NASA-CR-191887

IN-89-CR

141136

P.8

Semi-Annual Report on NASA Project NAG5-1657

Fluctuations at the Blue Edge of Saturated Wind Lines in IUE Spectra of O-Type Stars

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Period Covered: from 07/01/92 to 12/31/92

Report Date: 01/08/93

(NASA-CR-191887) FLUCTUATIONS AT THE BLUE EDGE OF SATURATED WIND LINES IN IUE SPECTRA OF O-TYPE STARS Semiannual Report, 1 Jul. - 31 Dec. 1992 (Delaware Univ.) 8 p

N93-18776

Unclas

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I. Introduction

The P Cygni profiles of UV resonance lines are the primary diagnostics of the stellar winds of OB stars. Since the *IUE* satellite began to provide routine access to this region of the spectrum, many observers have reported that the extreme blue edges of saturated P Cygni absorption troughs (particularly C IV $\lambda\lambda$1548, 1550) vary in position and strength on poorly determined time scales. These fluctuations imply that variable amounts of rarified gas exist at high velocities (*i.e.*, in excess of the terminal velocity) in the stellar winds of OB stars. We speculate that this high-velocity gas is caused by instabilities in the stellar wind, and have embarked upon a systematic exploration of this phenomenon. Our project consists of three distinct phases, with the following broad goals:

A: to investigate the observational characteristics of fluctuations at the extreme blue edge of strong wind lines for a few intensively observed O stars, in order quantify the characteristics of rarified, high-velocity gas in the winds of these objects;

B: to compare quantitatively the empirical properties of this gas with theoretical predictions (based on radiation-hydrodynamics simulations) for the presence of high-velocity gas due to the nonlinear growth of the line-driven instability; and

C: to examine the relationship between blue-edge fluctuations and other diagnostics of wind variability, especially the mysterious discrete absorption components (DAC).

We concentrated on Phase A during the first year of this project. As outlined in our previous progress reports, we have now developed an efficient method for acquiring spectra from the *IUE* archives and analyzing their variability characteristics. During the period covered by this report, we have focussed on developing software tools required by Phase B. These accomplishments are briefly outlined in §II. Our plans for the final 6 months of this grant are described in §III, and the abstract from a publication written under its auspices is attached as Appendix A.

II. Comparison with Properties of the Line-Driven Instability Model

During the interval covered by this report, we have shifted the focus of our investigation from the observations of blue-edge variability to direct comparison of these data with

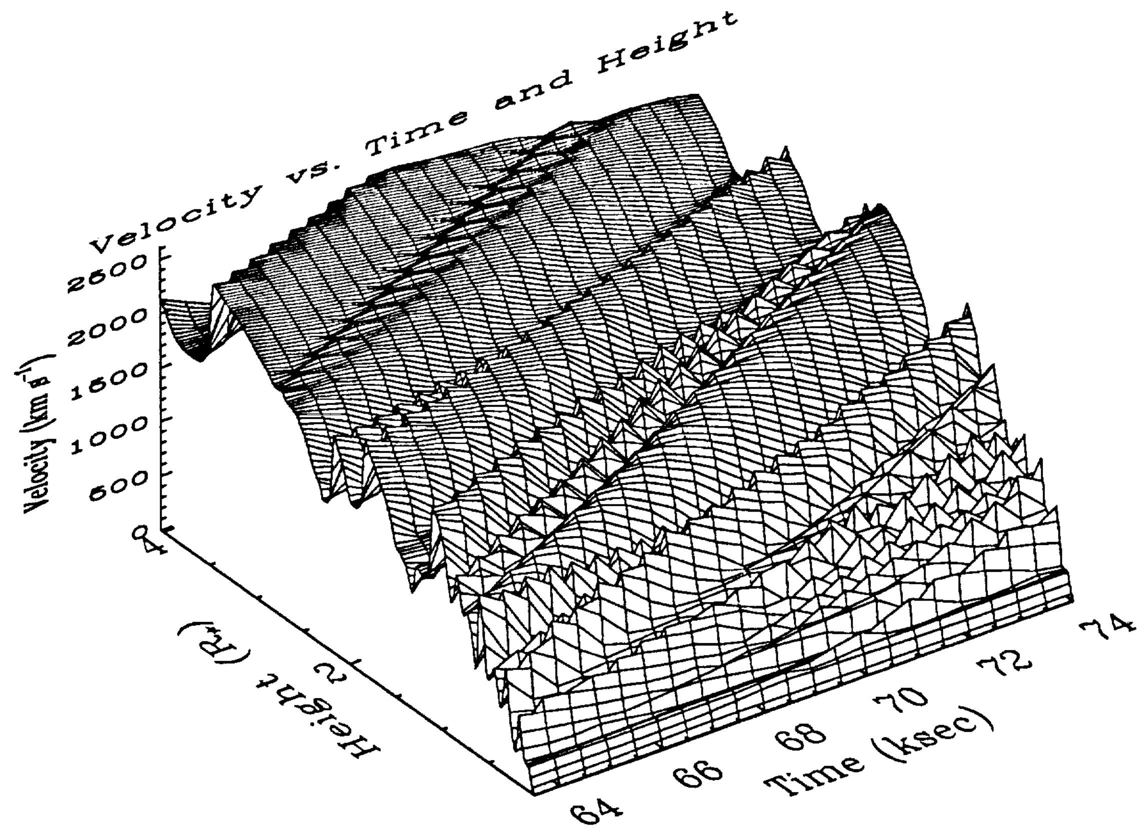

FIGURE 1. The velocity surface as a function of height above the stellar photosphere and time from and improved OCR-type time-dependent stellar wind calculation.

the predictions of radiation hydrodynamics simulations for the growth of the line-driven instability (Owocki, Castor, & Rybicki 1988; hereafter OCR). The OCR simulations show that small velocity perturbations introduced near the base of the wind undergo tremendous amplification, because the perturbed material is Doppler shifted into strong, unattenuated continuum flux. The unshadowed continuum flux increases the line force acting on the perturbed material, which in turn increases the size of the velocity perturbation, thereby leading to a rapidly growing instability. This strongly driven gas eventually crashes into slower-moving material in front of it, and is compressed into a dense clump as it decelerates through a reverse shock. Figure 1, which was generated from an improved OCR-type of calculation, shows a typical example of the nonmonotonic velocity structure that arises from these interactions. In contrast to time-steady models for the structure of stellar winds of OB stars, these hydrodynamical models suggest that much of the wind exists in dense clumps and that small amounts of gas are driven to large velocities in the regions between the clumps. Since temporal variability in the amount of rarified, high-velocity gas will manifest itself as small fluctuations in the blue edge of the absorption trough of a strong P Cygni profile, we believe that the observed variations constitute direct diagnostics of the line-driven instability.

Until recently, comparison of results from our radiation hydrodynamical simulations with *IUE* observations has been hampered by our inability to synthesize line profiles from arbitrarily structured stellar winds. To address this deficiency, we have spent much of the past six months completing a robust computer program to calculate line profiles from structured stellar winds. This work, which has been undertaken in collaboration with Dr. Joachim Puls (Institut für Astronomie und Astrophysik, Universität München), has produced a flexible computer program called TSMULTI. This program uses a generalization of the resonance-zone formalism developed by Rybicki & Hummer (1978) to calculate P Cygni profiles for singlet transitions in stellar winds with non-monotonic velocity laws. We have described the program in detail in a paper recently submitted to *Astronomy and Astrophysics* (Puls, Owocki, & Fullerton 1993; see Appendix A).

The capabilities of TSMULTI are demonstrated in Figures 2 and 3, which present P Cygni time profiles (calculated from the hydro models illustrated in Fig. 1) for a strong line and a moderate-strength line, respectively. As has become customary in this field (*e.g.,* Henrichs et al. 1988; Prinja et al. 1992), we present these time series in the form of grey-scale images, in which darker shades indicate deeper absorption depths. Time proceeds from bottom to top and arrows along the right-hand axis of the image indicate the time of each "mid-exposure." The velocity scale is shown in the bottom panel, which also shows all the spectra plotted on top of each other. Although this

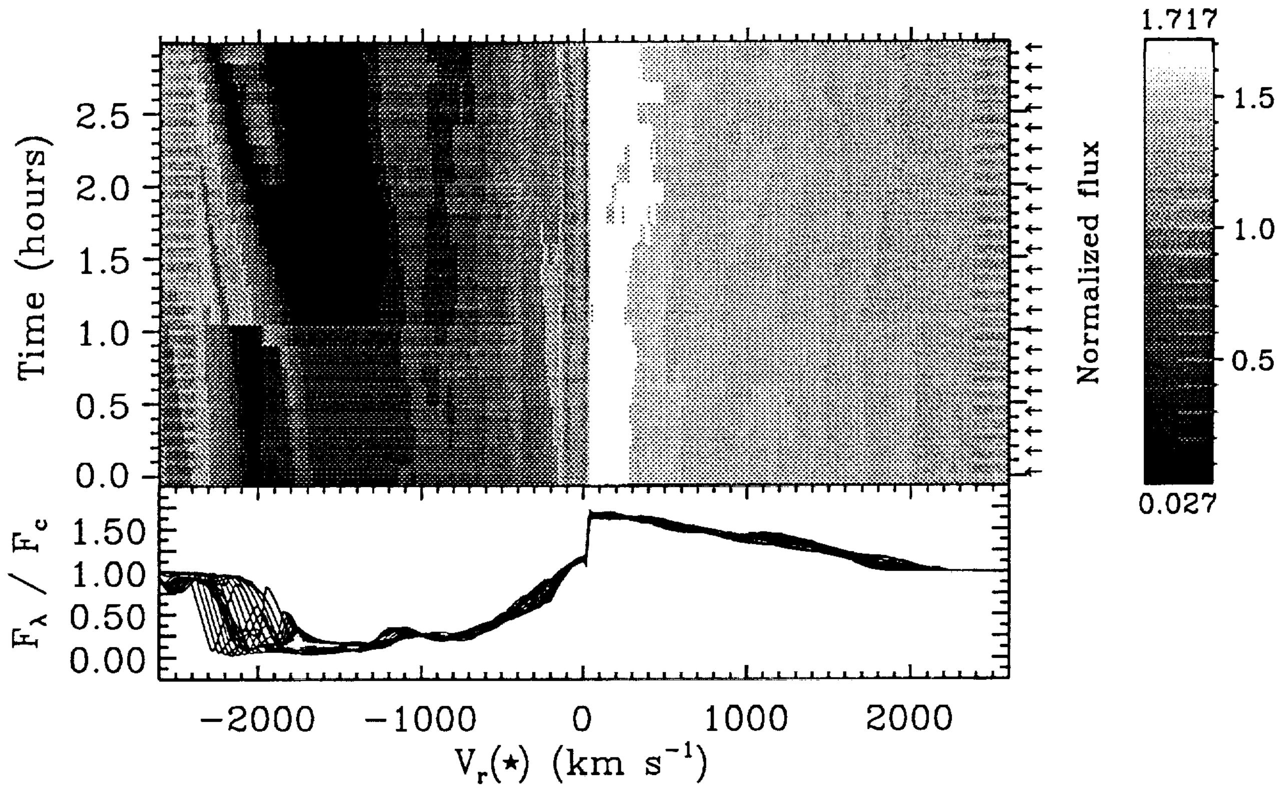

FIGURE 2. Spectral time series of strong line profiles synthesized from the radiation hydrodynamics simulation illustrated in Fig. 1. Note the high-velocity variations at the extreme blue edge of the P Cygni absorption trough.

particular hydro run was not intended to model specific observations, it is clear that the synthetic profiles generated from the simulations reproduce qualitatively several key features of observed wind variability, including blue-edge variability in strong lines (Fig. 2) and discrete absorption components (DAC) in weaker lines (Fig. 3). However, in both cases, the time scale associated with the line profile variability (less than 3 hours) obtained from the simulations is *much* shorter than observed in *IUE* spectra (typically 1–3 days).

TSMULTI provides us with a powerful new tool to interpret the variability of hot-star winds in a semi-empirical fashion. We are currently exploiting this new capability to

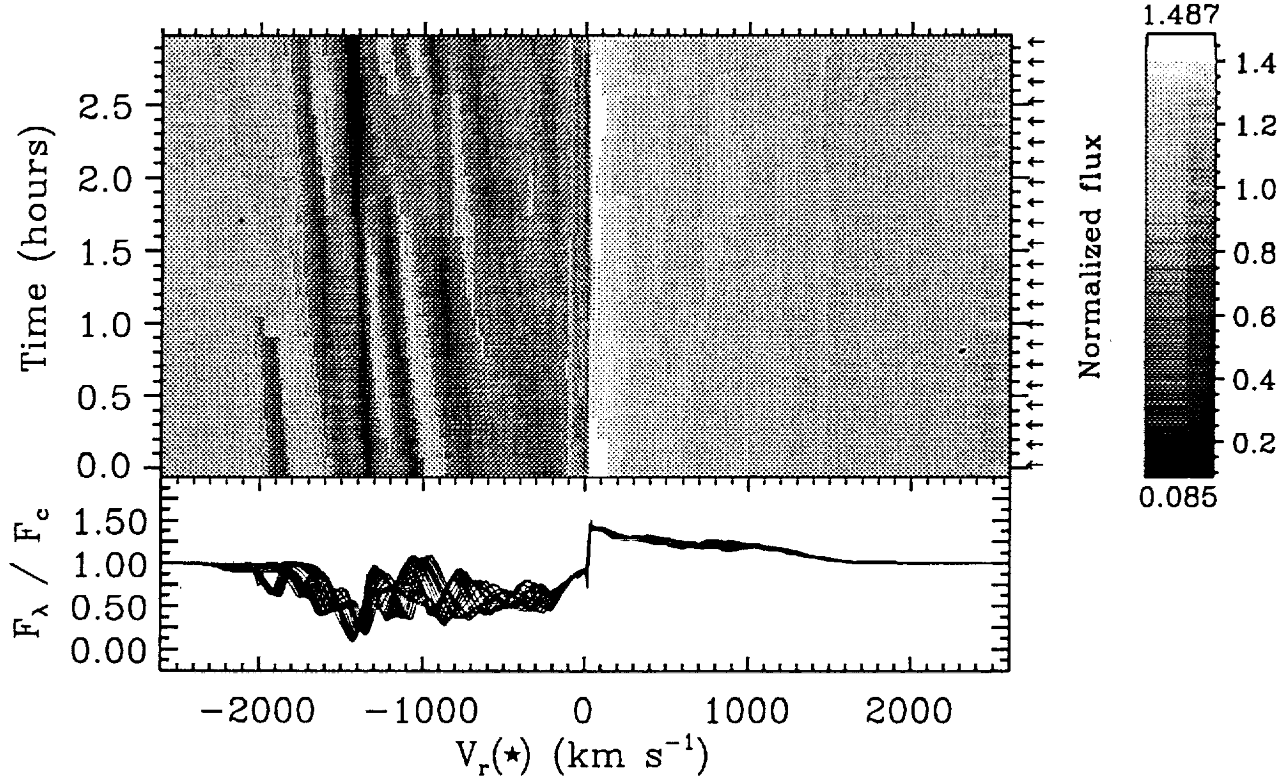

FIGURE 3. Same as Fig. 2, for a line of moderate strength. Note the prominent DACs that accelerate blueward through the absorption trough.

investigate the detailed relationship between blue-edge variability and DAC variability in our radiation hydrodynamic simulations. We are also computing column depths associated with the blue-edge variability exhibited by the simulated data. These latter estimates are directly comparable to the empirical measurements we have already obtained from our analysis of archival *IUE* spectra.

III. Plans for the Next Six Months of the Project

During the final six months of this project, we plan to:

(a) complete our comparison of the blue-edge variability exhibited in archival *IUE* spectra by ξ Per (which we have described in previous progress reports) with the results from radiation hydrodynamics simulations;

(b) perform similar analyses for several other O stars, including α Cam, 68 Cyg, and λ Cep; and

(c) begin Phase C of this project, which involves searching systematically for relationships between the blue-edge fluctuations and DAC in archival data, by using the relationships more plainly evident in the hydro simulations as a guide.

Before the end of this period, we plan to have submitted a manuscript describing the results of our analysis of ξ Per. We envisage that one or more papers describing our investigation of blue-edge variability in other stars will also be forthcoming.

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Appendix A:
Title Page and Abstract of Paper Prepared Under Auspices of NAG5–1657

ON THE SYNTHESIS OF RESONANCE LINES IN DYNAMICAL MODELS OF STRUCTURED HOT-STAR WINDS

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Submitted to *Astronomy & Astrophysics*, December 1992

Abstract. We examine basic issues involved in synthesizing resonance-line profiles from 1-D, dynamical models of highly structured hot-star winds. Although these models exhibit extensive variations in density as well as velocity, the density scale length is still typically much greater than the Sobolev length. The line transfer is thus treated using a Sobolev approach, as generalized by Rybicki & Hummer (1978) to take proper account of the multiple Sobolev resonances arising from the nonmonotonic velocity field. The resulting reduced-Lambda-matrix equation describing nonlocal coupling of the source function is solved by iteration, and line profiles are then derived from formal solution integration using this source function. Two more approximate methods that instead use either a stationary or a structured, local source function yield qualitatively similar line-profiles, but are found to violate photon conservation by 10% or more. The full results suggest that such models may indeed be able to reproduce naturally some of the qualitative properties long noted in observed UV line profiles, such as discrete absorption components in unsaturated lines, or the blue-edge variability in saturated lines. However, these particular models do not yet produce the black absorption troughs commonly observed in saturated lines, and it seems that this and other important discrepancies (e.g., in acceleration time scale of absorption components) may require development of more complete models that include rotation and other 2-D and/or 3-D effects.

Key words: Line: formation - Radiative transfer - Stars: atmospheres - Stars: early type - Stars: mass-loss