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## Spectroscopy of the Recurrent Nova V3890 Sagittarii 18 Days after the 1990 Outburst

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## ABSTRACT

The spectrum of the recurrent nova V3890 Sgr obtained from the Vainu Bappu Observatory, 18 days 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 Balmer, 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<sup>-3</sup>, and mass of the ejected ionized shell,  $\sim 10^{-7} M_\odot$ . The temperature and radius estimates of ionizing source are  $3 \times 10^5$  K and  $0.3 R_\odot$ . A helium abundance of 0.23 is estimated. Applying expansion models in which the fast moving nova ejecta interact with a slow moving pre-outburst wind, we conclude that the ejecta expanded into an inhomogeneous stellar wind.



# Spectroscopy of the Recurrent Nova V3890 Sagittarii 18 Days after the 1990 Outburst

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## 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 (IAU Circular 5002) and W. Liller (IAU Circular 5010). From a magnitude  $m_{vis}$  fainter than 13.0 on 1990 April 20.68, the nova rose to a magnitude of  $m_{vis} = 8.5$  on 1990 April 27.72 (IAU Circulars 5002, 5007 and 5010). Fig. 1 shows the 1990 outburst light curve, based on magnitudes from the IAU Circulars.

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 (Nos. 5006, 5007, 5015, 5019 and 5021). Williams et al. (1991) present the CTIO data obtained during the later stages of the outburst. The spectrum in the ultraviolet

region, obtained using the 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 days after the outburst maximum.

## 2 OBSERVATIONS

Three spectra were obtained on 1990 May 14.91, 15.94 and 16.97 from VBO. The observations were carried out using the UAG spectrograph and Photometrics CCD system at the Cassegrain focus of the 1.02m 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  $\sim 2.2$  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  $\sim 1.8$  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 Figure 2. The spectrum shows strong, high excitation forbidden lines, along with Balmer, He I, He II and Fe II lines. The most prominent lines are H $\alpha$ , H $\beta$ , H $\gamma$ , He I 587.6, 667.8, 706.5 and 728.1 nm, He

H 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, [A X] 553.5 nm and [A XI] 691.9 are also strong. The feature at 683 nm is most likely 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 contribution from the secondary star. In their spectrum obtained on 1990 May 14, Mukai et al (IAU Circular No. 5015) also note the presence of O I 777.2 and 844.6 nm, the coronal line [Fe XI] 739.1 nm and [S III] 906.9. The spectrum during 1990 May 14-16 may be classified as C<sub>He+</sub><sup>o</sup> in the CTIO classification scheme (Williams et al 1991). The spectral evolution sequence, based on data published in IAU Circulars and Williams et al is P<sub>HeHe+</sub> C<sub>He+</sub><sup>o</sup> A<sub>o</sub> during the period 1990 May 2-September 23.

The uncalibrated H $\alpha$  profile is shown in Figure 3. The profile shows both the narrow and the broad components. A two component Gaussian fit to the profile gives FWHM velocities 420 km s<sup>-1</sup> and 1630 km s<sup>-1</sup> for the narrow and broad components respectively. The fitted Gaussians are also shown in Figure 3.

## 4 RESULTS

### 4.1 Absolute magnitude, Reddening and Distance

The light curve of the 1990 outburst of V3890 Sgr (Fig. 1) indicates that the maximum was reached on 1990 April 27.72 (=JD 2448009.22), with a maximum magnitude  $V_{\max} = 8.5$ . A smooth fit to the light curve gives (i) magnitude at 15 days from maximum:  $V_{15} = 11.0$ , (ii) time of decline through 2 magnitudes in  $V$ :  $t_2 = 12$  days, (iii) time of decline through 3 magnitudes in  $V$ :  $t_3 = 18$  days (Gonzalez-Riestra (1992) estimates  $t_3 = 17$  days). Using the above estimates, the absolute magnitude of the nova at maximum is estimated using the various ( $M_{V,\max}$ ,  $t_{\text{decline}}$ )-relations in literature (Pfau 1976, Cohen 1985, van den Bergh & Younger 1987 and Capacchioni et al. 1989). The value of  $M_V$  for

V3890 Sgr as estimated from these relations range from  $M_V = -8.3$  to  $M_V = -8.7$  with the unweighted mean

$$M_V^{\max} = -8.6 \pm 0.2,$$

giving an uncorrected distance modulus of

$$(m - M)_V = 17.08 \pm 0.2.$$

The foreground reddening towards the nova is estimated here using the colour index of the nova two magnitudes below maximum. Photometry of the nova by Buckley, Wargau & Soltynski (IAU Circular No. 5019) 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 two magnitudes below maximum is  $(B - V)_0 \approx 0$  (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 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 H $\alpha$ /H $\beta$  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 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  $d = 5.4$  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  $t_3 = 18$  days (similar to V3890 Sgr) and a distance 1.6 kpc estimated from 21 cm observations (Hjellming et al) 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 distance is  $d = 1.8$  kpc. This indicates validity of the  $M_V - t_3$  relation. On the other hand for V745 Sco, which belongs to the same subclass of recurrent novae as RS Oph and V3890 Sgr, has a well determined distance estimate and a  $t_3 = 9$  days (Sekiguchi et al 1990b), 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 de-

day time of  $t_3 = 5$  days, 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, to recurrent novae. Gonzalez-Riestra (1992) assumes an absolute magnitude for V3890 Sgr similar to V715 Sco and Nova LMC 1990 #2 and obtains limits to the distance as  $2.6 < d < 5$  kpc. The distance estimated by us is in agreement with the upper limit. Assuming the conditions in V3890 Sgr are similar to RS Oph, in the following an  $E_{B-V} = 1.1$  and  $d = 5$  kpc is used.

## 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 H $\beta$  and H $\alpha$  lines and the relation  $f_\nu = \epsilon_\nu n_e n_A V/d^2$ , where  $\epsilon_\nu$  is the emissivity,  $V$  the volume and  $d$  is the distance to the nova. The volume is estimated assuming a sphere with a filling factor  $\phi = 0.1$ , and radius  $7 \times 10^{15}$  cm (a value to be justified in section 5).

The density as estimated from H $\beta$  flux is  $2.3 \times 10^9$  cm $^{-3}$  and from H $\alpha$  is  $2.5 \times 10^9$  cm $^{-3}$ , giving an unweighted mean of  $2.4 \times 10^9$  cm $^{-3}$ . This estimate may be compared with the estimate of  $\sim 10^{10}$  by Gonzalez-Riestra (1992) using ultraviolet lines. The estimated shell mass is  $3 \times 10^{-7} M_\odot$ .

### 4.2.2 Helium abundance

The He I and He II line fluxes may be used to estimate the relative numbers of singly ionized  $N(\text{He}^+)/N(\text{H})$  and doubly ionized  $N(\text{He}^{++})/N(\text{H})$  helium in the ejecta. The helium abundance, assuming no neutral helium is  $\frac{N(\text{He}^+)}{N(\text{H})} + \frac{N(\text{He}^{++})}{N(\text{H})}$ . Taking the emissivities of H $\alpha$  and H $\beta$  and He II 468.6 and 541.1 nm from Hummer & Storey (1987), of the He I lines 587.6 and 706.5 nm from Brocklehurst (1972), extrapolated for  $n_e = 10^9$  cm $^{-3}$ , and the He I emissivity correction for collisional effects according to Clegg (1987), the helium abundance is estimated. Table 2 gives the estimate using different lines. From Table 2, it is seen

that He I 667.8 nm line gives a much higher value for the abundance: 0.30 as compared to 587.6 nm and 667.8 nm lines. It is quite likely that the flux in 667.8 nm is enhanced due to contribution from the wings of the broad component in the H $\alpha$  line, and hence the helium abundance estimated using 667.8 nm is higher than the estimate using other He I lines. Ignoring the estimate from 667.8 nm line, we obtain  $\frac{N(\text{He I})}{N(\text{H})} = 0.23 \pm 0.03$ .

### 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 H $\beta$ , we estimate the Zanstra temperature to be  $T_* = 3 \times 10^5$  K. The corresponding radius of the source is estimated, using the H $\beta$  line flux, as  $R_* = 3 \times 10^{10}$  cm (assuming a covering factor of 0.1), giving a luminosity  $L_* \approx 10^{39}$  erg s $^{-1}$ .

### 4.2.4 The coronal line region

The presence of coronal lines in the spectrum indicate temperature  $\sim 10^6$  K in the coronal-line-emitting region. The temperature of the ionizing source, as estimated in section 4.3.3 indicates that the coronal lines are not due to photoionization of the shell. These lines are more likely to be formed due to shock excitation, as in the case of RS Oph (Bode & Kahn 1985, Evans et al 1989).

## 5 DISCUSSION

The spectrum of the recurrent nova V3890 Sgr 18 days after maximum is presented and classified. Interstellar reddening and distance to the nova, density and helium abundance in the ejected shell, and the temperature and radius of the ionizing source are derived. The physical parameters of the ionizing source indicate it is a white dwarf, and the outburst is a thermonuclear runaway event on its surface. The presence of permitted and high excitation coronal lines in the spectrum implies density and temperature stratification in the ejected medium. Further, the presence of coronal lines and the narrowing of the emission lines indicate possible shock interaction of the ejecta

with surrounding medium, as in RS Oph. The models in which the fast moving nova ejecta interact with a slow moving pre-outburst stellar wind (Bode & Kahn 1985; Seaquist et al 1989) may hence be applied to V3890 Sgr. The velocity of the ejecta in the momentum conserving phase of the ejecta is given by

$$v = v_0 (1 + t/t_*)^{1/2},$$

where  $v$  is the velocity of the ejecta at epoch  $t$ ,  $v_0$  the initial velocity and  $t_*$  the characteristic time given by

$$t_* = \frac{M_e u}{V_0 \dot{M}}.$$

In the above equation,  $M_e$  is the mass of the ejecta,  $\dot{M}$  the rate of mass loss from the M-giant secondary and  $u$  the terminal velocity of the stellar wind. Using the observed velocities, the characteristic time  $t_*$  and hence  $\frac{\dot{M}}{u}$  may be estimated. We consider the narrow and the broad components of the line profile separately. From the narrow component with FWHM velocities  $v_0 = 2140 \text{ km s}^{-1}$  and  $v = 420 \text{ km s}^{-1}$  18 days after outburst we obtain  $t_* = 0.72$  days and  $\frac{\dot{M}}{u} = 1.36 \times 10^{12} \text{ g cm}^{-1}$ . For  $t \gg t_*$ , the radius of the nova shell may be approximated to  $r_s = at^{2/3}$ , where  $a = 3.08 M_e^{1/3} v_0^{2/3} u^{1/3} \dot{M}^{-1/3}$  (Bode & Kahn 1985). Using this, the radius estimate is  $r_s = 7.7 \times 10^{13} \text{ cm}$ , and the velocity  $v_s$  is  $300 \text{ km s}^{-1}$ . The density of the stellar wind just ahead of the shocked ejecta given by

$$\rho_w = \frac{\dot{M}}{4\pi r v_s^2},$$

is estimated as  $1.8 \times 10^{-17} \text{ g cm}^{-3}$ . Similarly for the broad component with velocities  $v_0 = 4300 \text{ km s}^{-1}$  and  $v_{18} = 1630 \text{ km s}^{-1}$ , we obtain  $t_* = 3$  days,  $\frac{\dot{M}}{u} = 1.78 \times 10^{12} \text{ g cm}^{-1}$ ,  $v_s = 1100 \text{ km s}^{-1}$ , and the density of the stellar wind is  $\rho_w = 2.2 \times 10^{-18} \text{ g cm}^{-3}$ . It thus appears that the ejecta of V3890 Sgr expanded into an inhomogeneous stellar wind.

Although V3890 Sgr has a rate of decline similar to RS Oph, the evolution of the spectrum is much faster than RS Oph. The spectrum of V3890 Sgr on day 18 very closely resembles the spectrum of RS Oph 60 days after the 1985 outburst. The faster evolution of the narrow component of V3890 Sgr as compared to RS Oph can be attributed to its expansion

into a denser stellar wind ( $\rho_w = 2.4 \times 10^{-18} \text{ g cm}^{-3}$  for RS Oph: Bode & Kahn 1985); while the broad component, which expands into the less dense region of the stellar wind has an evolution similar to that of RS Oph.

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## REFERENCES

- Anupama, G.C., Prabhu, T.P. 1989, JA&A 10, 237  
 Bode, M.F., Kahn, F.D. 1985, MNRAS 217, 205  
 Brocklehurst, M. 1972, MNRAS 157, 261  
 Capaccioli, M., Della Valle, M., D'Onofrio, M., Rosino, L. 1989, AJ 97, 1622  
 Clegg, R.E.S. 1987, MNRAS 229, 31p  
 Cohen, J.G. 1985, ApJ 292, 90  
 Duerbeck, H.W. 1987, A Reference Catalogue and Atlas of Galactic Novae. Reidel, Dordrecht.  
 Evans, A., et al 1989, MNRAS 234, 755  
 Ferland, G.J. 1977, ApJ 215, 873  
 Gonzalez-Riestra, R. 1992, A&A 265, 71  
 Hummer, D.J. and Storey, P.J. 1987, MNRAS 224, 801  
 Hjellming, R.M., et al 1986, ApJL 305, L71  
 Osterbrock, D.E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, University Science Books, Mill Valley  
 Pfau, W. 1976, A&A 50, 113  
 Prabhu, T.P., Anupama, G.C. 1991, BASI 19, 97  
 Seaquist, E.R., Bode, M.F., Frail, D.A., Roberts, J.A., Evans, A., Albinson, J.S.,

1989, ApJ 311, 805

Sekiguchi, K., Stobie, R.S., Buckley, D.A.M.,  
Caldwell, J.A.R. 1990a, MNRAS 245, 28p

Sekiguchi, K., et al 1990b, MNRAS 246, 78

Schmid, H.M., 1989, A&A 211, L31

van den Bergh, S., Younger, P.F. 1987, A&AS  
70, 125

Whitney B., Clayton, G.C. 1989, AJ 98, 297

Williams R.E., Hamuy, M., Phillips, M.M.,  
Heathcote, S.R., Wells, L., Navarrete, M.  
1991, ApJ 376, 721

## FIGURE CAPTIONS

**Figure 1.** The light curve of the 1990 outburst of V3890 Sgr, based on magnitudes from IAU Circulars. JD 2448010 = 1990 April 28.5.

**Figure 2.** Spectrum of V3890 Sgr 18 days after outburst, uncorrected for interstellar reddening.

**Figure 3.** Spectrum of V3890 Sgr in the region 640–670 nm on 1990 May 18. The spectrum is not flux calibrated. Also shown are the Gaussian fits to the narrow and broad components.

Table 1 Line identifications and observed fluxes.

$\lambda_m$ nm	Identification		Flux $10^{-12}$ erg cm $^{-2}$ s $^{-1}$
435.3	434.05	H $\gamma$ (1)	4.915
	435.18	Fe II (27)	
439.8	438.54	441.68	0.785
	Fe II (27)		
448.1	4471.48	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	H $\beta$ (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		
	5710.76		
575.0	575.48	[N II] (3)	0.277

Table 1 Continued.

$\lambda_m$ nm	Identification	Flux $10^{-12}$ erg cm $^{-2}$ s $^{-1}$
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 H $\alpha$ (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

Table 2 Helium Abundance.

He I line	He <sup>+</sup> /H	
	using H $\beta$	using H $\alpha$
587.6	0.14	0.12
667.8	0.33	0.30
706.5	0.18	0.16

He II line	He <sup>++</sup> /H	
	using H $\beta$	using H $\alpha$
468.6	0.09	0.08
541.1	0.08	0.08

	He <sup>+</sup> /H*	He <sup>++</sup> /H	He/H
H $\beta$	0.16 ± 0.03	0.09 ± 0.006	0.24 ± 0.03
H $\alpha$	0.14 ± 0.03	0.08 ± 0.006	0.22 ± 0.03

\* Average of 587.6 and 706.5 lines only.

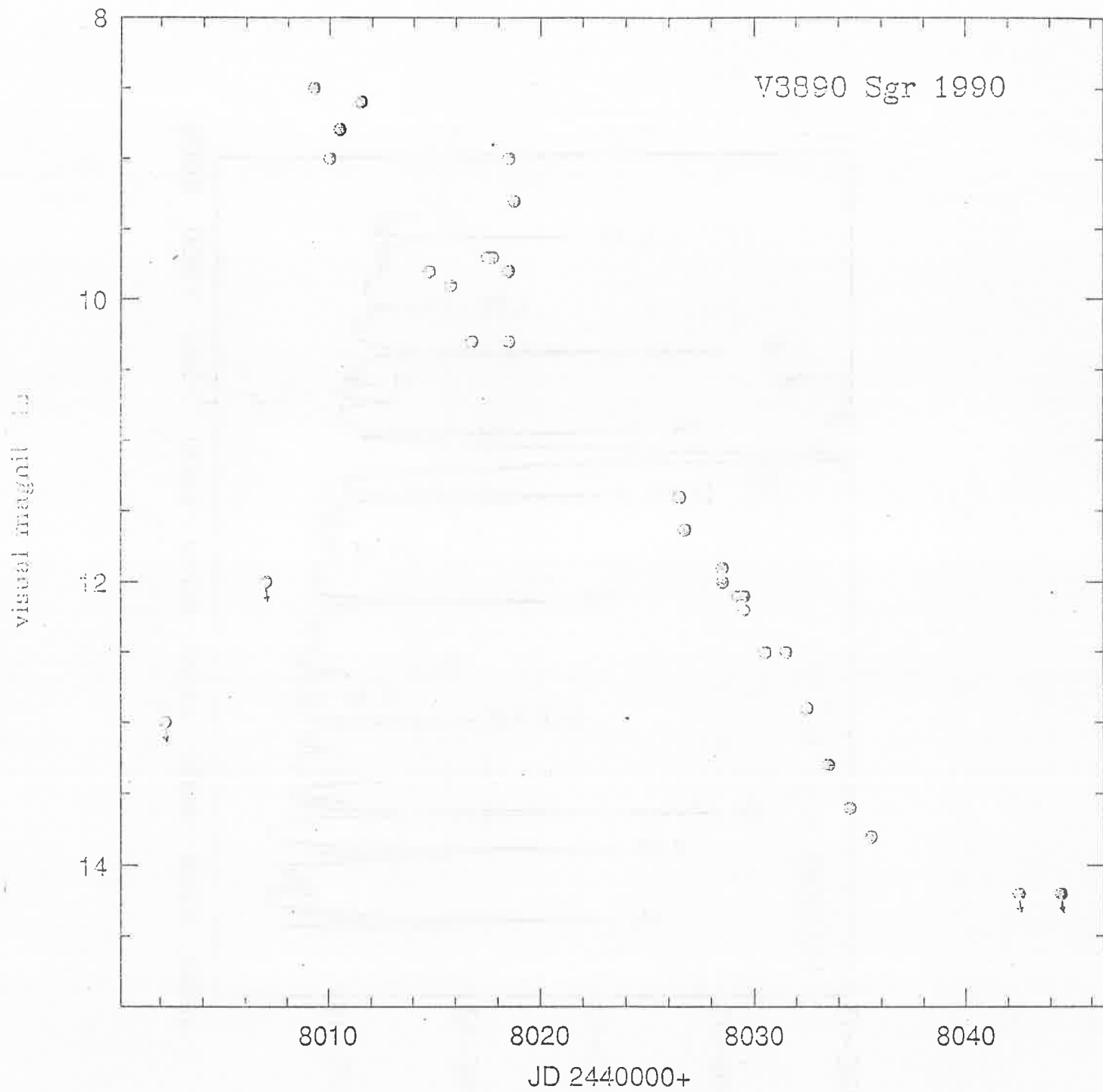
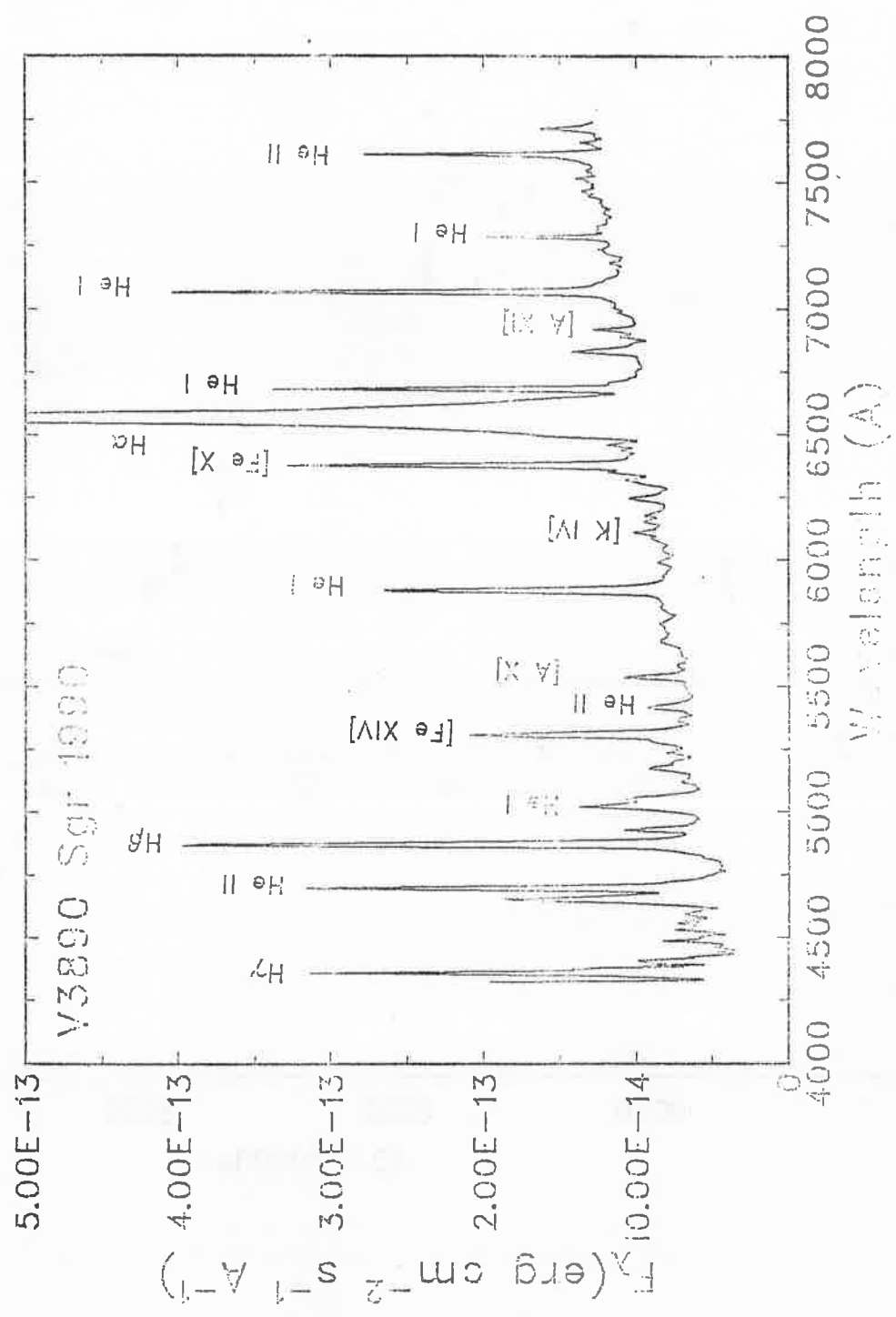


Figure 1



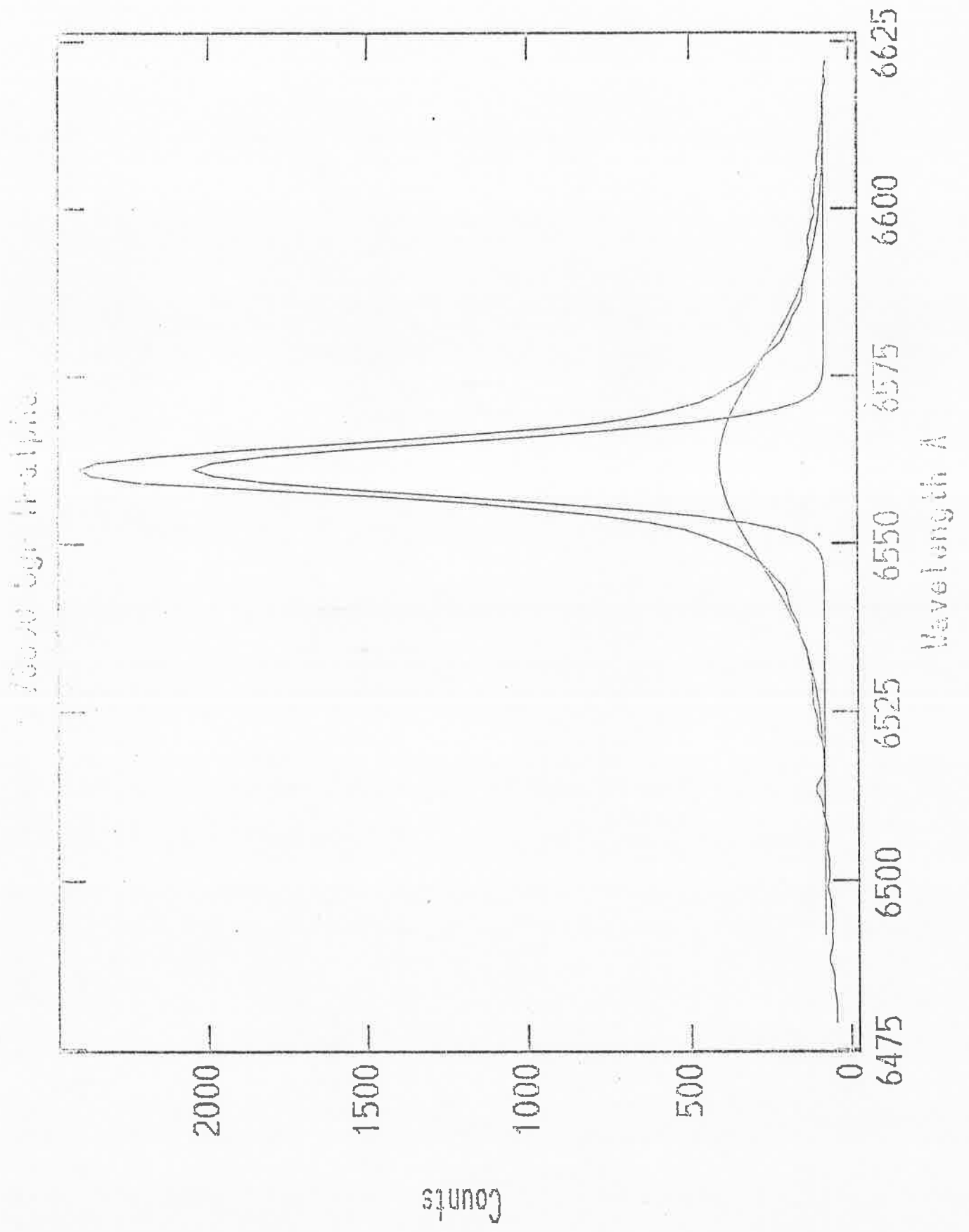


Figure 3

