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The 1979 outburst of U Scorpii

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Summary. Optical and ultraviolet observations are presented of the 1979 outburst of the recurrent nova U Sco. For the first time the evolution through outburst is documented photometrically and spectroscopically. Lines of the following ions are identified: H I, He II, C IV, N III, N IV, N V, O IV, O VI and Si IV. No forbidden lines were observed. Mg I was seen in absorption at a late stage in the decline. The Balmer lines have broad and narrow components which change with time. There is evidence that nitrogen is overabundant with respect to carbon and the helium to hydrogen number ratio is about 2.

1 Introduction

The recurrent nova U Sco underwent its fourth recorded outburst on 1979 June 24 reaching $m_V \sim 8.7$ and fading to quiescence by 1979 October. There are only about a dozen recurrent novae known (including the X-ray recurrent novae) and they appear to be a rather inhomogeneous group containing stars as dissimilar as T CrB (binary period 230 day) and WZ Sge (binary period 82 min). The outburst intervals are irregular and range from 10 to 100 yr and the optical amplitudes are around 6–10 mag.

Before this outburst almost nothing was known about U Sco. The three previous outbursts occurred in 1863 (Pogson, Brook & Turner 1908), 1906 and 1936 (Thomas 1940). The rate of decline is so rapid (it heads the speed league Table 1.6, in Payne-Gaposchkin 1957) that intervening outbursts may have been missed, although since 1953 the star has been monitored regularly by the Variable Star Section of the Royal Astronomical Society of New Zealand (Bateson, Jones & Menzies 1971; Bateson 1979a). Because U Sco is so faint in

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quiescence, no identification for the quiescent star existed until the work of Webbink (1978).

An early outburst spectrum taken on 1979 June 28.95 UT is given by Dürbeck & Seitter (1980). The first spectrum taken at the Anglo-Australian Telescope was on July 2, some eight days after outburst despite one of the co-discovery observations being made by T. Cragg at the AAT site (Narumi, Kuwano & Cragg 1979). Preliminary information on the early spectra taken at the AAT was given by Hill, Pringle & Whelan (1979), who also confirmed Webbink's identification to be correct (see Plate 1). During the succeeding months we have made a number of further observations of U Sco as it declined, and we report them here. The observations are described in Section 2 and discussed in Section 3. We summarize our findings in Section 4.

2 Observations

2.1 PHOTOMETRY

Photometric observations of U Sco were made by several techniques from 1979 June 29 to September 12. The measurements are shown in Table 1.

Five-colour *UBVRI* photoelectric photometry was carried out using the 'People's Photometer' attached to the 1.9-m telescope at SAAO. Two photomultipliers were used covering separately *UBV* and *VRI* wavebands. The reduction procedures were standard following Hardie (1962). Also shown are the *UBVRI* measurements of Whitney (1979) as corrected (private communication) for a misprint in *V–I*. In Table 1 magnitudes in the *V* column are *V* magnitudes for the SAAO observations. For the other observations the symbols 'TV', 'J' and 'Sp' are used. TV refers to magnitude estimates made using the AAT TV system through

Table 1. Photometry of U Sco during outburst.

Date (U.T.) 1979	V	B-V	U-B	V-R	V-I
June 26.16	10.30 ± 0.05 W	-0.13 ± 0.05	-0.58 ± 0.05	1.15 ± 0.05	0.96 ± 0.05
June 29.74	11.92 ± 0.03	-0.25 ± 0.02	-0.60 ± 0.02	0.39 ± 0.05	0.54 ± 0.05
June 30.81	12.01 ± 0.08	-0.15 ± 0.03	-0.63 ± 0.03	0.37 ± 0.05	0.60 ± 0.05
July 01.75	12.77 ± 0.03	-0.28 ± 0.03	-0.64 ± 0.03	0.41 ± 0.05	0.65 ± 0.05
July 02.51	13.5 ± 0.4 TV				
July 02.77	13.33 ± 0.05	-0.22 ± 0.03	-0.73 ± 0.03	0.34 ± 0.05	0.58 ± 0.05
July 03.37	> 12.9 TV				
July 06.58	13.95 ± 0.2 Sp				
July 12.43	15.0 ± 0.3 TV				
July 14.48	15.0 ± 0.3 J				
July 28.50	15.7 ± 0.7 TV				
Aug 13.41	17.5 ± 1.0 TV				
Aug 15.38	17.7 ± 0.6 J				
Sept 12.41	18.5 ± 1.0 TV				

W Whitney (1979) J UKSTU IIIaJ plate

TV AAT TV magnitude Sp AAT spectrophotometry (Flux at 4900 Å)

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the 24-inch finder telescope and/or direct through the 3.9-m main telescope. The red response of the TV photocathode implies that TV magnitudes correspond roughly to the *R* band. The July 2.51 TV and July 2.77 photoelectric estimates agree well with each other confirming that TV magnitudes are reasonably accurate. J refers to magnitudes measured from IIIaJ UK Schmidt plates of the field near U Sco. The *J* waveband corresponds roughly to 5000 Å. Details of these plates are reproduced in Plate 1. For TV and J the values were derived by comparing the diameters of images of stars of known brightness with that of U Sco using the methods described by King & Raff (1977), normalized to the sequence described by Bateson *et al.* (1971). The value labelled Sp is from a spectrophotometric scan of U Sco taken using the IPCS attached to the AAT, and corresponds to the flux at 4900 Å.

Fig. 1 shows the light curve of U Sco constructed from Table 1, and from the magnitude estimates given in the literature (Narumi *et al.* 1979; Bortle 1979; Bateson 1979a). We note that the faint end of the light curve given in Bateson (1979a), which was noted by him to be approximate, lies systematically above ours.

Also shown in Fig. 1 is an estimate $m_V = 19.3 \pm 0.5$ for the quiescent state of U Sco. This value was obtained by measuring image diameter on four Schmidt photographs – the Palomar O Survey plate, the ESO B Survey plate, and UK STU plates numbers J2465 (1976 July) and J4893 (1979 March). The quiescent values on all plates were near to the mean value quoted above. Webbink (1978) derived $m_V = 19.2 \pm 0.3$ from the Palomar O Survey plate.

The peak magnitudes of the previous recorded outbursts were 9.1 mag (Pogson *et al.* 1908) and 8.8 mag in 1906 and 1936 (Payne-Gaposchkin 1957). The brightest magnitude observed in the current outburst was $m_V = 8.7$ (Narumi *et al.* 1979). As can be seen from the light curve the initial decline is very rapid, falling at a constant rate of about 0.5 mag day^{-1}.

The time taken to fall by 3 mag is $t_3 = 6.0 \pm 0.2$ day which is similar to the value of 6.7 day for the maxima of 1863 and 1936 (Payne-Gaposchkin 1957). Below 14 mag the rate of

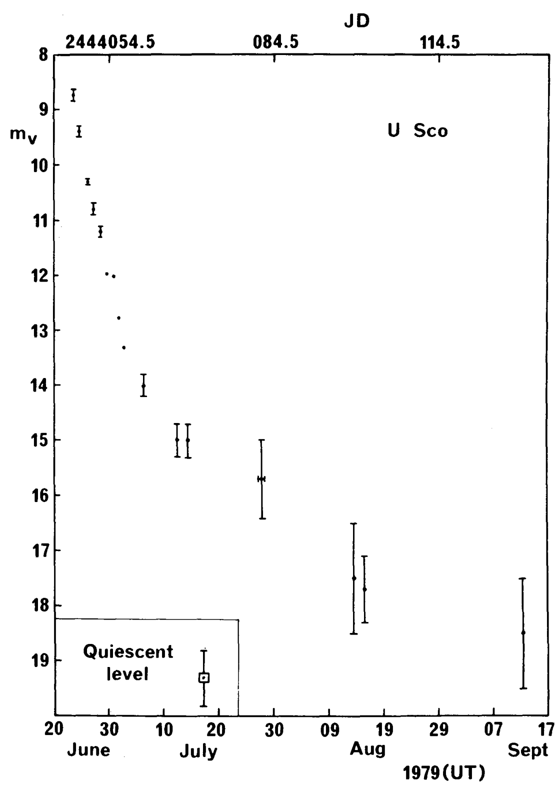

Figure 1. The outburst light curve of U Sco. The quiescent level is also shown.

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decline becomes slower averaging roughly 0.1 mag day^{-1} over the next 40 days. The observation on September 12, some 76 days after outburst, is consistent with the system having returned to quiescence.

2.2 SPECTROSCOPY

Spectroscopic observations of U Sco in outburst were obtained at various times during the interval 1979 July 2 to September 12 (UT). The Journal of Observations is shown in Table 2. All observations except one were obtained with the IPCS attached to the 25-cm camera of the RGO spectrograph mounted at the $f/8$ Cassegrain focus of the AAT. A variety of gratings, resolutions and wavelength ranges was used. Standard reduction procedures were employed. On July 6 a short wavelength ultraviolet spectrum was obtained using the *IUE* satellite. To ensure spectrophotometric accuracy the low resolution large aperture mode was used. The wavelength resolution is ~ 6 Å. The raw *IUE* data were processed by the ESA Madrid Observatory and include corrections for wavelength scales, background and relative intensities. Subsequently these data have been reprocessed at UCL to remove the ITF error present in the original processing, using correction algorithms in computer programs supplied by Snijders (1980) which included a transformation of relative intensities to absolute flux values.

In response to what later proved to be a false report of outburst (Bateson 1979b) a pre-outburst spectrum was obtained on 1979 March 26. The observing conditions were poor due

Table 2. Journal of spectroscopic observations of U Sco.

Date 1979	UT (mid exposure)	Exposure time (min)	Wavelength range Å	Resolution Å	Comments
Mar 26	19^h07^m	17	3500-7000	20	Pre-outburst
July 2	12 22	25	4110-5080	2	
July 3	09 09	33	4110-5080	2	Cloud
3	10 30	17	6200-7200	2	Cloud
July 6	04 28	40	1150-2000	6	IUE SWP5728 large aperture
6	14 09	4	3000-4030	-	Wide slit
6	14 28	5	3950-4950	-	Wide slit
6	13 58	12	3000-4030	1.6	
6	14 18	8	3950-4950	1.6	
July 8	13 59	5	3700-4230	0.8	
	13 46	18	4150-4630	0.8	
July 12	10 39	30	3860-5100	2	
July 27	13 40	33	3300-7200	7	
28	12 41	33	3300-7200	7	
Aug 13	10 17	17	3600-5450	4	weak
Sep 12	10 17	33	3500-7000	7	very weak, cloud.

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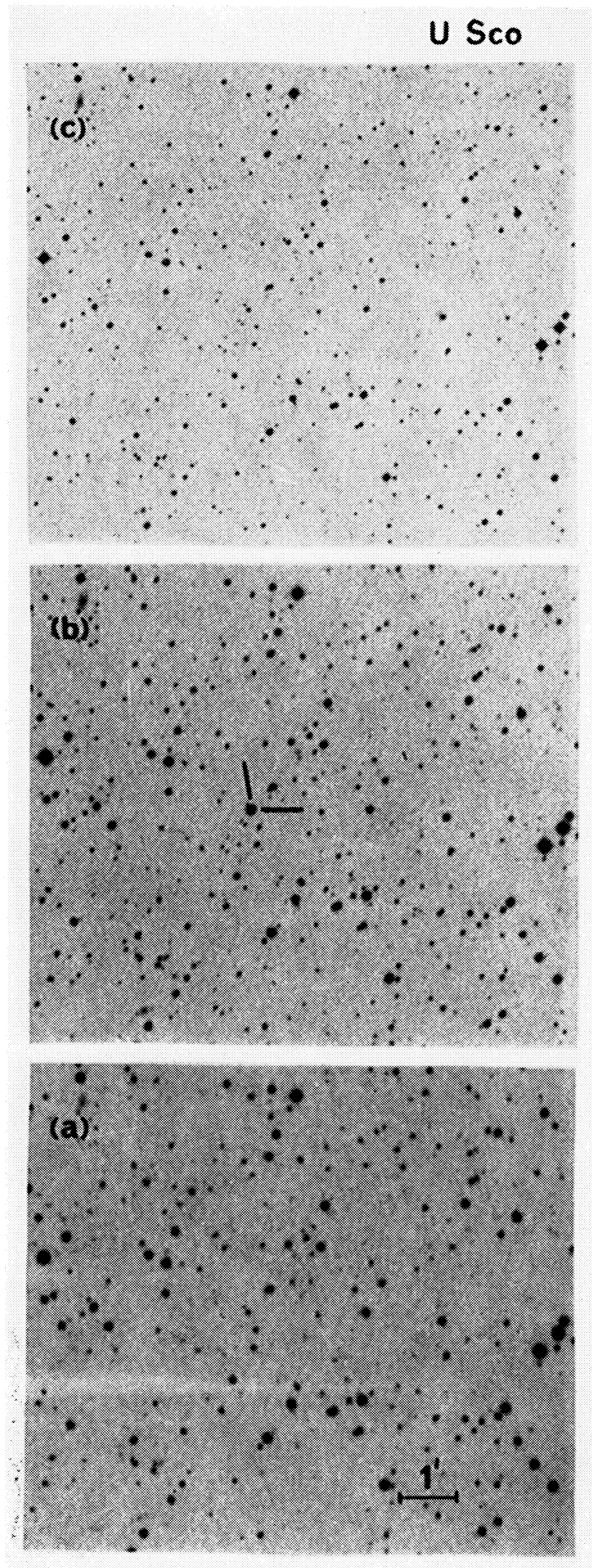

Plate 1. The field of U Sco. North is to the top and east to the left. The scale is shown. (a) is the Palomar O plate taken when U Sco was in quiescence, (b) is UKSTUIIIaJ 5177 taken on 1979 July 14, U Sco has $m_V=15$ and is marked and (c) is UKSTUIIIaJ 5279 taken on 1979 August 15, when U Sco had almost returned to its quiescent level.

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to approaching dawn but the spectrum proved usable. It was clear from this observation that U Sco was not bright. This is confirmed by Shao (1979) and by the UKSTU plate J4893 taken on 1979 March 26.

2.2.1 *General Description*

The evolution of the spectrum of U Sco through the outburst is shown in Fig. 2 for the wavelength range λλ 4100–5100 Å. The spectrum taken ~ 3 months before outburst is of poor signal to noise and the only distinguishable feature is the He II λ 4686 emission line.

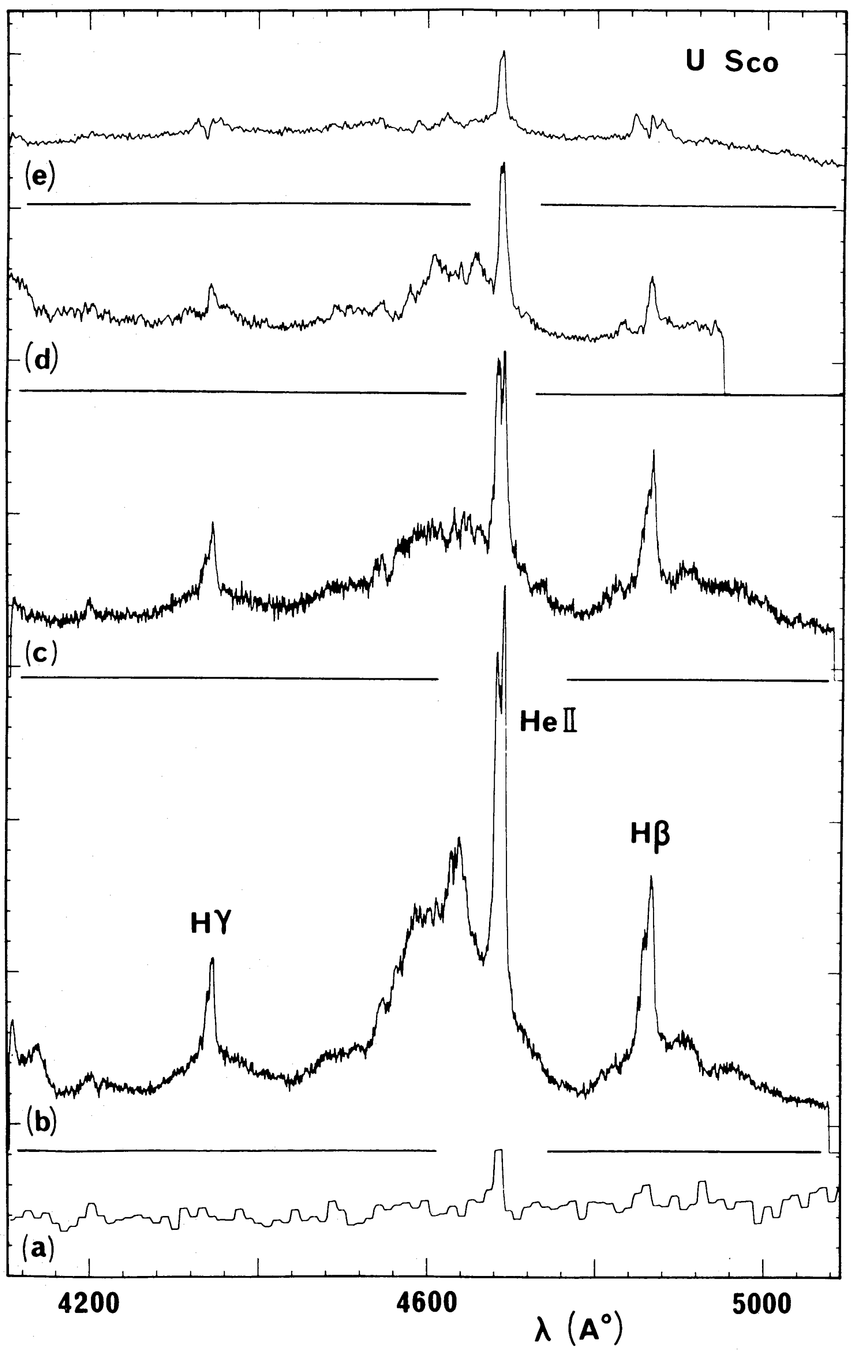

Figure 2. The early evolution of the spectrum of U Sco through the 1979 outburst in the wavelength range λλ4100–5100 Å. The dates of the exposures are (a) March 26 (preoutburst) (b) July 2 (c) July 3 (d) July 6 and (e) July 12. The zero level of each scan is shown, but the vertical scale is uncalibrated.

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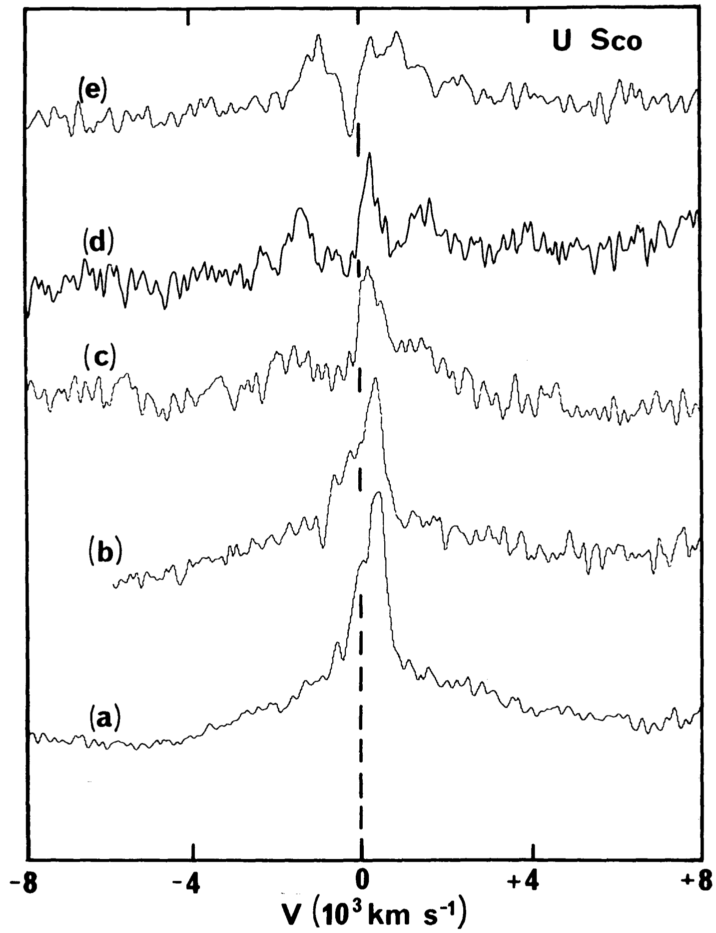

Figure 3. The Hγ profile of U Sco during the 1979 outburst drawn on a velocity scale. The dates of the exposures are (a) July 2 (b) July 3 (c) July 6 (d) July 8 and (e) July 12.

The first spectrum taken after outburst shows strong emission lines of He II λ4686 and the Balmer series and an emission complex at λλ4500–4700. The Balmer emission (see Fig. 5) has two distinct components: a broad one with FWZI ~ 10 000 km s^{-1} and a narrow asymmetric one split into two to four components separated by of order 500 km s^{-1}.

As the nova faded the emission features became weaker. The λλ4500–4700 complex and the broad components of the Balmer lines had vanished by 1979 July 12. The strongest line remains He II λ4686 emission. Fig. 3 shows the detailed changes in the Hγ profile.

Fig. 4 shows the later evolution of the spectrum at 5 to 7 weeks after the outburst. By July 28 the nova had faded by 7 mag (Fig. 1) and the only features evident are strong He II λ4686 emission, some Balmer lines and a feature at λ3480 probably due to N IV.

By 1979 August 13, the nova had faded by a further 2 mag and the spectrum now shows only He II λ4686 emission and an absorption feature near λ5180 which we identify as the Mg I *b* band seen in late-type stars.

Our final spectrum on September 13 (when the nova was near or at quiescence) is essentially identical to that of August 13, but with poorer signal to noise.

2.2.2 Detailed description of outburst spectra

July 2. The spectrum is shown in Fig. 2. The strong He II λ4686 emission shows a double peaked profile. The central dip has radial velocity 95 (± 50) km s^{-1} and the emission peaks are

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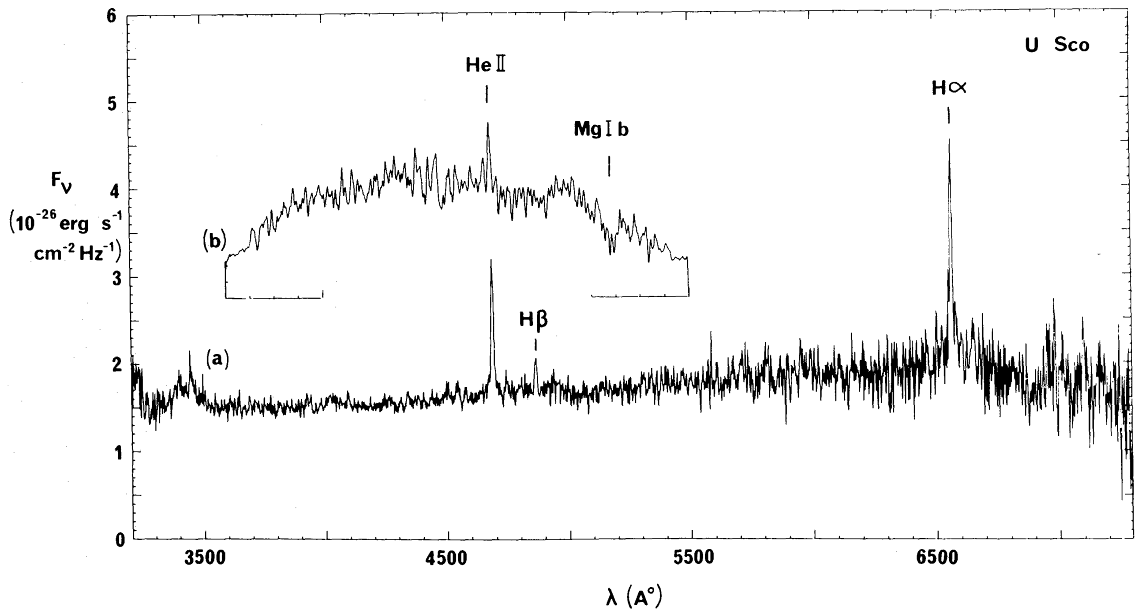

Figure 4. The spectrum of U Sco late in the 1979 outburst. The dates of the exposures are (a) July 27 and 28 and (b) August 13. Scan (a) has been calibrated approximately and for this scan we plot F_ν in units of 10^{-26} erg s^{-1} cm^{-2} Hz^{-1}. Scan (b) is not calibrated but its zero level is shown.

at velocities ±225 (±30) km s^{-1} relative to it. Note that relative velocities are more accurately determined than their absolute values. The errors given here are typical for the measurements quoted below. None of the velocities quoted includes the heliocentric correction which would be of order −20 km s^{-1}.

The narrow components of the Balmer lines (Hβ and Hγ) have FWZI ~ 1600 km s^{-1}. The peaks of the lines are at 320 and 417 km s^{-1} respectively. On the blue side of the profile there are two obvious components, the peaks of which are at −81 and −575 km s^{-1} (Hβ) and at +37 and −550 km s^{-1} (Hγ). The broad component determined from Hγ has FWZI 10 000 ± 1000 km s^{-1}. The broad component contains about 3 to 4 times as much flux as the narrow component. The flux in the narrow component of the Hγ line has 2.2 ± 0.5 times as much flux as in the Hγ line. Because of other features seen in the wings of the Hβ line the ratio of the fluxes in the broad components cannot be accurately determined.

There is a strong broad emission feature extending from about 4500 to 4700 Å. The various components of this feature are more evident in the spectrum taken on 1980 July 6 and 8 which were taken at higher resolution (see below). The components of this feature probably include complexes of emission lines due to N III, N V, C III, C IV and He II. Particularly evident is a narrow component on the peak of the feature between λλ4630 and 4640 Å which is probably due to N III λλ4634–4640. This feature has been noted in the outbursts of the recurrent novae RS Oph (Tolbert, Pecker & Pottasch 1967) and T CrB (Herbig & Neubauer 1946; Bloch *et al.* 1946).

Other features in the spectrum include an emission feature at 4908 Å which may be N III λ4905 and an emission feature near 4210 Å which may be He I λ4200 together with N III λλ4196, 4200, 4216.

July 3. The spectrum is shown in Fig. 2. The spectrum resembles that of the day before but the emission had weakened. The He II profile has not changed significantly. The Balmer lines Hα, Hβ and Hγ are shown in Fig. 5 where they have been plotted on a velocity scale. The Hβ and Hγ profiles are very similar. The Hα profile taken 80 min later has poorer signal to

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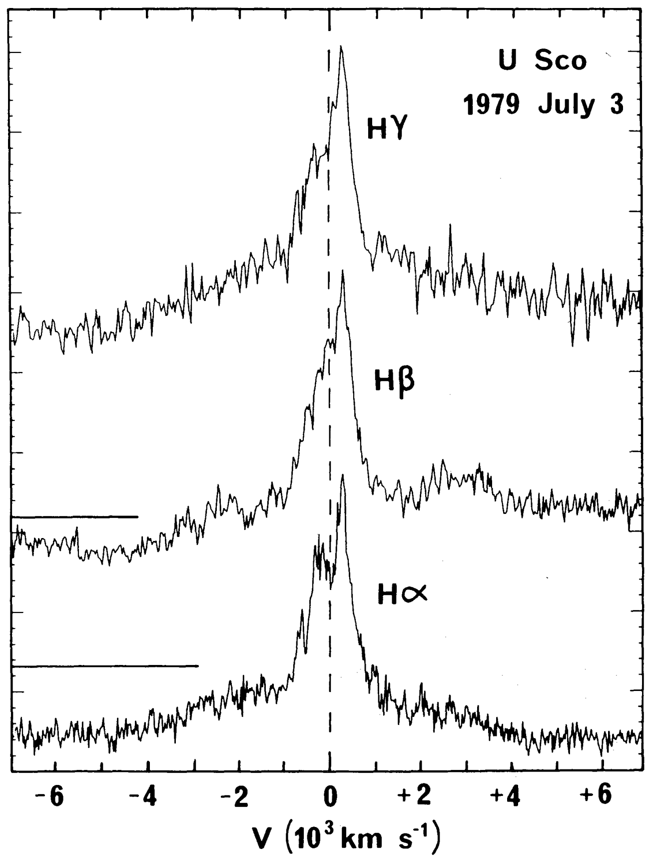

Figure 5. The Balmer line profiles of U Sco on 1979 July 3 plotted on a velocity scale. The zero level of each scan is shown.

noise and is probably not significantly different. The narrow component is still strongly asymmetric with the peak in all three lines at $350 \pm 40\,\mathrm{km\,s^{-1}}$. To the redward side of the peak the profile is steep, to the blueward side it is shallower and to within the limits imposed by the noise appears to show significant velocity structure. The FWZI of the narrow component is unchanged at $1600\,\mathrm{km\,s^{-1}}$ and in contrast to the profile as a whole is symmetric about zero velocity. The broad Balmer component still contains 3 to 4 times as much flux as the narrow one. The flux ratio in the narrow components is $F(\mathrm{H}\beta)/F(\mathrm{H}\gamma) \sim 2$. The flux ratio of the broad components could not be measured with significant accuracy.

The λλ4500–4700 emission feature has weakened more than the Balmer lines. In addition the narrow N III component seen on July 2 on the peak of the feature has vanished. The features at 4906 Å and near 4200 Å can still be seen. No features other than Hα were seen in the red scan.

July 6. The spectra taken on July 6 are shown in Fig. 6. The emission features have weakened further. The strongest feature is still He II λ4686 but now it is not so clearly double peaked. The peaks are at ± 100 $(\pm 30)\,\mathrm{km\,s^{-1}}$ relative to the central absorption dip at $+60$ (± 50) $\mathrm{km\,s^{-1}}$.

The Balmer profiles have changed significantly. The narrow component is narrower and more symmetric. In addition, there are other narrow features close to the line which may be shifted components of the line. In other words the symmetric broad components appear to have been replaced by narrower substructure. The narrow peaks of Hβ and Hγ are at $180 \pm 30\,\mathrm{km\,s^{-1}}$. The narrow component line ratio is $F(\mathrm{H}\beta)/F(\mathrm{H}\gamma) \sim 2$.

The optical spectra taken on July 6 (at a resolution of 1.6 Å) are shown in Fig. 6 and

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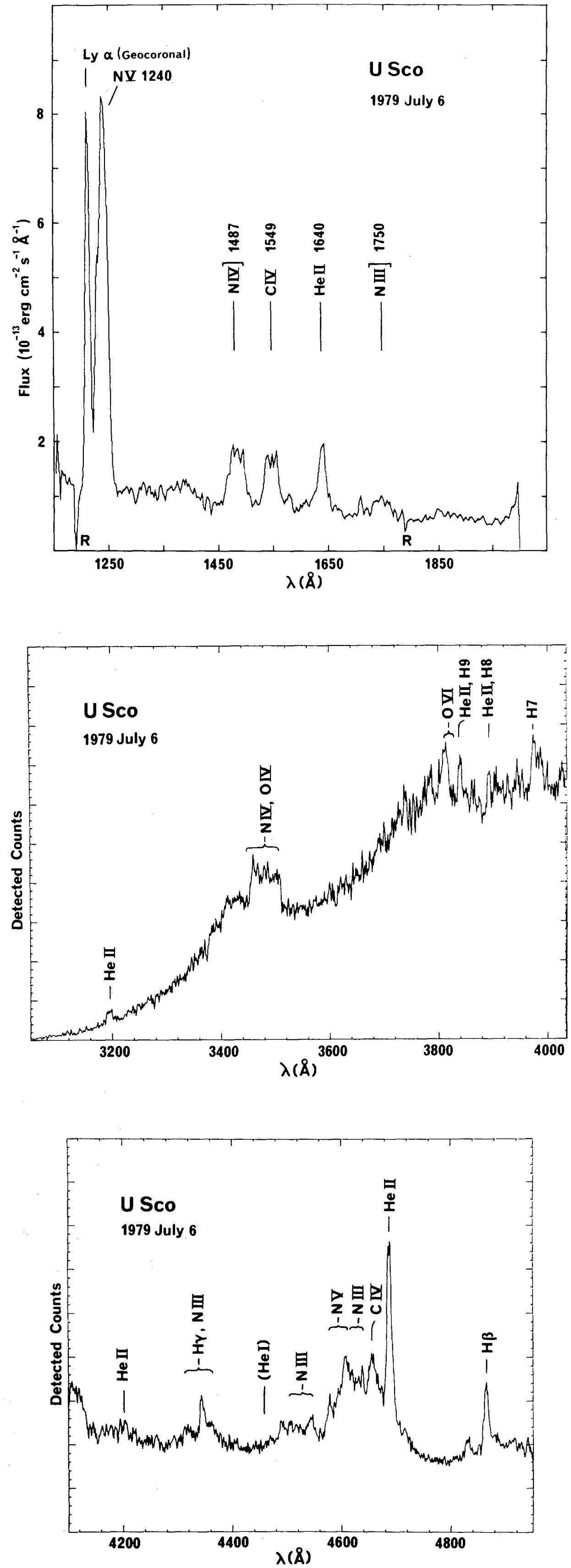

Figure 6. The spectra of U Sco obtained on 1979 July 6. The ultraviolet spectrum in the range λλ1150–2000 Å was obtained using *IUE*, and the optical spectra were taken at the AAT.

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Table 3. Emission line identifications for July 6 spectra.

Multiplet Wavelength (Å)	Ion	Multiplet No.	Transition
3342.7, 3355.5	NIII	7	$3s'\,^2P^o-3p'\,^2S$
3354.0, 3374.1	NIII	5	$3s'\,^4P^o-3p'\,^4P$
3348.1, 3349.1, 3378.1	OIV	4	$3s'\,^2P^o-3p'\,^2D$
3381.2, 3385.5, 3390.2, 3396.8, 3405.8, 3409.7, 3425.6	OIV	3	$3s'\,^4P^o-3p'\,^4D$
3403.5, 3411.7, 3413.6	OIV	2	$3p\,^2P^o-3d\,^2D$
3443.6, 3445.2, 3454.7, 3461.4, 3463.4, 3474.6	NIV	7	$3s'\,^3P^o-3p'\,^3P$
3478.7, 3483.0, 3485.0	NIV	1	$3s\,^3S-3p\,^3P^o$
3489.8, 3492.2, 3493.4	OIV	14	$3s'\,^2P^o-3p'\,^2D$
3689.9, 3694.1, 3701.1, 3707.4, 3714.4, 3735.4	NIV	12	$3p'\,^3D-3d'\,^3P^o$
3725.9, 3729.0, 3736.9, 3744.9, 3758.0	OIV	6	$3p'\,^4D-3d'\,^4F^o$
3745.9, 3754.7, 3771.1	NIII	4	$3s'\,^4P^o-3p'\,^4S$
3752.8, 3762.4, 3771.4, 3792.9	NIII	11	$3p'\,^4D-3d'\,^4P^o$
3811.4, 3834.2	OVI	1	$3s\,^2S-3p\,^2P^o$
3934.4, 3943.0	NIII	8	$3p'\,^2P-3d'\,^2D^o$
4057.8	NIV	3	$3p'\,^1P^o-3d\,^1D$
4088.9, 4116.1	SiIV	1	$4s\,^2S-4p\,^2P^o$
4097.3, 4103.3	NIII	1	$3s\,^2S-3p\,^2P^o$
4195.8, 4200.1, 4215.8	NIII	6	$3s'\,^2P^o-3p'\,^2D$
4318.8, 4321.3, 4325.4, 4327.8, 4332.9, 4336.9, 4345.7	NIII	10	$3p'\,^4D-3d'\,^4D^o$
4510.9, 4514.9, 4518.2, 4523.6, 4530.9, 4534.6, 4547.3	NIII	3	$3s'\,^4P^o-3p'\,^4D$
4539.7, 4544.9	NIII	12	$4p\,^2P^o-5s\,^2S$
4603.7, 4620.0	NV	1	$3s\,^2S-3p\,^2P^o$
4634.1, 4640.7	NIII	2	$3p\,^2P^o-3d\,^2D$
4658.0	CIV		5g - 6h
4858.8, 4867.2, 4873.6, 4881.8, 4884.1, 4896.6	NIII	9	$3p'\,^4D-3d'\,^4D^o$

cover the range 3100–4950 Å. This enables us to make a more complete discussion of the spectral features, although some were evident in the earlier spectra.

The Balmer lines of hydrogen are visible in emission as far as H10 and there is no Balmer Jump. There is strong He II emission at 4686 Å ($n = 4 \rightarrow 3$) and 3203 Å ($n = 5 \rightarrow 3$). The Pickering series of He II is also present in emission. The even members of the series coincide with hydrogen Balmer lines, but odd members of the series are visible as far as $n' = 17$ (3858 Å). No lines of He I are seen.

The very strong emission feature underlying He II λ4686 in Fig. 6, and stretching from 4570 to 4730 Å, appears to be due chiefly to the following transitions: C IV λ4658 ($n = 6 \rightarrow 5$); N III λλ4634, 4630 Å ($3d\,^2D \rightarrow 3p\,^2P$); and N V λλ4604, 4620 ($3p\,^2P^o \rightarrow 3s\,^2S$). The latter multiplet shows some evidence of P Cygni structure, with an absorption edge at 4578 Å, corresponding to a velocity of 1700 km s^{-1}, and emission peaking at 4605 Å. The presence of C III λλ4647, 4650 ($3p\,^3P^o \rightarrow 3s\,^3S$) is uncertain. The 3811, 3834 Å doublet of O VI ($3p\,^2P^o \rightarrow 3s\,^2S$) is present in emission on July 6, and its presence was also confirmed with the higher resolution observations of July 8. The strong plateau-shaped emission feature centred at 3480 Å in Fig. 6 appears to be mostly attributable to the N IV triplet at 3483 Å ($3p\,^3P^o \rightarrow 3s\,^3S$).

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The 3400 Å and 3750 Å regions of the spectrum of U Sco in Fig. 6 show heavily blended emission structure and in making identifications we have been guided by the fact that the spectrum bears a strong resemblance to that of a WN6 Wolf–Rayet star (see, e.g. Smith & Kuhi 1970). Table 3 lists our proposed emission line identifications for the 3300–4900 Å region of U Sco, for elements other than H and He. The multiplet identifications are taken from Moore (1945, 1970).

The presence of multiplets 2, 3 and 4 of O IV appears to be required to explain the broad emission in the region of 3400 Å, whilst we can find no strong evidence for the presence of the Bowen lines of O III at 3429 and 3444 Å. The well known unidentified emission lines at 4486 and 4504 Å (see, e.g. Conti 1973) are present in our July 6 spectrum and in addition there are unidentified emission features at 4075 Å and 4830 Å.

The presence of so many lines of N III and N IV in the spectrum of U Sco probably indicates a significant enhancement of the nitrogen abundance over cosmic values, by analogy to the case of the WN stars, but a quantitative analysis is unfortunately difficult to carry out. However, the relative abundances of hydrogen and helium *can* be derived by making use of the Pickering series method which has been applied to Wolf–Rayet stars (e.g. Castor & van Blerkom 1970). This makes use of the fact that alternate (even) members of the He II Pickering series coincide with hydrogen Balmer lines and that the higher members of the series ($n' \gtrsim 10$) should be optically thin, so that the ratio of the fluxes in even and odd Pickering lines gives $(H^+ + He^{2+})/He^{2+}$ (the transition probabilities times statistical weights of the H and He II lines at the same wavelength are virtually the same; Castor & van Blerkom 1970). We have taken the mean of the fluxes in the Pickering lines corresponding to $n' = 15$ and 17 and compared this with the flux in the blend corresponding to the $n' = 16$ Pickering line and the $n' = 8$ Balmer line. We find

$$H^+/He^{2+} = H/He = 0.5 .$$

This value applies to the narrow component emission region and does not necessarily apply to the broad Balmer component region.

At almost the same time an *IUE* shortwave low resolution spectrum was obtained. The *IUE* spectrum (Fig. 6) is dominated by strong emission lines at λ1240 (N V), λ1486 (N IV]), λ1550 (C IV), λ1640 (He II) and λ1750 (N III]). Broad weak emission is observed between 1360 and 1440 Å, likely contributors to which are O V λ1371, Si IV λλ1393, 1402 and O IV] λλ1397, 1407. The He II line seen at 1640 Å can be used with the optical He II line at 4686 Å as a measure of reddening (see Section 3.3).

The N V λ1240 resonance line is very strong (equivalent width $W_\lambda \sim 130$ Å), whilst by comparison the C IV λ1550 line is rather weak ($W_\lambda \sim 40$ Å). The observed line intensity ratio of N V/C IV ~ 5 is much higher than the usual value of ~ 0.2. This strengthens the conclusion from the optical data above that nitrogen is enhanced relative to carbon. Although ionization effects could be important we note that strong N IV and N III lines are also present. Further the C III] λ1909 intercombination line is not seen whilst the corresponding line in the isoelectronic species N IV] λ1487 is.

July 8. The spectral coverage on this day was from 3700 to 4630 Å with a resolution of ~ 0.8 Å. The Balmer lines (see Fig. 3) have evolved further into a more triple peaked structure. The wavelengths of the three peaks in Hγ correspond to velocities of – 1460, + 150, + 1410 km s^{-1}. The Hδ values agree to within the errors. Other evident emission lines are O VI λλ3811, 3834 and He II λ4542.

July 12. The wavelength coverage is 3860–5100 Å. Most of the spectrum is shown in Fig. 2. The most evident emission line is still He II λ4686. The Balmer line profile has developed

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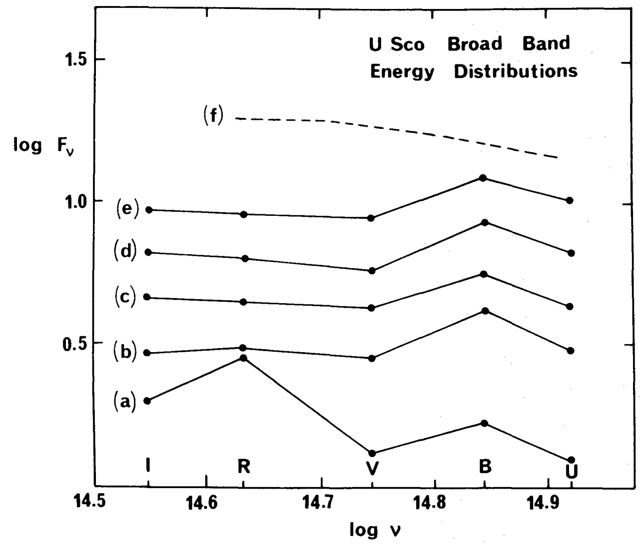

Figure 7. The broadband energy distribution of U Sco in the 1979 outburst. The dates are (a) June 26 (Whitney, private communication) (b) June 29, (c) June 30, (d) July 1, (e) July 2 and (f) July 6. Plots (a)–(e) are broadband colours in *UBVRI* and (f) the continuum only derived from AAT spectrophotometry. The logarithm of flux, F_ν, is plotted against the logarithm of frequency ν in Hz. The zero point of log F_ν is different for each scan.

further into the triple peak structure. There is a strong central absorption at about 150 km s^{-1} which gets deeper at higher members of the Balmer series. The central peak in Hε is at around 350 km s^{-1} compared to that in Hβ at ~ 135 km s^{-1}, which indicates that the position of the central peak may be determined by the strength of the absorption. The outer peaks are symmetric around zero velocity although their velocities increase along the series, being ± 820 km s^{-1} at Hβ, ± 930 km s^{-1} at Hγ, ± 1070 km s^{-1} at Hδ and ± 1150 km s^{-1} at Hε.

The λλ4500–4700 feature has essentially vanished, although there is still evidence of weak emission at 4200 Å (He II), 4542 Å (He II), 4586 Å (?) and 4622 Å (N V?).

July 27 and 28. The spectra taken on July 27 and 28 do not differ significantly and have therefore been added to improve signal to noise. The combined spectrum is shown in Fig. 4. The Balmer series is visible in emission possibly to Hδ. He II (λ 4686) remains strong. We find that $I(\lambda 4686)/I(\mathrm{H}\beta) \simeq 5$ which using the calibration of Miller (1974) would imply an overabundance of helium (He/H ≃ 0.7). This comparison, however, may be invalid in view of the different line profiles. The broad emission feature between λ 3450–3500 is probably the same as that seen on July 6 (see Fig. 6) and is due mainly to N IV. There is some evidence for a broad emission component in Hα.

August 13. U Sco had faded to below 17th magnitude by August 13 and the spectrum is shown in Fig. 4. By September 12 U Sco had faded by a further magnitude to almost its quiescent value. This spectrum was very noisy and does not differ significantly from that of August 13. On August 13 the only emission feature left is He II λ4686. The Balmer series could not be detected. However, an absorption feature at λλ5160–5200 is clearly present and is possibly the Mg I *b* band seen strongly in stars of spectral type later than about G0. This suggests that part of the continuum flux is now coming from an underlying star.

2.3 THE CONTINUUM ENERGY DISTRIBUTION

Five-colour photoelectric photometry (*U,B,V,R,I*) is available for U Sco on five nights (Table 1). These magnitudes have been converted to fluxes using the zero magnitude calibra-

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tion of Becklin (1969, private communication). Fig. 7 (a)–(e) shows these energy distributions, and Fig. 7(f) is derived from an AAT spectroscopic observation, excluding all emission lines, i.e. the continuum only. The date of observation increases upwards. It is clear from Fig. 7 that the energy distributions are similar over the period June 26 (a) to July 3 (e) with the exception of the *I* and *R* band measurement of the first observations.

Barring errors in observation or analysis for the June 26 data, we may attribute this difference to the presence of extremely strong Hα emission soon after outburst. If we are correct in this interpretation it is apparent that the Hα line strength decreases considerably relative to the continuum (Fig. 7a and b), over a time-scale of ~ 3 day. This decrease could be a result of recombination in a high density broad line region. If so we can use the recombination time τ between observations (a) and (b) to estimate the density from the formula $\tau = 3 \times 10^{12}/N_e$ seconds. For $\tau \lesssim 3$ day, we find that $N_e \gtrsim 10^7\,cm^{-3}$. This is in agreement with the absence of the forbidden [O III] λ4363 line in the July 6 spectrum.

The bump in the energy distribution caused by a flux excess in the '*B*' band may be attributed to the emission line blend Hβ, He II, C III/N III etc. But, to be consistent with our recombination argument above, we must require that Hβ does not contribute significantly to the blend.

In Fig. 8 we show the optical and UV continuum energy distribution of U Sco on July 6. The optical data are derived from wide slit AAT observations and the ultraviolet from the *IUE*. The dereddened continuum appropriate to an $A_V \sim 0.6$ mag (see Section 3.3) is also shown, with extinction coefficients taken from Code *et al.* (1976). It can be seen that the derived intrinsic energy distribution is critically dependent on the assumed reddening.

Over a large part of the dereddened optical and UV range the continuum can be approximated by a power law of the form $S_\nu \propto \nu^\alpha$ with $\alpha \sim 0.4$. However, this value should be treated with caution because of its strong A_V dependence. A striking feature of the dereddened continuum is the 'turn up' longward of $\log \nu = 15.25$ (λ = 1690 Å). This is a consequence of applying the reddening correction and could imply too big a correction. It is, however, difficult to accept that the continuum is not reddened by at least a few tenths of a magnitude in A_V, if U Sco is indeed at a distance beyond the galactic disc (Section 3.4).

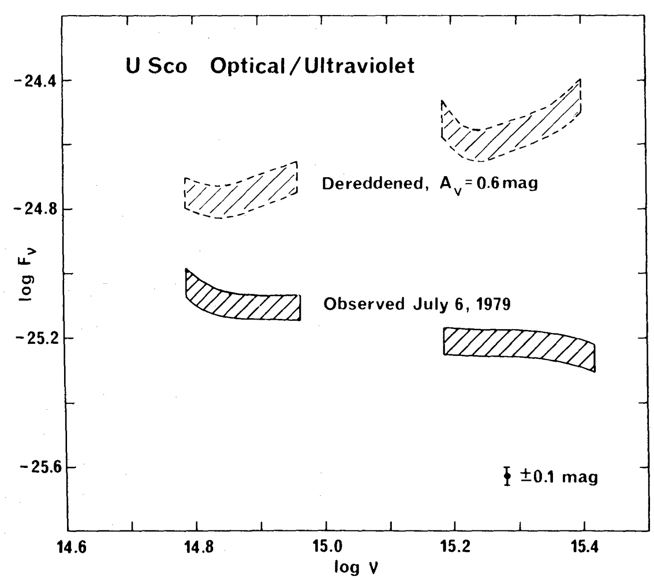

Figure 8. The observed continuum flux of U Sco on 1979 July 6, from a combination of AAT and IUE spectra. The logarithm of flux F_ν in units of erg $s^{-1}\,cm^{-2}\,Hz^{-1}$ is plotted against the logarithm of frequency ν in Hz. The two bands correspond to wavelength ranges λλ3300–4860 and λλ1250–2000. Also shown is the dereddened flux using $A_V = 0.6$ mag derived in Section 3.3.

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3 Discussion

3.1 COMPARISON WITH OTHER RECURRENT NOVAE

The two recurrent novae with rates of decline from maximum comparable to that of U Sco are T CrB and RS Oph. Descriptions of the spectra of T CrB during the outburst of 1946 are presented by Herbig & Neubauer (1946) and Bloch *et al.* (1946). In the first few days T CrB showed strong Balmer emission with both narrow and broad components, the broad having a half width of some 4000 km s^{-1}. As in U Sco strong emission was apparent around 4640 Å (N III) although the absence of Bowen lines (λ3132, λ3444) indicated that this was not excited by fluorescence. Various higher ionization lines, for example N V (λ4603), C IV (λλ5801, 5812), were also identified. Unlike U Sco, however, He I emission was visible at all times, and although He II emission was visible and strengthened relative to He I during the decline, it remained weak (the λ4686 line was initially comparable in strength to Hβ and stayed weaker than Hβ until about a month after outburst when the brightness had fallen by $\Delta m \sim 6$ mag and the nova was close to its quiescent level).

Descriptions of the spectra of RS Oph during the 1958 outburst are given by Tolbert *et al.* (1967), and the spectra of previous outbursts are summarized by Payne-Gaposchkin (1957). Again strong Balmer emission was seen which faded gradually as the brightness declined, although there was no evidence for components as broad as those seen in U Sco and T CrB. Also, although some emission appears at around λ4640 about three weeks after the outburst ($\Delta m \sim 2$ mag) there is no evidence for the broad and strong emission feature seen in U Sco. As in T CrB, He I is visible at all times, with He II appearing about three weeks after outburst and then strengthening relative to He I.

Both T CrB and RS Oph differ significantly from U Sco in that they both show emission from forbidden lines. Only three days after outburst in T CrB the forbidden lines λ6374 [Fe X] and λ5302 [Fe XIV] were 'unmistakably' present and by two weeks after outburst the [Fe X] line had become one of the strongest emission lines in the visible. At about that stage the lines of [O III] λλ4363, 5007 and [Ne III] also appear. Within a week of the outburst in RS Oph [N II] λ5755 and [O III] λ4363 were identified, with [Ne III] λλ3689, 3969 and [O III] λλ4959, 5007 appearing slightly later. In the 1933 RS Oph outburst the coronal lines [Fe X] λ6374 and [Fe XIV] λ5302 were seen about seven weeks after outburst when the star had declined by $\Delta m \sim 5$ mag although the former may have been present some four weeks earlier.

By the time T CrB has faded by $\Delta m \sim 4.5$ to $m_V \sim 7.5$, the M-type spectrum of the red companion star is apparent. At minimum light RS Oph is at about $m_V \sim 12$ ($\Delta m \sim 6$ mag). In 1933 this light level had been reached by about 240 days after outburst by which time the coronal lines had vanished and emission lines of H were prominent, of He I moderately strong and of N III λλ4630, 4640, C III λ4650 and He II λ4686 apparent. At minimum RS Oph is variable and the spectrum undergoes changes. It shows nebular emission and contains absorption lines of a late-type shell spectrum.

The recurrent nova T Pyx shows a much slower decline from outburst peak taking about 100 days to fall by $\Delta m \sim 3$ mag. Spectra of the 1966 outburst are presented by Catchpole (1969) and those of previous outbursts are summarized by Payne-Gaposchkin (1957). A spectrum at minimum light is given by Wyckoff & Wehinger (1977). The strongest emission lines are those of the Balmer series and, later, Fe II, all of which show P Cygni profiles in the first few weeks. He I is seen in emission and later He II which strengthens as He I fades. He II λ4686 strengthens throughout the decline and is weaker than Hβ at all times although by 191 days past maximum it is almost as strong. At the same time strong nebular lines of [O III] λλ4363, 4959, 5007 appear together with N III emission at λ4642. These lines

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eventually supercede the neighbouring Balmer lines of Hβ, Hγ and Hδ. At minimum light the spectrum of T Pyx may be variable, but has been seen to be comprised of a strong continuum plus emission lines of strong He II λ4686, moderate H, and [O III] λ5007.

No satisfactory spectra of the recurrent nova V1017 Sgr are available from the outbursts of 1901 and 1919 (Payne-Gaposchkin 1957). The spectrum at minimum light appears to be variable and is composed of a red stellar component consistent with a G5III star and a strong blue continuum (Brück 1935; Humason 1938; Kraft 1964).

The recurrent nova V616 Mon (the X-ray nova 2A 0620–00) declined even more slowly at optical wavelengths. The spectrum during decline is described by Oke & Greenstein (1977) and by Whelan *et al.* (1977). Compared to U Sco the emission lines seen are very weak. The strongest lines are those of the Balmer series, although lines of He I, He II, N III and possibly [Fe VII] are also seen. These lines are also seen in the decline spectrum of the recurrent X-ray source Aql X–1 (4U 1908 + 00) (Charles *et al.* 1980) when the optical object was at about 4 mag above the quiescent level of $m_V \sim 19$ (Thorstensen, Charles & Bowyer 1978).

3.2 COMPARISON WITH V SGE

The only object among the novae and nova-like variables whose spectrum resembles that of U Sco in outburst is the nova-like variable V Sge (Warner 1976). The optical spectrum of V Sge is discussed by Herbig *et al.* (1965). The common characteristics which distinguish both these objects are:

(i) the presence of high ionization emission lines such as O VI λλ3811, 3834;

(ii) the presence of strong He II λ4686 emission, other He II emission lines and the complete absence of He I;

(iii) the absence of forbidden lines, for example [O III] λ5007.

Ultraviolet spectra of V Sge are presented by Koch *et al.* (1979). In this wavelength range the similarity with U Sco is not so striking. For example, U Sco shows the semi-forbidden lines of N III] λ1750 and N IV] λ1487. A point of similarity is the weakness of the C IV λ1550 emission relative to N V λ1240.

3.3 REDDENING

The line of sight reddening toward U Sco (assuming it to lie beyond the galactic disc) may be estimated from the radio H I observations of Heiles (1975). Using these data Burstein & Heiles (1978) obtained a relation between the H I column and $E(B-V)$. Fortuitously, two of the globular clusters used to construct this relation lie within 5° of U Sco, they have colour excesses differing by ~ 0.1 mag in $E(B-V)$ and this gives an indication of the patchiness of galactic extinction in this direction. If we average these two values and apply the result to U Sco we obtain $E(B-V) \sim 0.24 \pm 0.1$ mag, and using $A_V = 3.1\,E(B-V)$ we find $A_V \sim 0.7 \pm 0.3$ mag.

We are also able to use emission line ratios to obtain reddening estimates. For example, the ratio of the He II lines $F_{\lambda 1640}/F_{\lambda 4686}$ is not very sensitive to either density or temperature because neither line involves ground level transitions so that the lines should be optically thin. This ratio measured from our closely separated AAT and *IUE* observations (1979 July 6) is found to be ~ 3.4 compared to the theoretical ratio of ~ 6.6 (Seaton 1978). Using the extinction coefficients given in Code *et al.* (1976) this corresponds to an $E(B-V)$ of ~ 0.2

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mag and $A_V \sim 0.6$ mag. The errors, due to deblending the He II feature and non-simultaneity of observations, are probably about ± 0.3 mag in A_V.

The third estimate, using the Balmer line ratio Hα/Hβ is made using data taken three weeks after the *IUE* and AAT observations described above. The implicit assumption here is case B recombination. If this is correct we obtain an $E(B-V)$ of ~ 0.35 mag ($A_V \sim 1.1 \pm 0.2$ mag) based on two independent observations (July 27, 28) of the Hα/Hβ ratio which are in good agreement at values 4.1 and 4.0. This estimate, using the Balmer decrement, is somewhat higher than our previous values and may be attributed to the breakdown of the case B approximation in high density regions.

We adopt $A_V = 0.6$ mag.

3.4 DISTANCE ESTIMATES FROM THE QUIESCENT MAGNITUDE

The quiescent magnitude of U Sco estimated from the survey plates is $m_V = 19.3 \pm 0.5$ (this paper). This is consistent with that obtained by Webbink (1978). If we assume that this magnitude corresponds to the red companion, then we may estimate a lower limit to the distance. Comparison of U Sco with the recurrent novae T CrB has been made on the basis of the speed of decline (Webbink 1978). This star has a giant (M3III, Kraft 1958) as companion. Using the absolute magnitude of giant stars taken from Allen (1973) and using the reddening estimate of $A_V \sim 0.6$ mag (Section 3.3), a giant companion for U Sco in the range G–M yields a distance modulus of 18.5 ± 1 mag, corresponding to distances in the range 30–80 kpc. Even a late-type sub-giant companion has $M_V \sim 3.0$ mag, giving a distance estimate of ~ 13 kpc. It may be more likely that the red component of U Sco is similar to those of V616 Mon (A 0620–00 Oke 1977; Murdin *et al.* 1980), Aql X–1 (4U 1908 + 00, Charles *et al.* 1980), or the dwarf novae whose companions are late-type main sequence stars. A main sequence star of spectral type in the range G5–M5 gives distance estimates in the range 0.2–7 kpc. If the companion of U Sco is a main sequence star and if it fills its Roche lobe then we expect the binary period to be in the range of a few hours to just over a day.

On the grounds that the observed reddening of U Sco corresponds to that expected for an object lying out of the plane in that direction (Section 3.3, $b^{II} \sim 22°$) we may estimate that U Sco is at least 300 pc distant. An alternative estimate is to assume that U Sco at maximum radiates at the Eddington limit for a solar mass object. This yields an *upper* limit to the distance (depending on the bolometric correction) of about 10 kpc. This supports the idea that the companion is dwarf-like.

3.5 BALMER LINE EMISSION

The observed flux in the Balmer lines may be used to give a rough estimate of the mass of emitting gas. The profiles of the Balmer lines during the early observations show a two component structure with most of the flux being in a broad emission band of FWZI corresponding to a velocity of $\sim 10^9\ \mathrm{cm\,s^{-1}}$. Our first calibrated spectrum is that obtained on July 6, 12 days after outburst. The measured flux in the broad component in Hβ on that day is $5 \times 10^{-13}\ \mathrm{erg\,s^{-1}\,cm^{-2}}$. Correcting this flux by a factor 1.9 corresponding to an extinction $A_V = 0.6$ mag (Section 3.3) and assuming case B recombination, uniform density and a temperature for the emitting gas of 10^4 K and using the recombination coefficient given by Osterbrock (1974) we obtain an estimate for the mass of ionized gas M_i,

$$M_i = \frac{0.7}{N_e}\left(\frac{D}{\mathrm{kpc}}\right)^2 M_\odot,$$

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where N_e is the electron number density in units of cm^{-3} and D is the distance to U Sco. The breadth of the N IV] λ1487 intercombination line in the *IUE* spectrum also taken on July 6 is comparable to that of the broad Balmer lines. If this emission comes from the same region as the Balmer emission we conclude that $N_e \lesssim 10^{10}\,cm^{-3}$ (Ferland, private communication).

The absence of forbidden line emission for example [O III] λ4363 implies that $N_e \gtrsim 2 \times 10^7\,cm^{-3}$ (*cf.* Osterbrock 1974). Using these two constraints we find that

$$7 \times 10^{-11}\,(D/\mathrm{kpc})^2 \lesssim M_i/M_\odot \lesssim 3 \times 10^{-8}\,(D/\mathrm{kpc})^2.$$

If we make further assumptions about the dynamics of the emitting region we may obtain a second relationship between M_i, N_e and D. In particular we shall assume that the ionized gas expands at a constant velocity of $5000\,km\,s^{-1}$ from the start of the outburst until July 6, that the ionized region is matter bounded and is of uniform density. This implies that the radius of the emitting gas sphere on July 6 is 5.2×10^{14} cm and hence that the volume is $V = 5.9 \times 10^{44}\,cm^3$. Assuming also that $N_e = N_p$, where N_p is the proton number density, we obtain

$$M_i = 6 \times 10^{-7} \left(\frac{D}{\mathrm{kpc}}\right) M_\odot$$

or alternatively,

$$N_e = 1.3 \times 10^6 \left(\frac{D}{\mathrm{kpc}}\right) \mathrm{cm}^{-3}.$$

If $N_e \gtrsim 10^7\,cm^{-3}$ this formula gives $D \gtrsim 8$ kpc. But we note that if the ionized region is radiation bounded or if the gas is clumpy, M_i and D are overestimated and N_e is underestimated.

4 Conclusion

We present observations of the 1979 outburst of U Sco. We confirm Webbink's (1978) identification of the quiescent object. The light curve fell rapidly as in previous outbursts, and for the first time it has been followed to the quiescent level. The spectral evolution of U Sco is unlike that of any other recurrent nova and shows, in particular, much higher excitation in the permitted lines and an absence of forbidden line emission. The evolution of the Balmer lines is complicated and we have not tried to present an explanation for either their asymmetric profiles or their development. We present evidence that nitrogen is overabundant relative to carbon, and helium overabundant relative to hydrogen. We draw attention to the similarity of the outburst spectrum to that of the nova-like variable V Sge. We find evidence for the presence of a late-type star inferred from the appearance of the Mg I *b* band as the object faded. We argue from distance considerations that the companion is likely to be a late-type dwarf star, rather than a giant.

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