

CLASSICAL CEPHEID LUMINOSITIES FROM BINARY COMPANIONS

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ABSTRACT

Luminosities for the classical Cepheids η Aql, W Sgr, and SU Cas are determined from *International Ultraviolet Explorer* (IUE) spectra of their binary companions. Spectral types of the companions are determined from the spectra by comparison with the spectra of standard stars. The absolute magnitude inferred from these spectral types is used to determine the absolute magnitude of the Cepheid, either directly or from the magnitude difference between the two stars. For the temperature range of the companions (A0 V), distinctions of a quarter of a spectral subclass can be made in the comparison between the companions and standard stars. The absolute magnitudes for η Aql and W Sgr agree well with the period-luminosity-color relation of Feast and Walker. Random errors are estimated to be 0.3 mag. SU Cas, however, is overluminous for pulsation in the fundamental mode, implying that it is pulsating in an overtone.

Subject headings: stars: Cepheids — stars: luminosities — stars: pulsation — stars: spectral classification — stars: visual multiples — ultraviolet: spectra

1. INTRODUCTION

Classical Cepheids are primary distance indicators in extragalactic studies, as well as studies of Galactic structure. Cepheids belonging to open clusters or associations are used to calibrate the period-luminosity relation. A detailed discussion of the problems involved in determining the Cepheid period-luminosity relation is given by Feast & Walker (1987). One of the limitations of the current list of calibrators is illustrated by Feast & Walker, who include association Cepheids in their list, despite larger uncertainty in their membership, in order to extend the list of calibrators to periods longer than 21 days.

We discuss a new class of Cepheid calibrators below: binary Cepheids. A binary star having components with different temperatures can be “temperature-resolved,” that is, each component can be studied in detail in some wavelength region. Specifically, for cool evolved Cepheids with a hot main-sequence companion, the companion dominates the spectrum at short wavelengths, while the Cepheid dominates in the visible. When orbital motion is seen, the two stars are unquestionably at the same distance. This study is based on ultraviolet spectra of Cepheid binary systems taken by the *International Ultraviolet Explorer* (IUE) satellite. A spectral type is determined for the companion stars in the region from 1300 to 1600 Å, where they dominate the spectrum, and an absolute magnitude is inferred from that spectral type. The absolute magnitude of the Cepheid is determined from the absolute magnitude of the companion, either directly from the distance modulus of the companion or by determining the magnitude difference between the Cepheid and the companion.

Several studies using a similar method have appeared previously. Our technique is very similar to that of Parsons (1981), who used *Astronomical Netherlands Satellite* (ANS) and *TD-1* satellite data to study nonvariable supergiants. Böhm-Vitense (1985) combined IUE spectra with model atmospheres and a zero-age main-sequence (ZAMS) calibration to derive Cepheid absolute magnitudes. She matched spectra of the companions to Kurucz models to determine the temperature of the com-

panion. The fluxes of the companions at 1550 and 1950 Å were then combined with fluxes from Kurucz (1979) models and with radii inferred from a ZAMS calibration. The absolute magnitudes found in her study are half a magnitude fainter than those from the period-luminosity-color relation of Sandage & Tammann (1969) (which is very similar to the one adopted by Feast & Walker). Although we use some of the same data as Böhm-Vitense, the approach here is different in two respects. First, instead of model atmospheres and radii, we use IUE spectra of spectral standards and a spectral type–absolute magnitude calibration to infer distances. Second, in addition to distances obtained from the dereddened fluxes at 1800 Å, our fitting technique also determines the magnitude difference between the Cepheid and the companion, which is combined with the absolute magnitude of the companion to derive the Cepheid distance. Preliminary versions of this approach have been presented by Evans & Arellano-Ferro (1986). Arellano-Ferro & Madore (1986) used a parallel method, except that Kurucz atmospheres were used instead of observed spectra to compare with the Cepheid spectra.

In this first paper we discuss the method in detail, and illustrate the results for three Cepheids, η Aql, W Sgr, and SU Cas. These stars have companions of similar spectral type (approximately A0), which are cool enough to be at most only slightly evolved off the main sequence. Work is in progress to determine the luminosities from other binary Cepheids. For the rest of this section we discuss background information for the stars in this paper.

Eta Aql is one of the best-studied Cepheids. However, one of the surprises in early IUE observations was the discovery by Mariska, Doschek, & Feldman (1980) that it has a hot companion. Even the radius analysis of Balona (1977), which is more sensitive to hot companions than many other ground-based techniques, shows no indication of a companion. Orbital velocity motion is, of course, needed to prove that the two stars are gravitationally bound. Jacobsen & Wallerstein (1981) discuss velocity observations, which are available since 1898, though with gaps of typically 20 yr. They find marginal evidence for a small ($\leq 1 \text{ km s}^{-1}$) velocity increase over 80 yr. More recent observations (Jacobsen & Wallerstein 1981;

¹ IUE Guest Observer.

Lloyd Evans 1982) are sampled at smaller intervals, and do not show evidence of short-term orbital velocity variations. A long-period orbit with a low velocity amplitude is compatible with the velocity data, although as yet orbital velocity variations are not well established.

W Sgr also has a long series of velocity observations. Orbital motion is present, in addition to velocity changes during the pulsation cycle, but because the orbital velocity amplitude is small, the orbit has been difficult to determine. Recently, Babel et al. (1989) have added a series of CORAVEL velocity measurements and derived an orbit with a period of 1780 days and an orbital velocity semiamplitude of $2.35 \pm 0.47 \text{ km s}^{-1}$. Morgan et al. (1978) reported resolving a companion by speckle interferometry. A subsequent attempt by Bonneau et al. (1980), however, failed to confirm this result.

While there is nothing to suggest that η Aql and W Sgr are anything but typical Cepheids, SU Cas may be unusual. It is one of the shortest period Population I classical Cepheids, and has a low pulsation amplitude. These are thought likely to be characteristics of a star pulsating in the first overtone mode rather than the fundamental mode. This suggestion was quantified by Simon & Lee (1981), who Fourier-analyzed the light curves of 50 Cepheids. In several of their diagrams of Fourier coefficients as a function of period, SU Cas stands out from the normal trend. It would be extremely useful if Cepheids pulsating in a single overtone mode could be recognized from their Fourier coefficients so that their luminosities could be correctly derived from a period-luminosity-color relation. However, the Fourier result needs to be confirmed by an independent luminosity determination from cluster membership or a binary companion. Currently, SU Cas is the only tentatively identified overtone pulsator for which it is possible to determine an independent absolute magnitude.

Arguments about the pulsation mode of SU Cas have also been made from its radius, both combined with a temperature to produce a luminosity, and also in comparison with the radii of other Cepheids. Gieren (1982) summarizes both radius and temperature determinations. He concludes that SU Cas has a large radius for its period, and is also overluminous for a fundamental mode pulsator ($M_V = -3.65 \text{ mag}$) and hence is an overtone pulsator. The range of radii he lists ($19\text{--}44 R_\odot$) suggests the difficulty in determining a radius even though the data available are excellent. Unfortunately, because SU Cas has a fairly sinusoidal, small-amplitude light curve, classical Baade-Wesselink radii are uncertain. In addition, the formulation of Balona, which solves for the radius and surface brightness coefficient simultaneously, is particularly sensitive to the effects of a companion. The radius solution which Balona (1977) gives is inconsistent in that it has a large surface brightness-color coefficient (typical of a hot companion) but a large radius. (A hot companion results in an underestimate of the radius.) Unfortunately, a recent radius summary (Gieren, Barnes, & Moffett 1989) omits SU Cas, possibly because of these difficulties.

Radial velocities for SU Cas are available from several epochs, so a search for orbital velocity motion is possible. Gieren lists the five velocity sources, and concludes that there is no evidence for orbital velocity variation. The velocities are from intermediate dispersion data, typically 20 Å mm^{-1} . The graph of the velocity data provided by Niva & Schmidt (1979) shows that orbital motion with a semiamplitude larger than 1 km s^{-1} should be detected, but has not been. Intervals between observations are 1, 3, 7, 20, 40, and 60 yr. This restricts any

orbital motion to a very low amplitude, probably with a long period.

Another method has been used to investigate the distance of SU Cas, in addition to the luminosity determined here from its binary companion. SU Cas and a few B and A stars illuminate reflection nebulosity. Turner & Evans (1984) summarize previous studies of the group, which we will do briefly here. Racine (1968) found three late B stars and one M supergiant which illuminate nebulosity within 6° of SU Cas. Spectral classification (and, in the case of the M star, the Ca H and K reversal line width) indicated that all were at the same distance, which was consistent with a Cepheid fundamental mode absolute magnitude. Schmidt (1978) measured Racine's three B stars and two additional stars in the *uvby* system. He found the five stars to be located at three distances. Only the nearest two stars were consistent with fundamental pulsation for the Cepheid. Turner & Evans (1984) examined a longer list of stars, some illuminating dust clouds, some without any associated reflection nebulosity. (They include a useful schematic showing the locations of the stars and the dust clouds.) They used *UBV* photometry, spectral classification, H γ equivalent widths, and velocity information to distinguish between stars associated with SU Cas and nonmembers. They found two of Racine's B-A stars (and the M star) and two of Schmidt's stars to be associated with SU Cas. Obviously the region is complex. Unfortunately, the distance determination of the Cepheid depends on only a few stars. As an example of the difficulty in distinguishing stars which illuminate the nebula, we will discuss the two stars within 2° of SU Cas which illuminate the same dust cloud. From the list of candidates, Turner & Evans find two stars at the same distance as SU Cas, HD 17443, and HD 16893. HD 16893 is a spectroscopic binary, which may distort the luminosity determination. In addition, the new H γ equivalent width-absolute magnitude calibration by Millward & Walker (1985) yields a fainter absolute magnitude for HD 16893 (D. G. Turner 1990, private communication). This gives it a distance modulus $V_0 - M_V = 6.3 \text{ mag}$, making it nearer than the previous determination. Turner cautions, however (1990, private communication), that the spectral type of HD 16893 (A3 V) is cooler than the Millward-Walker calibration, which stops at A2 V, hence the absolute magnitude is only an extrapolated value. For HD 17443, on the other hand, the absolute magnitudes from spectral classification, H γ equivalent widths, and *uvby* photometry (using the calibration of Balona & Shobbrook 1984) all agree on a true distance modulus close to 7.0 mag. This corresponds to an absolute magnitude of -1.9 mag for the Cepheid, which is in agreement with fundamental pulsation. This discussion of the stars close to the SU Cas line of sight illustrates the possibility of confusion and the difficulty in distinguishing association members.

In the following sections, we discuss first the *IUE* observations and then two parameters needed to determine the Cepheid luminosities, reddening and the main-sequence absolute magnitude calibration. We then discuss the individual results for η Aql, W Sgr, and SU Cas. Finally, we investigate a secondary method of analysis using Kurucz model atmospheres. The results are compared with previous results from similar techniques, and luminosities from the period-luminosity-color relation.

2. OBSERVATIONS

Spectra from the long- and short-wavelength regions of the *IUE* satellite (LWR and LWP spectra from 2000 to 3300 Å;

TABLE 1A
CEPHEID OBSERVATIONS

Star	IUE Spectrum	HJD -2,400,000	Phase <i>P</i>	V_0 (mag)	$(B-V)_0$ (mag)	Observer
η Aql	SWP 6198	44,101.94	0.14	3.20	0.57	Doschek
	LWR 5364	44,102.02	0.15			Doschek
	SWP 6214	44,103.96	0.42	3.49	0.76	Doschek
	LWR 5387	44,103.93	0.42			Doschek
	SWP 6227	44,105.96	0.70	3.82	0.87	Doschek
	LWR 5403	44,106.00	0.70			Doschek
	SWP 6251	44,107.94	0.98	3.03	0.44	Doschek
	LWR 5423	44,108.00	0.98			Doschek
W Sgr	SWP 16483	45,035.50	0.68	4.62	0.88	Evans
	LWR 12725	45,035.49	0.68			Evans
	SWP 15303	44,898.94	0.70	4.63	0.83	Evans
	LWR 11814	44,898.93	0.70			Evans
SU Cas	SWP 16480	45,034.57	0.37	5.22	0.51	Evans
	LWR 12723	45,034.58	0.38			Evans

TABLE 1B
CORRECTED MAGNITUDES AND COLORS

Star	Phase	V_0 (mag)	$(B-V)_0$ (mag)	$(R-I)_0$ (mag)
η Aql	Mean	3.48	0.71	0.40
	0.98	3.11	0.46	0.32
	0.15	3.28	0.60	0.37
	0.42	3.57	0.79	0.42
	0.70	3.91	0.91	0.49
W Sgr	Mean	4.30	0.68	0.35
	0.68	4.70	0.92	0.42
	0.70	4.71	0.86	0.43
SU Cas	Mean	5.19	0.49	0.30
	0.38	5.27	0.54	0.33

TABLE 1C
STANDARD STAR OBSERVATIONS

Spectral Type	Star	Image	V_0 (mag)	$(B-V)$ (mag)	$E(B-V)$ (mag)	M_V (mag)	Observer
B7 V	HD 29335	LWR 12159	5.25	-0.14	0.02	0.20	Imhoff
	49 Eri	SWP 15788					Imhoff
B8 V	HD 23324	LWR 7079	5.52	-0.11	0.04	0.52	Adelman
	18 Tau	SWP 8148					Adelman
B9 V	HD 38899	LWR 12875	4.91	-0.07	0.00	0.86	Adelman
	134 Tau	SWP 16639					Adelman
B9.5 V	HD 193432	LWR 12874	4.76	-0.05	0.00	1.06	Adelman
	ν Cap	SWP 16850					Ake
A0 V	HD 103287	LWR 7124	2.41	-0.01	0.01	1.29	Wu
	γ UMa	SWP 8198					Wu
A1 V	HD 166205	LWR 7863	4.36	0.02	0.00	1.53	Wu
	δ UMi	SWP 9132					Wu

SWP spectra from 1200 to 2000 Å) are used in this analysis. The spectra of η Aql, W Sgr, and SU Cas which have been used are listed in Table 1A, together with the Julian Date and phases of the observations. All spectra were taken in the low-dispersion mode, and were taken through the large aperture, except for the η Aql spectra discussed below. The phases have been computed from the periods listed in Table 2A, except that

for η Aql the quadratic form of the period was used:

$$JD_{\max} = 2,442,794.773 + 7.176735E + 2.18 \times 10^{-8}E^2,$$

also taken from Szabados (1980). Table 1A also lists V_0 and $(B-V)_0$, taken from the light curves of Moffett & Barnes (1984), adjusted to the period in Table 2B where necessary. $E(B-V)$ were taken from Dean, Warren, & Cousins (1978).

TABLE 2A
DATA FOR THE CEPHEIDS

Star	Period (days)	Epoch JD - 2,400,000	Source
η Aql	7.176735	42,794.773	Szabados 1980
SU Cas	1.949322	41,645.910	Szabados 1977
W Sgr	7.594904	43,374.622	Szabados 1989

TABLE 2B
REDDENING FOR THE CEPHEIDS

Star (1)	$E(B-V)$ DWC (mag) (2)	$E(B-V)$ Corrected (mag) (3)	$E(B-V)$ OB (mag) (4)
η Aql	0.14	0.12	0.14
SU Cas	0.24	0.23	0.26
W Sgr	0.13	0.11	0.12

Spectra of nonvariable supergiants with the same temperature as the Cepheids are used for comparison. The images selected and other relevant information are given in Evans et al. (1990, hereafter EWST). $E(B-V)$ values are taken from Parsons & Bell (1975), except for ν Aql, as discussed by EWST.

Spectra of main-sequence standard stars (Table 1C) are taken from the *IUE* spectral atlas (Wu et al. 1983). V , $B-V$, and $E(B-V)$ were taken from the atlas, except that negative reddenings are set to zero. Many of these stars are MK standard stars. Absolute magnitudes in Table 1C are discussed in § 5.

3. REDUCTIONS

The reductions were done at the Goddard Regional Data Analysis Facility (RDAF) or with the slightly modified version at the University of Toronto or the experimental SUN version at ISTS (York University). Reductions include corrections for camera temperature, the short-wavelength prime camera (SWP) intensity transfer function (ITF) flat-field error, camera rise time, exposure time quantization, and the correct aperture size. Reseaux and geocoronal Ly α have been removed by interpolation. Long-wavelength prime camera (LWP) fluxes have been converted to the new calibration (Oliversen 1988). The sensitivity degradation in the LWR camera, which is the largest for any camera, is automatically removed in the reductions. All the SWP images used were taken within the first few years of *IUE*, and the sensitivity degradation in the SWP exposures is at most a few percent (Garhart & Teays 1989) and has not been removed.

4. REDDENING

There are two aspects of the reductions which require further comment. First, observed magnitudes and colors (Table 1A) actually include a small contribution from the companion. Once we have determined the color and magnitude of the companion from the ultraviolet spectra (§§ 6 and 7), it is easy to correct the magnitudes and colors at the time of the *IUE* observations for the effect of the companions. Details of the corrections are provided by Evans (1990a). The corrected colors and magnitudes of the Cepheid alone are listed in Table 1B. Furthermore, since $E(B-V)$ is calculated from color-color relations, it also needs to be recalculated for the corrected

colors. Dean, Warren, & Cousins (1978), hereafter DWC) provide relations from which this can be easily done. Table 2B lists both the original reddening from DWC and also the corrected reddening. We actually calculated the corrections to the $E(B-V)$ found by DWC from Johnson system photometry (col. [9] in their Table 1). These corrections were then added to their adopted mean reddening (col. [14] in their Table 1). In this way, the reddening in Table 2B, column (3), is on the DWC system.

Second, the dereddening process requires a couple of steps. The $E(B-V)$ reddening for the Cepheid is a broad-band reddening. On the other hand, the *IUE* dereddening procedure uses the extinction law of Savage & Mathis (1979), applied monochromatically. Since the reddening law was determined for O and B stars, the observed Cepheid broad-band reddening must be corrected to the $B-V$ which an OB star would have before applying the dereddening curve. Buser (1978) has investigated this, using synthesized colors for energy distributions of various temperatures and log g . We use his results for modest reddening to estimate that $E(B-V)_{OB} = E(B-V)_{Cep}/0.90$ (Table 2B, col. [4]). This OB reddening (Table 2B) is then used to deredden the *IUE* spectra, using an A_λ value for each wavelength point interpolated between the tabulated values. Buser also provides values of $R = A_V/E(B-V)$ as a function of reddening. These are used to estimate that for a G0 Ib star with modest reddening, $R = 3.46$. This value was used with the Cepheid broad-band $E(B-V)$ to calculate V_0 (Table 1B).

Determining the ultraviolet extinction correctly is very important to the absolute magnitudes determined for the Cepheids. We must adopt a standard reddening curve, to be combined with the $E(B-V)$ of the Cepheid. It is important to assess what uncertainties result from deviations from the standard reddening law. There is no doubt that variations in the reddening law exist in the ultraviolet. However, the situation for the ultraviolet observations used here is not as uncertain as might be imagined. Many extinction curves which are termed peculiar have either a 2175 Å bump of an unusual size or an unusual "far-UV rise" short of 1600 Å. Since the parameter needed for the luminosity determination is the flux of the companion near 1600 Å, neither of the two regions most typically found to deviate from the standard relation has much influence on the luminosity. As discussed below, even extinction differences between 1600 and 1300 Å have only mild effects on the determination of the spectral type of the companion. In addition, most peculiarities have been found not in the diffuse interstellar medium but in denser regions and turbulent interstellar regions, or in circumstellar dust (Mathis 1987). Eta Aql and W Sgr are lightly reddened field stars. SU Cas is in a more complicated region. However, as a similar example, Witt, Bohlin, & Stecher (1981) have studied the extinction curve of HD 23512 in the Pleiades. Despite a small 2175 Å bump, $A(1600-V)$ matches the standard curve relatively well.

In order to make an estimate of the uncertainty in the extinction ratio $A(1600)/E(B-V)$, we use the compilation of Savage et al. (1985). They selected observations of 1415 stars with spectral types B7 or earlier from *ANS* data. Extinction in the various observed bands was derived from comparison with unreddened colors of stars of similar spectral types. The most useful result for our purposes is shown in their Figure 4l, where they plot $E(1500-V)$ versus $E(B-V)$. The correlation is good, although the scatter increases with $E(B-V)$. From this figure, we estimate that for a reddening larger than any discussed here, $E(B-V) = 0.5$ mag, the scatter in $E(1500-V)$ has a

standard deviation estimated to be ± 0.3 mag. Only a very few points fall at extreme values of $E(1500 - V)$. The rms deviation for points with $E(B - V) = 0.1$ mag is estimated to be half this size. This is a generous estimate of the uncertainties due to variations in the reddening law because some of the scatter comes from spectral type mismatch. They find that a mismatch of one spectral class results in an error of 0.32 mag in $E(1500 - V)$. Furthermore, although they have discarded peculiar objects, the stars used are not necessarily confined to the diffuse interstellar medium, but may come from more unusual regions as well.

We can also estimate the uncertainty in the ultraviolet flux from the extinction study of Fitzpatrick & Massa (1988). They parameterize extinction curves by three components: a linear function of λ^{-1} , the 2175 Å bump, and the far-ultraviolet rise ($\lambda \leq 1700$ Å). It is the uncertainty in $E(1700 - V)/E(B - V)$ that we want to assess, which is determined by the linear terms

$$\frac{E(\lambda - V)}{E(B - V)} = c_1 + c_2 \lambda^{-1}.$$

They deliberately examined extinction curves from diverse environments: diffuse regions, dense regions, and regions with recent star formation. Since we are working with field stars, we have used the data from their Table 1 for regions they term diffuse regions. We have computed the standard deviation of the linear term at 1700 Å using the coefficients c_1 and c_2 :

$$\sigma \frac{E(1700 - V)}{E(B - V)} = 0.36.$$

For $E(B - V) = 0.50$ mag, the uncertainty in $E(1700 - V)$ due to the uncertainty in the reddening laws is 0.18 mag. For the largest reddening we are considering here (0.3 mag for SU Cas), the uncertainty in $E(1700 - V)$ is 0.11 mag.

Thus, although it is important to assess the uncertainty of the reddening law in the ultraviolet in determining the uncertainty in the absolute magnitude determined from binary companions, it is not larger than other sources of error (§ 9). The $E(B - V)$ of SU Cas is discussed further below (§ 7 and Table 5).

5. ZERO-AGE MAIN SEQUENCE

In order to determine the luminosity of the Cepheid, a luminosity needs to be assigned to the companion. We have adopted the same zero-age main-sequence calibration as used by Feast & Walker (1987), the Pleiades main sequence from Turner (1976, 1979) adjusted to a Pleiades distance modulus of 5.57 mag (van Leeuwen 1983). This is equivalent to a Hyades distance modulus of 3.27 mag, which is then corrected by 0.22 mag because of the high metallicity of the Hyades. This $M_V - (B - V)_0$ sequence is nearly identical to the ZAMS relation given by Schmidt-Kaler (1982), so we have used the spectral types he provides to link our standard stars to absolute magnitudes. The absolute magnitudes in Table 1C are taken from the spectral type–absolute magnitude calibration.

Are ZAMS absolute magnitudes appropriate for Cepheid companions? We must use evolutionary tracks to check how much the luminosity of the companion has increased relative to the ZAMS. There are still unanswered questions about the evolutionary tracks of evolved stars. We present here a quantitative estimate based on one scenario, with the main result that the evolutionary changes in the companions are very small. For η Aql and W Sgr, the Cepheids are approximately $7 M_\odot$, using the evolutionary tracks of Becker, Iben, & Tuggle (1977).

Their Cepheid mass-luminosity relation for solar composition gives a mass very close to that observed for SU Cyg (Evans & Bolton, 1990). The hottest of the companions (see below) is a B9.5 V star, which would have a mass of $2.4 M_\odot$ (Harmanec 1988). We have used the models of Maeder & Meynet (1988) to estimate the age of a $7 M_\odot$ Cepheid, and from that the luminosity and temperature of a $2.5 M_\odot$ star of that age. The increase in luminosity for the main-sequence star at the age of the Cepheid is 0.04 mag. The mass of SU Cas is approximately $5 M_\odot$, and the luminosity change in its companion is about twice that for the companions of η Aql and W Sgr. The luminosity change for the SU Cas companion has been included in the calculation of the Cepheid luminosity; for η Aql and W Sgr, the luminosity change has been ignored. The change in temperature is less than one of our spectral type intervals (see below, § 6). If the Cepheid mass is smaller than the value above, the luminosity increase of the companion would, of course, be larger.

To check that we can accurately infer the V -magnitude of the companion from the ultraviolet spectral type, we have computed $V - m(1600)$ colors of the main-sequence stars from Table 1C which we use in the next section to determine the spectral type of the companion. This is done using the calibration 3.64×10^{-9} ergs $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ for a star with $V = 0.00$ mag. Both these colors and the absolute magnitude at 1600 Å are smooth functions of $(B - V)_0$. This means that we can use the spectral type of the companion from the ultraviolet to infer both the V -magnitude of the companion and its absolute magnitude.

Although we have been able to construct a consistent calibration as a function of color, we are working on a more direct calibration. Observations have been obtained (with R. Pitts and C. Imhoff) of stars with the relevant range of spectral types in the Pleiades, the α Per cluster, and NGC 2244. From these we will be able to construct directly a plot of absolute magnitude at 1600 Å and investigate the dispersion within the main sequence and the effects of rotation. We consider this an important check on the adopted calibration.

6. η AQUILAE

We begin with an investigation of η Aql because several spectra are available covering its range of light and temperature. Although the *IUE* archive contains additional spectra of η Aql, many of these have large areas which are overexposed. The set used here (Table 1A) are all within a single cycle and well exposed. The best exposures for the SWP are often the small-aperture exposures. In this case, the ratio of the large to the small aperture from 1300 to 1600 Å (where the large aperture was not overexposed) is used to set the absolute flux level of the small-aperture spectra. The ratio of the flux in the small aperture to the flux in the large aperture is 0.303 for SWP 6198, 0.209 for SWP 6214, and 0.271 for SWP 6227. The spectrum of the companion is very similar on all four spectra.

The spectrum of η Aql at wavelengths shorter than 1700 Å is used to determine the spectral type of the companion, since the contribution of the Cepheid is insignificant in this region at all phases. The spectra of main-sequence spectral type standards are scaled, using the mean flux between 1400 and 1600 Å, and compared with the η Aql spectra to determine the spectral type of the companion based on the flux distribution. Spectra of spectral types intermediate between the observed standards were synthesized by averaging the spectra of two adjacent spectral types (scaled to match the η Aql companion). In the

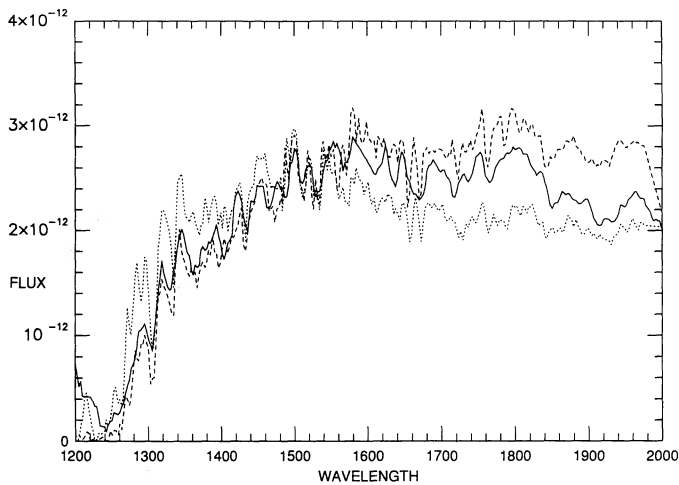


FIG. 1a

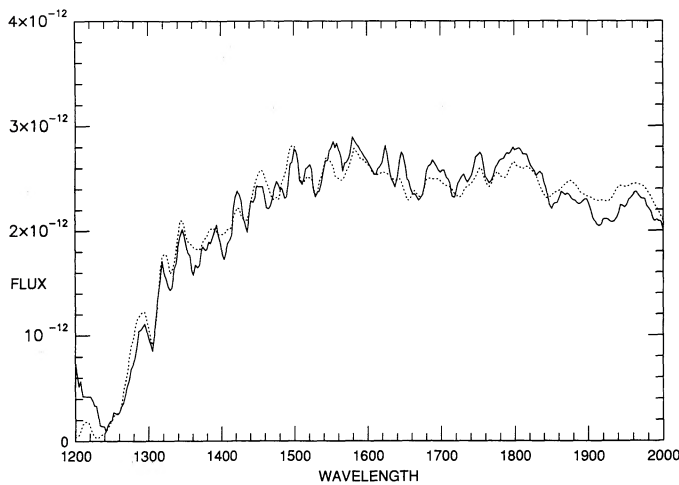


FIG. 1b

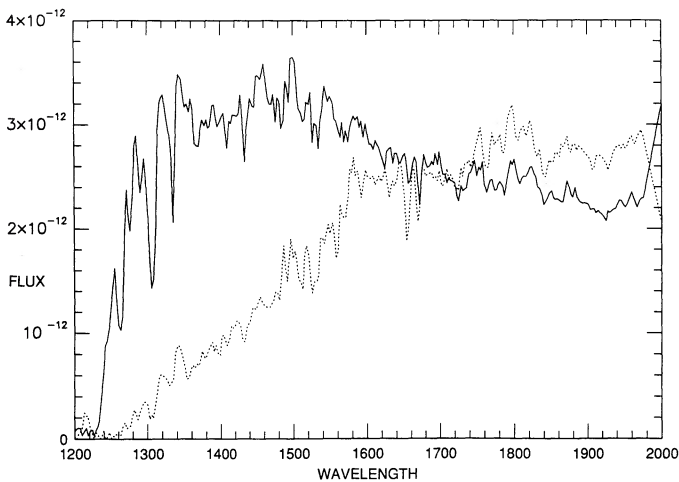


FIG. 1c

FIG. 1.—Short-wavelength spectra. Fluxes in all figures are in $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$; wavelengths are in angstroms. (a) The spectrum of η Aql B (at phase 0.70P of the Cepheid) is shown by the solid line. Scaled spectra of a B9.5 V star and an A0 V star are shown by short- and long-dashed lines, respectively. (b) The spectrum of eta Aql B (solid line) is compared with the B9.8 V spectrum (dashed line) formed from the mean of the two comparison spectra in (a). (c) B9 V (solid line) and A1 V (dashed line) spectra are compared.

temperature range of the Cepheid companions, experience shows that differences of a quarter of a spectral subclass can be differentiated. As a demonstration, the spectrum of the η Aql companion is classified as B9.8 V, the average of a B9.5 V spectrum (ν Cap) and an A0 V spectrum (γ UMa). No attempt is made to assign a luminosity class from the *IUE* spectra. Since the Cepheids are significantly more massive than the companions discussed here, the companions are assumed to be luminosity class V stars, although a small amount of evolution off the main sequence is sometimes allowed in assigning absolute magnitudes to the companions, as discussed above. Figure 1 shows the SWP spectrum for η Aql for Cepheid phase 0.70, when the Cepheid is coolest and faintest. The Cepheid makes an insignificant contribution at this phase, even at 1900 Å. Eta Aql B lies between a B9.5 V star and an A0 V star (Fig. 1a), and is well matched by the average of the two, designated B9.8 V (Fig. 1b).

Figure 1c demonstrates that the variation between B9 V (134 Tau) and A1 V (δ UMi) is dramatic in this wavelength region. It is important to stress this point, because of the question whether an error in the reddening can cause an error in the spectral type. Even though a small error in the reddening results in a large difference in the dereddened flux in this region, it has only a marginal effect on the flux distribution as a function of wavelength. Because the flux at 1400 Å (as compared with the flux at 1600 Å) changes so rapidly as a function of spectral type, a small error in reddening does not mimic changes in spectral type.

The V_0 magnitude of the companion is determined in the process, through the scaling factors needed to match the standard stars to η Aql B. In the case of companions which are best matched by the synthesized intermediate spectral types, the scale factor for each standard star plus its V_0 magnitude leads to a V_0 magnitude for the companion, and these values are then averaged.

The spectral type of the companion, and its absolute magnitude (inferred from the spectral type as discussed in § 5, including the evolutionary correction for SU Cas B), are listed in Table 3, as is the V_0 magnitude of the companion. This $M_V(\text{comp})$ and $V_0(\text{comp})$ provide the absolute magnitude of the Cepheid, $M_V(\text{Cep})$, which is also listed in Table 3. We assume that the spectral flux distribution of a ZAMS A0 V star, for example, is the same as the flux distribution of an A0 V main-sequence star in the MK system. We do, however, use a luminosity appropriate to the ZAMS.

There is another way to use *IUE* spectra to determine absolute magnitudes for Cepheids. If, in addition to matching the SWP spectrum with the spectrum of a main-sequence standard star, the Cepheid spectrum is matched with that of a nonvariable supergiant, the magnitude difference between the Cepheid and the companion can be determined. The absolute magnitude of the Cepheid is determined by using the absolute magni-

TABLE 3
ABSOLUTE MAGNITUDES: SHORT-WAVELENGTH SPECTRA

Star	Spectral Type of Companion	$V_0(\text{comp})$ (mag)	$M_V(\text{comp})$ (mag)	$M_V(\text{Cep})$ (mag)
η Aql	B9.8 V	8.39	1.17	-3.74
SU Cas	B9.5 V	9.41	0.98	-3.24, $E(B-V) = 0.23$
		9.08		-3.04, $E(B-V) = 0.27$
W Sgr	A0 V	9.57	1.29	-3.98

tude of the companion and combining it with the magnitude difference between the two stars. A correction must be added to the observed V -magnitude of the Cepheid at the time of observation so that the final result refers to mean light, $\langle V \rangle$. This method has the disadvantage of introducing an additional comparison star into the process. However, it is less sensitive to errors in reddening than determining the luminosity directly from the flux at 1500 Å. Using the Savage & Mathis (1979) reddening law, an error of 0.01 mag in $E(B - V)$ results in an error of 0.08 mag in an absolute magnitude determined from the companion flux at 1500 Å.

To determine the reddening sensitivity of the absolute magnitude from the second method, we have used an η Aql spectrum arbitrarily dereddened by $E(B - V)$ 0.04 mag, 0.14 mag, and 0.24 mag. In this case, a change in $E(B - V)$ of 0.01 mag results in a change of 0.048 mag in M_V . This is due to two causes. First, there is a difference in wavelength, and hence reddening, between the region where the companion is matched to a standard spectrum (1500 Å) and the region where the Cepheid is matched to a supergiant standard (2500–3000 Å). Second, as the $E(B - V)$ is varied, so is the synthesized supergiant which is matched to the Cepheid (see below). The difference in spectral slope between V and 2800 Å for supergiants of different colors accounts for part of the sensitivity of the absolute magnitudes to reddening.

The steps in the process are first to create a B9.8 V spectrum for the long-wavelength region, using the same standard stars and scaling as for the short-wavelength region. This spectrum is subtracted from the long-wavelength η Aql spectrum to recover the Cepheid spectrum. The Cepheid spectrum is then matched to scaled supergiant spectra bracketing it in $(B - V)_0$ in the wavelength region 2900–3000 Å. A supergiant spectrum is then synthesized by interpolating between these two spectra to match the Cepheid in $(B - V)_0$. An expanded discussion of the process is provided by EWST (1990). The observed spectrum, the spectra of the individual components (as modeled by standard stars), and the composite spectrum made by summing the two components are presented in Figure 2a. It shows that the observed η Aql spectrum matches this composite closely in the long-wavelength region as well as in the short-wavelength region (Fig. 1). Figure 2a shows the spectrum at Cepheid phase 0.70, near minimum light. For comparison, Figure 2b shows the same spectra for Cepheid phase 0.98, near maximum light. The relative proportions of the Cepheid and the companion for the extremes of the Cepheid pulsation range are illustrated in Figure 2.

The results for this second long- and short-wavelength method are listed in Table 4. Because an absolute magnitude is

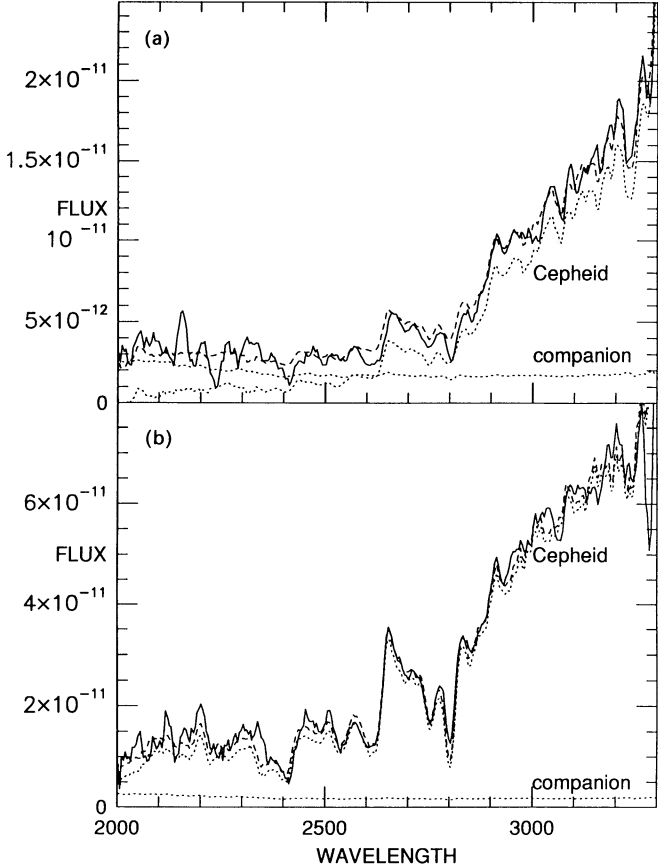


FIG. 2.—Long-wavelength spectra of η Aql. The observed spectra of the Cepheid plus companion are shown with solid lines. The short-dashed lines (labeled) show the companion (*bottom*) and Cepheid as modeled by standard star spectra (see text). The long-dashed line, which frequently disappears behind the observed spectrum, represents the sum of the short-dashed line spectra. (a) Cepheid at phase 0.70P (minimum light). (b) Cepheid at phase 0.98P (maximum light).

determined for each phase, it is possible to calculate an internal standard deviation from Table 4, which is 0.07 mag.

For comparison, absolute magnitudes were determined in the same way using spectra of the single Cepheid, δ Cep, instead of supergiants to model the Cepheid in the η Aql system. Four δ Cep spectra were used, which span its temperature range. The images are listed in EWST (1990). These absolute magnitudes are also listed in Table 4. One limitation of this approach is clear from Table 4: δ Cep can only be used as a comparison for some of the η Aql observations, since it does not become as cool as the redder phases of η Aql. The mean absolute magnitude of η Aql is 0.16 mag fainter when δ Cep is used than when the supergiants are used. This difference represents the most important limitation to the accuracy of the absolute magnitudes from combined long- and short-wavelength spectra. However, we understand the systematics of the difference, as illustrated by Figure 3.

Figure 3 shows the visual–ultraviolet color computed from the ultraviolet fluxes from 2900 to 3000 Å and V (at the time of the *IUE* observation) for many of the Cepheid spectra in the *IUE* archives. These spectra are discussed further by Evans (1990b, c). Most of the Cepheids are brighter than eighth magnitude, and the spectra are listed in Evans (1990c). Only reasonably well-exposed spectra are included (more than 100 DN

TABLE 4
ABSOLUTE MAGNITUDES: LONG- AND SHORT-WAVELENGTH SPECTRA

STAR (1)	PHASE (2)	M_V (mag)	
		Supergiant (3)	δ Cep (4)
η Aql	0.98	−3.86	−3.57
	0.15	−3.71	−3.57
	0.42	−3.69	...
	0.70	−3.66	...
SU Cas	0.37	−3.46	−3.22, $E(B - V) = 0.23$
	0.37	−3.31	−3.04, $E(B - V) = 0.27$
W Sgr	0.68	−4.11	...
	0.70	−3.93	...

[data units] of signal above the background, where 160 DN is an optimal exposure). The exception to this was that a few spectra of T Mon were included which were slightly less well

exposed. This was to include a few additional measures for $(B-V)_0 \geq 0.9$ mag, where few spectra are available. The companion of T Mon was determined to be B9.8 V, in the same way that spectral types were determined for the stars in this study, and the spectra were then corrected for the companion.

The δ Cep observations and the observations of nonvariable supergiants are indicated by separate symbols in Figure 3a, as are the Cepheid observations taken during the pulsation "piston" phase (phase 0.7–1.0). The Cepheids fall in a well-defined locus in Figure 3a. The high effective gravity "piston" phase colors agree with the "free-fall" phases at the same $B-V$. In Figure 3b the Cepheid observations during "free-fall" phases have been fitted to a parabola. The rms deviation from the parabola is ± 0.09 mag, indicating the uncertainty resulting from using a single Cepheid (δ Cep) to model the Cepheid in the η Aql system.

Figure 3c shows the η Aql data (corrected for the companion), the δ Cep observations, and the nonvariable supergiant data, together with the parabola from Figure 3b. The parabola, indicating the locus of Cepheid observations, is in good agreement with the δ Cep observations, and also the supergiant observations for $B-V$ cooler than 0.6 mag.

For Cepheid observations at hotter phases [$(B-V)_0$ of 0.4–0.6 mag], the δ Cep observations in Figure 3c agree well with the η Aql observations. The supergiant observations in this color range, however, systematically show a larger $m_{2950} - V$ color than η Aql. It is therefore to be expected that using the supergiants as comparison stars for η Aql will overestimate its absolute magnitude. We therefore adopt the absolute magnitudes found by using δ Cep as a comparison star for the $B-V$ range where it is applicable, and the supergiant absolute magnitudes for cooler phases. The mean value of the absolute magnitude of η Aql from Table 4 (-3.62 mag), for instance, is determined by taking the average of the value determined from δ Cep for the first two phases, and the supergiant determinations for the last two phases.

7. W SAGITTARII AND SU CASSIOPEIAE

The analysis of the W Sgr and SU Cas spectra proceeds in the same way as for η Aql. Figure 4 shows the comparison between the SWP spectra of the companion and the comparison spectrum of the adopted spectral type. Tables 3 and 4 summarize the results.

The reddening for SU Cas is more uncertain than that of η Aql for W Sgr, both because it is larger and because the star is located within a reflection nebula rather than the diffuse interstellar medium. Table 5 summarizes the reddening for various recent determinations. [DWC found $E(B-V) = 0.26$ mag from $BVRI$ photometry for SU Cas, but ultimately determined a mean value of 0.24 mag from several techniques.] The agree-

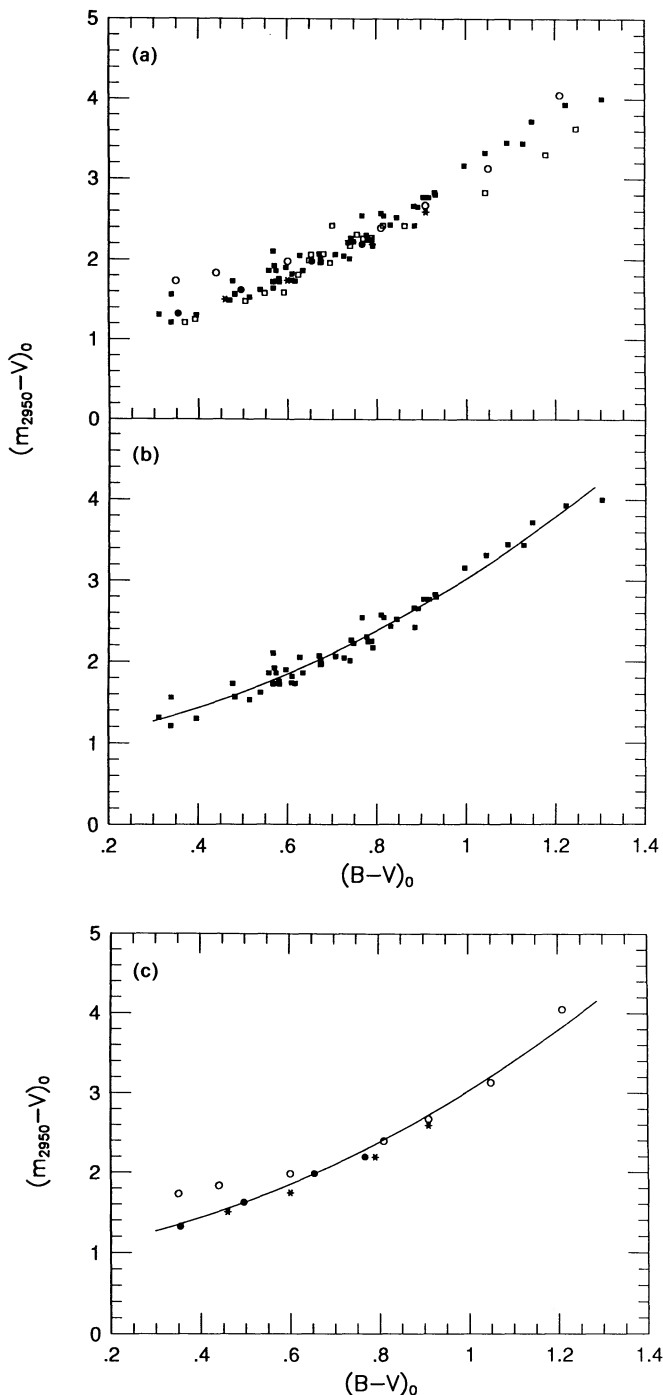


FIG. 3.—Visual — ultraviolet color $m(2950) - V$ (see text) as a function of $(B-V)_0$ for Cepheids and nonvariable supergiants. Both colors are in magnitudes. The symbols are as follows: open circles: nonvariable supergiants; filled circles: δ Cep; asterisks: η Aql, corrected for the companion; filled squares: other Cepheids in the phase range 0.0–0.7; open squares: other Cepheids in the phase range 0.7–1.0. (a) All data. (b) Cepheids from phases 0.0P to 0.7P and the parabola fitted to the data. (c) Nonvariable supergiants, δ Cep, η Aql, and the parabola from (b).

TABLE 5
REDDENING OF SU CAS

Source	$E(B-V)$ (mag)	Technique
Dean, Warren, & Cousins 1978	0.26	Johnson $BVRI$
Gray 1989, private communication	0.29	$uvby\beta$
Fernie 1990	0.287	Combined photometry
Turner & Evans 1984	0.27	Star counts
Fernie 1987	0.274	$uvby\beta$
Mean	0.276	...

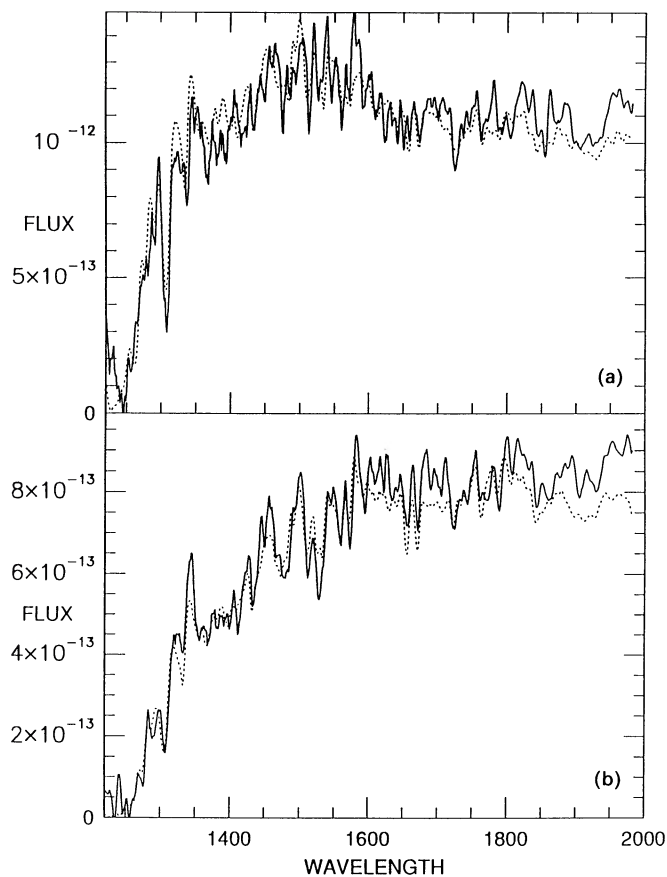


FIG. 4.—SU Cas B and W Sgr B. (a) Observed spectrum of SU Cas B (solid line) compared with the standard spectrum which matches it best, B9.5 V (dotted line). (b) W Sgr B (solid line) compared with an A0 V (dotted line) spectrum.

ment between the determinations is good. As an alternative for the average reddening listed by DWC (0.24 mag), we have also carried through solutions for a reddening of 0.27 mag.

Since the luminosity of SU Cas is particularly important, we present Figure 5 as a graphic display of the relative luminosity of the Cepheid and the companion for both SU Cas and η Aql. Clearly the relative companion/Cepheid contribution is quite similar for both systems. There are three factors which must be considered to determine whether the similarity between the flux ratios in the ultraviolet implies similar absolute magnitudes (M_V). First, what is the color difference between the ultraviolet and the visual for the two stars? The color $m(2950) - V$ is well correlated with $(B - V)_0$ (Fig. 3), and so the difference in $m(2950) - V$ between η Aql and SU Cas can be estimated from their respective values of $(B - V)_0$. This color difference is 0.7 mag in the sense that the flux difference between $m(2950)$ and V is larger for η Aql. A second correction is due to the small difference in temperature between the companions of the two stars, causing a difference in both absolute magnitude and ultraviolet color. This difference is less than 0.2 mag, estimated from our absolute magnitude calibration and the ultraviolet colors of Wesselius et al. (1980). These two corrections make the total difference between the absolute magnitudes of the Cepheids 0.9 mag. In addition, the difference between the V -magnitude at the time of the *IUE* observation and the mean magnitude of the Cepheid is nearly identical for

the two stars. In summary, Figure 5 shows that the absolute magnitude difference between SU Cas and η Aql is approximately 1 mag. This will be discussed below.

In Table 4, note that the difference between the absolute magnitude of SU Cas determined using supergiants as comparison stars and that using δ Cep for comparison is in the same sense as for the hottest phase of η Aql. It is at the hottest phases of η Aql that the supergiant and δ Cep magnitudes differ most. As with η Aql, we adopt the absolute magnitude from the δ Cep comparison for SU Cas.

8. KURUCZ ATMOSPHERES

The study of Cepheid luminosities by Böhm-Vitense (1985) found surprisingly faint absolute magnitudes. Because the absolute magnitudes of the companions were derived using temperatures determined by matching Kurucz (1979) atmospheres to the *IUE* spectra, it is not clear whether the difference between her luminosity scale and others (e.g., Feast & Walker 1987) is due to the use of these atmospheres or to the ultraviolet method itself. We investigate this in this section. However, we consider the luminosity calibration in §§ 6 and 7 based on the observed *IUE* spectra to be the primary calibration, since the atmospheres are deficient in several respects (Kurucz 1988), particularly in the ultraviolet opacities.

We have not followed the Böhm-Vitense technique exactly, but rather have used a method like that of Arellano-Ferro & Madore (1986) and Parsons (1981). Both components of the

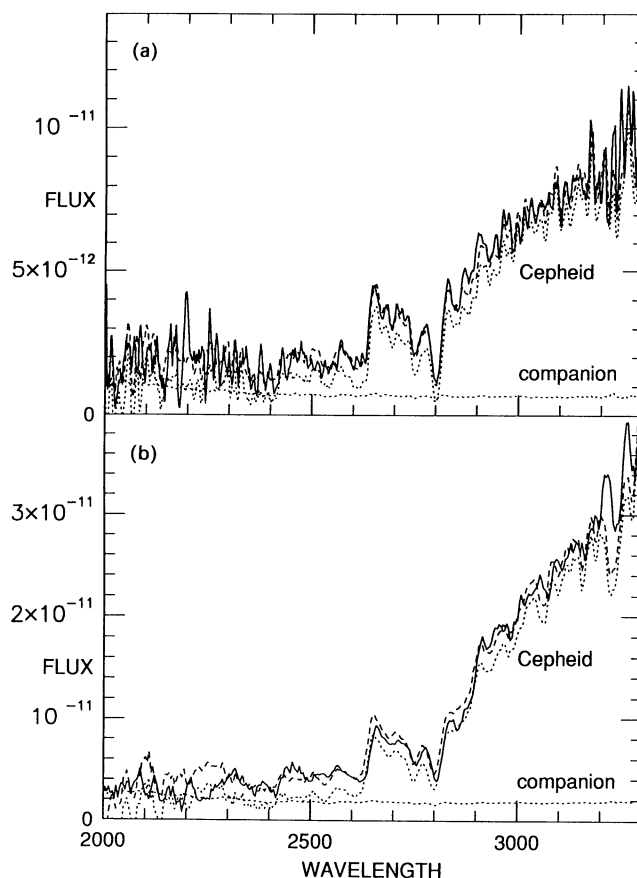


FIG. 5.—Comparison of the Cepheid/companion combination for SU Cas and η Aql. Symbols are the same as in Fig. 2. (a) SU Cas at Cepheid phase 0.38P. (b) Eta Aql at Cepheid phase 0.42.

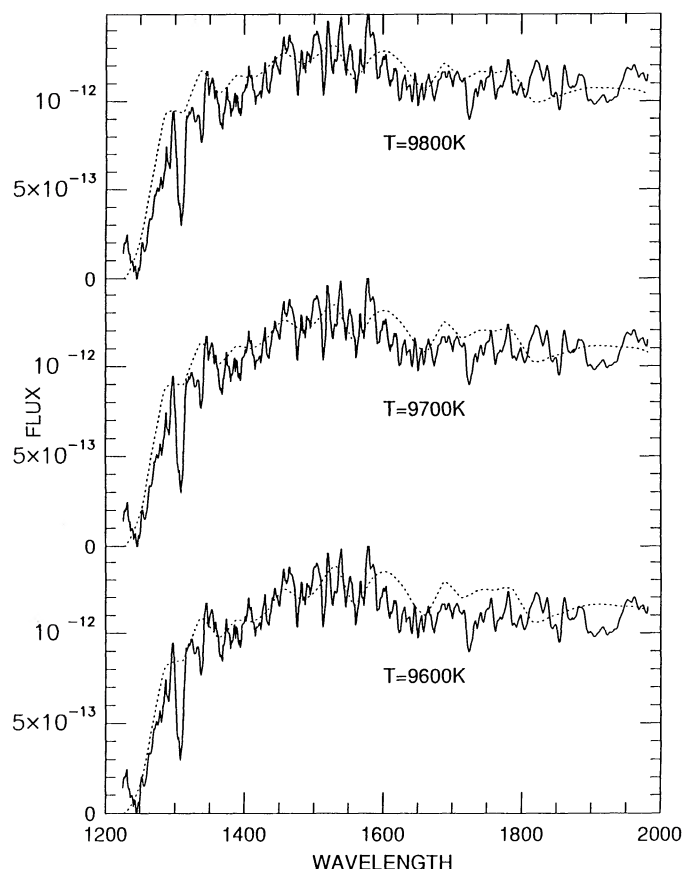


FIG. 6.—Comparison of SU Cas B and scaled Kurucz atmospheres. The temperatures of the atmospheres are shown. The spectra are arbitrarily offset.

system are matched to a Kurucz model. For the short-wavelength spectrum, fluxes were interpolated between the models to set up an intermediate grid in steps of 100 K, for $\log g = 4.0$. Figure 6 provides an example of the comparison between SU Cas B, and the models for three temperatures. We tried converting the spectral types from Table 3 to temperature using two different calibrations, but found that direct comparison with the models gave slightly different answers. We have used temperatures from the direct comparisons to derive absolute magnitudes.

In Figure 6 the models were scaled to match the spectrum of the SU Cas companion using the mean flux in both between 1500 and 1600 Å. The 9800 K model has too much flux between 1250 and 1350 Å in Figure 6. A better match is achieved for the two cooler temperatures. However, the 9600 K model flux from 1600 to 1950 Å is systematically higher than the spectrum. A temperature of 9700 K is adopted for the companion, with an uncertainty estimated to be 100 K. Similarly, the temperatures of the companions of η Aql and W Sgr are 9300 and 9200 K, respectively.

A procedure similar to that in § 6 was followed for the long-wavelength spectra. First the flux from the model representing the companion was subtracted from the observed spectrum, leaving the spectrum of the Cepheid alone. A temperature for the phase of the observation was then computed from the $(B-V)_0$ of the Cepheid, using the temperature calibration from Kraft as discussed by Cox (1979):

$$\log T_e = 3.886 - 0.175(B-V)_0.$$

Fluxes were interpolated between Kurucz atmospheres ($\log g = 1.5$) to match this temperature. The interpolated models were scaled to match the observed spectrum (corrected for the companion) from 2900 to 3000 Å.

It was discovered early in the analysis that if a flux were calculated from the V_0 magnitude at the time of observation, the flux from V_0 was systematically too large compared with the model (matched to the ultraviolet spectrum). This difference was not due to an incorrect temperature. Models with a range of temperatures were tried, and the excess flux from V_0 remained even for temperatures which were outside the range of reasonable matches for the *IUE* spectra alone.

The same effect was seen in δ Cep spectra. The spectra of δ Cep discussed earlier were used to derive a correction which needs to be added to make the V_0 fluxes match the models. Figure 7 shows the correction as a function of $(B-V)_0$. This correction was included in the derivation of absolute magnitudes using model atmospheres. We stress that we do not consider this calibration to be the primary calibration in this paper. It is merely a comparison with the previous techniques to see whether we can derive reasonable absolute magnitudes from *IUE* spectra using the models.

There is another correction which must be added to the results from the models. In his Table 5B, Kurucz (1979) lists the V -magnitudes of the models, derived by convolving them with the instrumental and filter transmission functions of Buser & Kurucz (1978), to take account of the conversion between monochromatic fluxes and broad-band colors. For temperatures between the computed models, we have interpolated between the V -magnitudes.

The magnitude differences we derive are the sum of the magnitude difference derived from the scale factors to match the hot and cool models to the *IUE* spectra, the magnitude difference from the monochromatic to broad-band conversion, and the flux correction (Fig. 7). Finally, as in § 6, a correction was added to take into account the difference between the V_0 of the Cepheid at the time of the observation, and $\langle V \rangle_0$, at mean light. The absolute magnitude of the companion is added to

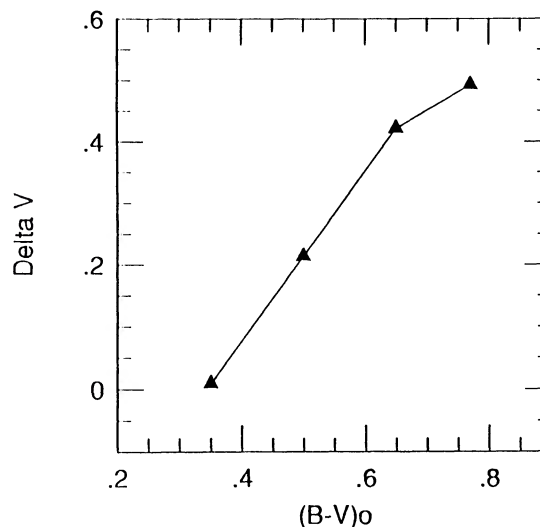


FIG. 7.—Correction to be subtracted from Kurucz V -magnitudes when the atmospheres have been scaled to match *IUE* observations. Both axes are in magnitudes. The correction has been derived from observations of δ Cep at four phases. The correction is in the sense that Kurucz V -magnitudes need to be brighter for cooler Cepheid phases.

TABLE 6
ABSOLUTE MAGNITUDES: KURUCZ ATMOSPHERES

Star	Phase	M_V
η Aql	0.98	-3.44
	0.15	-3.34
	0.42	-3.38
SU Cas	0.37	-3.08, $E(B-V) = 0.23$
	0.37	-2.94, $E(B-V) = 0.27$

this magnitude difference between the companion and the Cepheid at mean light, to produce the absolute magnitude of the Cepheid. The results are listed in Table 6. For one phase of η Aql and both phases of W Sgr, the observations were cooler than existing Kurucz models, so no results were derived for those phases.

9. DISCUSSION

Several sources of error have been discussed in the preceding sections. They are summarized in Table 7. The error due to an uncertainty in the reddening law should be less than 0.1 mag for the stars discussed here. The largest source of error in Table 7, the error due to uncertainty in $E(B-V)$, is estimated as 0.2 mag. This corresponds to an uncertainty in $E(B-V)$, $\Delta E(B-V)$, of 0.025 mag at 1700 Å and 0.042 mag at 2800 Å. A nearly comparable error is the difference between using non-variable supergiants and using δ Cep for comparison spectra for the Cepheid in the long-wavelength region (Fig. 3, Table 4). On the other hand, the standard deviation from the Cepheid spectra in Figure 3b (0.09 mag) suggests that the real uncertainty due to using comparison stars is smaller than the final entry in Table 7. The error in the absolute magnitude due to an error of a quarter of a spectral class in the spectral type of the companion is 0.1 mag. The internal errors are the standard deviation of the absolute magnitude of η Aql from different phases (Table 4, col. [3]). The uncertainty due to $\Delta E(B-V)$ is probably overestimated for the long- and short-wavelength spectra determination (Table 4). The last two error sources, on

TABLE 7
SOURCES OF ERROR

Source	Error (mag)
Reddening:	
Reddening law	≤ 0.1
$E(B-V)$	0.2
Absolute magnitude of companion: error of 0.25 spectral class	0.1
Internal errors: η Aql phases	0.09
Difference between δ Cep and supergiants (η Aql)	0.16

the other hand, are not relevant for the short-wavelength determinations (Table 3). Adding relevant errors quadratically, the total uncertainty is 0.3 mag for both the methods of determining the absolute magnitude (Tables 3 and 4).

We are working on extending this technique to other Cepheids with hot companions. This will provide an external error comparison from the scatter about a period-luminosity-color relation. A more direct test of the accuracy of this method will be provided by two cluster Cepheids which have companions.

There are two error sources which could affect the absolute magnitudes systematically, which we cannot assess. An error in either the absolute magnitude calibration of the main sequence or a systematic error in the reddening would alter the absolute magnitude scale.

Table 8 provides a comparison between the absolute magnitudes determined here and those from other sources. The *IUE* determinations from Tables 3 and 4 are listed, compared with the values predicted from the period-luminosity-color relation of Feast & Walker (1987):

$$\langle M_V \rangle = -3.53 \log P + 2.13(\langle B \rangle_0 - \langle V \rangle_0) - 2.13.$$

This relation is based on the same ZAMS calibration as the results in this paper. For η Aql and W Sgr, the agreement is very good, both between the two *IUE* determinations and between the *IUE* and Feast & Walker determinations. The differences are smaller than the error estimate from Table 7. SU Cas will be discussed below. For η Aql and W Sgr, the agreement with the Sandage & Tammann (1969) relation is also very good.

The Kurucz absolute magnitudes (§ 8) for η Aql and SU Cas are smaller than the other *IUE* absolute magnitudes.

The absolute magnitudes determined by Böhm-Vitense are significantly fainter than the *IUE* determinations from Tables 3 and 4. This is not necessarily the result of exactly the same causes as the differences from the Kurucz determinations that we found. Böhm-Vitense determined absolute magnitudes from the flux at 1950 and 1550 Å. Part of the difference comes from the fact that the ZAMS absolute magnitude calibration she used does not include a correction for the high metallicity of the Hyades. In addition, her treatment of the reddening is somewhat different from that of § 4. Finally, the temperatures she determines are slightly hotter than those determined here (+100 K for η Aql and +200 K for W Sgr). The absolute magnitudes we find from *IUE* spectra (Tables 3 and 4), however, are not systematically faint compared with other calibrations, as her results are.

The *IUE* luminosity of SU Cas in Table 8 differs from the period-luminosity-color calibrations. It is a magnitude brighter than predicted for fundamental mode pulsation, even somewhat brighter than predicted for pulsation in the first overtone.

TABLE 8
ABSOLUTE MAGNITUDE COMPARISONS

STAR	<i>IUE</i>			FEAST & WALKER		SANDAGE & TAMMANN Mode 0	BÖHM-VITENSE
	1700 Å	2600 Å	Kurucz	Mode 0	Mode 1		
η Aql	-3.74	-3.62	-3.39	-3.75	...	-3.84	-3.4
SU Cas (0.23)	-3.24	-3.22	-3.08	-2.06	-2.58	-2.24	...
SU Cas (0.27)	-3.04	-3.04	-2.94	-2.12	-2.64	-2.32	...
W Sgr	-3.98	-4.02	...	-3.92	...	-3.91	-3.3

NOTE.—Mode 0 = fundamental mode; mode 1 = first overtone.

The absolute magnitude of SU Cas would have to be a magnitude fainter to be consistent with fundamental pulsation. That is, the flux of the companion would be 2.5 times brighter in comparison with the Cepheid. The comparison of the relative fluxes of the two stars in the SU Cas and η Aql systems (Fig. 5) makes this seem impossible.

Could an error in the reddening account for the bright absolute magnitude? Table 8 lists absolute magnitudes for both $E(B-V)$ 0.23 mag and 0.27 mag. While an increase in $E(B-V)$ results in a fainter absolute magnitude, it also makes the difference in absolute magnitudes from 1700 and 2600 Å larger. A large enough reddening to result in an absolute magnitude of -2.1 mag would create inconsistencies both with the reddening determinations for the Cepheid and between the two *IUE* determinations. A slightly larger $E(B-V)$ could well cause the absolute magnitude to be more consistent with pulsation in the first overtone mode, however.

The result here supporting pulsation in an overtone mode disagrees with the reflection association luminosity as summarized by Turner & Evans (1984), especially if SU Cas is at the distance of HD 17443, which is close to it on the sky. We do not entirely understand this contradiction, but we suggest that since the list of stars identified as illuminating stars is short, if only one or two are at different distances, the results change significantly.

In view of the identification here of SU Cas as an overtone pulsator, one of its other physical characteristics is of interest. Its period has remained constant since the first decade of this century (Szabados 1977). This is in contrast to other small-amplitude, short-period "s" Cepheids (Szabados 1977). The mean unsigned period change for Cepheids with periods shorter than 5 days and V -amplitudes less than 0.5 mag is 3.3 yr^{-1} . This is a mean using the period data of Szabados (1977, 1989), for stars with a continuously changing period or a single period change at a previous epoch, as discussed by Willson et al. (1990). This contrasts with the mean period change (0.7 yr^{-1}) for short-period stars with larger amplitudes. In addition, 16 stars with periods less than 5 days have constant periods within the accuracy of the observations, of which only three have amplitudes smaller than half a magnitude. This means that the average rate of period change of all large-amplitude stars (with and without observed period changes) is even smaller than that of stars with observed period changes, and provides even more of a contrast with the small-amplitude group. Some small-amplitude Cepheids (for example, Polaris)

have very rapid period changes. A reasonable interpretation of the rate of period change is that it is an indication of the rate of evolution, presumably linked to which crossing of the instability strip the star is making. There is no reason that the mode of pulsation should affect the rate of period change, and the constancy of the period of SU Cas is consistent with the second crossing of the instability strip. The rapid period change of many other small-amplitude Cepheids suggests that they are stars in the third crossing. The fact that only one or two stars other than SU Cas have been suggested to be overtone pulsators on the basis of Fourier coefficients may be linked to SU Cas's unusually constant period in differentiating it from small-amplitude third-crossing stars. While SU Cas is distinct from other short-period, small-amplitude stars in both its Fourier coefficients and its constant period, there is an important problem with this simple picture. For both the large- and small-amplitude stars, a mixture of increasing and decreasing periods is seen. This is not expected if period change reflects a simple evolutionary progression across the instability strip.

In summary, we have demonstrated that it is possible to obtain absolute magnitudes for binary Cepheids from the ultraviolet spectra of their companions. The results for η Aql and W Sgr are in agreement with the predictions from the period-luminosity-color relation of Feast & Walker. The random uncertainties in the results are discussed, and are 0.3 mag. SU Cas, on the other hand, has an absolute magnitude which is a magnitude too bright to be a fundamental mode pulsator. This is strong evidence that it is pulsating in an overtone mode.

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REFERENCES

- Arellano-Ferro, A., & Madore, B. F. 1986, *ApJ*, 302, 767
 Babel, J., Burki, G., Mayor, M., Waelkens, C., & Chimielewski, Y. 1989, *A&A*, 216, 125
 Balona, L. A. 1977, *MNRAS*, 178, 231
 Balona, L. A., & Shobbrook, R. R. 1984, *MNRAS*, 211, 375
 Becker, S. A., Iben, I., & Tuggle, R. S. 1977, *ApJ*, 218, 633
 Böhm-Vitense, E. 1985, *ApJ*, 296, 169
 Bonneau, D., Blazit, A., Foy, R., & Labeyrie, A. 1980, *A&AS*, 42, 185
 Buser, R. 1978, *A&A*, 62, 411
 Buser, R., & Kurucz, R. L. 1978, *A&A*, 70, 555
 Cox, A. N. 1979, *ApJ*, 229, 212
 Dean, J. F., Warren, P. R., & Cousins, A. W. J. 1978, *MNRAS*, 183, 569
 Evans, N. R. 1990a, *PASP*, 102, 551
 ———. 1990b, *PASP Conf. Ser.*, 11, ed. C. Cacciari & G. Clementini (San Francisco: ASP), 224
 ———. 1990c, preprint
 Evans, N. R., & Arellano-Ferro, A. 1986, in *Stellar Pulsation*, ed. A. N. Cox, W. M. Sparks, & S. G. Starrfield (New York: Springer-Verlag), 183
 Evans, N. R., & Bolton, C. T. 1990, *ApJ*, 356, 630
 Evans, N. R., Welch, D. L., Scarfe, C. D., & Teays, T. J. 1990, *AJ*, 99, 1598
 Feast, M. W., & Walker, A. R. 1987, *ARA&A*, 25, 345
 Feast, M. W., & Walker, A. R. 1987, *AJ*, 94, 1003
 ———. 1990, *ApJS*, 72, 153
 Fernie, J. D. 1982, *ApJ*, 257, 193
 Fitzpatrick, E. L., & Massa, D. 1988, *ApJ*, 328, 734
 Garhart, M. P., & Teays, T. J. 1989, *NASA IUE Newsletter*, 40, 54
 Gieren, W. 1982, *PASP*, 94, 960
 Gieren, W. P., Barnes, T. G., III, & Moffett, T. J. 1989, *ApJ*, 342, 467
 Harmanec, P. 1988, *Bull. Astr. Inst. Czechoslovakia*, 39, 329
 Jacobsen, T. S., & Wallerstein, G. 1981, *PASP*, 93, 481
 Kurucz, R. L. 1979, *ApJS*, 40, 1
 ———. 1988, in *New Directions in Spectrophotometry*, ed. A. G. D. Phillip, D. S. Hayes, & S. J. Adelman (Schenectady: Davis), 25
 Lloyd Evans, T. 1982, *MNRAS*, 199, 925
 Maeder, A., & Meynet, G. 1988, *A&AS*, 76, 411
 Mariska, J. T., Doschek, G. A., & Feldman, U. 1980, *ApJ*, 238, L87
 Mathis, J. S. 1987, in *Exploring the Universe with the IUE Satellite*, ed. Y. Kondo (Boston: Reidel), 517
 Millward, C. G., & Walker, G. A. H. 1985, *ApJS*, 57, 63
 Moffett, T. J., & Barnes, T. G., III. 1984, *ApJS*, 55, 389
 Morgan, B. L., Beddoes, D. R., Scaddan, R. J., & Dainty, J. C. 1978, *MNRAS*, 183, 701

- Niva, G. D., & Schmidt, E. G. 1979, *ApJ*, 234, 245
Oliversen, N. A. 1988, *NASA IUE Newsletter*, 35, 55
Parsons, S. B. 1981, *ApJ*, 247, 560
Parsons, S. B., & Bell, R. A. 1975, *Dudley Obs. Rept.*, 9, 73
Racine, R. 1968, *AJ*, 73, 588
Sandage, A., & Tammann, G. A. 1969, *ApJ*, 157, 683
Savage, B. D., Massa, D., Meade, M., & Wesselius, P. R. 1985, *ApJS*, 59, 397
Savage, B. D., & Mathis, J. S. 1979, *ARA&A*, 17, 84
Schmidt, E. G. 1978, *AJ*, 83, 960
Schmidt-Kaler, T. 1982, in *Landolt-Börnstein, Group VI, Vol. 2b*, ed. K. Schai-
fers & H. H. Voigt (New York: Springer-Verlag), 14
Simon, N. R., & Lee, A. S. 1981, *ApJ*, 248, 291
Szabados, L. 1977, *Mitt. Sternw. Ungarische Akad.*, 70, 1
———. 1980, *Mitt. Sternw. Ungarische Akad.*, 76, 1
———. 1989, *Mitt. Sternw. Ungarische Akad.*, 94, 1
Turner, D. G. 1976, *AJ*, 81, 97
———. 1979, *PASP*, 91, 642
Turner, D. G., & Evans, N. R. 1984, *ApJ*, 283, 254
van Leeuwen, F. 1983, Ph.D. thesis, Univ. Leiden
Wesselius, P. R., van Duinen, R. J., Aalders, J. W. G., & Kester, D. 1980, *A&A*,
85, 221
Willson, L. A., Brunish, W., & Evans, N. R. 1990, in preparation
Witt, A. N., Bohlín, R. C., & Stecher, T. P. 1981, *ApJ*, 244, 199
Wu, C. C., et al. 1983, *NASA IUE Newsletter*, 22, 1