to study mass loss effects in the O-stars of the Magellanic Clouds (Garmany and Conti, submitted). Previous studies (Hutchings 1982; Bruhweiler, Parsons and Wray 1982) had found evidence for weaker stellar winds in the LMC and SMC. This is expected on theoretical grounds because of the lower metallicity in the clouds. Our study differs in that we observed a more normal population of O-type stars which could be directly compared with galactic stars for which mass loss rates had already been determined. (Our technique for isolating these stars will be discussed in Section 3). In the LMC we observed 10 O-type and 1 B-type star; in the SMC, 3 O-type and 4 B stars. The results are provocative.

The wind terminal velocity is the most direct measurement in a P Cygni profile. Fig. 2 compares this velocity, V_∞, for stars in the galaxy, LMC, and SMC as a function of spectral type. From this figure it appears that although there is a large range in terminal velocity for a given spectral subtype, the

LMC stars are generally about 20% lower in velocity than the Galactic stars. However, there are not enough SMC stars to tell if we are seeing only the upper edge of the range or a representative sample.

The question of mass loss is not as direct. In the Clouds we are using low dispersion IUE spectra which must be calibrated with results from high dispersion spectra. We cannot perform the same analysis for mass loss because of the lower resolution. Therefore the technique we employed with the LMC stars was to compute a mass loss parameter for both LMC and galactic stars. As the galactic stars had previously been analyzed from high dispersion IUE observations, we were able to calibrate the mass loss parameter from them. In the LMC our results indicate that, if the ionization balance is similar to corresponding galactic stars, the mass loss rates are comparable to galactic stars (Fig. 3). This is not what is predicted from line radiation theory (Abbott 1982).

As the metal abundance in the SMC is about 3 times lower than in the LMC, observations of stellar winds there will test theory much more dramatically.

III. The Continuum Radiation from Wolf-Rayet Stars.

Until recently, our knowledge of the magnitudes and colors of W-R stars has been based on photoelectric photometry done with intermediate band filters selected to avoid a few of the stronger emission lines (e.g., Smith 1968a,b: Lundstrom and Stenholm 1979). It is now possible to improve significantly on these results with recent advances in detectors (Massey 1982). We have therefore begun an extensive observational program using the Intensified Reticon Scanner (IRS) at KPNO, the SIT Vidicon at CTIO and the International Ultraviolet Explorer satellite (IUE). These data allow us, in principle, to determine absolute fluxes and continuum energy distributions in the wavelength range from 1200 A to 7000 A by direct measurements between emission lines.

Wolf-Rayet stars are rare in our galaxy and so none are found very close to the sun. Their close confinement to the galactic plane thus means that all of them are reddened: some extremely so. An important problem is therefore to determine the reddening. We will discuss the methods of derivation of unreddened continua from a subset of our data and compare it to previous determinations.

With the absolute spectrophotometry such as presented here, we are able to determine reddened continua of W-R stars, taking account of the regions between the numerous emission lines. The interstellar extinction in the ultraviolet varies greatly from star to star and is not well understood as yet. One cannot use a standard extinction law to derive intrinsic continua for W-R stars, and more involved methods will be necessary. The ultraviolet extinction in front of Cyg OB1 differs among the W-R stars in that association. The intrinsic continuum of the well-studied W-R star HD 192163 does not fit the published model; conclusions about the effective temperatures or the nature of the emergent continua of these objects are still very premature.

IV. Variability in Stellar Winds

Since the launch of IUE there have been many investigations of the ultraviolet spectra of WR stars both in the Galaxy and in the Magellanic Clouds. These ongoing programs have led to many significant improvements in our understanding of the WR physical properties, their chemical nature, the characteristics of their stellar winds and mass loss rates which has shed light on the evolutionary status of this enigmatic stellar class. However, despite the advances that have been made over the past decade many unresolved, yet crucial questions remain, in particular with regard to the mechanism(s) involved in initiating and maintaining the extraordinary high rates of mass loss (2-8x10^{-5} $M_\odot$/yr) and the detailed physical characteristics of the WR stellar winds, together with uncertainties concerning the origin of observed variability at optical and UV wavelengths. Of increasing importance is the realization that, in addition to radiation pressure forces, stellar structural pulsations may be occurring in massive, hot stars and that such effects may be instrumental in determining many of the observed mass loss and wind properties.

In the 6th *IUE* round we were allocated observing time to monitor the WN5 star HD 50896 (at that time the most promising WR+collapsar candidate) continuously over its purported 3.7 day binary cycle. We wanted to search for variability in the P-Cygni profiles as a function of binary phase which could be compared with the corresponding pattern of variations known to be common to massive X-ray binaries (cf. Dupree *et al*. 1980, Bonnet-Bidaud *et al*. 1981, 1982). The main results are summarized as follows (Willis *et al*. 1984a):

(i) Extensive variability *is* seen in the P-Cygni profiles of NV λ1240, CIV λ1550, HeII λ1640 and NIV 1718 but with *no* phase dependence which can be likened to those observed regularly in X-ray binaries. Our data thus provide no evidence for the postulated neutron star companion to HD 50896 and cast some strong doubts about its reality and possibly, by implication, the whole evolutionary scenario proposed for the production of WR+collapsar systems (van den Heuvel 1976).

(ii) We have discovered extensive short time-scale variability in the P-Cygni profiles occurring on scales ∿3 hours. Moreover, that this rapid variability occurs over all phases in the purported 3.7 day binary period. These changes are clearly to be identified with rapid variability phenomena occurring in the star itself. This is exemplified in Fig. 1 (taken from Willis et al. 1984) which plots the measured equivalent width of the P-Cygni absorption component to NIV 1718 as a function of 'binary phase' in our 1983 data.

(iii) A clear example in our data of the character of the rapid variability in the same line is shown in Fig. 2 which plots the ratio of two SWP spectra of HD 50896 obtained three hours apart. Variations in this line profile (and similar effects are seen in NV, CIV and HeII lines) occur over a restricted range of wind velocities, from about -1000 to -1800 km/s in this case. Corresponding changes in the same two spectra in NV extend to -2500 km/s and in HeII to -2100 km/s reflecting wind stratification effects.

(iv) We have also extracted and analyzed all the available IUE data for HD 50896 over the period 1978-82 and the combined results for NIV λ1718 (analogous to Fig. 1) for these data and our September 1983 run are shown in Fig. 3. From these data we see clear evidence for secular changes (possibly linked to changes in the models of pulsation(?) -- see below). At the epoch when the W_{abs} of NIV λ1718 has increased by a factor of two over the average displayed in our 1983 data, the overall P-Cygni profile extends to much higher velocities, -2600 km/s, implying a significant, secular change in the wind velocity/temperature structure. Also evident, but less clear, from the earlier epoch data are rapid varitions of the kind we monitored in our 1983 campaign, so that it is clear that what we have observed cannot be attributed to a "one-off occurrence."

The timescale (∿3 hours) of these variations and the character of the profile changes leads us to believe that they are probably due to changes in the physical properties of the accelerating part of the WN5 wind linked to the occurrence of radial or non-radial oscillations in the star itself. We are confident that such effects should also be seen in other WR stars. Such pulsational phenomena may well be of crucial importance in understanding the level and character of the mass loss observed in this stellar class which cannot be explained by current radiatively-driven wind models. The confirmation and analysis of such phenomena may well provide the major breakthrough in our understanding of WR mass loss (possibly also for OB stars) and it is clearly vital that our extensive data base for HD 50896 be extended to other WR stars. As discussed below, no other WR stars have to date been observed with IUE with the required time resolution for this purpose, and this proposal aims at securing these crucial data for two further WN stars which are known to show some degree of optical and UV variability. We propose to monitor these stars for a sufficient period in the manner so successfully accomplished for HD 50896 in order to build up, in each case, the required data base for a meaningful statistical study. Although some degree of variability in WR spectra is known at optical wavelengths the effects are usually very small and generally open to ambiguous interpretation and credibility. However, in the UV we have demonstrated that the variability is much larger, unambiguous and provides a sensitive probe of the interaction of any sub-wind oscillatory phenomena with the wind itself. UV observations are thus likely to play the key role in furthering our understanding of this exciting and topical subject.

Recently Vreux (1984a,b) has reassessed published proposed periods for the current WR+collapsar candidates listed by Moffat (1983) and also examined small scale changes in the optical radial velocities for HD 192163 (WN6). He suggests that the observed line variability in such stars is more likely due to single star non-radial pulsations rather than spiralling-in neutron star scenarios. Clearly we are beginning to witness an accumulation of evidence for oscillatory phenomena in early-type stars.

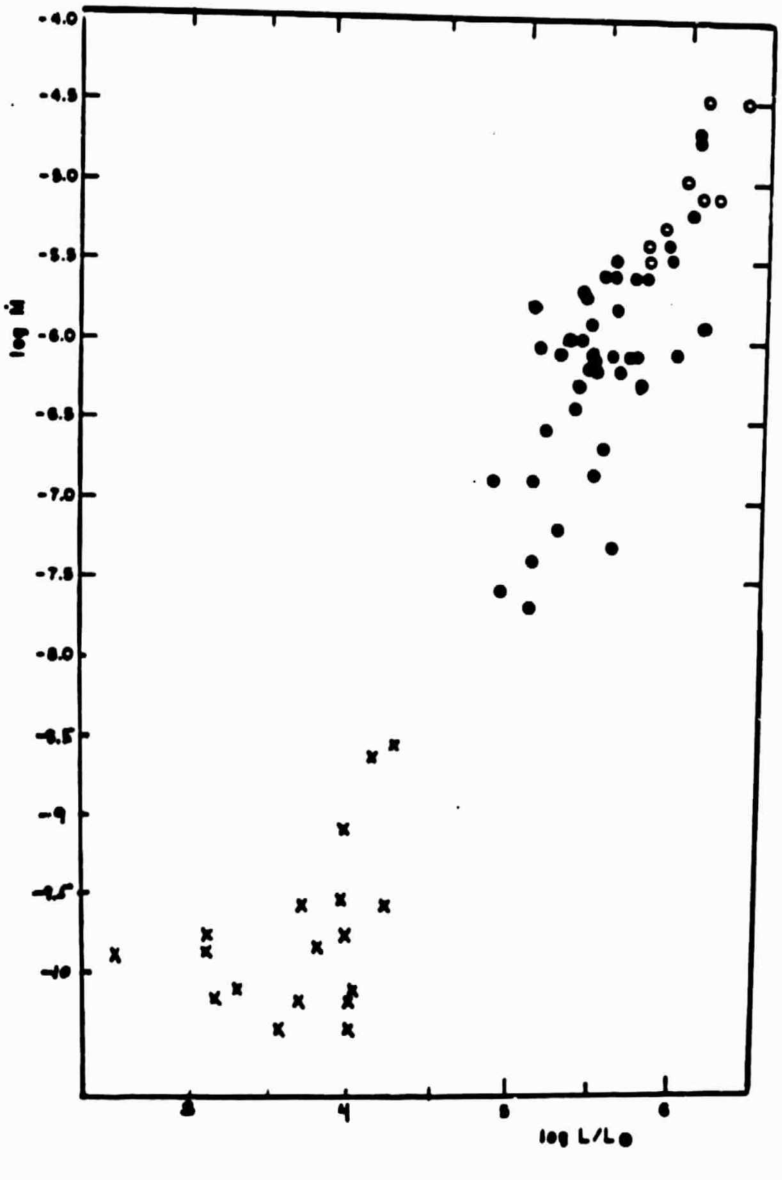

Figure 1. The relation between mass loss and luminosity for O- and B-type stars. Open circles - radio observations, filled circles - UV data from C IV and NV, X - UV data from Si III and Si IV.

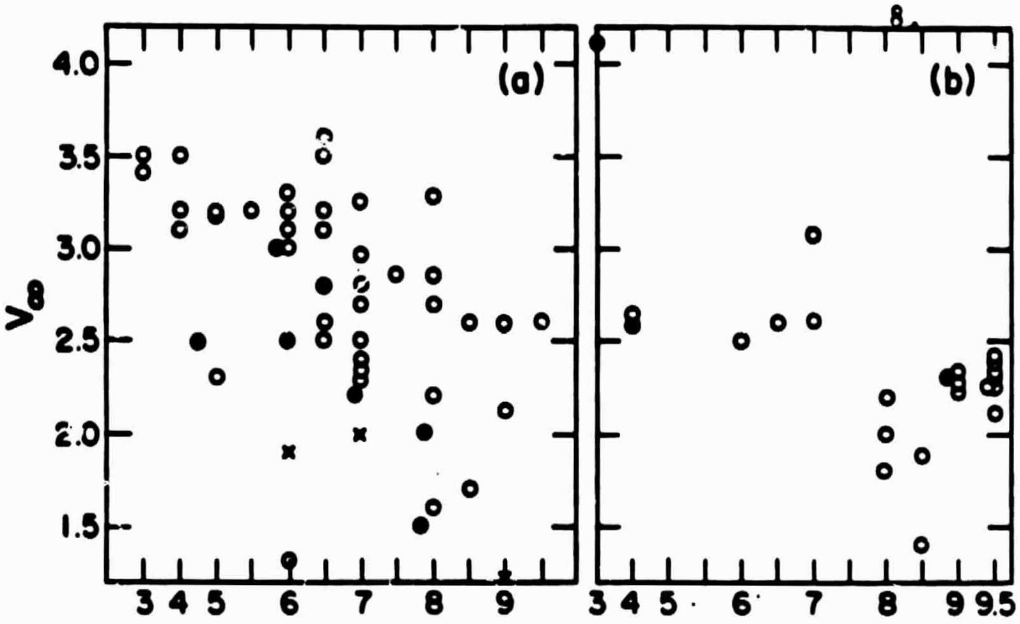

Fig. 2. Wind terminal velocities as a function of spectral subtype for O stars in the Galaxy, LMC and SMC (Galactic (○), LMC (●), SMC (+)). (a) Luminosity class III and V, (b) Luminosity class I.

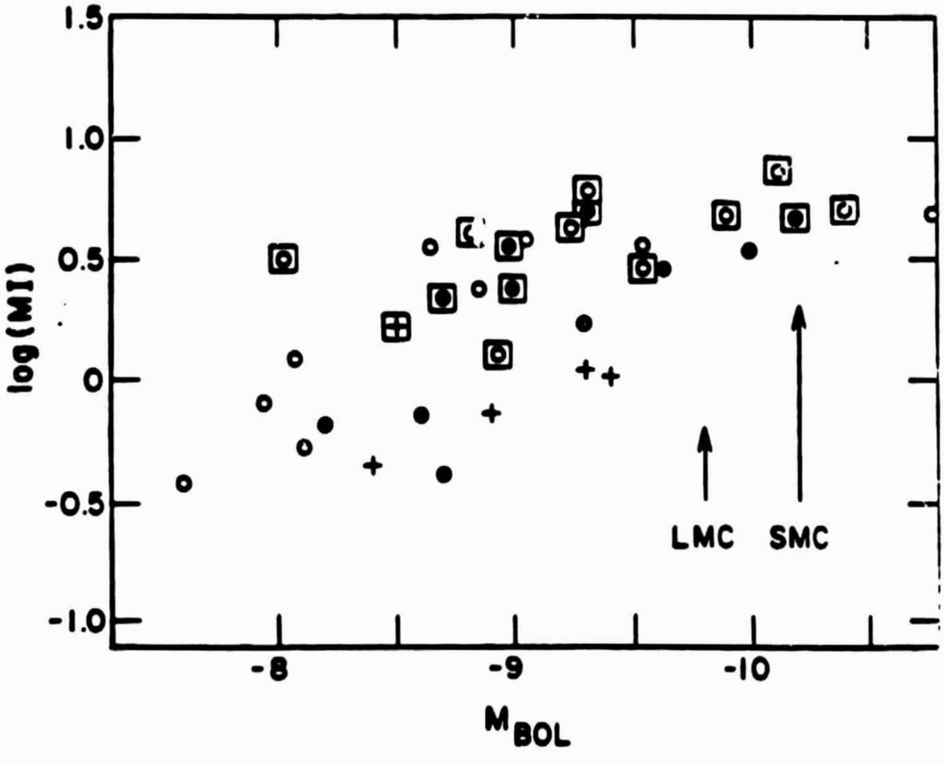

Fig. 3. Snow's mass loss index versus M_{Bol} for galactic stars (o), LMC stars (●) and SMC stars (+). Boxed data are based either on saturated line profiles (galactic) or on probable saturated line profiles (LMC, SMC).

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