

## THE DETECTION OF WIND VARIABILITY IN MAGELLANIC CLOUD O STARS

D. MASSA,<sup>1</sup> A. W. FULLERTON,<sup>2,3</sup> J. B. HUTCHINGS,<sup>4</sup> D. C. MORTON,<sup>4</sup> G. SONNEBORN,<sup>5</sup> A. J. WILLIS,<sup>6</sup> L. BIANCHI,<sup>3</sup>  
K. R. BROWNSBERGER,<sup>7</sup> P. A. CROWTHER,<sup>6</sup> T. P. SNOW,<sup>7</sup> AND D. G. YORK<sup>8</sup>

Received 2000 March 20; accepted 2000 June 9; published 2000 July 20

### ABSTRACT

We present *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) spectra for three Magellanic Cloud O stars (Sk 80, Sk –67°05, and Sk –67°111) with repeated observations. The data demonstrate the capabilities of *FUSE* to perform time-resolved spectroscopy on extragalactic stars. The wavelength coverage of *FUSE* provides access to resonance lines due to less abundant species, such as sulfur, which are unsaturated in O supergiants. This allows us to examine wind variability at all velocities in resonance lines for stars with higher mass-loss rates than can be studied at longer ( $\lambda \geq 1150 \text{ \AA}$ ) wavelengths. The *FUSE* wavelength range also includes resonance lines from ions that bracket the expected dominant ionization stage of the wind. Our observations span 1–4 months with several densely sampled intervals of 10 hr or more. These observations reveal wind variability in all of the program stars and distinctive differences in the ionization structure and timescales of the variability. Sk –67°111 demonstrates significant wind variability on a timescale less than 10 hr, and the coolest O star (Sk –67°05) exhibits the largest variations in O VI.

*Subject headings:* Magellanic Clouds — stars: winds, outflows — ultraviolet: stars

### 1. INTRODUCTION

Not long after the first observations of UV wind lines by Morton (1967), repeated observations with the *Copernicus* satellite discovered that these lines were time variable (York et al. 1977; Snow 1977). Subsequent *IUE* observations established that discrete absorption components (DACs) are ubiquitous in hot stars with well-developed but unsaturated wind lines (e.g., Howarth & Prinja 1989) and that the presence of DACs is indicative of wind variability. Later work by Kaper et al. (1996) demonstrated the universality UV wind line variability directly, through time series observations of selected O stars. Massa et al. (1995) and Kaper et al. determined that the wind lines in many stars vary on their stellar rotation timescale, verifying Prinja’s (1988) suggestion that wind line activity is linked to the stellar rotation period. This has led researchers to consider physical explanations that rely on phenomena present on the stellar surface, such as magnetic fields (Henrichs et al. 1998) or nonradial pulsations (Gies et al. 1999). Whatever the origin, Owocki, Cranmer, & Fullerton (1995) have shown that winds with large-scale spiral patterns are consistent with some of the observations (Fullerton et al. 1997; Kaper et al. 1999), although other aspects of the variability remain unexplained.

<sup>1</sup> Raytheon Information Technology and Scientific Services, Code 681.0, NASA Goddard Space Flight Center, Greenbelt, MD 20771; derck.massa@gsfc.nasa.gov.

<sup>2</sup> Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC V8W 3P6, Canada.

<sup>3</sup> Department of Physics and Astronomy, John Hopkins University, 3400 North Charles Street, Baltimore, MD 21218.

<sup>4</sup> Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council, 5071 West Saanich Road, Victoria, BC V8X 4M6, Canada.

<sup>5</sup> Laboratory for Astronomy and Solar Physics, Code 681.0, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

<sup>6</sup> Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, England, UK.

<sup>7</sup> Center for Astrophysics and Space Astronomy, University of Colorado, Campus Box 389, Boulder, CO 80309.

<sup>8</sup> Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.

All of the previous results were deduced from observations of Galactic stars. Although there is no reason to doubt similar variability in normal extragalactic stars (Prinja & Crowther 1998 have detected DACs in several Magellanic Cloud stars), direct observations of wind variability have not been obtained. Besides demonstrating its universality, observing wind variability in the Large and Small Magellanic Cloud (LMC, SMC) stars with *FUSE* is important in other respects. First, the lower metallicity of the clouds provides an opportunity to study how instabilities in line-driven winds are affected by abundances. Second, the ions available to *FUSE* complement those normally observed at longer wavelengths. This is especially true for the S IV and S VI lines, which can be used to determine the ionization structure of wind variability. Third, because sulfur is less abundant than ions with comparable ionization potentials accessible at longer wavelengths, its resonance lines are less optically thick and can be used to probe activity at deeper levels in the winds.

### 2. OBSERVATIONS

As part of in-orbit checkout (IOC), extended observational sequences were performed on three O stars in the Magellanic Clouds (Table 1). The observations were obtained during several visits over intervals spanning 1–4 months. They include a few continuous time streams of several hours and several cases with multiple exposures obtained over the course of a single day.

All of the observations were obtained in time-tagged mode through the low-resolution apertures (Moos et al. 2000). Because the observations were obtained early in the mission, the SiC channels were not aligned. Consequently, we have repeated observations only for the LiF channels and currently lack repeated observations for the important S VI  $\lambda\lambda 940$  doublet.

Because much of the IOC data were obtained to determine the locations of the apertures for the LiF and SiC channels, the position of the target was moved in the aperture during an observation. In fact, the target was often completely out of the LiF aperture for part of the observation. As a result of these intentional, large-image motions, normal pipeline reduction

TABLE 1  
PROGRAM STARS

Name	Spectral Type	$v_{\infty}$ (km s <sup>-1</sup> )	$V$ (mag)
Sk 80 .....	O7 Iaf <sup>+</sup> <sup>a</sup>	1400 <sup>b</sup>	12.36
Sk -67°05 .....	O9.7 Ib <sup>c</sup>	1665 <sup>d</sup>	11.34
Sk -67°111 .....	O7 Ib(f) <sup>a</sup>	1800 <sup>b</sup>	12.57

<sup>a</sup> From Walborn 1977.

<sup>b</sup> From Bianchi et al. 2000.

<sup>c</sup> From Fitzpatrick 1988.

<sup>d</sup> From Patriarchi & Perinotto 1992.

was not feasible. Instead, the data were reduced by a suite of interactive data language procedures that proceeded in two stages. In the first stage, the photon lists were divided into 5 minute subexposures. A spectrum was extracted for each subexposure by summing all counts at a constant  $x$  (where  $x$  is in the dispersion direction) within a prespecified  $y$ -range to obtain the total counts at each  $x$ . Background corrections are insignificant for our bright program stars and were neglected. During this stage, the total counts in a prespecified wavelength band were determined for each subexposure, and a “postage stamp”  $64 \times 64$  binned image of the detector was produced. In the second processing stage, the individual subexposures were examined for event bursts (see Sahnou et al. 2000) and uniformity of flux levels. Subexposures that were affected by bursts or that had discrepant flux levels were discarded. Finally, the remaining subexposures were aligned by using their mean as a template and then shifting and fitting (in a least-squares sense) the individual subexposures to the mean. The minimum

$\chi^2$  shifts were applied to each subexposure to create the set of aligned spectra.

### 3. RESULTS

Since we have repeated observations only for the LiF channels, we concentrate on the LiF1A data ( $987 \text{ \AA} \leq \lambda \leq 1082 \text{ \AA}$ ), which contain the S IV and O VI wind lines. The data are displayed in Figures 1–3 as dynamic spectra. These are two-dimensional images of time-ordered spectra. The ordinate is sequential spectrum number, and the abscissa is velocity relative to the blue component of the doublet (adjusted for the stellar radial velocity). Each horizontal strip is a 5 minute subexposure normalized by the sample mean spectrum (shown at the bottom). Sequential stacking avoids the large time gaps, which appear when irregularly sampled data are displayed on a linear timescale. Each figure also contains a temporal plot, which gives the relative observation time for each subexposure. A nearly vertical line implies that several spectra were obtained over a very short time period.

#### 3.1 *Sk 80* = AV 232

This SMC star (Fig. 1) has distinctively subsolar metallicity (see Fullerton et al. 2000). We obtained four sets of observations between 1999 September 25 and 1999 November 17. Notice that, although the S IV  $\lambda 1063$  line and  $\lambda\lambda 1073$  doublet are stable throughout the individual observations (which span up to 12 hr), they vary strongly from one set of observations to the next. There is also some indication of an overall brightening of the object at  $\Delta t = 30$  days as well as marginal evidence

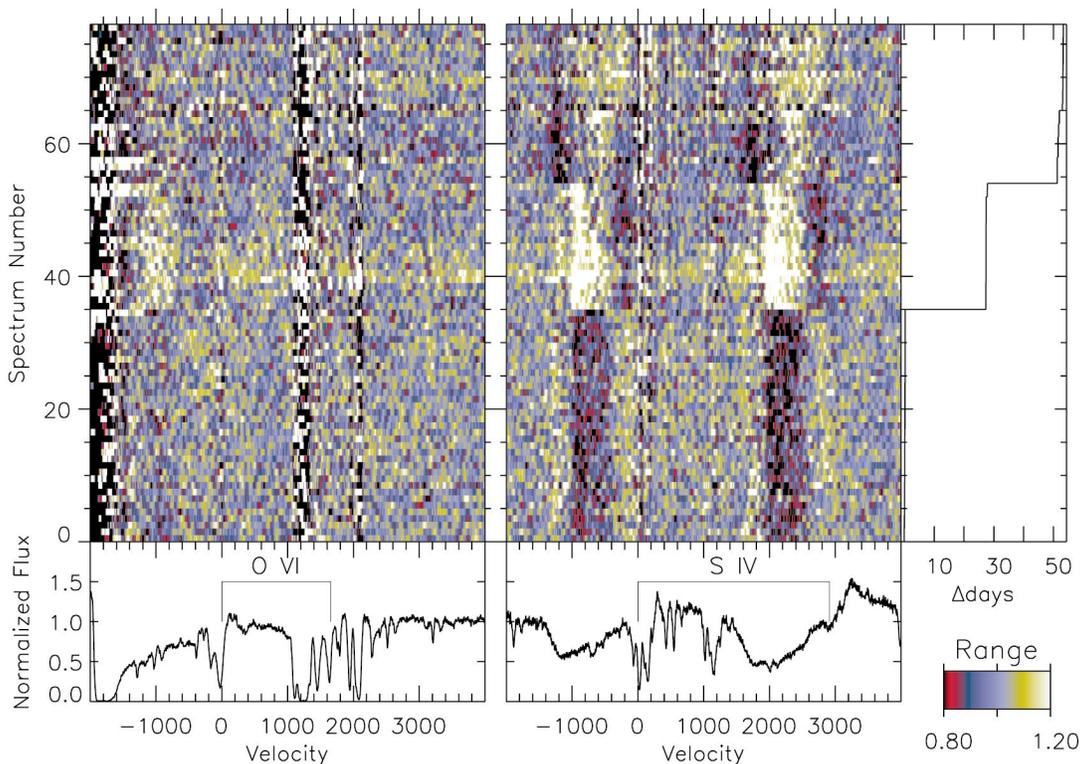


FIG. 1.—Dynamic spectrum for Sk 80. The ordinate is sequential spectrum number, and the abscissa is velocity relative to the blue component of the doublet in the stellar rest frame. Each horizontal strip is a 5 minute subexposure normalized by the sample mean spectrum (shown at the bottom). At right is a temporal plot, which gives the relative time of each subexposure. The rest wavelengths of the O VI doublet and the S IV lines are indicated on the mean spectrum.

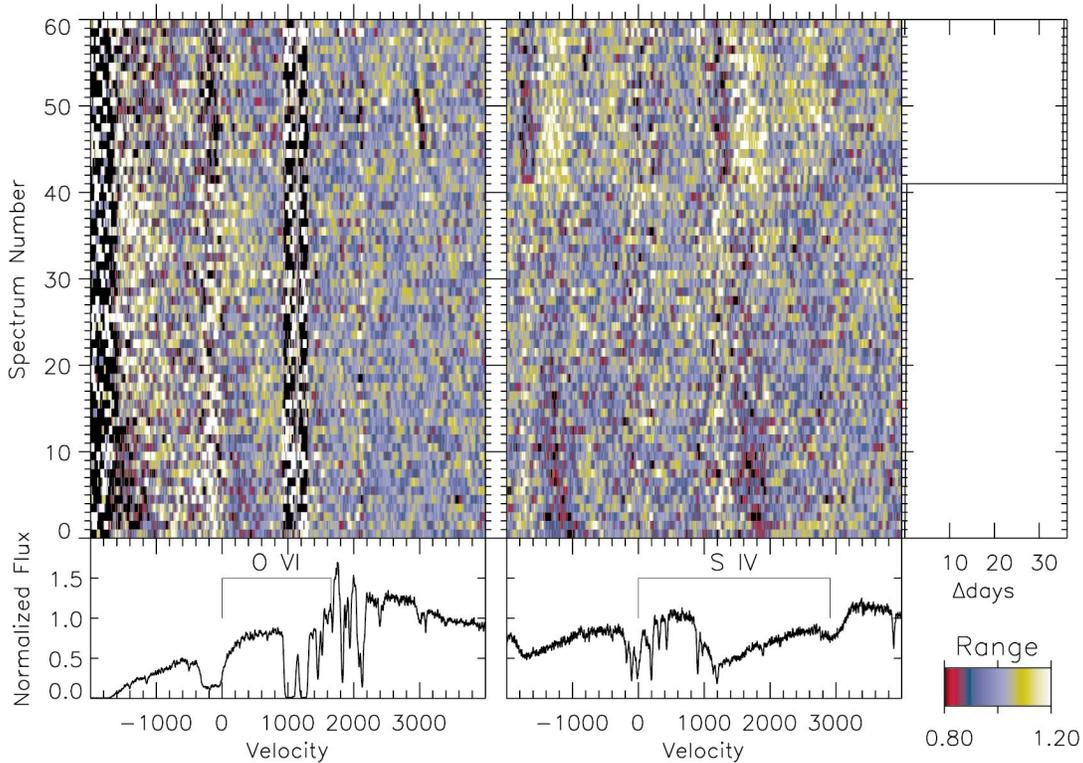


FIG. 2.—Same as Fig. 1, but for the LMC O7 supergiant Sk  $-67^{\circ}111$

for a change in the O VI  $\lambda\lambda 1030$  doublet (which is intrinsically very weak). However, given the nature of the observational sequence, absolute flux levels are uncertain.

The form of the variability affects the entire profile, but the current data set is not suitable for addressing the temporal evolution of wind variability because adjacent observations are separated by several wind flushing times. The presence of several interstellar molecular hydrogen lines throughout the region and strong Ly $\beta$  absorption affecting the blue component of O VI (see Fullerton et al. 2000) make it difficult to verify whether an isolated absorption observed in one component of a doublet is part of a DAC.

### 3.2 Sk $-67^{\circ}111$

Sk  $-67^{\circ}111$  (Fig. 2) is an LMC analog of Sk 80 that has a higher metallicity (Fullerton et al. 2000). We obtained spectra on 1999 September 26 and 1999 October 31, with the September set spanning 10 hr. In this case, the overall S IV variability is weaker than in Sk 80, but there is better evidence for O VI variability. However, it is especially interesting that the S IV lines clearly vary during the 10 hr September observation. Throughout this time, a broad absorption band centered near  $-1200 \text{ km s}^{-1}$  in S IV weakened, narrowed, and propagated toward higher velocity. A similar feature is discernible in the red component of O VI, but the blue component is lost in Ly $\beta$  absorption.

### 3.3 Sk $-67^{\circ}05 = \text{HD } 268605$

This LMC star (Fig. 3) is more than two full spectral subclasses later than the others (Table 1). Our data span nearly 4 months, from 1999 August 23 to 1999 December 13. In this

case, the O VI variability is quite strong and in phase with much weaker S IV variability. There is no evidence for short-term variability.

## 4. DISCUSSION

Although we lack well-sampled temporal coverage and repeated observations for S VI at this time, the current data still provide a glimpse of the capabilities of *FUSE* to perform wind variability studies. The combination of *FUSE* wavelength coverage and the reduced metallicity of the Magellanic Cloud stars enabled us to examine wind variability in new density regimes and new ionization states. In many respects, S IV and Si IV  $\lambda\lambda 1400$  are sensitive to similar plasmas. However, the reduced abundance of sulfur allows us to probe more massive flows. Both O VI and N V sample very hot plasma, although the wider separation of the O VI  $\lambda\lambda 1032, 1038$  doublet removes the complications introduced by the overlap of the N V  $\lambda\lambda 1240$  components in many stars (however, interstellar Ly $\beta$  contaminates O VI  $\lambda 1032$ ). These features allowed us to detect wind variability at intermediate velocities in O7 supergiants. In Galactic O7 supergiants, all of the wind lines in the *IUE* or *Hubble Space Telescope* range are saturated, and it is not until O6 and earlier supergiants that Si IV desaturates enough for variability to be detected (see  $\lambda$  Cep in Kaper et al. 1996). Even then, N V remains completely saturated, so ionization information cannot be obtained. In contrast, the P Cygni profiles of S IV are well developed and unsaturated in the *FUSE* spectra of both O7 supergiants. O VI is similarly well suited for studying variations in spectra of Sk  $-67^{\circ}111$  but is too weak to be useful in Sk 80.

Several aspects of the current data are noteworthy. First, to provide an indication of the magnitude of the physical changes

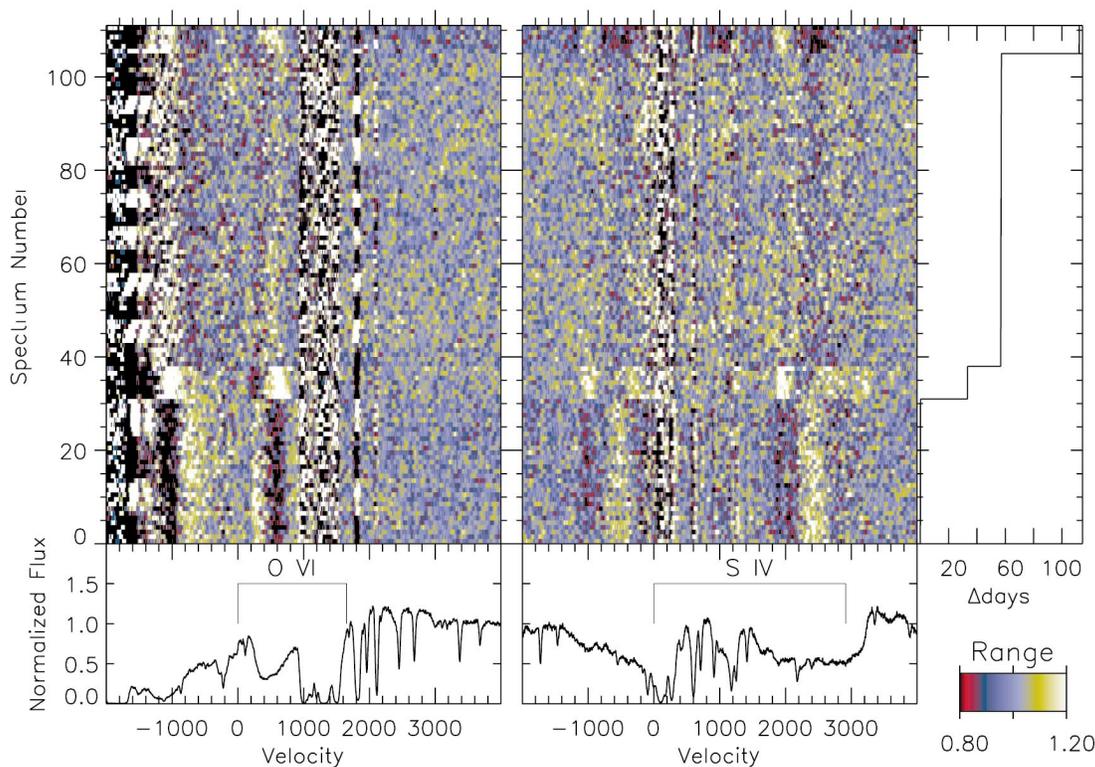


FIG. 3.—Same as Fig. 1, but for the LMC O9.7 supergiant Sk  $-67^{\circ}05$

implied by the morphological variability, consider the results from Bianchi et al. (2000) for S IV in Sk 80 and Sk  $-67^{\circ}111$ . Analyzing the same observations displayed here, they determined that the line-of-sight wind column density varied by 68% in Sk 80 and 45% in Sk  $-67^{\circ}111$ . We see, therefore, that the variability is not a small perturbation on top of an otherwise steady flow. Instead, variability is a fundamental property of the winds. Second, the wind lines vary in every Magellanic Cloud O star with repeated observations separated by more than a few days, a result that is similar to that observed in Galactic O stars (Kaper et al. 1996). Third, although the S IV variability in Sk 80 is stronger than in Sk  $-67^{\circ}111$ , its O VI variability is weaker, if present at all: an effect that may be due to the relative abundances of the two stars. Fourth, although Sk  $-67^{\circ}05$  is cooler than either Sk 80 or Sk  $-67^{\circ}111$ , its O VI variability is much stronger. This implies that the variability we happened to

observe is of a higher ionization state than in the two O7 stars. Fifth, while there is no evidence of short-term ( $\leq 1$  day) variability in two of the program stars, it is clearly present in Sk  $-67^{\circ}111$  on timescales similar to those observed for the Galactic O6 supergiant  $\lambda$  Cep (Kaper et al. 1996).

From our very limited data, it appears that the overall wind variability of the Magellanic Cloud O stars is similar to Galactic stars. However, longer and better sampled time series will be needed to determine whether the timescale of the variability is related to the rotation period of the stars, as it is in many Galactic O stars and B supergiants.

This work is based on data obtained for the Guaranteed Time Team by the NASA-CNES-CSA *FUSE* mission operated by Johns Hopkins University. Financial support to US participants has been provided by NASA contract NAS5-32985.

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