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The Rate of Mass Loss and Variations in the Wind from the Be Star δ Centauri

(NASA-CR-163427) THE RATE OF MASS LOSS AND VARIATIONS IN THE WIND FROM THE BE STAR DELTA CENTAURI (Colorado Univ.) 19 p HC A02/MF A01 CSCL 03A G3/89 N80-30241 Unclas 27240

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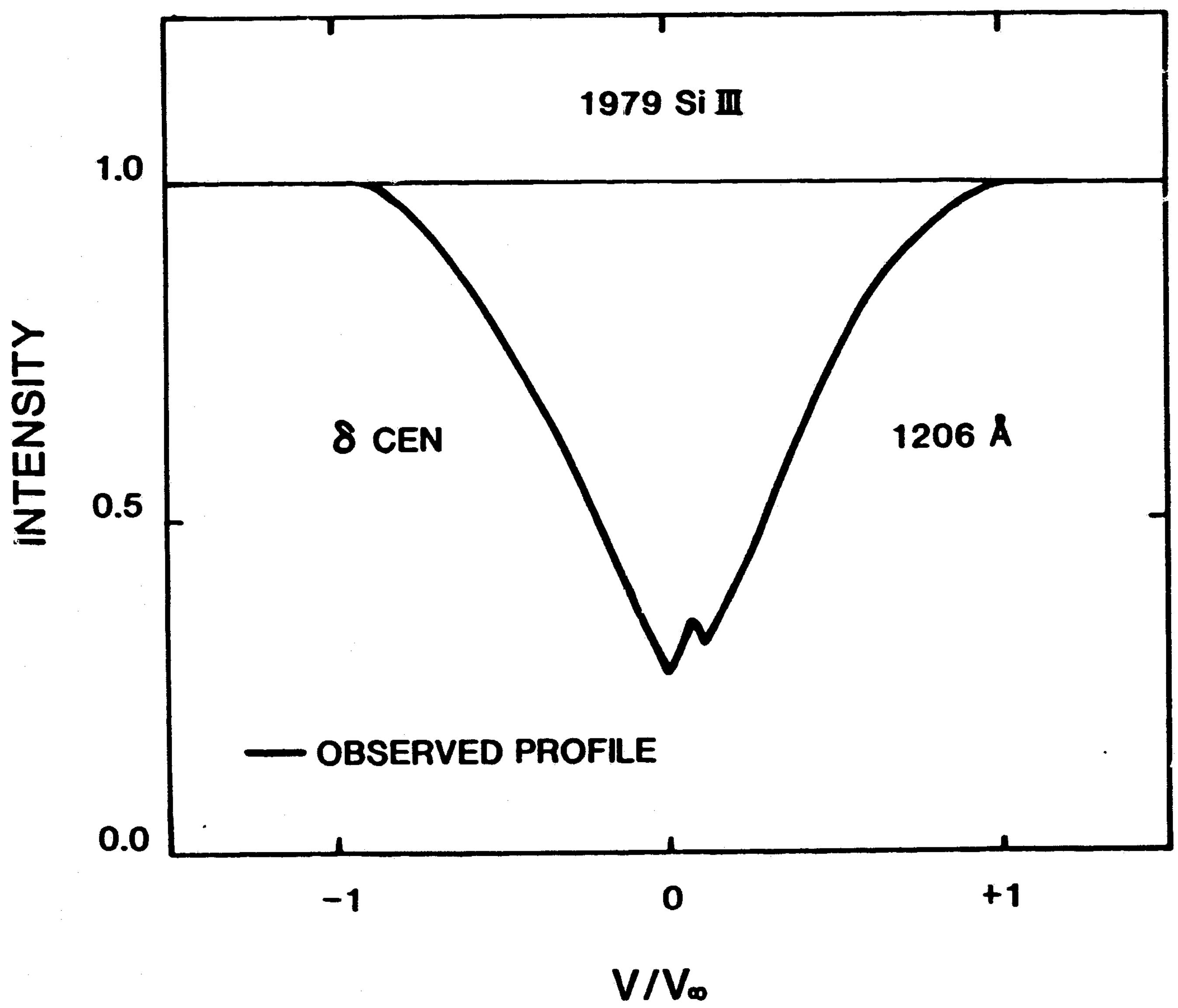

1979 Si III
1.0
0.5
0.0
INTENSITY
δ CEN
1206 Å
OBSERVED PROFILE
−1
0
+1
V/V∞

Abstract

Copernicus ultraviolet scans of the Be star δ Centauri, obtained in 1976 and 1979, show a significant variation in the Si III $\lambda1206$ profile, the strong asymmetry that was present in 1976 having disappeared by 1979. The Si IV $\lambda1400$ doublet was also asymmetric in 1976, but was not observed in 1979. A quantitative fit of the line shapes to theoretical wind profiles shows that the mass-loss rate in 1976 was 2×10^{-8} yr^{-1}, and that the rate of mass loss in Si III was at least one order of magnitude less in 1979. It is not possible to determine whether the variation represented an overall change in the mass-loss rate, or whether it was due to a change in the ionization balance. The profile-fitting procedure resulted in the adoption of assumed underlying photospheric Si III and Si IV profiles, and the equivalent widths measured from these profiles are most consistant with T_{eff} between 30,000 and 35,000 K, somewhat hotter than implied by the spectral classification normally assigned to this star. The ultraviolet photospheric line widths, coupled with published theoretical analyses of rotational gravitational darkening, imply an intrinsic equatorial velocity of about 310 km s^{-1} and an angle of inclination of the rotational axis to the line of sight of $i \lesssim 44^{\circ}$.

I. INTRODUCTION

Variability in the visible-wavelength spectra of Be stars is a common phenomenon with a long observational history (cf. several articles in Slettebak, 1976, and references cited therein), and in recent years similar effects in ultraviolet spectra have been found as well (e.g. Molnar 1975; Panek and Savage 1976; Marlborough, Snow, and Slettebak 1978; Slettebak and Snow 1978; Doazan, Kuhi, and Thomas 1980; Marlborough and Snow 1980). Several Be stars are now included in a survey of ultraviolet variability being conducted with *Copernicus* by Oegerle *et al*. (1980), and a few are being studied similarly with the *International Ultraviolet Explorer* (Doazan *et al*. 1980), so that many more details of the phenomenon should be revealed shortly.

The ultraviolet data, some from rockets (e.g. Bohlin 1970), but particularly the high dispersion and photometrically accurate scans obtained with *Copernicus*, have also revealed the presence of stellar winds in some Be stars (Snow and Marlborough 1976; Lamers and Snow 1978), although to date no well-defined picture has developed of the relationship of these winds (with velocities up to 1000 km s^{-1}) and the nearly-stationary circumstellar material giving rise to emission and, in some cases, shell absorption lines. The winds from Be stars appear to be similar in nature to those from the more luminous OB stars, and the Be stars lie at the boundary of the region in the H-R diagram where winds normally arise (e.g. Snow and Morton 1976). It is by now well established that the strong winds from luminous OB stars are subject to variability (cf. Rosendhal 1973a, b; Snow 1979; Snow and Linsky 1980 and references cited therein), so it might be expected that the winds in Be stars should also vary. Some evidence for this has already been reported; i.e. Snow and Marlborough (1976) found that the 450 km s^{-1} wind in γ Cas seen earlier by Bohlin (1970) had decreased in strength over five years, and Marlborough, Snow and Slettebak (1978) found variations in the N V profile in the same star in times less than one hour.

The present paper reports a change found in the wind of the Be star δ Cen. This change, resulting in the disappearance of any evidence of what had been a substantial wind, took place in a time of three years. In the next section optical and previous ultraviolet data on δ Cen are summarized, and section III describes the *Copernicus* observations. A quantitative assessment of the rate of mass loss before and after the change is made in section IV, and the final section contains a discussion of the photospheric line profiles.

II. PREVIOUS OBSERVATIONS OF δ CEN

This star is a member of the Sco-Cen association (Moreno and Moreno 1967), and was first detected as an emission-line object by Flemming (1890). Variability has been reported by Jaschek, Jaschek, and Kucewicz (1964), who found V/R changes in emission profiles, and by Coyne (1976), who described variable intrinsic linear polarization.

Panek and Savage (1976) included δ Cen in their survey of ultraviolet resonance line strengths in Be and normal B stars observed with OAO-2, and Lamers and Snijders (1975) made a similar study of Mg II profiles observed with the high-resolution S/59 spectrometer aboard the European satellite TD1. In the former study, the authors found good agreement between computed and observed Si IV and C IV line strengths for δ Cen, indicating relatively little effect on these lines of an extended atmosphere or wind. In the latter study, however, evidence for Mg II emission was found. Lamers and Snow (1978) then discovered asymmetries in the Si III and Si IV resonance lines, which they interpreted as being due to a stellar wind. These asymmetries were probably weak enough not to have had a significant effect on the equivalent widths measured by Panek and Savage from the low-resolution OAO-2 data, so it is not warranted to conclude that the wind was absent at the time of that observation, presumably in the early 1970's.

Finally, Snow, Peters and Mathieu (1979) included δ Cen in their Copernicus survey of ultraviolet shell lines in Be stars, reporting this object to have in mid-1976 a very weak Fe III shell with an expansion velocity of -40 km s^{-1}.

III. THE *COPERNICUS* DATA

The first *Copernicus* data on δ Cen were obtained in May, 1976, by one of us (TPS), and have been used as part of a survey of winds in B stars published by Lamers and Snow (1978); some of these data were also included in the survey of ultraviolet shell lines published by Snow, Peters, and Mathieu (1979). The 1976 observation included scans with photomultiplier U2 of the Fe III shell-line region between 1120 and 1140 A and of the Si III resonance line at 1206 A; and U1 scans of the Si IV doublet at 1400 A. The U2 spectral resolution is 0.2 A, and that of U1 is 0.05 A (Rogerson, Spitzer *et al*. 1973). Both the Si III and Si IV features in 1976 showed asymmetries indicative of the presence of a wind.

The 1979 data on δ Cen were obtained in April, nearly three years following the initial scans, and only the Si III λ1206 region was covered, revealing no asymmetry.

For the present study the U2 scans were corrected for stray light following the algorithm of Bohlin (1975) and backgrounds due to charged particles were removed from all the scans using standard Princeton procedures. The 1979 scan was scaled to 1976 instrumental sensitivity following Upson (1979).

Figure 1 shows the Si III profiles observed in 1976 and 1979, and Figure 2 shows the Si IV lines as they appeared in 1976.

IV. THE MASS-LOSS RATE

Castor and Lamers (1979) have published a compendium of theoretical line profiles arising in spherically-expanding winds with a variety of velocity laws, and their work has been used to derive the mass-loss rate in δ Cen in 1976, as well as an upper limit from the 1979 data. As the following discussion indicates, the results for the observed ions are quite secure, but uncertainty in the overall mass-loss rate remains, particularly in the 1979 data, because of uncertainties in the ionization balance.

In order to compare the theoretical and observed profiles, it was necessary to renormalize the observed profiles and convert from a wavelength scale to a velocity scale expressed in terms of V_∞, the wind terminal velocity derived from the short-wavelength edge of the absorption. For δ Cen, the 1976 data reveal $V_\infty = -870$ km s^{-1} (this can be considered a lower limit, since the wind could persist to higher velocities, but with insufficient density to noticeably affect the profile at shorter wavelengths). It was also necessary to adopt intrinsic photospheric profiles, since both Si III and Si IV are expected in the atmosphere of an early B star. These adopted photospheric profiles must then be used to modify the theoretical wind profiles before comparison with the observations, following procedures specified by Castor and Lamers.

Figure 3 shows the renormalized observational profile, the adopted photospheric profile, and the best fit theoretical (i.e. composite photospheric plus wind) profile for the 1976 Si III observation. The indicated theoretical profile is based on a velocity law of the form

$$W = V/V_\infty = 0.01 + 0.99\,[1-(r/R_*)^{-1}]^\beta,$$

with $\beta = 1.0$, and a radial optical depth dependence

$$\tau_{rad} = \mathcal{T}(\gamma+1)\,(1-V_0/V_\infty)^{-1-\gamma}\,(1-V/V_\infty)^\gamma,$$

where $\gamma = 0.5$ and the total optical depth $\mathcal{T}$ was found from the fit to be 0.25 (the initial wind velocity, V_0, was taken to be 0.01 V_∞, following the convention of Castor and Lamers). A less acceptable fit was found for $\beta = 1$, $\gamma = 1$, and $\mathcal{T}$=0.25, which, if adopted, would affect the mass-loss rate by only 13%.

The absence of an emission reversal in the line core, expected from the model profile, can be attributed to interstellar absorption, since the SiIII λ1206 line is always very strong and broad, even in the spectra of lightly-reddened stars.

The smoothed profile and the fit neglect the relatively narrow features at 1203.5 and 1205.0A. These may be shell components of SiIII, at expansion velocities of 740 and 380 km s^{-1}, respectively; if so, they contribute to the mass-loss rate. This contribution is relatively minor, however, because the lines are not saturated, and hence contribute to the total opacity roughly in proportion to their contribution to the total equivalent width due to absorption by the wind material. This appears to be about 30% at most.

The Si IV lines were fit by the same law that best fit Si III, but with $\mathcal{T}$ = 0.1, as shown in figure 4. This fit is based on the 1393 A line, since λ1402 was sufficiently optically thin that it showed no marked asymmetry.

From the adopted fits, mass-loss rates for Si III and Si IV separately were derived for the 1976 data, yielding $\dot{\mathcal{M}}(\mathrm{Si}) = 9.07 \times 10^{-13} \mathcal{M}_\odot\ \mathrm{yr}^{-1}$, if all silicon is either Si III or Si IV. Adoption of a cosmic Si/H ratio of 3.55 x 10^{-5} (Withbroe 1971) then leads to an overall mass-loss rate of $\dot{\mathcal{M}} = 2.55 \times 10^{-8}$ $\mathcal{M}_\odot\ \mathrm{yr}^{-1}$ for δ Cen in May, 1976.

The renormalized Si III line observed in 1979 is shown in figure 5, where it is seen that no asymmetry is evident. From this figure and the weak wind formalism developed by Castor, Lutz and Seaton (1980), it is conservatively estimated that the total optical depth of the wind is less than 0.091 of the

1976 value. Hence the mass-loss rate in Si III was at least a factor of 10 less in 1979 than in 1976. Unfortunately, the Si IV doublet was not observed in 1979, so the effect of the observed change on the total mass-loss rate is not known.

Indirect evidence against an ionization change may be found in the fact that the SiIII multiplet (blended feature at 1201A) and the SiII multiplet (similar feature at 1197.4A) seen in Figure 1 each remained nearly unchanged in the 1979 data, whereas an ionization enhancement would have strengthened SIII while weakening the SiII feature, and a decrease in ionization would have had the opposite effect. It is, of course, probable that these SiII and SIII lines arise at different levels than the resonance lines of SiIII and SiIV, so this is only a circumstantial argument that an ionization change did not affect the SiIII/SiIV ratio in the wind.

The observed variations in the strong winds in more luminous OB stars have not been assessed in as much quantitative detail as in the present case, but there are indications that these changes typically represent at most a variation by a factor of 1.5 or so in the overall rate (e.g. Conti and Niemala 1976; Snow, Wegner, and Kunasz 1980). Hence δ Cen has apparently been affected by a more significant change than those typical of the more luminous objects. This star will be observed in more detail in the future, to provide better coverage of ionization states and of variability timescales.

V. THE PHOTOSPHERIC PROFILES

A spin-off from the present study was the derivation of photospheric Si III and Si IV profiles, from which equivalent widths were measured. Values of 0.89 A and 0.56 A were found for $\lambda\lambda$1393, 1402, respectively, and 2.55 A for λ1206. A comparison with the theoretical silicon line strengths for B stars (Kamp 1978) then was made in an attempt to derive a value for the effective temperature of δ Cen, but no consistent match could be found, the Si III appearing most consistant with T_{eff} = 27,500 K (log g = 3.5) or T_{eff} = 30,000 K (log g= 4.5), while the Si IV strength implies T_{eff} = 35,000 K (log g = 3.8). It appears that a value between 30,000 and 35,000 K may be best, since this at least provides reasonable agreement in log g. In any case these results are quite strongly in contrast with the spectral classification of B2IVne (Lesh 1972) and the value T_{eff} = 23,000 K adopted by Lamers and Snow (1978).

The discrepancy between the effective temperature derived here and that based on the spectral classification of δ Cen is not unprecedented. Heap (1976) reported a similar discrepancy in ζ Tau, a Be star classified as B4 IV but whose spectrum is best matched by assuming T_{eff} = 27,500 K, and both Molnar (1975) and Panek and Savage (1976) found unexpectedly strong lines of highly-ionized species in several cases (but not δ Cen), indicative of higher temperatures than implied by the spectral class. It may be that this phenomenon is typical of Be Stars.

The widths of the photospheric profiles are also of interest, in view of the earlier discovery by Heap (1976) that the velocity widths of ultraviolet lines in Be stars are often much less than those of visible-wavelength lines. An explanation in terms of gravitational darkening in the equatorial regions was offered by Hutchings (1976) and elaborated upon by Sonneborn and Collins (1977), who showed that a rapidly-rotating star could be sufficiently distended and cool near the equator that the ultraviolet flux, hence the ultraviolet line profiles, would form predominantly at high latitudes, where the projected rotational velocity is relatively small.

It appears that δ Cen does not show this effect, since Slettebak et al. (1975) reported a FWHM for HeI λ4471 of 6.43A, leading to expected line widths of 1.73 and 2.01A for $\lambda\lambda$1206 and 1900, respectively, if the width scaled simply with λ. The observed widths for the adopted photospheric profiles from the present data are 1.7 and 2.0A, respectively; i.e. to within the measurement uncertainties, these lines have the same velocity width as the visible-wavelength line. This shows that gravitational darkening is not important for δ Cen, with the corollary implication that δ Cen is not intrinsically an extremely rapid rotator. This conclusion is verified by the study of Sonneborn and Collins (1977), who showed that for an early-B dwarf, the velocity widths of photospheric lines will remain constant from visible through ultraviolet wavelengths if the angular velocity is less than $0.6\omega_c$, where ω_c is the critical velocity. This initial velocity corresponds to a surface equatorial velocity of about 517 km s^{-1} for a B1V star (Sonneborn and Collins, 1977), which may be a reasonable representation of δ Cen, in view of the foregoing discussion of its effective temperature.

Therefore, it seems justified to conclude that the true rotational velocity at the equator of δ Cen is less than about 310 km s^{-1}, indicating that the inclination angle i must be less than 44%, since the projected rotational velocity Vsin*i* is 215 km s^{-1} (Slettebak *et al*., 1975).

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FIGURE CAPTIONS

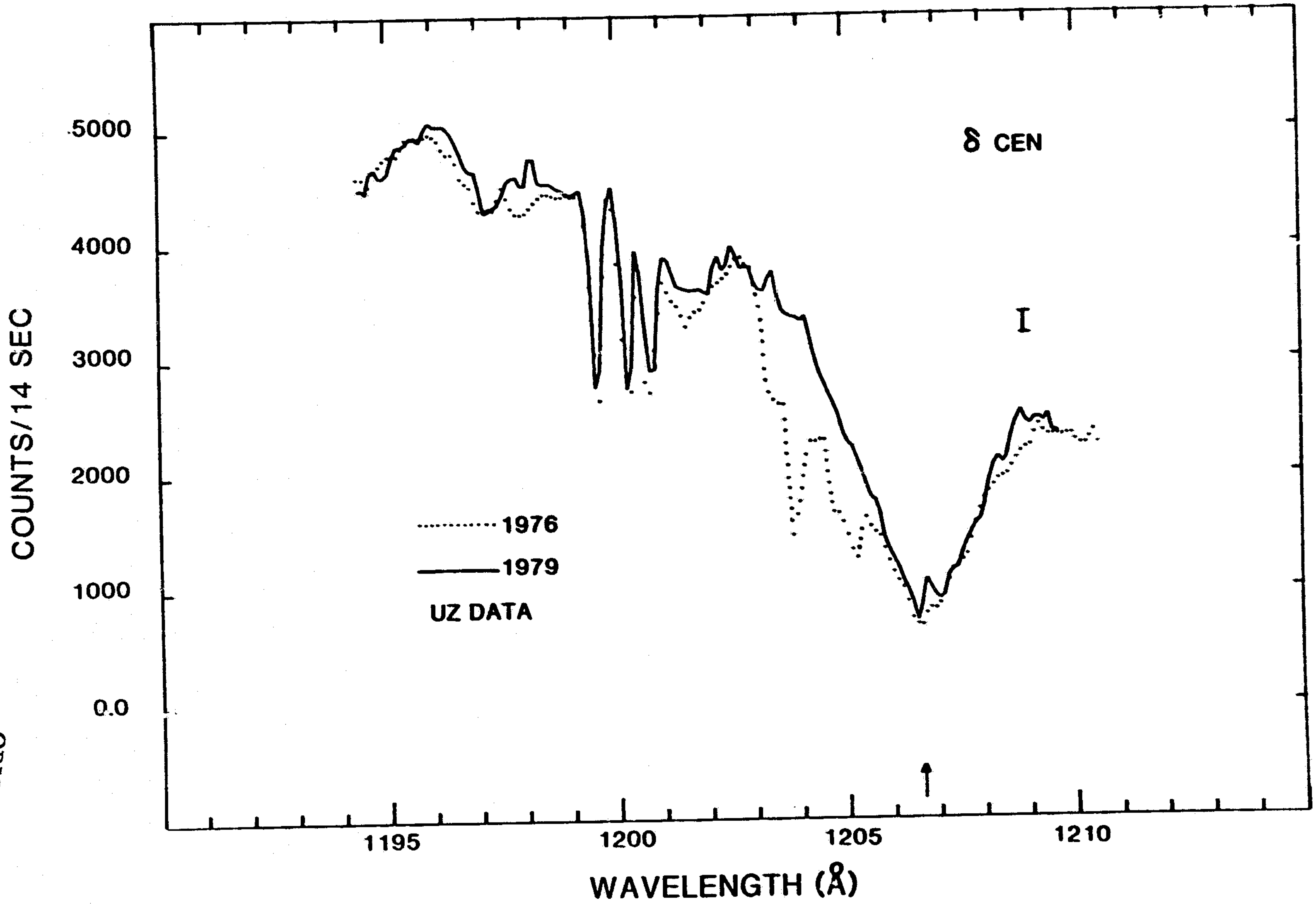
Fig. 1: The SiIII λ1206.510 profile in 1976 (dotted line) and 1979 (solid line). The 2σ photometric uncertainty is shown. The sharp triplet near 1200A is due to interstellar NI, while broad features at 1197 and 1201A are blended multiplets of SiII and SIII, respectively.

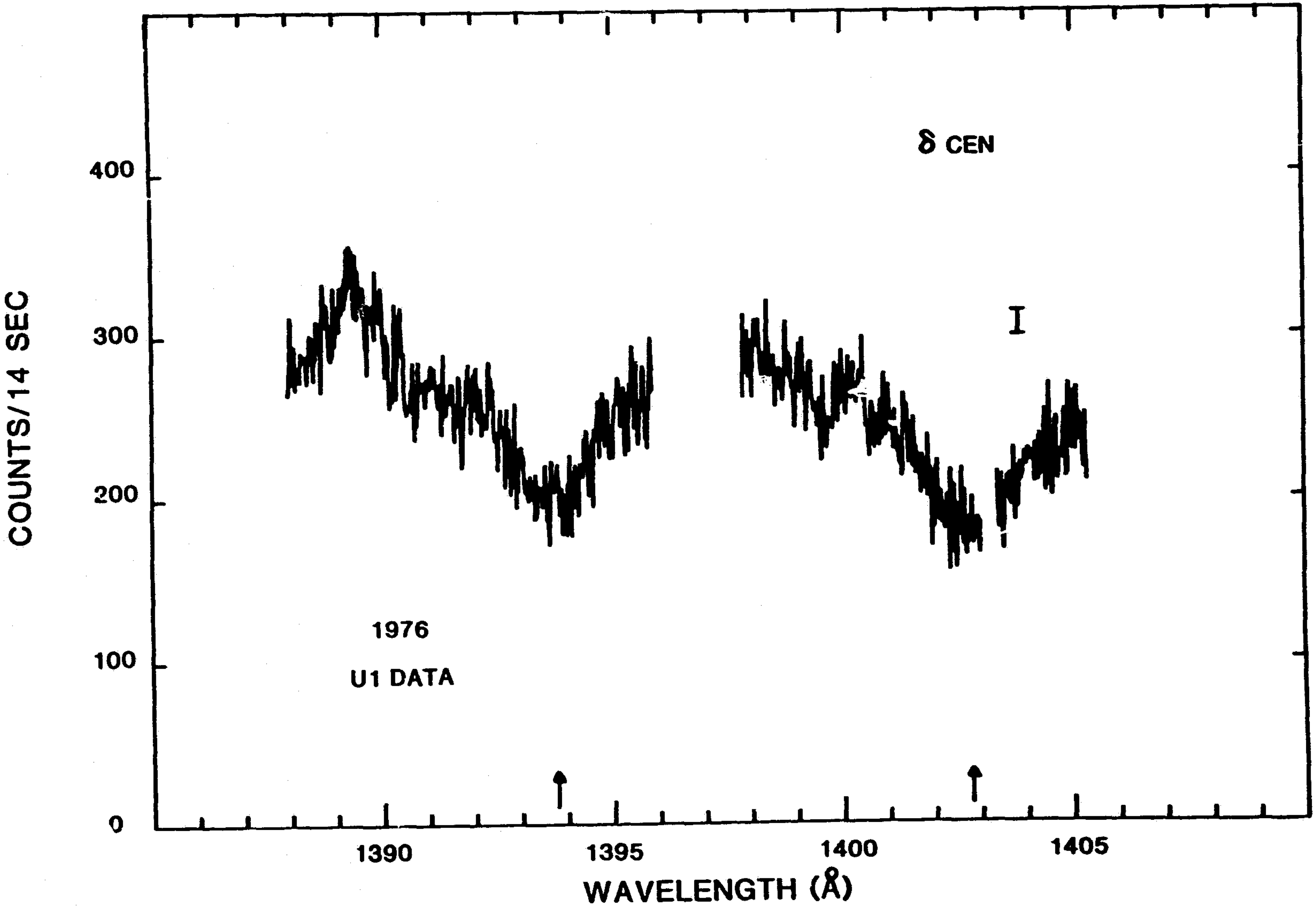
Fig. 2: The SiIV λ1400 doublet, observed at high resolution in 1976. Arrows at the bottom mark the rest positions of the lines. The 2σ photometric uncertainty is indicated.

Fig. 3: The fit to the 1976 SiIII profile. The solid line shows the observed profile, renormalized and plotted in terms of V/V_∞; the dashed line shows the adopted underlying photospheric profile; and the dots show the computed fit.

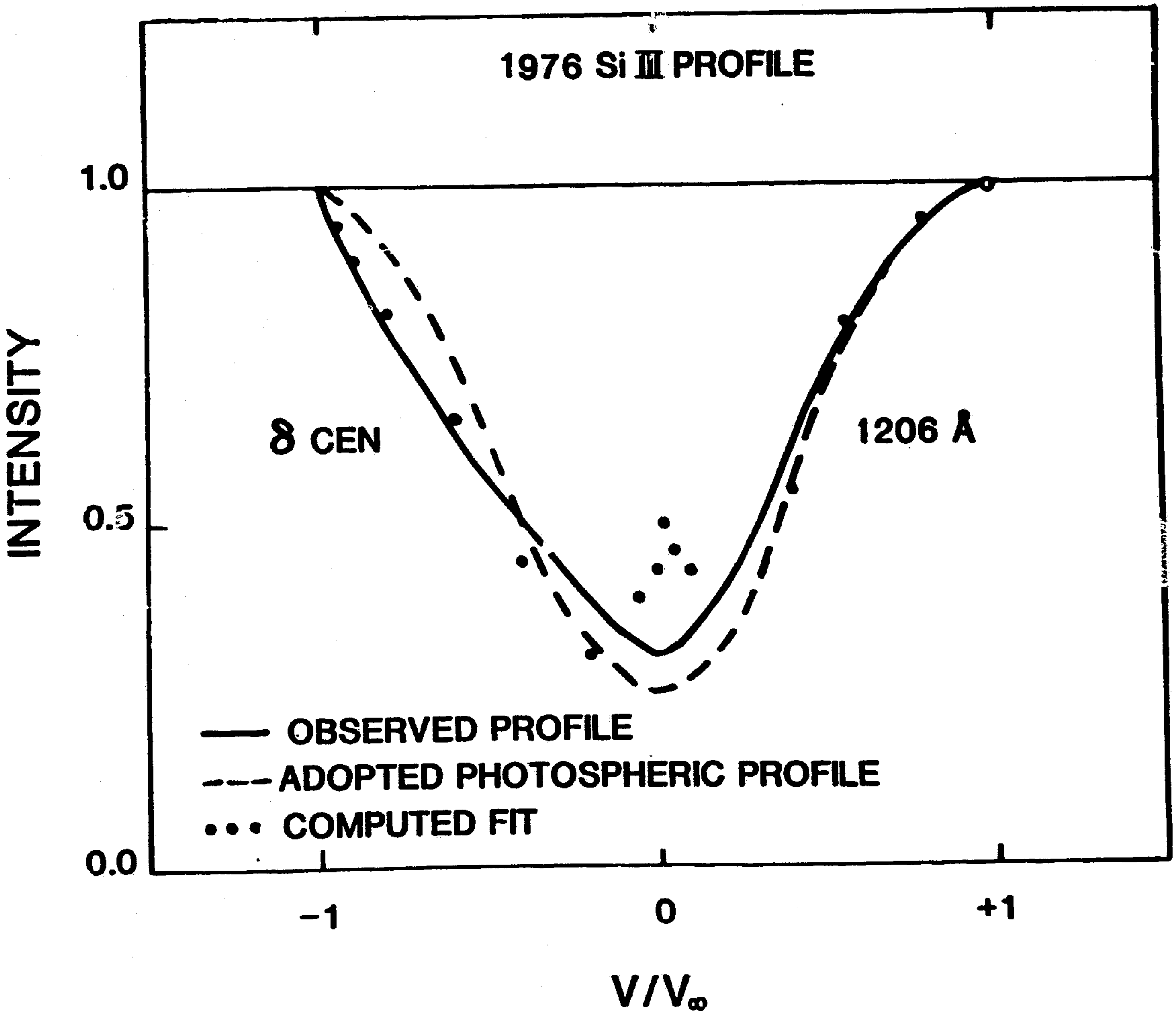
Fig. 4: The fit to the 1976 SiIV profiles. As in figure 3, the solid line represents the renormalized observational data, the dashed line the adopted photospheric profile, and the dots the best fit theoretical profile. No attempt was made to fit the weaker λ1402 line, since the wind was evidently too optically thin to produce a detectable asymmetry in this feature.

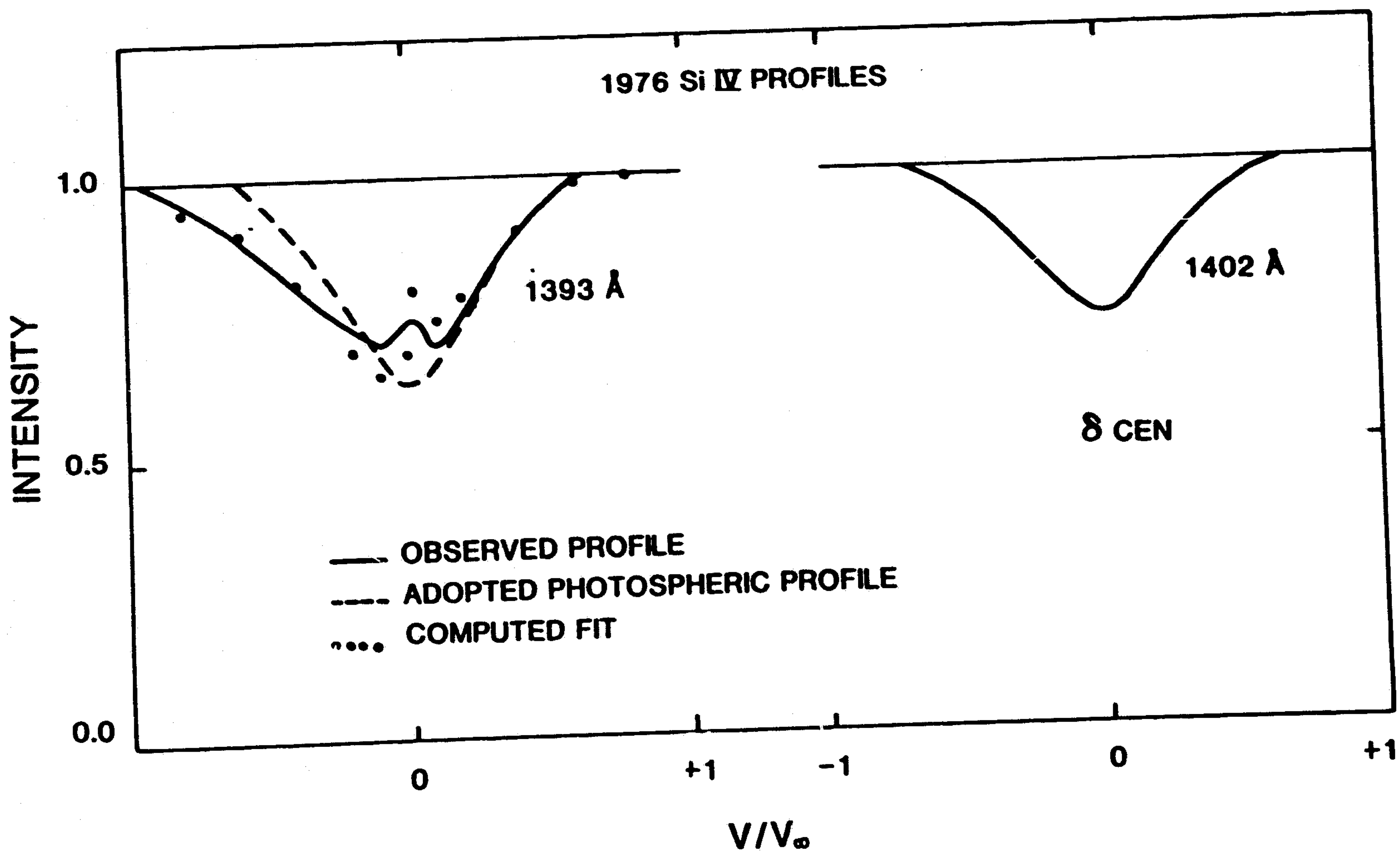
Fig. 5: The renormalized SiIII line in 1979. This shows no asymmetry towards the short-wavelength side, and hence led to an estimated upper limit on the SiIII outflow at the time of the observation.


δ CEN
COUNTS/14 SEC
5000
4000
3000
2000
1000
0.0
1976
1979
UZ DATA
1195
1200
1205
1210
WAVELENGTH (Å)



δ CEN
400
300
200
100
0
COUNTS/14 SEC
1976
U1 DATA
1390
1395
1400
1405
WAVELENGTH (Å)


1976 Si III PROFILE
1.0
0.5
0.0
INTENSITY
δ CEN
1206 Å
OBSERVED PROFILE
ADOPTED PHOTOSPHERIC PROFILE
COMPUTED FIT
−1
0
+1
V/V_∞


1976 Si IV PROFILES
1.0
0.5
0.0
INTENSITY
1393 Å
1402 Å
δ CEN
OBSERVED PROFILE
ADOPTED PHOTOSPHERIC PROFILE
COMPUTED FIT
0
+1
-1
0
+1
V/V∞