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A study of variable stars in the ultraviolet

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Some of the OAO-2 ultraviolet observations of intrinsically variable stars are discussed. New data is presented for the Ap variable ι Cassiopeiae. The cepheid variables are illustrated by α Ursae Minoris. The explosive variables Nova Serpentis 1970, Nova Aquilae 1918, SS Cygni, and the 1972 supernova in NGC 5253 are compared. The hypothesis that novae and dwarf novae maintain a constant luminosity, becoming visually bright only when an extended envelope is formed, is considered and rejected on the basis of observational evidence.

1. Introduction

The Wisconsin instruments on the OAO-2 (Code *et al.* 1970) were used for extensive observations of about 55 variable stars (table 1) during the 50 months between its launch on 7 December 1968 and its turn off following the failure of the high voltage power supply on 14 February 1973. Observations of variable stars from orbit have advantages over ground-based observations. In addition to providing data at wavelengths inaccessible from the surface, the satellite observatory is able to observe uniformly through the day and is not subject to bad weather. Since observations could be made once every orbit (0.0696 days), light curves for stars whose periods were close to an integer multiple of days could be quickly obtained. Such light curves would require surface observations through many cycles. The observations from orbit also permit good light curves to be compiled for stars with variable or non-cyclic light curves. The exceptions to these statements are variables with periods equal to a small multiple of the observatory's orbital period. Light curves for such variables were difficult to obtain because observations could only be made during the 15–30 % of the orbit lying in the Earth's shadow. In this paper I intend to review the observations of a representative sample of intrinsic variables with some emphasis upon problems involving flux redistribution. Therefore, the discussions will mostly stress the value of data at wavelengths inaccessible from the Earth's surface.

2. Instruments and data reduction

The Wisconsin instruments have been described in detail by Code *et al.* (1970). All of the data presented here were collected by the four stellar photometers unless specifically attributed to one of the other instruments. Each stellar photometer had a mirror with a 20 cm aperture and a filter wheel containing three interference filters, a ^{90}Sr Cherenkov source for calibration, and a dark slide. Some details of data reduction procedures have been discussed elsewhere (Doherty 1972; Leckrone 1973). The 12 filters had effective wavelengths (for a constant energy source) ranging from 4250 to 1330 Å with widths at half-maximum of 200–500 Å. When discussing the data I will always use this effective wavelength to label the output of a given filter-photometer combination. Ultraviolet colours and magnitudes were calculated using a preliminary ultraviolet calibration (Code 1972) and the Oke & Schild (1970) calibration of Vega. Errors due to changes in the calibration are expected to be small because most of the discussion involves only the comparison of observations. The observations have been corrected for changes in filter transmission by emperical functions determined from repeated observations of OB stars.

TABLE 1. A SAMPLE OF VARIABLE STARS OBSERVED BY OAO-2

type	name	period day	published or in print	investigators
		1. Eclipsing variables		
EA	δ Cap	1.023	—	—
	CW Cep	2.729	P	Sobieski
	32 Cyg	406.8	P	Doherty, McNall, Holm
	31 Cyg	3784.0	P	Doherty, Jung
	V444 Cyg	4.212	—	—
	AI Dra	1.99	—	Wu
	U Oph	1.677	P	Eaton, Ward
	β Per	2.867	—	Eaton
	W UMi	1.701	—	Wu, Eaton, Holm
EB	o And	1.600	—	—
	LY Aur	4.002	P	Heap, Kondo, McCluskey
	UW CMa	4.393	—	Eaton
	68 Her	2.051	—	—
	β Lyr	12.908	P	Houck, Kondo, McCluskey
	VV Ori	1.485	—	Eaton
		2. Intrinsic variables		
Cepheid	RT Aur	3.728	—	Hutchinson
	δ Cep	5.366	—	Hutchinson
	β Dor	9.842	—	Hutchinson
	Y Oph	17.123	—	Hutchinson
	α UMi	3.970	—	Hutchinson
RR Lyr	RR Lyr	0.567	—	—
δ Sct	γ Boo	suspected	—	—
	β Cas	0.104	—	Bless, Hartman
	ε Cep	0.042	—	Bless, Hartman
	84 Cet	suspected	—	—
	o Eri	0.08	—	—
	δ Sct	0.194	—	Bless, Hartman
	HD 24832	0.16	—	—
β Cep	β Cep	0.190	P	Fischel, Sparks
	δ Cet	0.161	—	—
	DD Lac	0.193	—	Wu
	EN Lac	0.169	—	Wu
	α Lup	0.260	—	Wu
	θ Oph	0.140	—	—
	γ Peg	0.157	—	—
	σ Sco	0.247	—	—
	BW Vul	0.201	—	Wu
α CVn	SX Ari	0.728	—	Leckrone
	AX Cam	8.015	—	—
	α CVn	5.469	P	Molnar
	ι Cas	1.740	—	Holm, Molnar
	AF Dra	20.270	P	Leckrone
	GL Lac	9.475	P	Leckrone
	ε UMa	5.089	P	Molnar

Table 1. (*cont.*)

type	name	$\frac{\text{period}}{\text{day}}$	published or in print	investigators
		3. *Explosive variables*		
Supernova	NGC5253	(1972)	P	Holm, Wu, Caldwell
Nova	V603 Aql	(1918)	P	Gallagher, Holm
	RR Pic	(1925)	P	Gallagher, Holm
	FH Ser	(1970)	P	Gallagher, Code
U Gem	SS Cyg	50.4	P	Holm, Gallagher
		4. *Miscellaneous*		
	γ Cas	—	—	—
	a Cen	8.81	P	Molnar
	P Cyg	—	—	—
	BN Gem	—	—	—
	EW Lac	—	—	—
	δ Per	—	P	Molnar
	Sco X-1	—	—	Hoffman, Code
	γ Vel	—	P	West
	2U 1700–37	3.412	P	Heap

3. PERIODIC VARIABLES

ι Cassiopeiae is a spectrum variable chromium–strontium star (Morgan 1932, 1933). It was also found to be variable in visual light (Provin 1953) with a period of 1.74 days. Figure 1 illustrates the ultraviolet light curves of ι Cas along with the 5500 Å light curves by Provin (1953) and Klock (1965). The elements of Klock (1965) have been used to reduce all observations to a common phase. The light curve at 5500 Å has a small amplitude – 0.03 m – and has large scatter. The far ultraviolet light curves are in anti-phase to the visual. This phenomenon has previously been noted in OAO-2 observations of α^2 CVn (Molnar 1973*a*) and ε UMa (Molnar 1973*b*). The amplitude increases into the ultraviolet. The ultraviolet light curves – showing both a primary and a secondary maximum – are much better defined than the visual light curve. The general appearance is as might be expected from an oblique rotator. However, a simple model of a symmetric oblique rotator with a spot at either pole is inadequate to explain the observations.

Figure 2 is a plot of the magnitude–wavelength relation for ι Cas at ultraviolet maximum (phase = 0.36) and ultraviolet minimum (phase = 0.0). The A3V star β Leo is included for comparison. The ι Cas magnitudes in figure 2 have not been corrected for the presence of secondary stars. Therefore, the magnitudes may be in error by 0.10 m and the amplitudes by 0.01 to 0.02 m. The filter degradation functions from studies of OB stars will cause the magnitudes at 1550, 1430 and possibly 1910 Å to be incorrect. However, the differences in magnitude at each wavelength will be unaffected by the degradation corrections. It is obvious that the increase of visual light comes at the expense of the ultraviolet. A crude integration over the energy lost between 1550 and 3200 Å and the energy gained between 3200 and 5500 Å shows that the energy lost in the ultraviolet is about four times that gained in the visual. Molnar (1973*a*) found that the effective temperature of α^2 CVn remains constant throughout the cycle. In order for the same to be true of ι Cas there must be variability in the red and infrared in

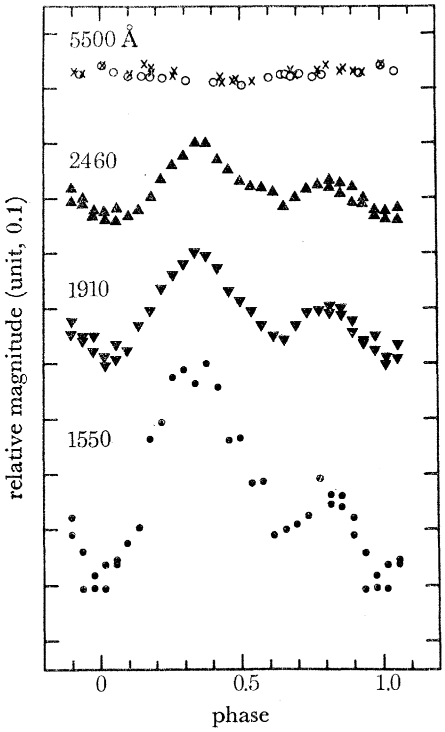

FIGURE 1. Light curves of the Ap variable ι Cassiopeiae. The measurements at 5500 Å are from(×)Provin (1953) and from (○) Klock (1965).

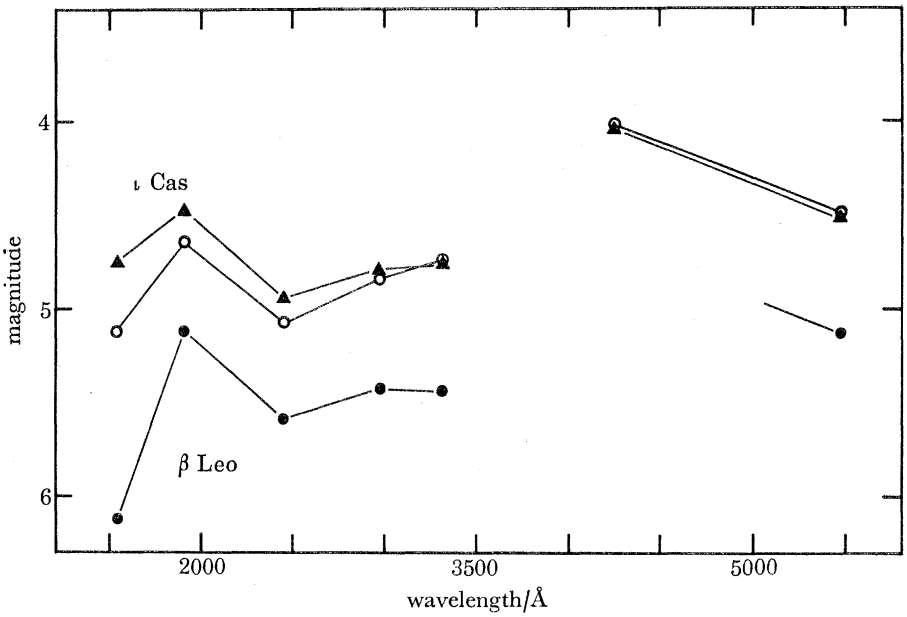

FIGURE 2. Magnitude–wavelength relation for ι Cassiopeiae and β Leonis. ○, ι Cas at phase 0.0, visual maximum; ▲, ι Cas at phase 0.35, ultraviolet maximum. All of the magnitudes of β Leonis have been increased by 2.0 in order to bring it closer to ι Cas in this illustration. β Leo was too bright at 4250 Å to be measured with the OAO-2 telescopes.

phase with the visual. We can estimate the amplitude of the red and infrared light curves by using the photometry of Mitchell & Johnson (1969) and by making simple assumptions about how the flux is redistributed. If the amplitude is constant between 5500 and 11000 Å ($\Delta F_\lambda = kF_\lambda$), the amplitude over that interval is 0.05 *m*. If the energy is redistributed evenly ($\Delta F_\lambda = K$), the amplitude increases smoothly from 0.025 *m* at 5500 Å to 0.16 *m* at 11000 Å.

We have some spectra of ι Cas and are analysing them to determine what absorption process is causing the redistribution of the flux.

As a contrast with those variables in which flux redistribution is a major effect, the cepheid variable Polaris (α UMi), will be discussed next. The analysis of the observations of Polaris and four other cepheids was accomplished by Hutchinson (1974). Polaris has a small visual amplitude and a period which is approximately 4 days (Kukarkin *et al.* 1970). The ultraviolet light curves are illustrated in figure 3. It is clear from this figure that the amplitude increases towards shorter wavelengths as it does for ι Cas. However, unlike ι Cas, the ultraviolet light curves are in phase with the visual. In some of the cepheids there is a small phase shift with wavelength, but that phase shift can be explained as an effect of the variable radius.

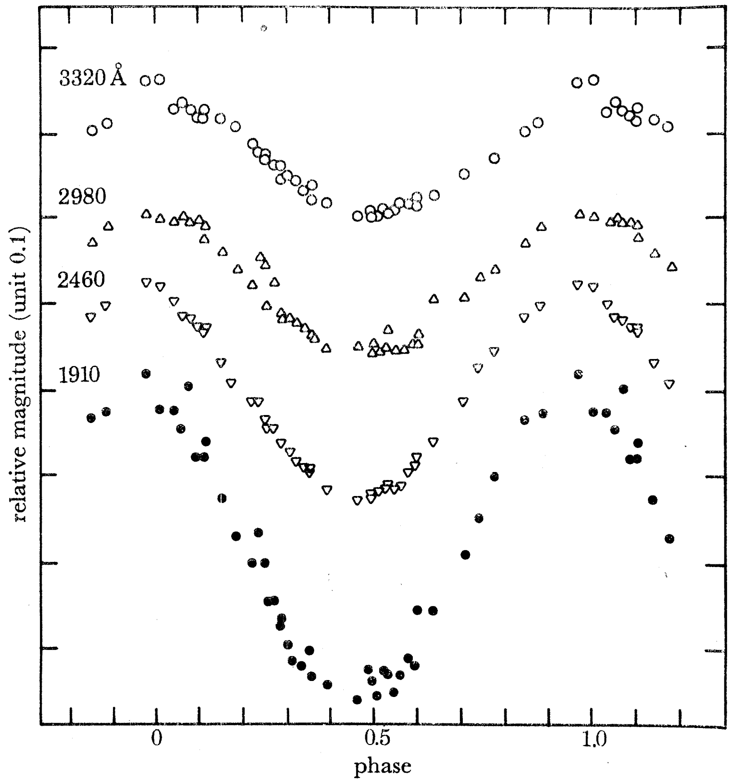

FIGURE 3. Light curves of the cepheid Polaris from Hutchinson (1974). The data were obtained in two observing sessions, April–May 1970 and July 1971.

There is no evidence for this star that energy is removed from one frequency range and reradiated in another. Hack (1956) found that in the Wien approximation to the black-body law

$$A_\lambda = 5\,\lg\left(\frac{R_\lambda}{r_\lambda}\right) - 1.563\,\frac{1}{\lambda}\left(\frac{1}{T} - \frac{1}{t}\right),$$

where R_λ is the photospheric radius at maximum, r_λ is the radius at minimum, T is the effective temperature at maximum, t is the temperature at minimum, and A_λ is the amplitude at λ. In this approximation the amplitude ought to be a linear function of inverse wavelength if the variations in the radius are small. Hutchinson found that such a linear relation exists for Polaris over a large range of wavelength (table 2). In table 2 the observations of Stebbins (1946) are included to extend the data into the red and infrared. Thus we see that the ultraviolet light variations of the cepheids are entirely consistent with variability in effective temperature and, since the change in radius is small, in bolometric magnitude.

Table 2. Linear relation between amplitude and inverse wavelength for Polaris

λ/Å	$\lambda^{-1}/10^4$ Å^{-1}	A_λ (mag.)	λA_λ
10300	0.971	0.036†	371
7190	1.391	0.060†	431
5700	1.754	0.104†	593
4880	2.049	0.118†	576
4220	2.370	0.152†	641
3530	2.833	0.166†	586
3357	2.979	0.16	544
3075	3.252	0.16	498
2589	3.862	0.25	649
2107	4.746	0.37	773

† From Stebbins (1946).

4. Explosive variables

We will discuss the explosive variables for the remainder of this paper. It was fortunate that a bright nova and the brightest supernova in 30 years both occurred during the four years of OAO-2 operations.

The observations of the moderately fast nova, Nova Serpentis 1970, have been analysed by Code (1972), Gallagher (1972) and Gallagher & Code (1974). They found that maximum light occurred with an increasingly larger phase lag towards shorter wavelengths (figure 4). This behaviour of the light curves obtained by filter photometry could indicate an increase of photospheric temperature as the visual light from the nova declined. However, with filter photometry alone it is not possible to rule out a second interpretation – that the development of strong emission bands centred in each filter causes an apparent increase while the continuum is actually falling. Gallagher (1972) examined spectrometer scans of the nova in the region 2500–3600 Å and found that while emission bands, especially Mg II at 2800 Å, do become strong the continuum also increases at shorter wavelengths in agreement with the filter photometry.

The physical properties derived for this nova are highly dependent on the corrections for interstellar extinction. After reviewing five independent methods for determining the extinction, Gallagher adopted $E_{\mathrm{B-V}} = 0.8$. The ultraviolet colours of Nova Serpentis after correction for extinction are indicated in the colour–colour diagram shown in figure 5. The points shown are for visual maximum (J.D. 2440636, Kodaira 1970) and for visual maximum plus 54 days. It is clear that the evolution of the nova is towards a higher temperature as was indicated by the light curves. It is also clear that the colours of the nova do not match those of any of the main sequence stars. The nova appears to be too faint at 2460 Å for its 4250–3320 Å colour. Perhaps this indicates the presence of circumstellar grains as advocated by Geisel, Kleinmann & Low (1970) or the presence of strong ultraviolet line blocking such as suggested by Mustel (1971) for supernovae.

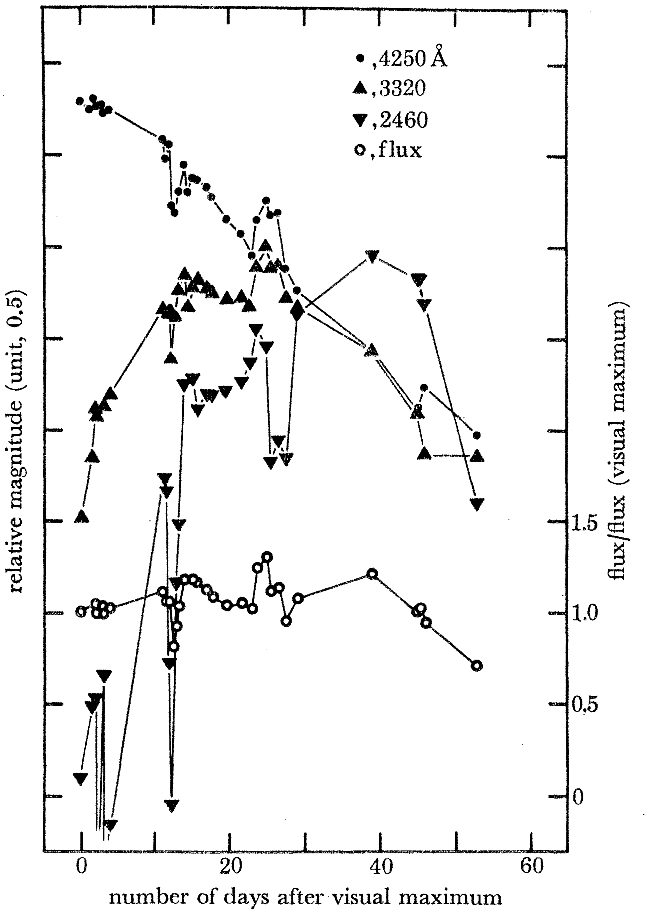

FIGURE 4. Light curves and flux of Nova Serpentis 1970 from Gallagher (1972). The light curves are in magnitudes arbitrarily normalized to appear in the same illustration. The flux is the result of an integration over the spectrum between 5500 Å and 1430 Å. The flux has been corrected for extinction corresponding to an $E_{B-V} = 0.8$.

What are the consequences of this increase in temperature as the visual light declined? Figure 4 shows that the flux integrated between 1430 and 5500 Å and corrected for extinction remains nearly constant during the entire period of OAO observations. The flux may be dropping at 40 days after visual maximum. However, Geisel *et al.* (1970) found that the infrared emission from the nova began to rise at 43 days after visual maximum, reached peak after 70–90 days, and remained large until at least 106 days after visual maximum. When the infrared data is combined with the visual and ultraviolet the possibility arises that the nova's luminosity may have remained constant for at least 100 days after maximum.

Gallagher (1972) found that the observed ultraviolet behaviour could be reproduced qualitatively by a grey atmosphere model in which the luminosity remained constant and the mass loss rate declined exponentially. In this 'fluorescent bulb' model, the flux of high energy photons from the central star is redistributed by the material in the envelope. As long as the mass loss rate is large, the photosphere remains at a large distance from the central star and the effective temperature is low. When the mass loss rate declines, the photosphere moves closer to the central star and the effective temperature must rise to compensate for the loss in radiating area.

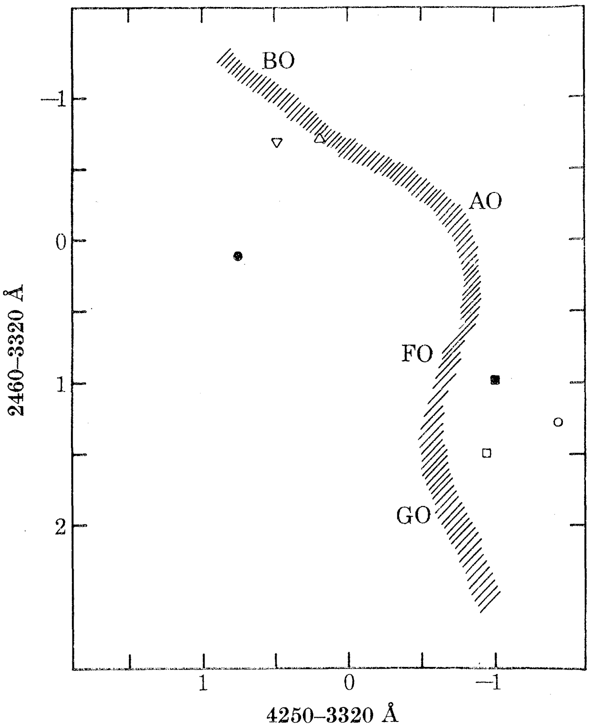

FIGURE 5. Colour–colour plot featuring colours of explosive variables. The region occupied by the main sequence is indicated by the lines. ○, Nova Ser visual maximum; ●, Nova Ser maximum +54 days; □, supernova maximum +20 days; ■, supernova maximum+35 days; ▽, V603 Aql; △, SS Cyg maximum.

These observations and theory suggest the possibility that the nova phenomena is as much the result of flux redistribution as is the variability of A peculiar stars, the possibility that novae are always extremely luminous but become visually bright only when they form an envelope which redistributes the flux into the visual. This hypothesis implies that the effective temperature of novae would fall until visual maximum when the maximum extension of the photosphere would occur. This is consistent with the observation that for many novae the pre-maximum spectral type is earlier than the maximum spectral type (Payne-Gaposchkin 1957). The effective temperature of a nova at minimum predicted in this constant luminosity hypothesis can be estimated from the effective temperature at maximum and from the observed range in the visual. If we take the temperature at maximum to be 5700 K (Kodaira 1970) and the magnitude range to be 11.6 (Payne-Gaposchkin 1957), then the effective temperature at minimum must be about 6×10^5 K in the black-body approximation. This temperature is more than an order of magnitude higher than the excitation temperature – 30000–35000 K – assigned by Greenstein (1960) to V603 Aql (Nova Aql 1918).

An additional test of the constant luminosity hypothesis is to examine the OAO observations of old novae. This was done by Gallagher & Holm (1974). Figure 6 illustrates the magnitude–

wavelength relation for V603 Aql 52 years after maximum. The star is very faint but the data looks good and reproducible. Its colours are indicated in figure 5. An average ultraviolet colour temperature of 25000 K was obtained by comparison with the observed colours of main sequence stars. If this represents the effective temperature, the present luminosity of V603 Aql is 12 $L_{\odot}$. However, two spectral features – the absence of a Balmer discontinuity and the presence of He II 4686 (Humason 1938) – imply that the effective temperature is actually much higher. These features and our ultraviolet colours can be reconciled if the star has an extended atmosphere such as calculated by Cassinelli (1971) for the central stars of planetary nebulae.

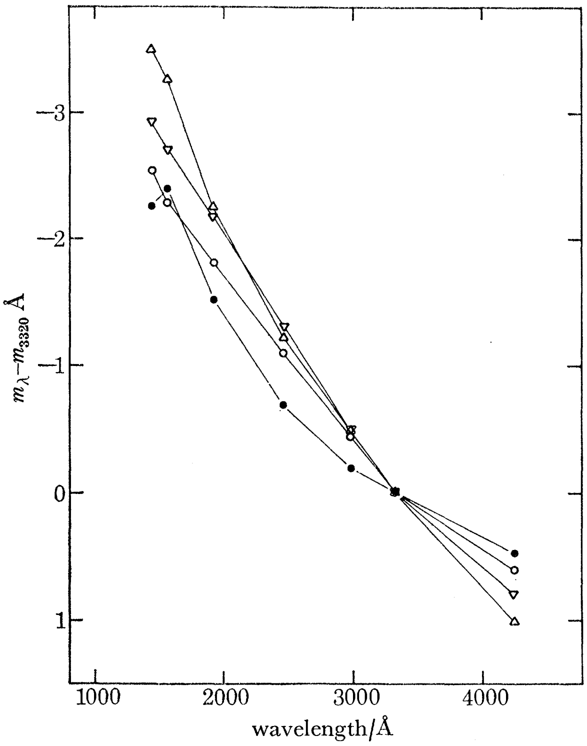

FIGURE 6. Wavelength–magnitude relation for the old nova V603 Aquilae (•), the subdwarf BD+28° 4211 (▵), and two standard stars from OAO-2 filter photometry: ○, 19 Mon B1 IV; ▿, 15 Mon O7.

The argument that the atmosphere of V603 Aql is extended is strengthened because the observed spectral lines are in emission (Humason 1938). If a bolometric correction appropriate for the Cassinelli (1971) model with $T(\tau = \frac{2}{3}) = 37500$ K and $R(0.001)/R(\frac{2}{3}) = 1.95$ is used, the V603 Aql luminosity is increased to 60 $L_{\odot}$. However, it is difficult to increase the luminosity to 10^4 $L_{\odot}$ as required by the constant luminosity hypothesis. Therefore, we must conclude that while ordinary fast novae remain at maximum luminosity much longer than previously imagined they eventually do return to a luminosity that is 1–0.1 % of maximum.

Perhaps more suitable candidates for the constant luminosity hypothesis might be found among the dwarf novae. If for a typical dwarf nova the range, corrected for the presence of red companion (Kraft 1962), is about 5 magnitudes and the temperature at maximum is 15000 K (Hinderer 1949), then the constant luminosity hypothesis predicts a temperature at minimum of 10^5 K.

OAO-2 observations were made of the dwarf nova SS Cygni on three occasions – at minimum 10 days after the decline from maximum, at maximum 6 days after maximum was reached, and during the rise to maximum about 4 days before maximum. Holm & Gallagher (1974) have found that the relative energy distribution of SS Cyg varies only slightly from minimum to maximum (figure 7). These observations suggest that the increase in visual magnitude is not the result of the redistribution of a constant luminosity but is the result of a rapid increase in energy generation. However, this conclusion is not final because the observation of SS Cyg at minimum has large observational errors due to sky background and is contaminated by circumstellar Balmer emission.

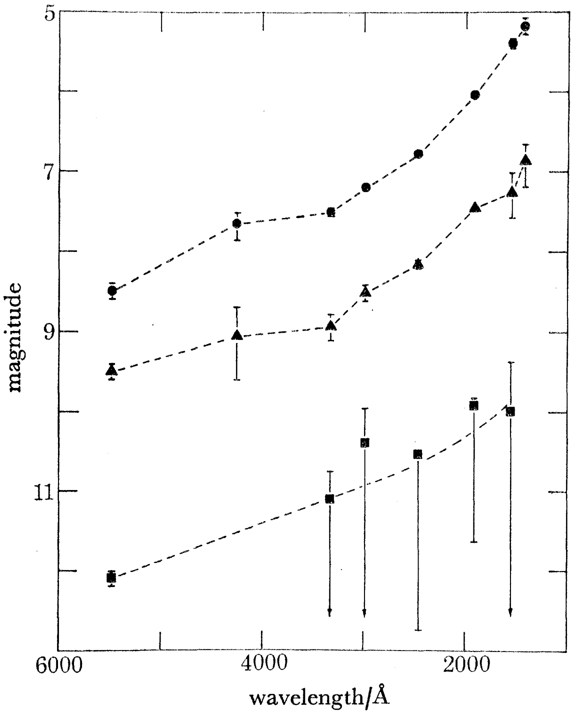

Figure 7. Wavelength–magnitude relation for SS Cygni on three occasions: ●, near maximum; ▲, rising to maximum; ■, at minimum.

Colour temperatures for SS Cyg at maximum light have been derived in a manner similar to that for V603 Aql. For reasonable values for the extinction ($0.0 < E_{B-V} < 0.16$), the average colour temperature ranges from 17000 to 22000 K. These temperatures are in fair agreement with those obtained from the slope of the Paschen continuum (Hinderer 1949; Walker & Chincarini 1968) and from the Balmer jump (Holm & Gallagher 1974). Therefore we assume that they are a good approximation to the effective temperature. The corresponding luminosity at maximum is 30–360 $L_{\odot}$, where the greatest uncertainty is in the distance to SS Cyg. Here we used a range of distance from 140 to 330 pc. The luminosity derived for SS Cyg at maximum is a factor of 100 smaller than that of normal novae at maximum and it overlaps the possible range of luminosities for novae at minimum.

Before continuing this discussion of variable star observations, I want to digress for a few words concerning hot subdwarfs, a topic relevant to the papers presented here by Code and by Wilson. OAO-2 observations were made of 16 hot subdwarfs and white dwarfs. The candidates for observation were selected because they were relatively bright visually and relatively blue. The magnitude–wavelength relation for BD + 28° 4211 is shown in figure 6. Greenstein & Oke (1966) classify it as sd 07 p. The ultraviolet data shows that BD + 28° 4211 is about 0.6 *m* brighter at 1550 Å relative to 3320 Å than the 07 star 15 Mon. 15 Mon has been corrected for $E_{\mathrm{B-V}} = 0.07$; BD + 28° 4211 has not been corrected for any extinction. The energy distribution of BD + 28° 4211 agrees better with a very hot ($T = 10^5$ K) black-body than with any observed normal star. Other stars observed that appear to show a far ultraviolet excess are BD + 25° 4655, Feige 24, and possibly BD + 75° 325 and HD 49798.

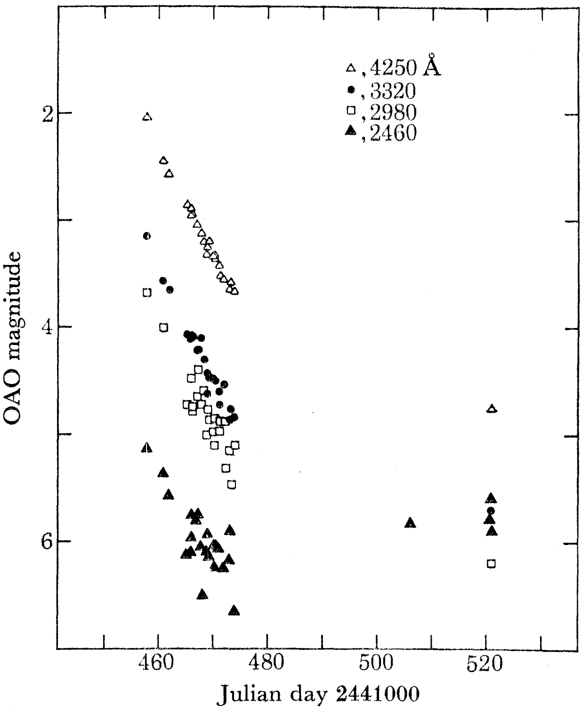

FIGURE 8. Ultraviolet light curves of the 1972 supernova in NGC 5253.

Extreme among variable stars, the type I supernova in NGC 5253 was observed by OAO-2. An initial analysis has been made by Holm, Wu & Caldwell (1974). Figure 8 illustrates the light curves of this supernova at 4250, 3320, 2980 and 2460 Å. The 4250 Å light curve agrees well with ground-based B light curves. At 1910 Å and shortward the object was too faint to be detectable. Unlike Nova Ser 1970, all of the supernova light curves decline simultaneously – with the possible exception of the 2460 Å curve after J.D. 2441506. Those last 2460 Å measurements are marginal. Evidence suggests that the increase is real, as it was in Nova Ser 1970, but an apparent increase could also be caused by a number of possible observational errors. Even if the increase were real most of the energy is still radiated longwards of 3000 Å at J.D. 2441520.

During the period of OAO-2 observations the photosphere of the supernova was cool. The colour excess for the supernova was estimated to be 0.22 by three independent methods. Its colours corrected for extinction are indicated in figure 5 for maximum plus 20 days and plus 35 days. (Maximum light occurred close to J.D. 2441438 according to Ardeberg & de Groot (1973).) At maximum plus 20 days, the supernova closely resembled i^1 Sco, F2Ia, in the colours 2980–3320 and 2460–3320 Å. Between J.D. 2441458 and J.D. 2441520 only 30 % of the flux was radiated shortward of 3320 Å. These results are in general agreement with the temperatures derived from the visual and infrared photometry of Kirshner *et al.* (1973*a*). However, the average ultraviolet colour temperatures at maximum plus 20 days are only 7000 K while Kirshner *et al.* (1973*a*) obtain a best fit with 10000 K. The phenomenon may be the same as has been previously described as a near ultraviolet depression (Zwicky 1965). Kirshner, Oke, Penston & Searle (1973*b*) suggest that the envelope of the supernova is hydrogen poor. If so, the importance of line blocking by metals would be enhanced and the middle ultraviolet (3500 Å $> \lambda >$ 2000 Å) could be depressed relative to the visual.

There are large differences between the three types of explosive variables considered here. But they all have in common a rapid increase in energy generation and the development of an extended envelope which redistributes the emitted radiation into the visual and brings about the visual maximum. The temperatures of the photosphere are related to the radiative luminosity and the mass loss rate. The supernova was very luminous, but its mass loss rate must have been sufficiently large during the period of OAO observations that most of the radiation was converted to visual light. The decline in its visual light was paralleled by a corresponding decline in total luminosity. Since the temperature of the photosphere did not change significantly during this period a decline in the mass loss must have accompanied the decline in luminosity. The dwarf nova is not very luminous, but so little mass is in its envelope that the photosphere appears hot. The rapid decay of the light of the dwarf nova after maximum also indicates that the thermal inertia, and therefore mass, of the envelope is small. The nova was intermediate between these two extremes. Shortly after maximum its mass loss rate was sufficiently large to give it a cool photosphere. But the mass loss rate then fell while the luminosity remained large so that the photospheric temperature rose.

5. Conclusion

The OAO-2 has done useful pioneering work in the study of variable stars in the ultraviolet. Its observations have provided a few surprises – for example, the phase reversal in Ap variables and the extended maximum of Nova Serpentis 1970. It has also been used to survey many of the known types of variable stars. A number of these observations remain to be analysed but it is expected that eventually a sequel to this paper will be able to include new data on many of the stars in table 1 as well as on variables for which less extensive observations were made.

In the study of variables we have found that close cooperation between ultraviolet and visual observers is essential. The measurement in the two spectral regions complement each other. The visual and infrared photometry and the visual estimates of extinction were essential to the creation of the picture we have of Nova Ser. The continuous study of SS Cygni carried on by the American Association of Variable Star Observers was vital to the interpretation of the ultraviolet observations of that star. Also of great importance is the role of ground-based observers in discovering explosive variables and rapid changes in other stars. I want to urge here that news of a discovery be communicated as rapidly as possible to observers with ultraviolet and X-ray satellites in order that the best possible use will be made of these unique resources. The more rapidly observations can be started the more valuable they will be to the astronomical community.

We are finding that the ability to measure the total flux, infrared through ultraviolet, provides a useful tool in determining the physical processes involved in variable stars.

I wish to thank Dr R. Bless and Dr A. Code for giving me the opportunity to observe with the OAO-2 and for making it possible for me to present this paper. This paper could not have been given without the work of Dr A. D. Code, Dr J. S. Gallagher, Dr C.-C. Wu, Dr M. R. Molnar, Dr J. D. Hutchinson, and Dr J. J. Caldwell in analysing the variable stars discussed here. I thank Dr J. Hutchinson for permission to use the analysis of Polaris before publication. Special thanks are due to Dr T. Houck who taught me how to observe with the Wisconsin instruments on OAO-2. Dr C. F. Lillie and Dr D. M. Gottlieb were also involved in obtaining some of these observations. Finally, it is a pleasure to acknowledge that the section on explosive variables relies heavily upon work currently in progress with Dr J. S. Gallagher.

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