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THE *IUE* MEGA CAMPAIGN: WIND VARIABILITY AND ROTATION IN EARLY-TYPE STARS

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ABSTRACT

Wind variability in OB stars may be ubiquitous, and a connection between projected stellar rotation velocity and wind activity is well established. However, the origin of this connection is unknown. To probe the nature of the rotation connection, several of the attendees at the workshop on Instability and Variability of Hot-Star Winds drafted an *IUE* observing proposal. The goal of this program was to follow three stars for several rotations to determine whether the rotation connection is correlative or causal. The stars selected for monitoring all have rotation periods ≤5 days. They were HD 50896 (WN5), HD 64760 (B0.5 Ib), and HD 66811 [ζ Pup: O4 If(n)]. During 16 days of nearly continuous observations in 1995 January (dubbed the "MEGA" campaign), 444 high-dispersion *IUE* spectra of these stars were obtained. This Letter presents an overview of the results of the MEGA campaign and provides an introduction to the three following Letters, which discuss the results for each star.

Subject headings: stars: activity — stars: early-type — stars: mass loss — ultraviolet: stars

1. INTRODUCTION

UV wind line variability in OB stars was first noted in repeated *Copernicus* observations by Snow (1977) and York et al. (1977). However, the true nature and details of this behavior were not even remotely understood until the advent of *IUE* (Boggess et al. 1978a, b). *IUE* observations established that wind activity is actually an entirely new class of variability in hot stars that is ubiquitous among those objects with wind lines sufficiently well developed to reveal variability but not so saturated as to mask it (see the reviews presented at the workshop on Instability and Variability of Hot-Star Winds [Moffat et al. 1994]). The ubiquity of the variability implies that it is an intrinsic property of hot star winds, and that steady state descriptions of them are, at best, representations of the mean flows.

The fact that hot star winds are structured in space and variable in time has wide-ranging consequences. For instance, observational mass-loss rates derived from steady state mass-loss models must be reconsidered. Accurate mass-loss rates are essential for stellar evolution calculations (necessary to determine the chemical evolution of galaxies and the nature of stellar remnants) and to determine the rates of energy and momentum deposition by stellar winds into the interstellar medium. In addition, wind variability also provides a rare opportunity to observe the time evolution of an astrophysical plasma.

Time series observations with *IUE* have demonstrated several interesting aspects of wind variability in hot stars. Perhaps the most enticing of these is the strong correlation between the acceleration and recurrence of discrete absorption components (DACs) and the projected rotation velocity, $v \sin i$, of the star (Prinja 1988, 1992; Henrichs, Kaper, & Zwarthoed 1988; Kaper 1993). The physical origin of this connection has been elusive.

Both theoretical (Owocki 1994) and semiempirical (Moffat & Robert 1994) pictures of wind activity suggest that the winds are unstable and that the instabilities fragment the wind into numerous, small clumps that individually do not cover a very large solid angle, and whose large number may account, e.g., for the stability of the X-ray fluxes observed from OB stars. However, the strong, coherent variable absorption observed in the UV wind line profiles requires structure on a much larger scale. Since these features can be quite strong at relatively low velocity, the structures responsible for them must be two-

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dimensional and spatially coherent over a sizable fraction of a stellar hemisphere. Numerical simulations show that such large-scale features can also form in wind flows but that lateral coherence must be introduced explicitly by an unspecified disturbance near the wind base (see Owocki 1994, Cranmer & Owocki 1994).

In order to distinguish whether or not wind activity is rooted in the photosphere, an observational time series long enough to span several rotation cycles is required. Such a series would establish whether wind features repeat in a regular pattern, as might be expected if they are due to the influence of surface phenomena on the wind, or occur in a random fashion, as might be expected from a stochastic wind phenomenon excited by rapid rotation of the star.

Prior to the approval of this program, the longest continuous *IUE* runs had spanned only about 6 days for stars with rotation periods of 5 days or so. This lack of adequate time coverage has been widely understood as a major factor in limiting our understanding of the nature of hot star wind variability. The attendees of the workshop on Instability and Variability of Hot-Star Winds (Moffat et al. 1994) identified a *continuous* time series, long enough to sample the stellar rotation period, as one of the most outstanding pieces of observational evidence needed to gain deeper insights into the physical processes responsible for the wind variations. As a result, it was agreed to submit an *IUE* observing proposal to monitor three stars, representative of the range of hot stars observed to have strong wind variability, for several rotation periods in order to determine whether the rotation connection is functional or correlative.

2. OBSERVATIONS

2.1. *The Program Stars*

We demanded that the program stars had verified wind activity from previous observations and that their rotation periods were short enough for several rotations to be observed during a reasonable time series. However, we also required that they not be such rapid rotators that the state of their atmospheres is dominated by rotation. In addition, we selected our program stars to be close together on the sky and to have high-dispersion SWP exposure times ≤5 minutes. These conditions enabled us to attain the maximum sampling rate possible for *IUE* coverage of three different objects.

The stars selected for monitoring were the following:

HD 50896 (EZ CMa).—This is a well-studied WN5 star. Although an exact value of $v \sin i$ cannot be determined for a WR star, variability in optical photometry, polarimetry and spectroscopy repeatedly shows a 3.766 day period which may be associated with binary motion, stellar rotation, or both (see, e.g., Antokhin et al. 1994). Three previous high-resolution *IUE* time series exist for HD 50896. An initial one spans 7 days in 1983 (Willis et al. 1989), another 6 days in 1988 (St-Louis et al. 1993), and a densely sampled one spans 5 days in 1991 (St-Louis 1994). Each series revealed extensive wind variability. While the 3.766 day period is present in these data, epoch-to-epoch variations are also apparent.

HD 64760.—This B0.5 Ib star has a $v \sin i$ of 238 km s^{-1} and an expected rotation period of 4.8 days (Humphreys & McElroy 1984). A 6 day *IUE* time series obtained in 1993 was recently studied by Massa, Prinja, & Fullerton (1995). They showed that while its mean spectrum is completely normal, its wind lines demonstrate extremely strong variability. The variability was observed in wind lines due to a wide range in ionization, covering C II to N V. Consequently, the ionization structure of its wind could be analyzed and was also shown to vary.

HD 66811 (ζ Pup).—This O4 If(n) star has a $v \sin i$ of 210 km s^{-1} and an expected rotation period of 4.9 days (Humphreys & McElroy 1984)—consistent with the period derived by Howarth, Prinja, & Massa (1995) using more fundamental data. This star has been studied extensively, and its fundamental stellar and wind parameters are well determined (Pauldrach et al. 1994, and references therein). The longest *IUE* time series for ζ Pup prior to the one presented here covered 5.5 days in 1989 and was analyzed by Prinja et al. (1992). Significant variability in the Si IV λλ1400 and N IV λ1718 wind lines was observed throughout the 1989 run.

2.2. *The Observing Program*

The observations were obtained during 1995 January 13–29, spanning 15.9 days, or more than three rotation periods for each program star. Two 8 hr gaps appear in the data, due to interruptions by an AGN monitoring program. Smaller time gaps in the data resulted from the program being scheduled during the *IUE* shadow season, when operations cease for a few hours each day.

In all, we obtained 444 spectra (*IUE* image numbers SWP 53338–53783, except for SWP 53465 and SWP 53651, which went to the AGN program). The mean sampling time for the run was 2.6 hr for each star.

2.3. *The Data Reduction*

The spectra presented in this Letter were reduced with the standard *IUE* Spectroscopic Image Processing Software (hereafter SIPS; Turnrose & Thompson 1984). Spectra in the following Letters were extracted with the IUEDR (Giddings & Rees 1989) software. Data reduced by these two packages do not differ significantly at the wavelengths discussed here. However, because IUEDR handles order overlap better than the SIPS, IUEDR-processed spectra become superior at wavelengths ≤1300 Å, and their relative quality increases with decreasing wavelength. Two of the 444 MEHI files used for the SIPS extracted spectra were corrupted. One image, SWP 53351 of HD 50896, has gaps throughout the SIPS extracted spectrum and was eliminated from further consideration. Another image, SWP 53451 of ζ Pup, has a very poor SIPS extraction at wavelengths below 1300 Å, which makes it discordant with the others. Nevertheless, the extraction in the region of the Si IV λλ1400 resonance line discussed below is adequate, and so it was retained. In all, 147 spectra were obtained for HD 50896 (146 retained), 148 for HD 64760, and 149 for HD 66811.

3. RESULTS

The observed profile variability for a representative line in each program star is displayed in two-dimensional format in Figures 1–3 (Plates L11–L13). The individual profiles which make up the plots were normalized by a minimum absorption (maximum flux) spectrum, and a nearest neighbor time interpolation was used to place them onto a linear time grid (the individual spectra can be distinguished in the figures). Gaps appear whenever 5 hr or more (roughly two mean sampling intervals) elapsed between observations. The minimum absorption template was obtained as follows: (1) The spectra were smoothed by a 50 km s^{-1} boxcar filter in the velocity direction. (2) Each velocity point of the smoothed spectra was replaced by the value determined from a five-point quadratic fit in the time direction centered at that point. (3) This smoothed version of the spectra was searched at each velocity for the maximum flux at that velocity to produce the maximum flux (minimum absorption) template. The minimum absorption normalization causes all changes to appear as absorptions, so it is particularly convenient for a qualitative assessment of the observations.

We show the N IV λ1718 line, which arises from an excited level, in HD 50896 (Fig. 1), and the Si IV λλ1400 resonance doublet in HD 64760 (Fig. 2) and HD 66811 (Fig. 3). The particular line for each star was selected to be well developed but unsaturated. As a result, the lines displayed are very sensitive to optical depth changes in the stellar winds. While these lines provide clear examples of the variability in each star, other lines also show strong variability, and considerably more information concerning ionization ratios and other important wind properties also exist in the data.

4. DISCUSSION

A detailed discussion of each program star is contained in the accompanying three Letters (St-Louis et al. 1995; Prinja, Massa, & Fullerton 1995; Howarth et al. 1995). However, there are a few global points which are best made here.

1. All three stars showed continuous wind activity throughout the run.
2. All three display apparent periodicity, which is coherent for at least a few rotation cycles, though not necessarily on longer intervals.
3. The relationship between activity and rotation can be *either* causal *or* statistical. For HD 50896 (St-Louis et al. 1995) and HD 64760 (Prinja et al. 1995), the connection is manifestly causal, with distinct absorption structures repeating from one cycle to the next. However, in both cases there is evidence that these patterns change from epoch to epoch. For ζ Pup (Howarth et al. 1995), the connection turns out to be more statistical, with the activity occurring at the expected rotation period but not repeating feature by feature. In HD 64760 and ζ Pup there are also less frequent, slowly evolving absorption enhancements (classical discrete absorption components, DACs; see, e.g., Prinja 1992) that appear to move through the wind independently of other variability and recur on timescales that are not well determined and that are not clearly linked to any of the relevant physical timescales.
4. Given the range of physical parameters spanned by the program stars and the fact that all of them display continuous wind activity, our results suggest that variability is an intrinsic property of most stellar winds. Therefore, the notion of a steady state wind is, at best, a mean description of the wind, and variability will be a necessary ingredient of a comprehensive stellar wind model.
5. Although the winds of all three stars displayed some sort of rotational modulation, no two are exactly alike.

The observations have also raised some important questions. Among these are the following:

1. The existence of repeatable wind features in HD 64760 and possibly in HD 50896 suggests that they are somehow driven by photospheric features. What is nature of these surface features, and how do they couple to the wind?
2. Is the rotational modulation of early-type star winds ubiquitous? If the observed forms of rotational modulation occur only for rapidly rotating stars, then they provide important new insights into the hydrodynamics and physics of line-driven outflows under extreme conditions. However, if the connection is ubiquitous, then the entire notion of a steady state wind emanating from a homogeneous photosphere must be reconsidered.
3. What is the nature of the slowly evolving absorption enhancements? Do they recur periodically on some longer timescale? Are they the signatures of corotating interaction regions (CIRs; see Cranmer & Owocki 1994)?

Overall, we feel that the *IUE* MEGA project has been a resounding success, pointing the way toward the next level of sophistication required in the modeling of the atmospheres and winds of early-type stars and raising several new questions. These fascinating new results highlight *IUE*'s unique capabilities for hot star research. Unfortunately, the future of *IUE* is precarious, with NASA withdrawing most of its support over the next year. It would be a shame if operations of the satellite were terminated while it is still fully operational.

A debt of gratitude is owed to the *IUE* staffs at both the GSFC and VILSPA facilities since almost all of the observing was done in service mode and to the US and European telescope allocation committees for allotting us such a large block of time. D. M. acknowledges financial support from NASA grant NAS5-32782.

REFERENCES

Antokhin, I., Bertrand, J.-F., Lamontagne, R., & Moffat, A. F. J. 1994, AJ, 107, 2179
Boggess, N., et al. 1978a, Nature, 275, 372
Boggess, N., et al. 1978b, Nature, 275, 377
Cranmer, S. R., & Owocki, S. P. 1994, BAAS, 26, 1446
Giddings, J. R., & Rees, P. C. T. 1989, SERC Starlink User Note 37
Henrichs, H. F., Kaper, L., & Zwarthoed, G. A. A. 1988, in A Decade of UV Astronomy with the *IUE* Satellite (ESA SP-281), 2, 145
Howarth, I. D., Prinja, R. K., & Massa, D. 1995, ApJ, 452, L65
Humphreys, R. M., & McElroy, D. B. 1984, ApJ, 284, 565
Kaper, L. 1993, Ph.D. thesis, Univ. of Amsterdam
Massa, D., Prinja, R. K., & Fullerton, A. W. 1995, ApJ, in press
Moffat, A. F. J., Owocki, S. P., Fullerton, A. W., & St-Louis, N., ed. 1994, Instability and Variability in Hot-Star Winds (Dordrecht: Kluwer)
Moffat, A. F. J., & Robert, C. 1994, ApJ, 421, 310
Owocki, S. P. 1994, in Instability and Variability in Hot-Star Winds, ed. A. F. J. Moffat, S. P. Owocki, A. W. Fullerton, & N. St-Louis (Dordrecht: Kluwer), 3
Pauldrach, A. W. A., Kudritzki, R. P., Puls, J., Bulter, K., & Hunsinger, J. 1994, A&A, 283, 525
Prinja, R. K. 1988, MNRAS, 231, 21P
———. 1992, in ASP Conf. Ser., 22, Nonisotropic and Variable Outflows from Stars, ed. L. Drissen, C. Leitherer, & A. Nota (San Francisco: ASP), 167
Prinja, R. K., et al. 1992, ApJ, 390, 266
Prinja, R. K., Massa, D., & Fullerton, A. W. 1995, ApJ, 452, L61
Snow, T. P. 1977, ApJ, 217, 760
St-Louis, N. 1994, in Workshop on Instability and Variability of Hot-Star Winds, ed. A. F. J. Moffat, S. P. Owocki, A. W. Fullerton, & N. St-Louis (Dordrecht: Kluwer), 197
St-Louis, N., Dalton, M. J., Marchenko, S. V., Moffat, A. F. J., & Willis, A. J. 1995, ApJ, 452, L57
St-Louis, N., Howarth, I. D., Willis, A. J., Stickland, D. J., Smith, L. J., Conti, P. S., & Garmany, C. G. 1993, A&A, 267, 447
Turnrose, B. E., & Thompson, R. W. 1984, *International Ultraviolet Explorer* Image Processing Information Manual, CSC/TM-84/6085
Willis, A. J., Howarth, I. D., Smith, L. J., Garmany, C. D., & Conti, P. S. 1989, A&AS, 77, 269
York, D. G., Vidal-Madjar, A., Laurent, C., & Bonnet, R. 1977, ApJ, 213, L61

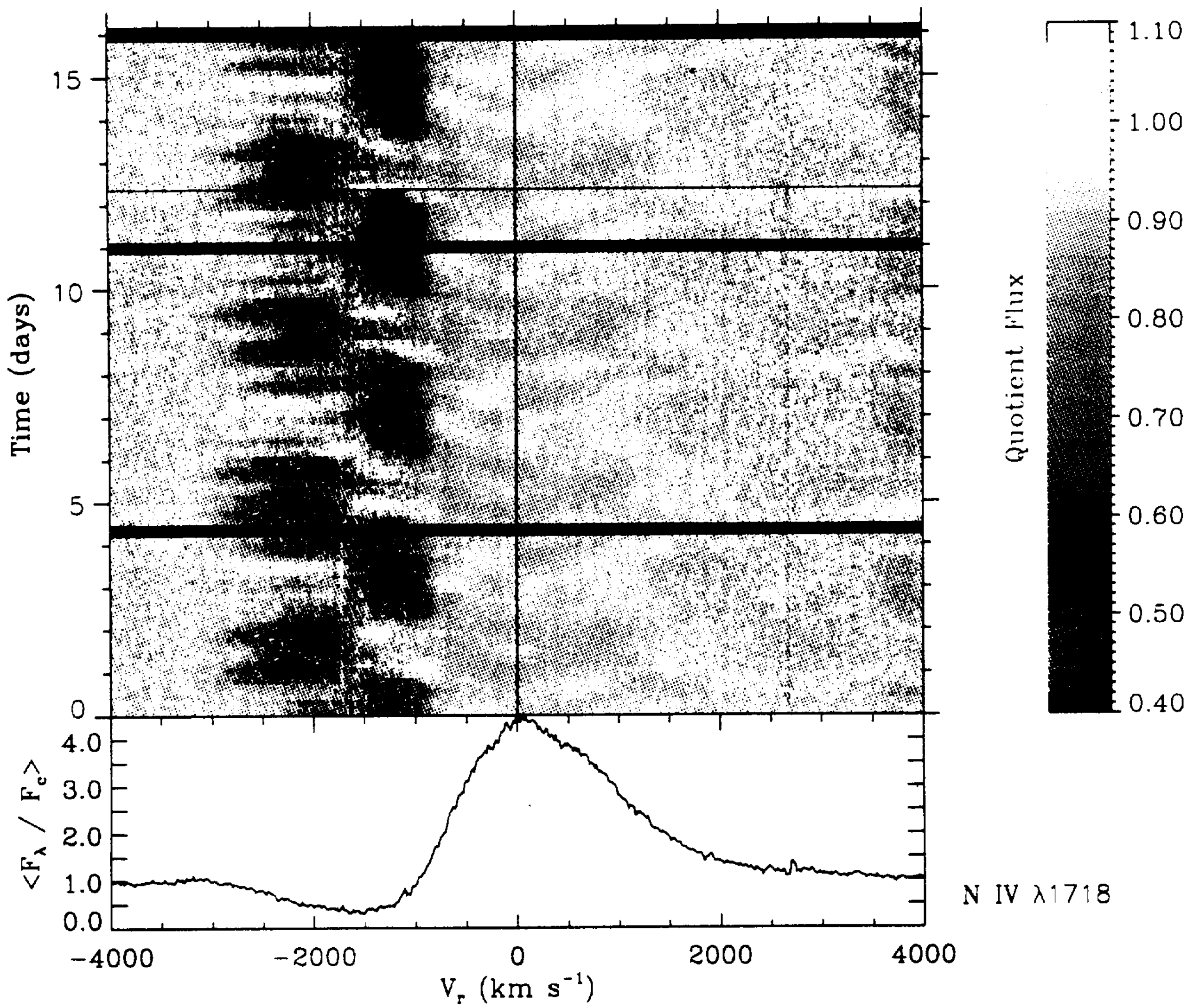

FIG. 1.—Color representation of the time variability in the N IV λ1718 wind line in HD 50896. Time (in days from the beginning of the series) increases upward. The spectra were converted to a linear time grid by nearest a neighbor interpolation, and gaps appear whenever more than 5 hr elapsed between exposures. The individual spectra were normalized by a minimum absorption (maximum flux) spectrum so that all changes appear as absorptions. The rest wavelength of the line is shown as a vertical line. The color bar alongside the plot shows the scaling used.

MASSA et al. (see 452, L54)

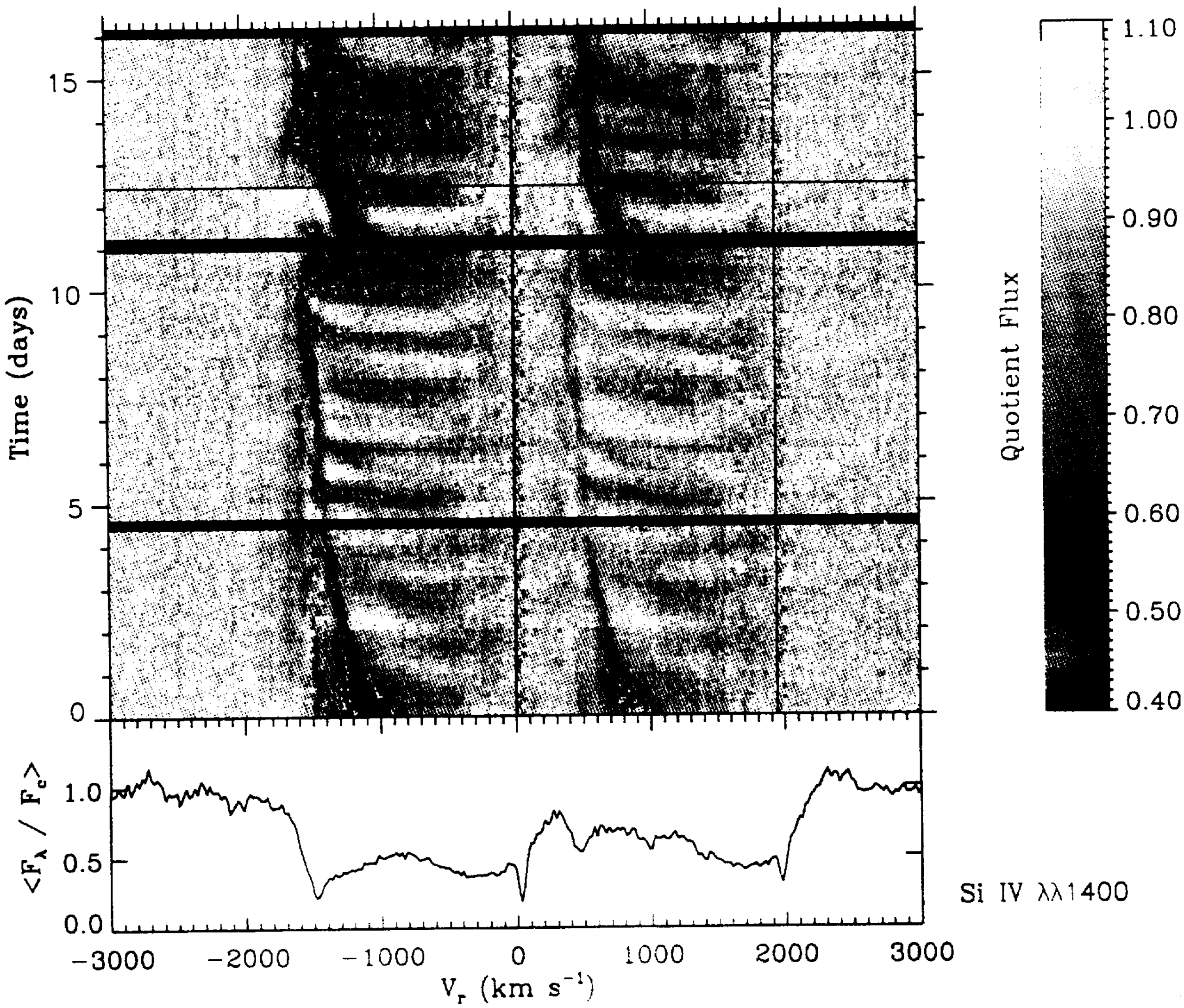

FIG. 2.—Same as Fig. 1 for the Si IV λλ1393, 1402 resonance doublet in HD [illegible]. The rest wavelengths of the doublet are shown as vertical lines.

MASSA et al. (see 452, L54)

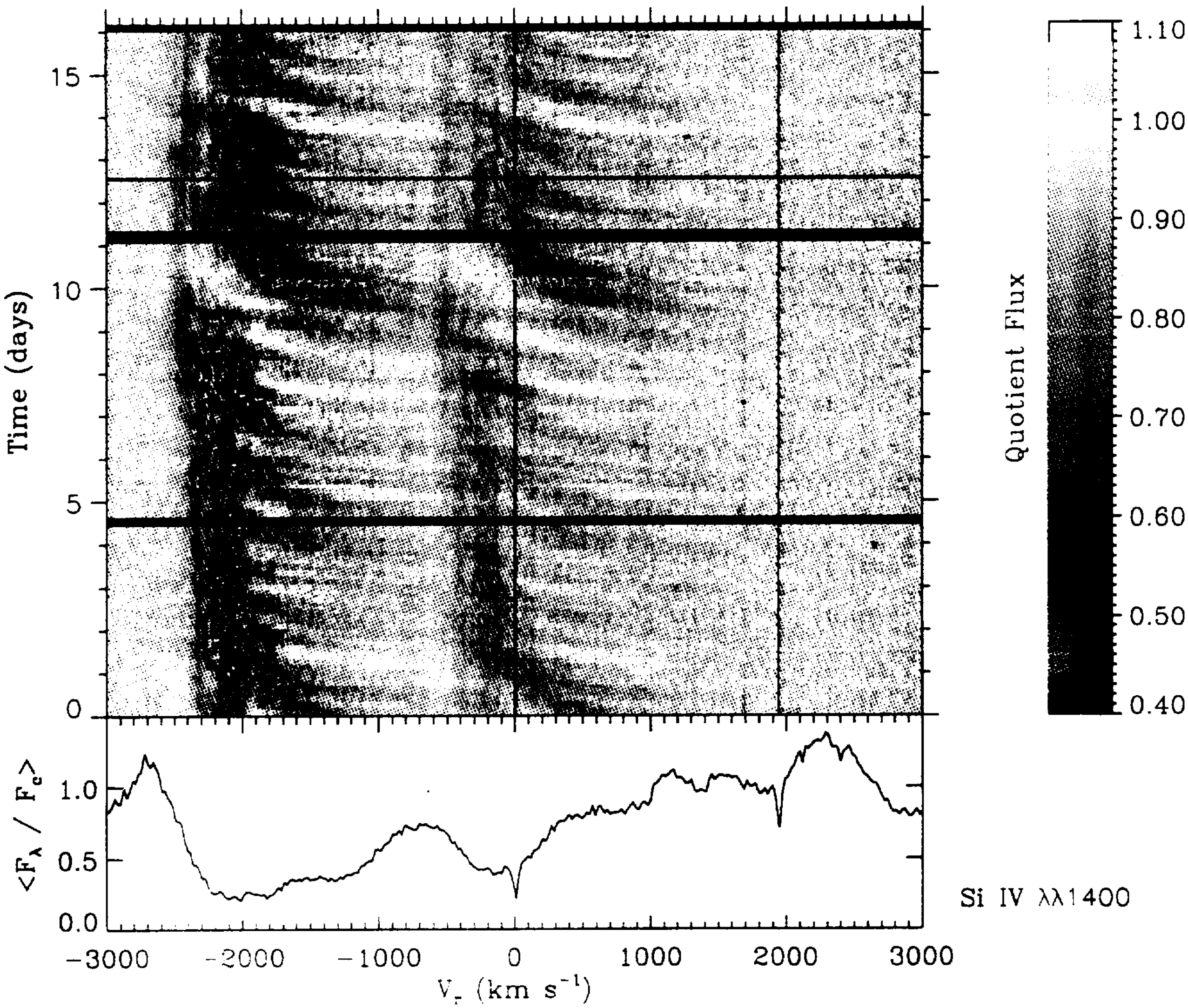

FIG. 3.—Same as Fig. [illegible] λλ1393, 1402 resonance doublet in HD 66811. The rest wavelengths of the doublet are shown as vertical lines.

MASSA et al. (see 452, L54)