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The 1987 outburst of the recurrent nova U Sco

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Summary. Optical and infrared observations of U Sco during its 1987 outburst are presented. The interval since the last outburst (8 yr) is exceptionally short and places constraints on the thermonuclear runaway model. Spectra early in the decline show broad (FWZI~10 000 km s^{-1}) near-flat topped lines. On the model of Webbink *et al.* this would be interpreted as ejection of an optically thin shell. On this model the later data suggest the presence of a brightened disc in the system. The possibility that the disc seen in quiescence is heated by the ejecta is discussed. Similarities between U Sco and the nitrogen flaring stage in classical novae are mentioned. The emission line ratio N III 4634/4640+4641 Å is unusually large during the early development of the U Sco outburst.

1 Introduction

U Sco is a recurrent nova of particular interest. It has the fastest visual decline rate of all the known novae (Payne-Gaposchkin 1957) and its outbursts may be due to thermonuclear runaways on a white dwarf near the Chandrasekhar limit, with the object evolving towards a type I supernova outburst (Starrfield, Sparks and Truran 1985; Webbink *et al.* 1987). The previously recorded outbursts (1863, 1906, 1936, 1979) were spaced at ~39 yr intervals and only for the 1979 outburst were spectra and photoelectric photometry obtained. A fifth outburst was discovered by one of us (Overbeek 1987) on 1987 May 16 making this the shortest period between outbursts (8 yr) for any known recurrent novae. This paper reports and discusses the light curve, the first infrared observations of U Sco obtained during an outburst, and optical spectra extending from earlier in an outburst than any previously obtained.

2 Optical and infrared photometry

The magnitude of U Sco between outbursts is $V_{\rm min}$~17.9 (*cf.* Williams *et al.* 1981; Hanes 1985). The star is regularly monitored by Overbeek and was found to be at m_v=10.8 on 1987 May 16.09

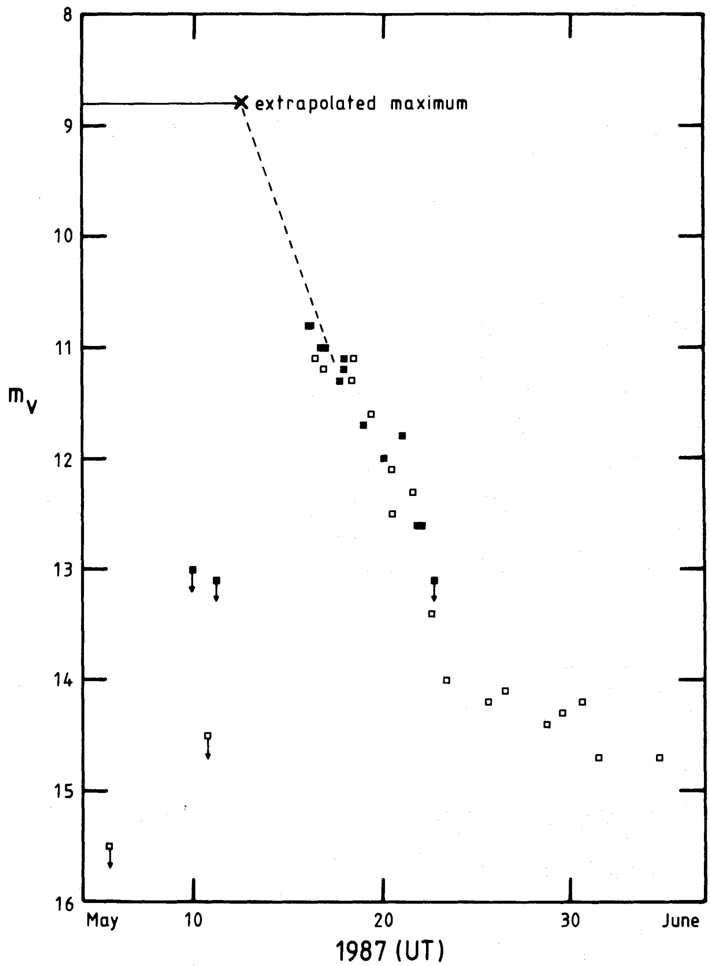

Figure 1. The visual light curve of U Sco during its 1987 outburst. Solid squares are observations by Overbeek. Open squares are observations from *IAU Circ. Nos 4395–4405*. The time of maximum light was extrapolated assuming a decline rate of 0.5 mag day^{-1} and a maximum brightness of m_v=8.8.

(UT). Fig. 1 shows the light curve of U Sco constructed from the observations of Overbeek and other visual estimates (McNaught 1987; Cragg 1987; Seargent 1987; Verdenet 1987; Sakuma 1987). Overbeek found m_v to be fainter than 13.1 on 1987 May 11.25. Maximum brightness therefore occurred somewhere in the interval May 11–16. During most of this time U Sco was close to a near-full moon and was not observable by Overbeek (or probably any other normal variable star observer). By May 23.45 the brightness had fallen to m_v=14.0. Thus the time taken to fall 3 mag was 6.9 days which is comparable to the time of 6.6 days taken to change over the same magnitude interval in 1979 (Barlow *et al.* 1981). If we assume that the star reached a similar peak brightness in 1987 as at the other outbursts [9.1 in 1863 (Pogson 1908), 8.8 in 1906 and 1936 (Thomas 1940), 8.7 in 1979 (Narumi 1979)] then the observed rate of decline (0.5 mag day^{-1}) indicates a maximum close to May 12–13. Whilst we cannot prove that the 1987 outburst reached the brightness found on previous occasions, the similar rate of decline suggests that this was a normal maximum. In addition, the *UBVRI* colours (Cousins system) on May 19.03 (UT) given in Table 1 (F. Marang, 0.5-m reflector SAAO Sutherland) are close to the colours at a similar visual magnitude in 1979 (Barlow *et al.* 1981, table 1). The spectroscopic development discussed below seems broadly similar to that in 1979 and also points to a normal maximum in 1987.

JHK infrared photometry of U Sco during outbursts is listed in Table 2. The observations were made at SAAO Sutherland, the first three sets with the 0.75-m reflector and the last with the

Table 1. Photoelectric photometry of U Sco

UT	V	$B-V$	$U-B$	$V-R$	$V-I$
1987 May 19.03	12.47	−0.30	−0.58	0.47	0.65

Table 2. Infrared photometry of U Sco

UT	J	H	K	$(J-H)_0$	$(H-K)_0$	m_v
1987 May 17.99	10.84±0.02	10.85±0.04	10.40±0.05	−0.10	+0.42	11.2
18.92	11.17±0.03	11.14±0.05	10.65±0.05	−0.05	+0.46	11.7
20.84	11.81±0.06	11.45±0.06	11.31±0.08	+0.28	+0.10	12.3
June 14.00	14.46±0.07	14.07±0.05	13.83±0.07	+0.32	+0.20	
1982 July 8/9	16.87±0.06	16.44±0.07	16.44±0.08	+0.35	−0.04	V~17.6

1.9-m reflector. The observations are with respect to the standards of Carter (in preparation). The table also contains 1982 observations of U Sco in quiescence (Hanes 1985) transformed to the Carter system (*cf.* Glass 1985). The dereddened colours listed in Table 2 were obtained by adopting $E(B-V)=0.24$ (*cf.* Webbink *et al.* 1987).

It is clear that, very roughly, the increase in brightness in the infrared was similar to that in the visible and that the infrared faded at about the same rate as m_v. The $(J-H)_0$, $(H-K)_0$ colours are unusual, especially on the first two days when the negative $(J-H)_0$ values must be due to the effects of strong emission in the J band, possibly the He I line at 1.08μm (*cf.* Whitelock *et al.* 1984). Later the colours are similar, within the errors, to those at minimum. This is interesting since it suggests that it may be inappropriate to use the infrared colours at minimum to infer a spectral type of the companion star (Hanes 1985). Indeed Hanes himself suggests that the optical spectrum at minimum is not purely stellar but is contaminated by another source of radiation, presumably an accretion disc and hot spot (see also Webbink *et al.* 1987). The development of the infrared colours with time is rather similar to that found for the recurrent nova RS Oph

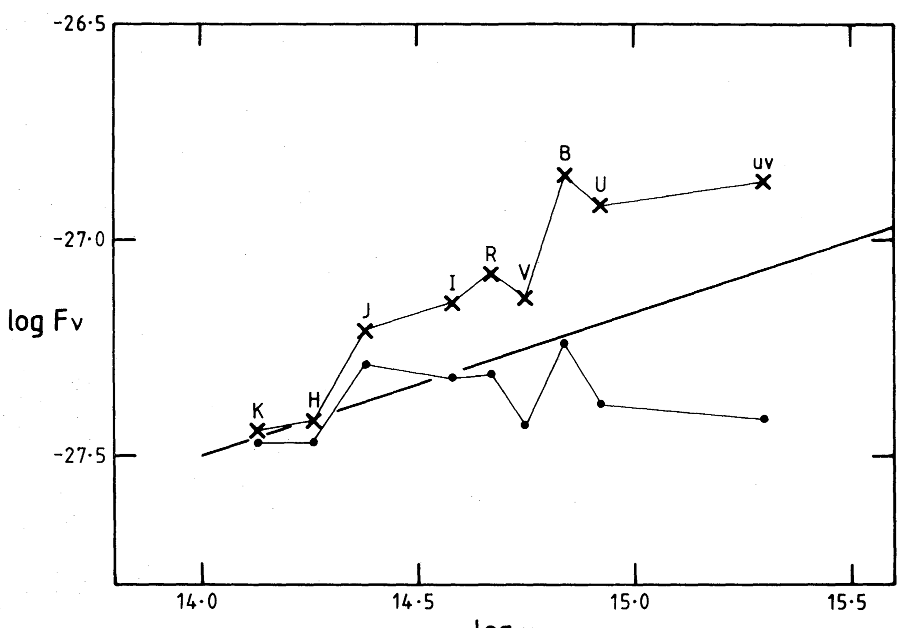

Figure 2. *UBVRIJHK* fluxes for U Sco on 1987 May 19.0, the UV point is from the 1979 observations (Barlow *et al.* 1981) scaled according to the visual magnitudes. Circles are observed fluxes; crosses are after correction for reddening assuming $E(B-V)=0.24$. The straight line has the slope predicted for a disc emitting as $S_\nu \propto \nu^{1/3}$.

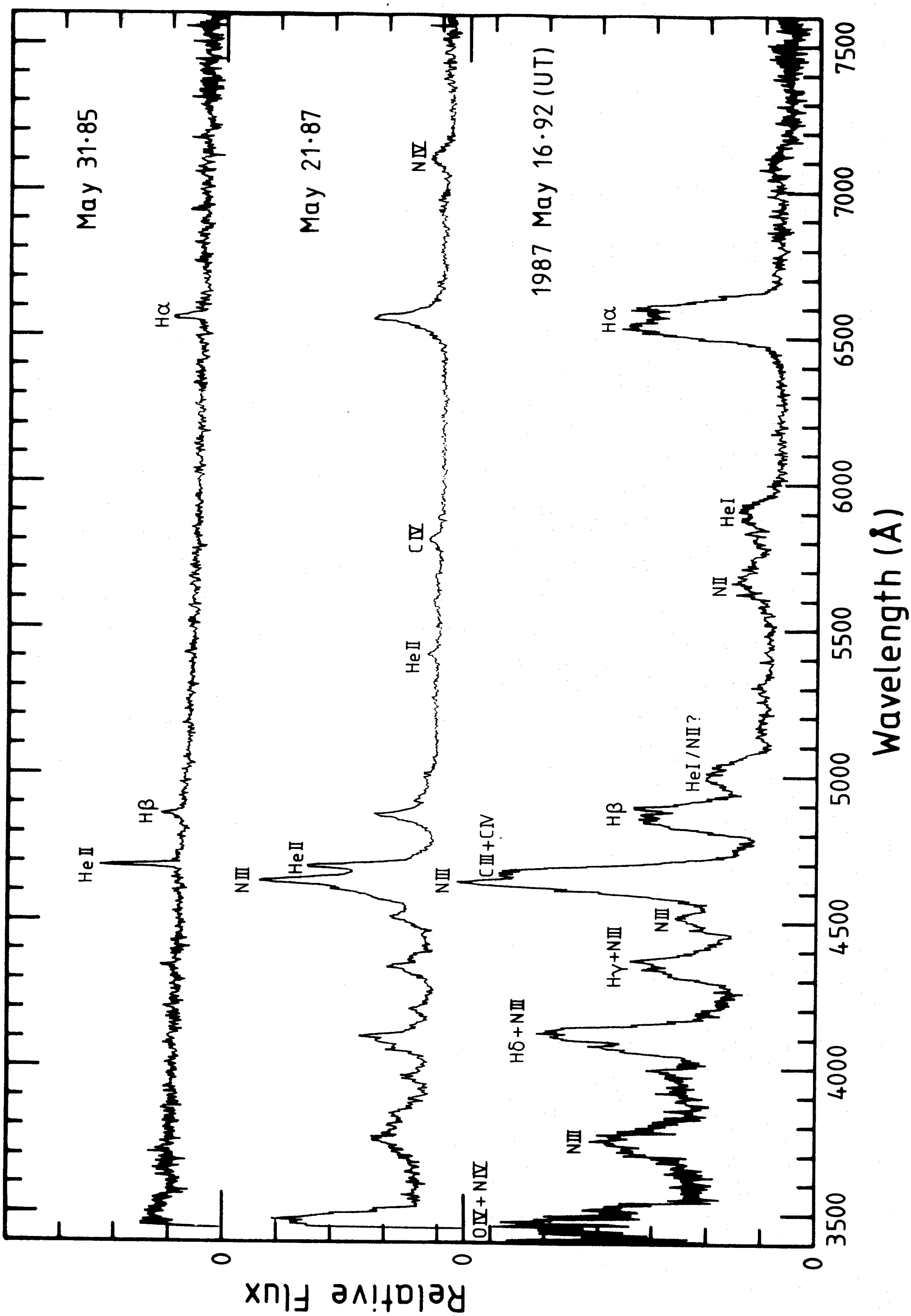

Figure 3. Spectra of U Sco taken approximately 4, 9 and 19 days after the predicted time of maximum visual light are shown on arbitrarily normalized flux scales.

(SAAO IR-group, in preparation), a system whose nature is possibly different (e.g. Webbink *et al.* 1987, but *cf.* Snijders 1987).

Fig. 2 shows the *UBVRIJHK* fluxes on 1987 May 19.0 (data from Tables 1 and 2; flux calibrations from Bessell 1979, and Wilson *et al.* 1972). The results are shown as observed and also corrected for an extinction corresponding to $E(B-V)=0.24$. Barlow *et al.* (1981) pointed out that on 1979 July 6 about 13 days after maximum during the previous outburst, the blue and far ultraviolet continuum flux could (roughly) be approximated by a power law $S_\nu \propto \nu^\alpha$ with $\alpha \approx 0.4$. The ratio of the far ultraviolet continuum flux to visual flux remained approximately constant from day 4 to day 16 after maximum in the 1979 outburst (Williams *et al.* 1981; note that the flux ratio they plot in the lower panel of their fig. 3 is the flux per 10^2 Å at 1300 Å divided by the flux per 10^4 Å at 5500 Å). If we assume that the far ultraviolet behaviour was the same in 1987 as in 1979, we can scale the observed ultraviolet flux (read from fig. 8 of Barlow *et al.* 1981, at log $\nu=15.3$) to the visual magnitude at the time of our observation. The deduced points are shown in Fig. 2. Given the uncertainties regarding the value of $E(B-V)$ (*cf.* Webbink *et al.* 1987) and the complications introduced by the presence of emission lines, the overall trend can reasonably be represented by a power law. The line drawn shows the slope of the relation $S_\nu \propto \nu^{1/3}$ which is the flux distribution expected for an optically thick, steady-state disc (Lynden Bell 1969). Evidently the overall slope is close to this. These results might be taken to indicate that at least part of the outburst behaviour of U Sco is to be attributed to the brightening of an accretion disc.

3 Spectroscopy

A series of optical spectra of U Sco taken during the 1979 outburst is discussed by Barlow *et al.* (1981). The earliest of these (1979 July 2) was obtained about 9 days after maximum when the star had faded to $V \sim 13.3$. A low signal to noise spectrum of the blue region (1979 June 28.95), taken 5.5 days after maximum ($m_v \sim 11.5$), is reproduced by Duerbeck & Seitter (1980).

Spectroscopic observations of U Sco in the 1987 outburst were made with the two-channel intensified Reticon photon counting system (RPCS) attached to the grating spectrograph at the Cassegrain focus of the 1.9-m SAAO reflector (Sutherland). A grating of 300 lines mm^{-1} was used in the first order to cover the spectral range 3400–7600 Å at a resolution of about 7 Å. Reduction of the data was carried out using the SKIP program on the VAX computer at SAAO Cape Town. Three spectra of U Sco at different stages in the outburst are shown in Fig. 3. The spectra are dominated by emission lines and the principal features are identified in the figure.

The gross features of our spectra and their development are similar to those seen by Barlow *et al.* (1981) in 1979, but a number of new points arise, primarily due to the fact that our series goes to earlier phases of an outburst than did theirs. Barlow *et al.* find a 'narrow' component in the hydrogen lines (FWZI$\sim$1600 km s^{-1}) which has structure near its peak, together with a broad component which is evident as wings to the composite line extending out to a total FWZI of $\sim$10 000 km s^{-1}. The broad component faded more rapidly than the narrow one. This broad component is found in far ultraviolet spectra of U Sco taken from 4 to 16 days after the 1979 maximum (Williams *et al.* 1981).

On 1987 May 21.87 ($\sim$9 days after deduced maximum) our spectrum (Fig. 3) shows Hα to have the typical narrow emission component together with the extensive wings (FWZI$\sim$10 000 km s^{-1}) of the broad component. By 1987 May 31.85 ($\sim$19 days after maximum) only the narrow component of the Hα (FWZI$\sim$1500 km s^{-1}) is evident. Our earliest spectrum (1987 May 16.92, $\sim$4 days after maximum) is strikingly different (Fig. 3). Here we see only a broad component to Hα (FWZI$\sim$10 000 km s^{-1}) with a roughly flat top. There is no evidence for a narrow component in the hydrogen lines at this stage. Indeed these lines show instead a central depression.

4 Initial discussion

The FWZI of the He II 4686 Å emission line seen in U Sco during quiescence (2560±320 km s^{-1}, Hanes 1985) is interpreted by Webbink *et al.* (1987) as indicating an accretion disc seen nearly pole on (axis~7° to the line of sight). In the following we discuss the consequences of this interpretation as applied to our observations.

It is notable that the FWZI of the emission lines of the narrow component in outburst (~1600 km s^{-}1) is comparable to, but somewhat less than that of He II 4686 Å in quiescence. It would seem on this model, therefore, that the narrow line component in outburst should be attributed to a brightened accretion disc. The disc-like energy distribution on 1987 May 19.0 (when the narrow line component may already be dominant) (see Section 2) would be consistent with the hypotheses.

The broad wings to the emission lines observed in 1979 have generally been interpreted as evidence for ejection of material at high velocity (Williams *et al.* 1981; Webbink *et al.* 1987). Indeed the flat topped profile observed at the earliest stage in 1987 can be interpreted as the signature of an optically thin shell expanding at constant velocity (see the summary by Mihalas 1978, of the early work by Beals). On this view there is a brief initial ejection of matter at high velocity in U Sco. The radiation from this gas fades rapidly leaving the later stages of development dominated by an enhanced disc.

The structure in the tops of the lines of the broad component (Hα, etc.; 1987 May 16; Fig. 3) indicates departures from purely spherical symmetry in the high velocity expanding shell. In particular, profiles with central depressions are (for radially expanding material) characteristic of shells with a deficiency of material moving in the plane of the sky. As we have just seen, Webbink *et al.* (1987) propose that this is the plane of the (quiescent) accretion disc. This suggests a model in which a high velocity spherical shell ejected from the white dwarf in the system is impeded in the plane of the disc.

Changes with time in the emission complex 4500–4700 Å (*cf.* Fig. 3) are particularly interesting. At the time (1987 May 16) when the broad component dominates the spectrum, He II 4686 Å emission is weak or absent. This line is however strong in the narrow line component (May 21) and rapidly increases in intensity relative to the rest of the blend, becoming the only strong feature by May 31. On May 16, the blend must be mainly due to N III/C III/C IV. By May 21, not only is He II 4686 Å strong but a wing has developed on the blue side of the blend. This is almost certainly N V 4604/4620 Å which became quite strong in the late development of the 1979 outburst (Barlow *et al.* 1981). The structure of the blend on May 16 is very striking. There is a plateau on the red side about 20 Å wide and centred near 4665 Å. This is presumably the red side of the blend C III 4647/4650 Å and/or C IV 4658 Å. In addition there is a narrow peak at 4634 Å. A strong peak at the same wavelength is present on May 21. This peak is remarkable for two reasons. First, the fact that it is narrow and unchanged from May 16 to May 21 may be taken to indicate the presence of the narrow component in the spectrum from at least May 16. This narrow component is not seen in any other line at this early stage although in a number of cases (e.g. N II, C III, etc.) the observed lines are blends so that we cannot always rule out the presence of narrow line components. Secondly the line is almost certainly N III 4634 Å. This line is part of the well-known multiplet 4634/4640/4641 Å. In U Sco at this stage 4634 Å must be much the strongest emission line of the group. This appears to be an unprecedented occurrence. In the laboratory 4640 Å is somewhat stronger than 4634 Å (Fowler 1920, gives intensity ratios of 8/10/3). In gaseous nebulae the ratio 4634/4640+41 tends to be considerably less than in the laboratory and this effect is attributed to the details of the Bowen fluorescent mechanism which is responsible for the great strength of the multiplet in nebulae (Bowen 1934, 1935; Wright 1934). Variations of the ratio during an outburst of the recurrent nova T CrB have been reported (Herbig & Neubauer

1946) but it is not known whether 4634 Å ever became dominant. The fact that in U Sco the line is present in the narrow component, associates it (on the model discussed above) with emission from the disc. The curious relative intensities within the multiplet could then be due to effects of doppler shifts on the operation of the fluorescent mechanism (though no specific scheme suggests itself), to the effects of collisional excitation which may well operate at this stage, or to optical depth effects. The overall strength of this N III multiplet relative to He II 4686 Å at this stage is reminiscent of the 'nitrogen flaring' or '4640 Å stage' in classical novae (Payne-Gaposchkin 1957; McLaughlin 1960). This stage has never been adequately explained.

5 The distance of U Sco

It would be easier to distinguish between various models for U Sco if its distance could be estimated. The following is a brief summary of distance estimates, unfortunately all of them are quite uncertain.

(1) The rapid rate of decline of U Sco after outburst ensures that if the absolute magnitude–rate of decline relation for classical novae applies, one will obtain a very high luminosity and a very large distance. The most recent application of this method (Warner 1987) gives $M_{v(\max)}=-10.0$ and hence $d=60$ kpc, making the object extragalactic which seems unlikely.

(2) Webbink *et al.* (1987) conclude that the high velocity of ejection and the rapid development of a U Sco outburst, point to a super-Eddington event and that this yields $d>10$ kpc if the bolometric correction near maximum is negligible. However, the bolometric correction may not be small. Thus the distance could be less than 10 kpc.

(3) Several workers have attempted to derive a distance from the features attributed to the companion in the quiescent spectrum (Hanes 1985). Because only a few weak features are seen, estimates of the spectral type and luminosity class are quite uncertain and this difficulty is compounded by the fact that the companion is possibly hydrogen-poor (see Section 6). Hanes (1985) found $d=3.5\pm1.5$ kpc assuming the companion to be a dwarf.

(4) It has recently been pointed out by Warner (1987) that the mean absolute magnitude of classical novae at minimum is $M_v=4.4$ which is close to the luminosities of dwarf novae in outburst. This luminosity is for systems of average inclination, for a face-on disc, one finds (*cf.* Warner 1987; Paczynski and Schwarzenberg-Czerny 1980) $M_v=3.4$. If this is the luminosity of the disc in U Sco in quiescence (seen face on, Webbink *et al.* 1987), and if the disc provides most of the luminosity in quiescence at *V*, then $d\approx6$ kpc. Since Warner regards his result as indicating an upper limit to the rate of mass transfer in an accretion disc, we should probably take this distance as an upper limit.

6 Further discussion

The above discussion suggests that if we adapt the model of Webbink *et al.* (1987) we are led to deduce that at least in the later development of the U Sco outburst, a significant amount of the radiation is coming from a brightened face-on disc. In view of this, a possible outburst model would be one involving increased mass transfer to the disc at outburst, associated with instabilities in the companion in the (presumed) binary system (i.e. one of the proposed models for dwarf novae, *cf.* Bath 1985).

The observations of Barlow *et al.* (1981) and Williams *et al.* (1981) suggest that the ejecta have a high helium to hydrogen ratio (He/H~2) and a high nitrogen abundance. This unusual chemical composition is not a particular problem in an accretion model since we also require material of a similar composition to be transferred to the disc during quiescence to explain its similar He/H ratio (Williams *et al.* 1981; Williams, Phillips and Heathcote 1987). Amongst uncertainties in this model is the possible difficulty of providing bursts of mass transfer, superimposed on a relatively high background mass transfer (Webbink *et al.* 1987), though it has not been shown that this is impossible. It is also not clear that a highly evolved companion (with a low atmospheric hydrogen abundance) will be capable of undergoing the necessary dynamic instabilities. Nor has it been shown how this mechanism will lead to the high velocity ejecta. None of these objections to the model is absolutely compelling. Nevertheless, it may be worth considering whether one can incorporate a thermonuclear runaway model with a brightened disc. The thermonuclear runaway has the attraction that it can apparently explain the low mass, high velocity ejecta (Starrfield *et al.* 1985). There are however, severe problems (as pointed out by an anonymous referee) with this model as it predicts a prolonged phase of constant high bolometric luminosity following the outburst. The observations of U Sco in outburst do not provide evidence of such a plateau. We have already suggested (Section 3) that the dip in the centres of the broad hydrogen lines may indicate interaction between the ejecta (which must then come from the white dwarf) and the disc. These line profiles would not be inconsistent with interaction of ~10 per cent of the ejected shell with the disc. For a spherical shell of mass $\sim 10^{-7} M_{\odot}$, the shell mass estimated by Williams *et al.* (1981), and velocity 5000 km s^{-1}, the kinetic energy is 2.5×10^{43} erg. If 10 per cent of this can be transferred to the disc by collision, and converted to radiation, this may provide the necessary heating of the disc. The total energy radiated during outburst (Williams *et al.* 1981) is $\sim 10^{43}$ erg but this estimate depends on the bolometric correction and the distance. For constant bolometric correction 90 per cent of this is radiated during the first four or five days when the high velocity component must be dominant. The model is somewhat analogous to the hot spot model for cataclysmics except that now the disc is being heated internally by matter from the white dwarf. If this mechanism operates in U Sco it might also be expected to operate in classical novae. However, in that case the mass of the ejecta is much higher ($\sim 10^{-4} M_{\odot}$ *cf.* Gallagher & Starrfield 1987) and of lower velocity (~1500 km s^{-1}). Thus whilst, in U Sco, the radiation from the ejecta may cease to dominate the optical event after a few days, in classical novae this radiation may be dominant for essentially the entire outburst.

In light of the above discussion, it would seem possible to associate the early decay seen in the visual light curve (Fig. 7) of about 0.5 mag day^{-1} with the thermonuclear runaway and the slower decay of 0.2 mag day^{-1} seen later in the outburst with the cooling accretion disc.

The short recurrence time of U Sco was long considered a difficulty for thermonuclear runaway models. However, Starrfield *et al.* (1985) were able to produce models in which thermonuclear runaways occurred on a time scale as short as 33 yr by assuming that the mass of the white dwarf was at the Chandrasekhar limit. This recurrence time is close to the previously adopted spacings of outbursts in U Sco (~39 yr). The observation of the present outburst suggests that this spacing may have been over-estimated. Not only is the present outburst only 8 yr after the last one but it is clear that it might well have gone unobserved, being detected only on the decline at $m_v = 10.8$, due to its proximity to the full moon at (presumed) maximum. The very rapid decline of U Sco is such that the loss of a few days observing due either to the moon or poor weather at the sites of the few regular observers, could well lead to some outbursts being overlooked. Thus the restrictions on the thermonuclear runaway model may be even more stringent than previously thought. In addition Truran *et al.* (1987) have very recently suggested that if the He/H is as high as 2 (see above) then it will be difficult to produce a thermonuclear runaway. They suggest that such a high He/H ratio would make a disc instability model more likely.

Much depends on the interpretation of the narrow line region (both in quiescence and in outburst) as due to a near face on disc. We might alternatively think of the broad line region as due to a near edge on disc rather than ejection. The interpretation of the narrow lines in such a model is not immediately obvious.

Further quantitative modelling, when compared with these and earlier observations should test the viability of proposed models for U Sco.

Acknowledgments

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References

Barlow, M. J., Brodie, J. P., Brunt, C. C., Hanes, D. A., Hill, P. W., Mayo, S. K., Pringle, J. E., Ward, M. J., Watson, M. G., Whelan, J. A. J. & Willis, A. J., 1981. *Mon. Not. R. astr. Soc.*, **195**, 61.

Bath, G. T., 1985. *Rept Prog. Phys.*, **48**, 483.

Bessell, M. S., 1979. *Publs astr. Soc. Pacif.*, **91**, 589.

Bowen, I. S., 1934. *Publs astr. Soc. Pacif.*, **46**, 146.

Bowen, I. S., 1935. *Astrophys. J.*, **81**, 1.

Cragg, T., 1987. *IAU Circ. Nos. 4395, 4396, 4397.*

Duerbeck, H. W. & Seitter, W. C., 1980. *Inf. Bull. var. Stars, No. 1738.*

Fowler, A., 1920. *Mon. Not. R. astr. Soc.*, **80**, 692.

Gallagher, J. S. & Starrfield, S., 1978. *Ann. Rev. Astr. Astrophys.*, **16**, 171.

Glass, I. S., 1985. *Irish astr. J.*, **17**, 1.

Hanes, D. A., 1985. *Mon. Not. R. astr. Soc.*, **213**, 443.

Herbig, G. H. & Neubauer, F. J., 1946. *Publs astr. Soc. Pacif.*, **48**, 196.

Lynden Bell, D., 1969. *Nature*, **223**, 690.

McLaughlin, D. B., 1960. In: *Stellar Atmospheres*, p. 585, ed. Greenstein, J. L., University of Chicago Press.

McNaught, R. H., 1987. *IAU Circ. Nos. 4395, 4396, 4397, 4399, 4405.*

Mihalas, D., 1978. *Stellar Atmospheres*, p. 477, W. H. Freeman, San Francisco.

Narumi, H., 1979. *IAU Circ. No. 3373.*

Overbeek, M. D., 1987. *IAU Circ. No. 4395.*

Paczynski, B. & Schwarzenberg-Czerny, A., 1980. *Acta Astr.*, **30**, 127.

Payne-Gaposchkin, C., 1957. *The Galactic Novae*, North-Holland, Amsterdam.

Pogson, N. R., 1908. *Mem. R. astr. Soc.*, **58**, 90.

Sakuma, S., 1987. *IAU Circ. No. 4397.*

Seargent, D. A. J., 1987. *IAU Circ. No. 4396.*

Snijders, M. A. J., 1987. *Astrophys. Space Sci.*, **130**, 243.

Starrfield, S., Sparks, W. M. & Truran, J. W., 1985. *Astrophys. J.*, **291**, 136.

Thomas, H. L., 1940. *Harvard Obs. Bull.*, **912**, 10.

Truran, J. W., Livio, M., Hayes, J., Starrfield, S. & Sparks, W. M., 1987. Preprint.

Verdenet, M., *IAU Circ. No. 4395.*

Warner, B., 1987. *Mon. Not. R. astr. Soc.*, **227**, 23.

Webbink, R. F., Livio, M., Truran, J. W. & Orio, M., 1987. *Astrophys. J.*, **314**, 653.

Whitelock, P. A., Carter, B. S., Feast, M. W., Glass, I. S., Laney, D., Menzies, J. W., Walsh, J. & Williams, P. M., 1984. *Mon. Not. R. astr. Soc.*, **211**, 421.

Williams, R. E., Phillips, M. M. & Heathcote, S. R., 1987. *Astrophys. Space Sci.*, **131**, 681.

Williams, R. E., Sparks, W. M., Gallagher, J. S., Ney, E. P., Starrfield, S. G. & Truran, J. W., 1981. *Astrophys. J.*, **251**, 221.

Wilson, W. J., Schwartz, P. R., Neugebauer, G., Harvey, P. M. & Becklin, E. E., 1972. *Astrophys. J.*, **177**, 523.

Wright, W. H., 1934. *Publs astr. Soc. Pacif.*, **46**, 149.