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Spectroscopy of the recurrent nova V3890 Sagittarii 18 d after the 1990 outburst

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ABSTRACT

The spectrum of the recurrent nova V3890 Sgr, obtained from the Vainu Bappu Observatory 18 d after the 1990 outburst maximum, is presented. The nova was in the coronal line phase. The spectrum is similar to that of the recurrent nova RS Oph. An extinction $E(B-V)=1.1$ is derived from the $B-V$ colours, and from Balmer and He I line ratios. From the maximum magnitude–rate-of-decline relations for a nova, $M_V=-8.6$ mag is estimated, which places the nova at a distance of about 5 kpc. Balmer line fluxes are used to derive the density, $\sim 10^9$ cm^{-3}, and the mass of the ejected ionized shell, $\sim 10^{-7}$ M$_\odot$. The temperature and radius estimates for the ionizing source are 3×10^5 K and 0.06 R$_\odot$. A helium abundance of 0.23 is estimated.

Key words: stars: fundamental parameters – stars: individual: V3890 Sgr – stars: mass-loss – novae, cataclysmic variables.

1 INTRODUCTION

The classical nova V3890 Sagittarii 1962 (Duerbeck 1987) was established as a recurrent nova with its second outburst in 1990 April, independently discovered by A. Jones (1990) and W. Liller (1990). From a magnitude $m_{\rm vis}$ fainter than 13.0 on 1990 April 20.68, the nova rose to a magnitude of $m_{\rm vis}=8.5$ on 1990 April 27.72 (IAU Circ. 5002, 5007 and 5010).

The nova was spectroscopically studied by several observers in both northern and southern hemispheres. The spectral development during the early phases is described in IAU Circulars (Wagner, Bertram & Starrfield 1990; Harrison & Johnson 1990; Mukai et al. 1990; Buckley, Wargau & Soltynski 1990; Gonzalez-Riestra et al. 1990). Williams et al. (1991) present the CTIO data obtained during the later stages of the outburst. The spectrum in the ultraviolet region, obtained using *IUE*, is presented by Gonzalez-Riestra (1992). In this paper we discuss the optical spectrum of the nova, obtained from the Vainu Bappu Observatory (VBO) about 18 d after the outburst maximum.

2 OBSERVATIONS

Three spectra were obtained on 1990 May 14.91, 15.94 and 16.97 from the VBO. The observations were carried out using the UAG spectrograph and Photometrics CCD system at the Cassegrain focus of the 1.02-m telescope. Spectra were recorded in the range 430–770 nm at a linear dispersion of 0.55 nm per pixel, with a resolution element of ~ 2.2 pixel. Spectrophotometric standards were observed on each night to derive the instrumental response. The spectra were individually de-biased and flat-field-corrected, and the one-dimensional spectra extracted. An Fe+Ne hollow cathode source spectrum was used for wavelength calibration.

A single spectrum was obtained on May 18, under poor observing conditions, in the range 640–670 nm at a linear dispersion of 0.14 nm per pixel, with a resolution element of ~ 1.8 pixel. No standard star was observed on this night, and the spectrum has hence not been flux-calibrated.

Reductions were performed using the RESPECT (Prabhu & Anupama 1991) and IRAF software packages.

3 THE SPECTRUM

The mean spectrum of 1990 May 14.91, 15.94 and 16.97 is shown in Fig. 1. The spectrum shows strong, high-excitation forbidden lines, along with Balmer, He I, He II and Fe II lines. The most prominent lines are Hα, Hβ, Hγ, He I 587.6, 667.8, 706.5 and 728.1 nm, He II 468.6 and 541.1 nm, lines of Fe II multiplets 27, 42, 48, 49, 73 and 74, and the N/O blend at 464.0 nm. The coronal lines [Fe XIV] 530.3 nm, [Fe X] 637.4 nm, [Ax] 553.5 nm and [Axi] 691.9 nm are also strong. The feature at 683 nm is probably the Raman-scattered UV line of O VI 103.2 nm (Schmid 1989). Nebular lines are weak or absent. The observed line fluxes are given in Table 1. The spectrum very closely resembles the spectrum of RS Oph on day 60, during the coronal line phase (Anupama & Prabhu 1989). There is no indication of a contribution from the secondary star. In their spectrum obtained on 1990 May 14,

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1994MNRAS.269..105A

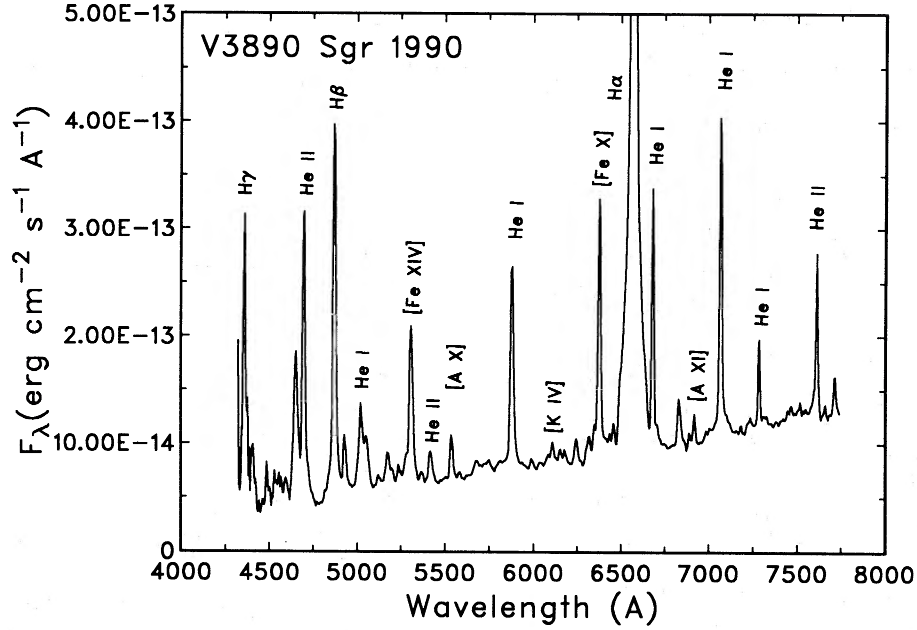

Figure 1. Spectrum of V3890 Sgr 18 d after outburst, uncorrected for interstellar reddening.

Table 1. Line identifications and observed fluxes.

λ_m nm	Identification		Flux 10^{-12} erg cm^{-2} s^{-1}
435.3	434.05	Hγ (1)	4.915
	435.18	Fe II (27)	
439.8	438.54	Fe II (27)	0.785
	441.68		
448.1	447.15	He I (6)	0.580
	448.10	Mg II	
464.5	'464.00'	N/O bl.	4.274
469.2	468.60	He II (1)	6.043
486.4	486.13	Hβ (1)	8.220
492.5	492.39	Fe II (42)	1.058
	492.19	He I	
501.6	501.57	He I (4)	2.305
	501.84	Fe II (42)	
505.7	504.11		1.324
	505.60	Si II (5)	
511.9	511.60	[Ni XIII] (1)	0.196
516.9	516.90	Fe II (42)	0.750
520.0	519.76	Fe II (42)	0.219
523.5	523.46	Fe II (49)	0.380
526.8	527.60	Fe II (49)	0.490
530.2	530.29	[Fe XIV] (1)	4.451
532.2	531.66	Fe II (49)	1.720
	531.68	Fe II (48)	
536.4	536.29	Fe II (48)	0.243
541.4	541.15	He II (2)	0.903
549.5	549.58	[Fe II] (17)	0.076
553.3	553.46	[A X] (1)	0.948
558.0	557.74	[O I] (3)	0.150
569.0	566.66		
	567.60		
	567.96	N II (3)	1.291
	568.62		
	571.08		

Table 1 – *continued*

λ_m nm	Identification		Flux 10^{-12} erg cm^{-2} s^{-1}
575.0	575.48	[N II] (3)	0.277
587.5	587.56	He I (11)	4.750
598.7	599.14	Fe II (46)	0.226
603.7	603.67	He II (8)	0.201
607.7	607.41	He II (8)	0.304
	608.41	Fe II (46)	
610.9	610.11	[K IV] (1)	0.516
614.9	614.77	Fe II (74)	0.329
618.0	617.81	Fe II (46)	0.310
624.2	624.76	Fe II (74)	0.698
630.9	631.08	He II (7)	0.715
	630.02	[O I] (1)	
634.3	634.71	Si II (2)	0.363
637.3	637.41	[Fe X]	4.390
	637.14	Si II (2)	
643.2	634.27	Fe II (40)	0.363
645.4	645.64	Fe II (74)	0.275
656.2	656.28	Hα (1)	75.130
667.8	667.82	He I (46)	3.549
682.8	683.00	O VI	0.993
691.6	691.91	[A XI] (1)	0.501
706.4	706.52	He I (10)	5.285
728.0	728.13	He I (45)	1.076
731.4	730.80		0.287
	732.07	Fe II (73)	
746.2	746.24	Fe II (73)	0.121
751.0	751.59	Fe II (73)	0.170
759.2	759.27	He II (6)	1.520
770.9	771.19	Fe II (73)	0.631

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1994MNRAS.269..105A

Mukai et al. (1990) also note the presence of O I 777.2 and 844.6 nm, the coronal line [Fe XI] 789.1 nm and [S III] 906.9 nm. The spectrum during 1990 May 14–16 may be classified as $C^{o}_{he^+}$ in the CTIO classification scheme (Williams et al. 1991). The spectral evolution sequence, based on data published in IAU Circulars and by Williams et al., is $P_{he,he^+}C^{o,s}_{he^+,fe}A_o$ during the period 1990 May 2–September 23.

The uncalibrated Hα profile is shown in Fig. 2. The profile shows both the narrow and the broad components. A two-component Gaussian fit to the profile gives FWHM velocities of 420 and 1630 km s^{-1} for the narrow and broad components respectively. The fitted Gaussians are also shown in Fig. 2.

4 RESULTS

4.1 Absolute magnitude, reddening and distance

The light curve of the 1990 outburst of V3890 Sgr indicates that the maximum was reached on 1990 April 27.72 (=JD 244 8009.22), with a maximum magnitude $V_{max}=8.5$. A smooth fit to the light curve gives the following: (i) magnitude at 15 d from maximum: $V_{15}=11.0$; (ii) time of decline through 2 mag in V: $t_2=12$ d; (iii) time of decline through 3 mag in V: $t_3=18$ d [Gonzalez-Riestra (1992) estimates $t_3=17$ d]. Using the above estimates, the absolute magnitude of the nova at maximum is estimated using the various $M_{V,\mathrm{max}}$–t_{decline} relations in the literature (Pfau 1976; Cohen 1985; van den Bergh & Younger 1987; Capaccioli et al. 1989). The values of M_V for V3890 Sgr as estimated from these relations range from $M_V=-8.3$ to $M_V=-8.7$, with unweighted mean

$$M_V^{\max}=-8.6\pm0.2,$$

giving an uncorrected distance modulus of

$$(m-M)_V=17.1\pm0.2.$$

The foreground reddening towards the nova is estimated here using the colour index of the nova 2 mag below maximum. Photometry of the nova by Buckley et al. (1990) gives the colour indices $B-V=+0.84$ on day 10 and $B-V=+0.91$ on day 11. The unreddened index of a nova 2 mag below maximum is $(B-V)_0\approx0$ (van den Bergh & Younger 1987). The observed $B-V$ colour thus implies $E(B-V)=0.91$ for V3890 Sgr.

Reddening may also be estimated using the He I 587.6/447.1 line ratios, as well as by using Balmer decrements (Ferland 1977; Whitney & Clayton 1989). Using the observed He I line ratios, we obtain $E(B-V)=1.12$, and the observed Hα/Hβ ratio gives $E(B-V)=1.2$. A mean of all the above three estimates gives $E(B-V)=1.1$, in agreement with the estimate of Gonzalez-Riestra (1992) based on the Balmer line ratio during quiescence and ultraviolet lines of He II during outburst. This estimate for the reddening, together with the estimated distance modulus, gives a value of $d=5.4$ kpc for the nova.

It is not certain whether the standard M_V–t_3 relation used here, which is derived for classical novae, applies to recurrent novae also. The absolute magnitude of the recurrent nova RS Ophiuchi, which has a decay time of $t_3=18$ d (similar to V3890 Sgr) and a distance of 1.6 kpc estimated from

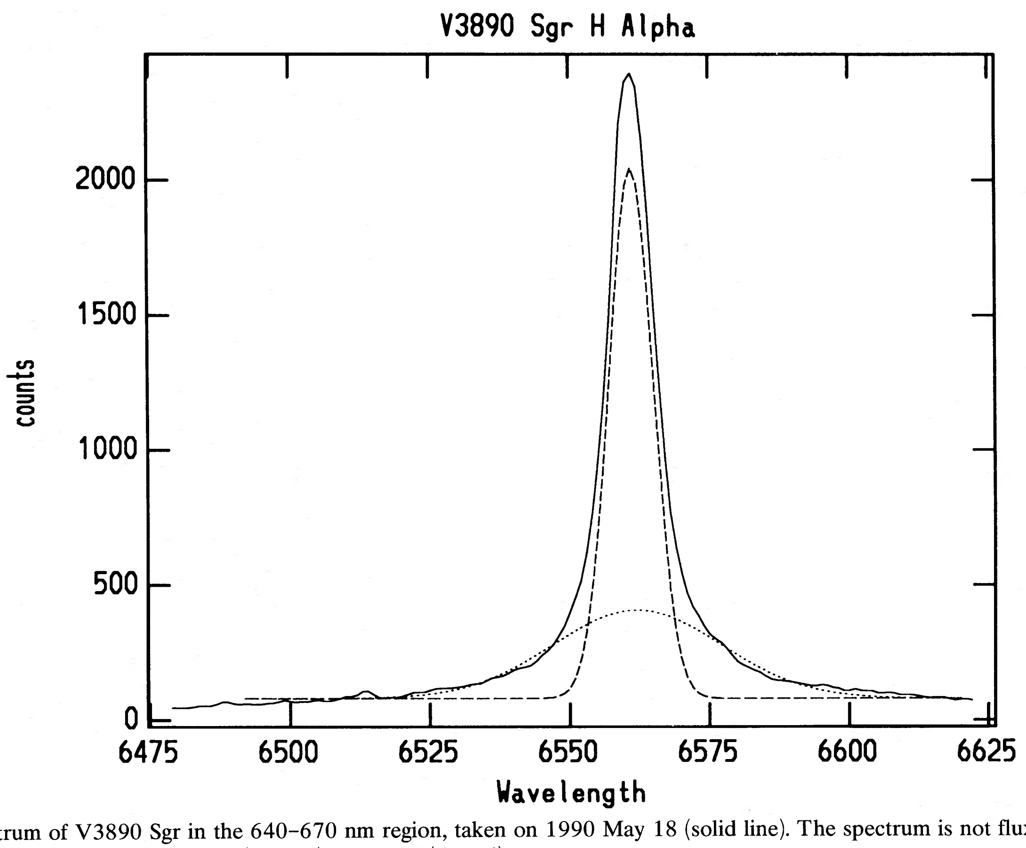

Figure 2. Spectrum of V3890 Sgr in the 640–670 nm region, taken on 1990 May 18 (solid line). The spectrum is not flux-calibrated. Also shown are the Gaussian fits to the narrow (dashed) and broad (dotted) components.

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1994MNRAS.269..105A

21-cm observations (Hjellming et al. 1986), is $M_V = -8.6$. Applying the M_V–t_3 relation and using $E(B-V)=0.73$ (Cassatella et al. 1985) for RS Oph, the estimated absolute magnitude is $M_V = -8.6$ and the distance is $d = 1.8$ kpc. This indicates validity of the M_V–t_3 relation. On the other hand, V745 Sco, which belongs to the same subclass of recurrent novae as RS Oph and V3890 Sgr, has a well-determined distance estimate and $t_3 = 9$ d (Sekiguchi et al. 1990b), but the absolute magnitude is estimated to be -7.9, independent of the M_V–t_3 relation. Similarly, for Nova LMC 1990 #2 which has a decay time of $t_3 = 5$ d, the absolute magnitude estimate is $M_V = -7.5$ (Sekiguchi et al. 1990a). These recurrent novae should have been intrinsically more luminous than RS Oph if the M_V–t_3 relation were valid for recurrent novae. Gonzalez-Riestra (1992) assumes an absolute magnitude for V3890 Sgr similar to those of V745 Sco and Nova LMC 1990 #2, and obtains limits to the distance of $2.6 < d < 5$ kpc. The distance estimated by us is in agreement with Gonzalez-Riestra's upper limit. Assuming that the conditions in V3890 Sgr are similar to those in RS Oph, in the following we use $E(B-V)=1.1$ and $d=5$ kpc.

4.2 Physical conditions

4.2.1 *Density and mass of the shell*

The spectrum of V3890 Sgr shows no nebular forbidden lines, and hence an estimate of the temperature and density using the [O III] line ratios and [N II] line ratios cannot be made. We estimate the density using the line flux in the Balmer Hβ and Hα lines, and the relation $f_\nu = \varepsilon_\nu n_e n_A V/d^2$, where ε_ν is the emissivity, n_e and n_A are the electron and hydrogen ion densities respectively, V is the volume and d is the distance to the nova. The volume is estimated assuming a spherical shell of thickness one-tenth of radius, i.e. a sphere with a filling factor $\phi = 0.1$, and a radius of 7×10^{13} cm estimated from the mean FWHM velocity of the emission lines.

The density as estimated from the Hβ flux is 2.3×10^9 cm^{-3}, and as estimated from Hα is 2.5×10^9 cm^{-3}, giving an unweighted mean of 2.4×10^9 cm^{-3}. Using the ultraviolet lines, Gonzalez-Riestra (1992) estimates $n_e \sim 10^{10}$ cm^{-3}. The difference in the two density estimates indicates that the filling factor is less than the assumed value of 0.1. The estimated hydrogen shell mass is $\lesssim 3 \times 10^{-7}$ M$_\odot$. This value is lower than the estimate for RS Oph ($\sim 10^{-6}$ M$_\odot$) by Bohigas et al. (1989) and Anupama & Prabhu (1989), but is similar to the estimate of Bode & Kahn (1985). The estimated mass is also similar to those of the other recurrent novae U Sco (Barlow et al. 1981) and V745 Sco (Duerbeck et al. 1993).

4.2.2 *Helium abundance*

The He I and He II line fluxes may be used to estimate the relative number of singly ionized [N(He$^+$)/N(H)] and doubly ionized [N(He^{++})/N(H)] helium ions in the ejecta. The helium abundance, assuming no neutral helium, is [N(He$^+$)/N(H)] + [N(He^{++})/N(H)]. Taking the emissivities of Hα, Hβ, and He II 468.6 and 541.1 nm from Hummer & Storey (1987), those of the 587.6-, 667.8- and 706.5-nm He I lines from Brocklehurst (1972), extrapolated for $n_e = 10^9$ cm^{-3}, and the He I emissivity correction for collisional effects from Clegg (1987), the helium abundance is estimated. Table 2 gives the

Table 2. Helium abundance.

	He$^+$/H		
He I line	using Hβ	using Hα	
587.6	0.14	0.12	
667.8	0.33	0.30	
706.5	0.18	0.16	
	He^{++}/H		
He II line	using Hβ	using Hα	
468.6	0.09	0.08	
541.1	0.08	0.08	
	He$^+$/H*	He^{++}/H	He/H
Hβ	0.16± 0.03	0.09± 0.006	0.24± 0.03
Hα	0.14± 0.03	0.08± 0.006	0.22± 0.03

*Average of 587.6- and 706.5-nm lines only.

estimate using different lines. From Table 2, it is seen that the He I 667.8-nm line gives a much higher value for the abundance (0.30) as compared to the 587.6- and 706.5-nm lines. It is quite likely that the flux in the 667.8-nm line is enhanced due to a contribution from the wings of the broad component in the Hα line. Ignoring the 667.8-nm line, we obtain N(He)/N(H) $= 0.23 \pm 0.03$.

4.2.3 *The central ionizing source*

The Zanstra temperature T_* of the ionizing source may be estimated from the helium and hydrogen line ratios (Osterbrock 1989). Using the observed fluxes of He II 468.6 nm and Hβ, we estimate the Zanstra temperature to be $T_* = 3 \times 10^5$ K. The corresponding radius of the source is estimated, using the Hβ line flux, as $R_* = 0.06$ R$_\odot$, giving a luminosity $L_* \approx 10^{38}$ erg s^{-1}.

4.2.4 *The coronal line region*

The presence of coronal lines in the spectrum indicates a temperature of $\sim 10^6$ K in the coronal line-emitting region. The temperature of the ionizing source, as estimated in Section 4.2.3, indicates that the coronal lines are not a result of photoionization of the shell. These lines are more likely to be formed via shock excitation, as in the case of RS Oph (Bode & Kahn 1985; Evans et al. 1988).

5 DISCUSSION

The radius and temperature of the ionizing source estimated in Section 4.2.3 indicate that it is a white dwarf that has not yet turned off. The presence of permitted and high-excitation coronal lines in the spectrum implies density and temperature stratification in the ejected medium. Furthermore, the presence of coronal lines and the narrowing of the emission lines indicate possible shock interaction of the ejecta with the surrounding medium, as in RS Oph. The decrease of the emission linewidths can be explained by the transfer of momentum from the expanding shell to the medium. Models in which the fast-moving nova ejecta interact with a slow-moving pre-outburst stellar wind (Bode & Kahn 1985) may hence be applied to V3890 Sgr.

The line profiles in V3890 Sgr indicate the presence of at least two components, as seen from the Hα line profile pre-

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1994MNRAS.269..105A

sented here and also from other observations reported in the IAU Circulars. This indicates an asymmetry in the nova envelope. A bipolar structure was seen in the VLBI map of the envelope of RS Oph at 5 GHz, with a central component containing the bulk of the flux and two accompanying lobes (Taylor et al. 1989). The radio lobes are probably formed by the ejection of high-velocity material which is relatively undecelerated. The ejection of such high-velocity blobs along an axis of symmetry would result in both fast and slow shock components (O'Brien, Bode & Kahn 1992). Assuming a similar geometry for V3890 Sgr, we consider the evolution of the narrow and the broad components separately.

There is no reported estimate of the initial ejection velocity. The earliest velocity estimates available on May 2, 4.7 d after outburst, are FWHM (narrow) = 2140 km s^{-1} and FWZI (broad) = 8600 km s^{-1} for the Hα line (Wagner, Bertram & Starrfield 1990). Our observations of the Hα line on day 21 give FWHM (narrow) = 420 km s^{-1} and FWHM (broad) = 1630 km s^{-1}. These estimates imply that the narrow component decelerated as $t_{\rm day}^{-1.1}$, while the broad component decelerated as $t_{\rm day}^{-0.65}$. The observed velocities on days 4.7 and 21 (both narrow and broad components) indicate an initial velocity $v_0 \sim 11\,600$ km s^{-1}.

Although V3890 Sgr has a rate of decline similar to that of RS Oph, the evolution of the spectrum is much faster than that of RS Oph. The spectrum of V3890 Sgr on day 18 very closely resembles the spectrum of RS Oph 60 d after the 1985 outburst. This faster evolution is probably a result of lower mass ejection and higher initial velocity.

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