THE ASTROPHYSICAL JOURNAL, **286**:741–746, 1984 November 15

ROTATIONAL VELOCITIES OF LATER B TYPE AND A TYPE STARS AS DETERMINED FROM ULTRAVIOLET VERSUS VISUAL LINE PROFILES

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Received 1984 March 12; accepted 1984 June 6

ABSTRACT

Theoretical line profiles of the Si III 1299 and Fe II 2756 lines are computed for rotating B5–A7 model stars, and compared with observed profiles from *IUE* spectra to derive rotational velocities. Real differences in widths for ultraviolet as compared with visual line profiles exist in our sample of B type stars (but not for the A type rapidly rotating stars), although these are not as large as previously reported in the literature. Comparison with our theoretical line profiles gives rotational velocities that are in good agreement with visually determined $v \sin i$ values for the same stars, which suggests that our shape-distorted, gravity-darkened models are reasonable.

Subject headings: line profiles — stars: early-type — stars: rotation — ultraviolet: spectra

I. INTRODUCTION

Most recently, Marlborough (1982) reviewed and commented on the observed discrepancy between rotational velocities ($v \sin i$) of Be stars as estimated from widths of absorption lines in ultraviolet as compared with visual spectra. He pointed out that perhaps the first to find such an effect were Morton *et al.* (1972), who observed several ultraviolet absorption lines (primarily C II and C III) in the rapidly rotating star ζ Ophiuchi to be unusually narrow. They suggested that the narrow lines may be formed predominantly in the more slowly rotating polar regions or that they may originate in a shell that has a lower rotational velocity than the visual photosphere. Not long after, Heap (1975, 1976, 1977) found ultraviolet lines of C III, C IV, Si III, and Si IV in the spectrum of the shell star ζ Tauri to be relatively narrow, corresponding to a considerably lower rotational velocity than is estimated from visual line profiles.

Hutchings (1976*a*), in attempting to interpret Heap's (1975, 1976, 1977) observations, suggested also that in the far-ultraviolet spectrum of a star with a temperature gradient across its surface, the underlying continuum radiation may come preferentially from polar regions, where $v \sin i$ is expected to be small. He followed this up (Hutchings 1976*b*) with a quantitative analysis, finding that $v \sin i$ from an assumed line profile at 4500 Å may be twice that at 1000–1200 Å under certain conditions. Sonneborn and Collins (1977) performed a similar but more refined analysis by assuming a rotationally distorted star and including the temperature and gravity dependence of actual lines. Their results were qualitatively similar to those of Hutchings (1976*a*, *b*), but they found a smaller variation in rotational line broadening than that predicted by Hutchings or observed in ζ Tauri by Heap.

There are problems in both the observational and theoretical areas, however, as Marlborough (1982) pointed out. In light of more recent ultraviolet observations of a number of Be stars, Heap's (1975, 1976, 1977) assumptions that all strong resonance lines in the ultraviolet are photospheric and that the circumstellar envelope would not contribute to lines of high stages of ionization are probably not correct. On the theoretical side, not only rotational shape distortion and the temperature-gravity variations of the line profile across the gravity-darkened stellar disk should be included but also (in principle) the effects of stellar winds, nonradial pulsations, and (possibly) differential rotation. All of the latter may affect the line profiles, but cannot easily be taken into account at this time.

As Hutchings (1976*b*) and Sonneborn and Collins (1977) have pointed out, if rotational broadening is indeed a measurable function of wavelength, it becomes possible in principle to gain knowledge of global properties of rotating stars and, specifically, to determine v and i separately. Indeed, such determinations have been attempted in recent years by Hutchings and Stoeckley (1977), Hutchings, Nemec, and Cassidy (1979), and Ruusalepp (1982). Are these results meaningful, in view of the uncertain assumptions and difficulties that have been pointed out by Marlborough (1982)?

In the hope of clarifying the situation somewhat, we have calculated new theoretical line profiles based on line-blanketed rotating model atmospheres, which include shape distortion and gravity darkening, plus the latest atomic data, and compared our results with ultraviolet line profiles in a number of later B type and A type stars observed with the *IUE* satellite.

II. THE THEORETICAL ULTRAVIOLET LINE PROFILES

Atomic absorption lines chosen for rotational velocity analysis should be (1) as free as possible from broadening or profile-distorting mechanisms other than rotation and (2) sufficiently strong and isolated from other lines to allow accurate profiles to be determined. These conditions present difficulties in the ultraviolet, where the lines tend to be crowded together and the strongest lines are inevitably resonance lines. Resonance line profiles can indeed often be measured with high precision but are also likely to be distorted by stellar winds, in normal B type as well as in Be stars, even in the later B types (cf. Marlborough 1982; Snow 1982; Slettebak and Carpenter 1983).

We have chosen two moderately strong nonresonance lines, which we assume to be photospheric and broadened essentially by rotation in our sample of later B type and A type stars. For the spectral range B5–B8, we use the feature near 1299 Å which is produced by the Si III (UV4) lines at 1298.960 and 1298.891 Å. These lines have their lower states at about 6.5 eV and their

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higher energy levels near 16.1 eV. The neighboring Si III lines at 1297 and 1301 Å were included in our calculations but were judged to be too weak in the observed spectra to be useful in the analysis. Finding suitable lines for the A type stars is more difficult, since they have little energy shortward of 1500 Å and the spectra are crowded with lines. The best compromise we could make was the 2755.733 Å line of multiplet UV62 in the spectrum of Fe II. This line is fairly strong and relatively isolated, and is produced from a lower energy level at 0.98 eV to a higher level at 5.46 eV.

While not resonance lines, both the Si III λ1299 and Fe II λ2756 lines have lower levels that do not connect strongly to the ground state. In this sense, these are metastable levels, and absorption lines arising from them will be enhanced under low-density conditions, which will overpopulate these levels. Our lines, therefore, should not be used for determining rotational velocities of shell stars, since they would yield estimates too low relative to the values of $v \sin i$ measured from lines that originate solely in the photosphere.

Synthetic spectra of regions 6 Å wide, approximately centered on each of the two lines, were computed by using a modified version of the ATLAS6 (Kurucz 1979) model atmosphere code, the global intensity integration routines of Collins and Harrington (1966), and previously computed model atmospheres described in Slettebak, Kuzma, and Collins (1980). The physical parameters for these line-blanketed model atmospheres, which account for the shape distortion and gravity darkening caused by rapid rotation (resulting in the variation of the photospheric continuum brightness with latitude), are given in the latter reference. Data for the atomic lines included in each of these synthetic spectra were obtained by screening the million-line list of Kurucz (1979) to obtain data for the strongest lines in each wavelength region under the physical conditions expected in each model. Since data for the Si III (UV4) lines are not in the Kurucz (1979) compilation, their wavelengths, *gf*-values, and lower energy levels were taken from Wiese, Smith, and Miles (1969). The Kurucz data were screened by computing approximate line-center opacities corresponding to the temperatures, pressures, and densities near Rosseland optical depth $\tau \sim \frac{2}{3}$ in the midlatitude atmospheres ($\sim 45°$) of each stellar model. The 100–200 strongest lines were segregated by retaining for each model only those lines with central opacities greater than 9.0 cm^2 g^{-1}. The Fe II line and all the background lines were computed using the wavelengths, energy levels, and *gf*-values from the Kurucz tape, and the broadening approximations described by Kurucz (1979) and Kurucz and Furenlid (1979). The approximate damping constants are defined as follows:

$$\Gamma(\text{Stark}) \approx 1 \times 10^{-8} N_e n_{\text{eff}}^5 \,,$$

$$\Gamma(\text{radiative}) = \frac{2.223 \times 10^{15}}{\lambda^2} \quad (\lambda \text{ in Å}) \,,$$

$$\Gamma(\text{van der Waals}) = 2.8393081 \times 10^{-10}(N_{\text{H I}} + 0.42 N_{\text{He I}}) T^{0.3} R^2 \,,$$

where

$$R^2 = 2.5 n_{\text{eff}}^4 Z_{\text{eff}}^{-2}$$

and

$$n_{\text{eff}}^2 = \frac{13.595 Z_{\text{eff}}^2}{(\psi - E_{\text{lower level}} + 0.1)} \,,$$

with $N_{\text{H I}}$ and $N_{\text{He I}}$ the number densities of H I and He I, respectively, n_{eff} the effective quantum number, and Z_{eff} the ionization stage. The ratio A of the damping to the Doppler width is defined by

$$A = \frac{\Gamma(\text{radiative}) + \Gamma(\text{van der Waals}) + \Gamma(\text{Stark})}{4\pi \Delta\nu_{\text{D}}} \,.$$

Collisional broadening of the Si III (UV4) lines was approximated using the semiclassical results of Sahal-Bréchot and Segre (1971), for which

$$\Gamma_e = Q_1 N_e T^{Q_2} \,.$$

The values of $Q_1 = 3.5 \times 10^{-5}$ and $Q_2 = -0.3$ used in this equation were taken from Kamp (1976). The radiation damping constants, Γ(radiative), for Si III (UV4) were approximated by the upper-state Einstein A-values. A microturbulent velocity of 2 km s^{-1} was assumed for all lines in all of the models. These spectra were calculated with a wavelength spacing $\Delta\lambda = 0.05$ Å, with the central wavelength of each line rounded to the nearest grid point to ensure that each line is represented in the spectrum.

Since rotational broadening dominates the profiles of the lines being considered for the $v \sin i$ values of interest, our results should not be strongly dependent on the above assumptions.

Table 1 lists the rotational parameters of the models for which line profiles were computed, including values of the fractional angular velocity $w = \omega/\omega_c$ (where ω_c is the critical angular velocity for which the centrifugal force at the star's equator balances the gravitational force), the equatorial rotational velocity v, and the inclination angle i between the rotation axis and the line of sight. Si III line profiles were calculated for the B5–A0 models, and Fe II line profiles for the A0–A7 models. Figures 1–3 show selected examples of these theoretical line profiles. For each profile, the full width of the line at half-maximum depth (FWHM) was measured, with the continuum taken to be at a residual intensity of 1.00, and assumed to be an indicator of the rotational velocity of that model. The signal-to-noise ratio in the observed *IUE* line profiles does not justify the use of additional line-width parameters in the analysis, in our opinion. Calibration curves with the measured FWHMs as a function of $v \sin i$ were then plotted for each line and model. Figure 4 shows such calibration curves, as an example, for the Fe II λ2756 line in A5 models.

TABLE 1

ROTATIONAL PARAMETERS OF MODELS FOR WHICH LINE PROFILES WERE COMPUTED

		$v \sin i$ (km s^{-1}) AT EACH SPECTRAL TYPE					
w	i	B5	B7	A0	A2	A5	A7
0	...	0	0	0	0	0	0
0.5.........	0°	0		0	0	0	0
	30	70		64	66	65	65
	45	98		91	93	92	92
	60	120		111	114	112	113
	90	139		128	132	129	130
0.9.........	0	0	0	0	0	0	0
	30	145	136	134	138	135	135
	45	205	193	189	195	191	191
	60	251	236	232	239	234	234
	90	290	273	268	276	270	270

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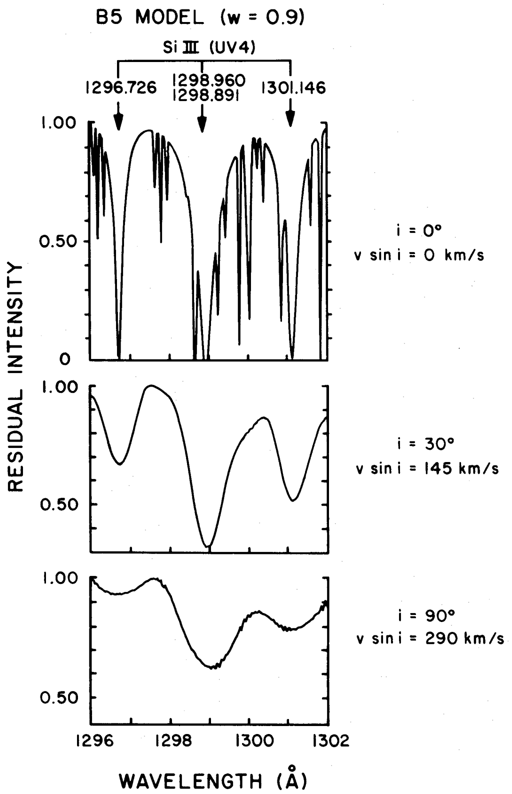

FIG. 1.—Theoretical line profiles of Si III multiplet UV4 lines in the wavelength range 1296–1302 Å, computed for B5 models with $w = 0.9$ and three values of the inclination i.

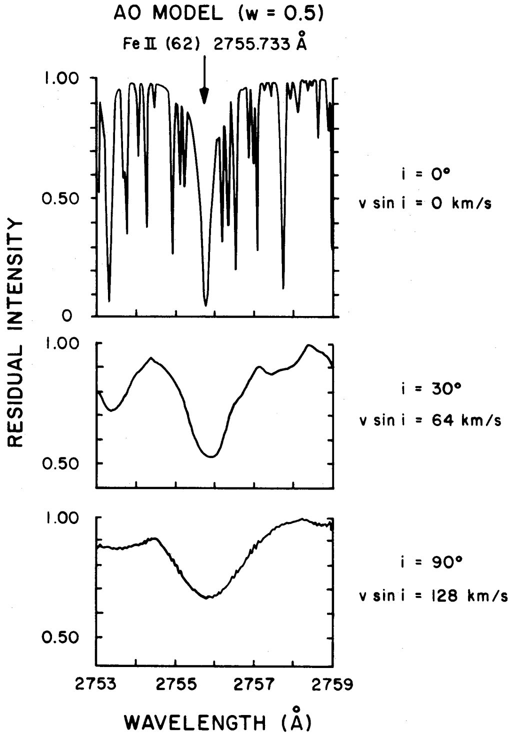

FIG. 2.—Theoretical line profiles of the Fe II multiplet UV62 line at 2755.733 Å, computed for A0 models with $w = 0.5$ and three values of the inclination i.

III. THE PROGRAM STARS

a) Spectral Types and Rotational Velocities from Visual Spectra

Since we already had *IUE* high-resolution spectra of a number of rapidly rotating standard stars of late B type and A type, we decided to concentrate on this spectral-type range. Our requirements were that the program stars have well-determined spectral types and rotational velocities (from visual spectra) and that high-resolution *IUE* spectra exist. We also tried to include stars with a range of rotational velocities in our sample, although highest priority was given to rapid rotators, where gravity-darkening effects are predicted to be the largest. Our 17 program stars are listed in Table 2. The spectral types and rotational velocities are from Slettebak *et al.* (1975), Slettebak (1982), and Slettebak and Carpenter (1983), or references therein. Details regarding how the visual $v \sin i$ values were determined, as well as error discussions, may be found in the aforementioned references. We estimate uncertainties of 10–15% of the values listed in Table 2.

b) The Observed Ultraviolet Line Profiles and Rotational Velocities

Table 3 lists the ultraviolet spectroscopic information for our program stars. All were observed with the *IUE* satellite in the high-dispersion mode, through the large aperture. We obtained eight of the spectra directly during the fifth and sixth observing episodes of the *IUE* (1982–1983) and the remaining nine from the *IUE* archives of the National Space Science Data Center (NSSDC). The star name and either the short-wavelength prime (SWP) or the long-wavelength redundant (LWR) camera image number are given in the first three columns of the table. Line widths (FWHM) were measured on the *IUE* spectra, corrected for the finite resolution of the *IUE* high-resolution camera, and compared with the line widths of the appropriate theoretical line profiles to obtain rotational velocities. Here an ambiguity enters, which is shown in Figure 4 and was discussed earlier by Collins (1974) and by Slettebak *et al.* (1975). These, as well as our present computations, show

TABLE 2

THE PROGRAM STARS

Star	HD	Spectral Type	Visual $v \sin i$ (km s^{-1})
ρ Aur	34759	B5 V	90
ψ^2 Aqr	219688	B5 V	280
β Psc	217891	B5 Ve	100
θ CrB	138749	B6 III(e)	320
ϕ And	6811	B6.5 IIIe	80
α Leo	87901	B7 V	280
η Tau	23630	B7 IIIe	140
β Cyg B	183914	B8 Ve	250
ι And	222173	B8 V	90
α Peg	218045	B9.5 III	120
δ Cyg	186882	B9.5 III	140
β Car	80007	A1 IV	125
α PsA	216956	A3 V	85
80 UMa	116842	A5 V	210
δ Cas	8358	A5 III–IV	100
α Oph	159561	A5 III	215
α Aql	187642	A7 V	225

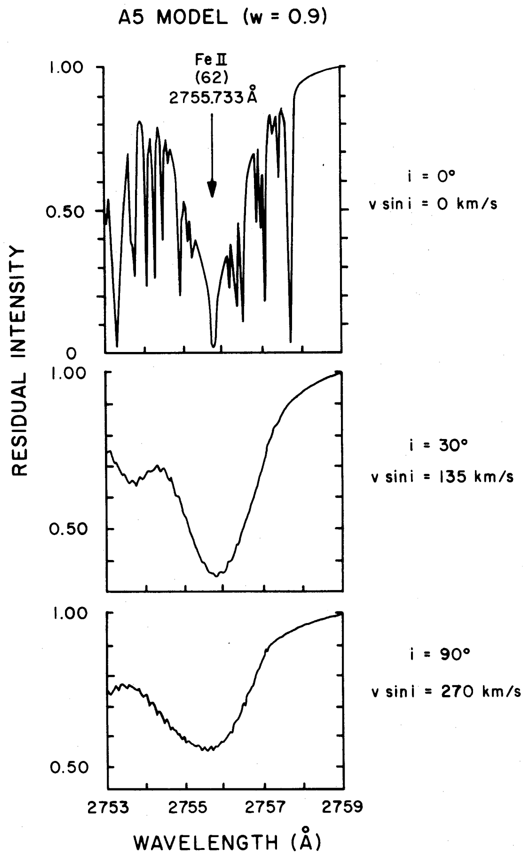

FIG. 3.—Theoretical line profiles of the Fe II multiplet UV62 line at 2755.733 Å, computed for A5 models with $w = 0.9$ and three values of the inclination i.

that the half-intensity width does not uniquely specify a rotational velocity for large values of w. We therefore took an average $v \sin i$ where both $w = 0.5$ and $w = 0.9$ models were applicable. This ambiguity introduces an uncertainty of 15–20% in our rotational velocities, listed in Table 3.

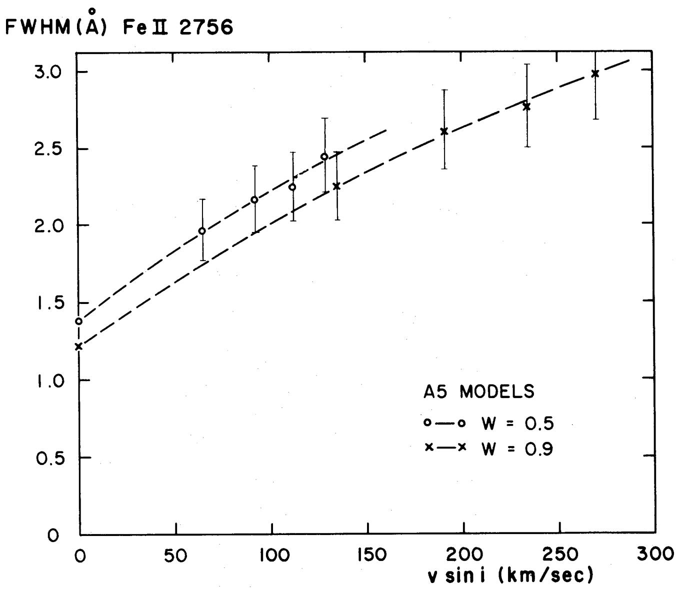

FIG. 4.—Line widths (FWHM) of theoretical line profiles of the Fe II λ2756 line in A5 model rotating stars, plotted against their rotational velocities, $v \sin i$. The circles and crosses represent computed values for $i = 0°, 30°, 45°, 60°$, and 90°; the dashed curves approximate the mean relations. Error bars of ±10%, which should represent maximum errors in view of uncertain continuum placements, are shown on the FWHM.

IV. RESULTS AND DISCUSSION

Figures 5 and 6 show the ultraviolet rotational velocities derived in this study from the Si III λ1299 and Fe II λ2756 lines, respectively, plotted against the visually determined $v \sin i$ values for the B5–B8 and B8–A7 program stars. The agreement between the values of $v \sin i$ is quite good in both cases, and we conclude that our models reasonably represent the observed line widths.

Sonneborn and Collins (1977) introduced the dimensionless parameter

$$Q = (\mathrm{FWHM}/\lambda)_1/(\mathrm{FWHM}/\lambda)_2$$

TABLE 3

ULTRAVIOLET DATA FOR THE PROGRAM STARS

Star	Camera Image No. SWP	Camera Image No. LWR	Si III λ1299 FWHM (Å)	Fe II λ2756 FWHM (Å)	UV $v \sin i$ (km s^{-1})
ρ Aur	10389	...	0.80	...	70
ψ² Aqr	10385	...	1.52	...	255
β Psc	10386	...	0.86	...	85
	15512	...	0.84	...	
θ CrB	14431	...	1.63	...	335
	16288	...	1.69	...	
φ And	10387	...	0.77	...	65
α Leo	10379	...	1.55	...	280
η Tau	10378	...	1.19	...	185
β Cyg B	5369	...	1.41	...	235
ι And	10376	...	0.82	...	85
		9057	...	1.31	80
α Peg	...	2386	...	2.23	145
δ Cyg	...	3041	...	2.11	140
β Car	...	2970	...	1.69	105
α PsA	...	11022	...	1.81	110
80 UMa	...	11712	...	2.57	190
δ Cas	...	11214	...	1.92	75
α Oph	...	5925	...	2.72	220
α Aql	...	2449	...	3.06	190
	...	3012	...	2.79	

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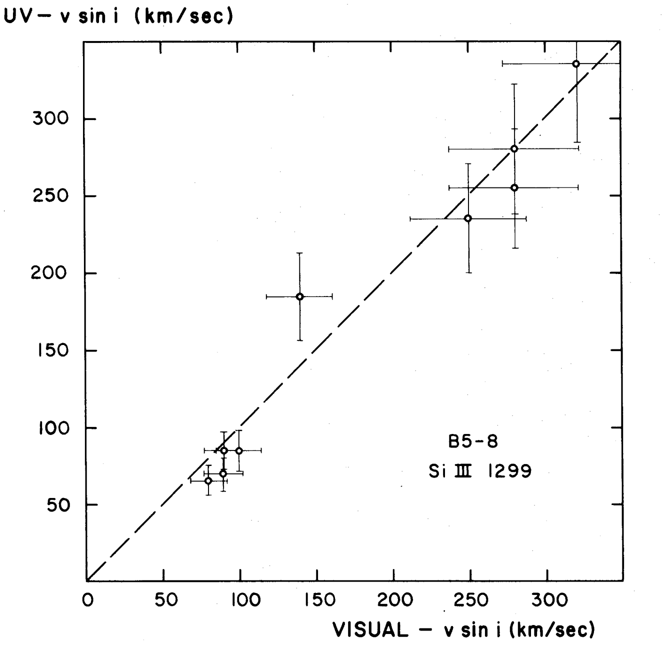

FIG. 5.—Visually determined rotational velocities ($v \sin i$) plotted against ultraviolet $v \sin i$ values (from Si III λ1299 line profiles) for the B5–B8 program stars. Error bars of ±15% have been placed on each point. The dashed line is a 45° line representing perfect agreement between the visual and ultraviolet $v \sin i$ values.

as a measure of the difference in rotational line broadening as a function of wavelength. We can compute Q from our ultraviolet computations in this paper and the visual line profiles calculated by Slettebak, Kuzma, and Collins (1980). This gives values of Q between 1.2 and 1.3 for B5 models with $w = 0.9$ and $i = 90°$, and agrees quite well with observed Q-values for the rapidly rotating B5–B7 stars in this study obtained from *IUE* spectra compared with He I λ4471 line widths for the same stars in Slettebak *et al.* (1975). This confirms that there is an effect of wavelength dependence on rotational line broadening in the B type stars, that it can be understood in terms of gravity-darkened models, but that it is probably not as large as previously thought.

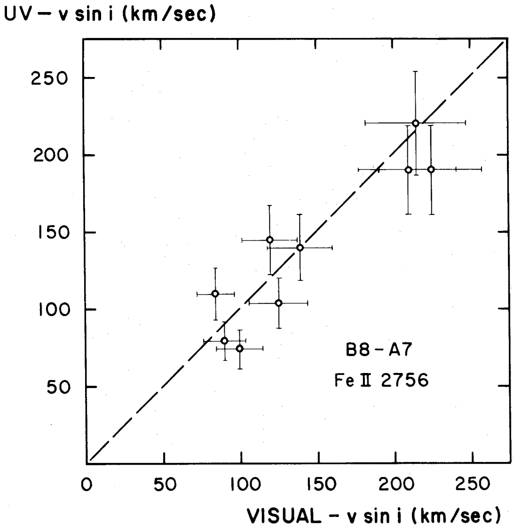

FIG. 6.—Visually determined rotational velocities ($v \sin i$) plotted against ultraviolet $v \sin i$ values (from Fe II λ2756 line profiles) for the B8–A7 program stars. Error bars of ±15% have been placed on each point. The dashed line is a 45° line representing perfect agreement between the visual and ultraviolet $v \sin i$ values.

Our Q-values for the A type stars in this study, on the other hand, are near unity, even for the most rapidly rotating objects. There are probably several reasons for this. (1) Even the most rapidly rotating A type stars appear to have fractional angular velocities that are not sufficiently close to unity to produce striking gravity-darkening effects. (2) Since the temperature difference between pole and equator in a rapidly rotating A type star is considerably less than in a rapidly rotating B type star, the gravity-darkening effects would be expected to be much smaller in any case. (3) The Fe II λ2756 line, which we chose for analysis in the A type spectra, is not so widely separated in wavelength from the Mg II λ4481 line usually chosen for visual $v \sin i$ determinations as to show a large wavelength-dependence effect.

Before our conclusions are taken too seriously by the reader, however, we feel it is necessary to comment on the accuracy of our observed and theoretical line profiles, as well as on some ambiguities in our analysis:

1. Placing the continuum for the observed line profiles is extremely uncertain. The high-resolution *IUE* spectra are obtained with an echelle spectrograph, and establishing continuity between echelle orders is difficult and not always successful. The problem of locating the continuum becomes worse when the line profiles to be measured are broad and other strong lines are in the vicinity. Also, for broad lines, a small error in continuum placement can result in a relatively large error in measured line width and, therefore, rotational velocity.

2. There is also some uncertainty in the location of the continuum for the theoretical line profiles, because of the restricted (by limitations on available computing time) wavelength extent of the spectra computations.

3. Figure 4 shows two problems introduced in using the FWHM versus $v \sin i$ calibration curves. The first, which we have already discussed, is that there is an essential ambiguity in using line widths to estimate rotational velocities for rapidly rotating stars, as is shown by the difference between the $w = 0.5$ and $w = 0.9$ curves. A second source of uncertainty arises from the flattening out of the FWHM versus $v \sin i$ curves for large values of $v \sin i$. A small difference in the measured line width thus leads to a large change in $v \sin i$.

The above discussion suggests that Figures 5 and 6 be regarded with some caution. The rather good correlation between the visually determined and ultraviolet $v \sin i$ values shown there is probably somewhat fortuitous. On the other hand, we feel that our analysis is sufficiently accurate to reveal striking differences, and these do not seem to be present.

Improvements in both theory and observation could be made in future work. As we have already stated, we feel that our theoretical treatment is sufficiently accurate to deal with this problem in view of the fact that rotational broadening dominates the line profiles. It would be advantageous, however, to compute synthetic spectra covering a larger wavelength range than was possible in this paper, to define the theoretical continuum more precisely. On the observational side, we anticipate that the quality of the line profiles obtained with the high-resolution spectrograph on the Space Telescope would permit a comparison of the entire line profile, rather than only the FWHMs used in this investigation, and therefore would lead to more accurate results. The choice of suitable lines for analysis presents real problems, since all strong, unblended ultraviolet lines seem to arise either from ground states or from metastable levels. We have chosen what we consider to be the best lines for our purpose, but higher resolution, less noisy data may permit the use of more suitable lines.

The many uncertainties inherent in analyses involving large rotational line broadening also suggest to us that attempts to separate v and i from line profiles must be carried out with great caution, and, indeed, it is not clear to us that such a separation is even feasible.

We can summarize our results as follows. Real differences in widths for ultraviolet versus visual line profiles in rapidly rotating B type stars exist, but these are not as large as previously reported in the literature. This discrepancy may be due in part to the earlier use of resonance and metastable lines that have substantial nonphotospheric contributions from winds and/or circumstellar envelopes. The good agreement we obtain between ultraviolet and visually determined rotational velocities suggests that our shape-distorted, gravity-darkened models are reasonable and may bear some resemblance to the real world.

We acknowledge very helpful conversations with George Collins. The *IUE* team at Goddard Space Flight Center was most cooperative, as was Wayne Warren of the National Space Science Data Center at Goddard. We thank also the Ohio State University Instruction and Research Computer Center for providing computer time and facilities, and NASA for support via grant NAG 5-52.

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