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Spectroscopy of novae and supernovae

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Abstract. Many novae have been studied spectroscopically since 1975 and many supernovae since 1980 using the telescopes at VBO. The programme on novae has intensified since 1985, and that on supernovae has found renewed interest since SN 1987A. The availability of the CCD detector in 1989 and of the Boller & Chivens spectrograph at the Vainu Bappu Telescope in 1991 have added impetus to these studies. The motivation for these studies are summarized in this review together with some of the important results obtained with the VBT. The desirable improvements at the VBT are summarized at the end.

Key words : novae, spectroscopy—novae, N Oph 91, N Her 91, N Cyg 92—supernovae, spectroscopy—supernovae, SN 1991T, SN 1991 AA—Vainu Bappu telescope

1. Introduction

Novae and supernovae derive their names from the fact that they appear as new stars in positions where nothing was visible earlier. They are now known to be periodic or once in a life-time outbursts of preexisting stars. The precursors have been identified on existing photographs in some cases and recurrence of nova phenomenon has been identified in some objects with shorter interoutburst periods. Old novae have been followed up in a large number of cases.

It is fairly well-established now that novae are interacting binary systems in which the Roche-lobe filling secondary transfers mass to a white dwarf through an accretion disc (see Starrfield 1989). When a certain amount of mass is accumulated on the surface of the white dwarf, runaway thermonuclear reactions take place causing an explosive ejection of most of the accreted material. This scenario predicts nova explosions to take place in the binary progenitor periodically. There is indirect statistical evidence for such a periodicity with the expected recurrence timescales of $\sim 10^4$ years. Some novae are known to have recurrence timescales of decades and it is difficult to explain them theoretically.

Most supernovae can be classified spectroscopically into type I devoid of hydrogen emission and type II where hydrogen emission lines are intense (see Harkness & Wheeler 1990). At least type II stars are certainly last stages of the evolution of a single star where an implosion of the core resulting in a neutron star or a black hole causes explosive ejection

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of material from the rest of the star. Some type I supernovae may be analogues of this model at lower masses. However binary evolution with strong mass exchange appears to be an easier way of producing such events theoretically.

Both novae and supernovae are not sufficiently well monitored in statistically significant numbers. Though many novae are sufficiently bright during quiescence, spectroscopic and photometric monitoring has generally not been done on long baselines in time. This was the main motivation in making a long-term programme at Vainu Bappu Observatory (VBO), Kavalur, for spectroscopic monitoring of novae in outburst and quiescence and of supernovae in outburst. We detail the motivation further in the following, with examples of results obtained from VBO, in particular, using the 2.3m Vainu Bappu Telescope (VBT). The references listed at the end are biased towards the papers based on results from VBO because of lack of space. Three most useful sources of information on the topics discussed here are available in the form of books (see under the following references : Starrfield 1989; Harkness & Wheeler 1990; Williams 1990).

2. Novae in outburst

The early spectra of novae during outburst resemble supergiants though with the lines broadened due to expanding atmosphere at several hundreds to a few thousands of km s^{-1}. As the atmosphere expands, the photosphere recedes; consequently the emission lines appear and gain in strength. Depending on the photospheric temperature, and density in the atmosphere, the spectra show different excitation at different evolutionary stages, termed in chronological order as the principal, diffuse-enhanced, Orion, transition and nebular. Inhomogeneities in the envelope can cause a variety of excitation conditions to be present even at a given epoch. Though novae emit at a constant bolometric luminosity for considerable duration after maximum, the optical light curve decreases as the receding photosphere becomes hotter emitting a larger fraction in the ultraviolet. The speed of decline in the optical light varies in different novae.

McLaughlin (1960) showed that the spectra of novae are similar at a given magnitude below the peak. This fact suggested that the decline of optical light and the increase in excitation in the spectrum are controlled by the same physical mechanism. We identify this now with the increase in photospheric temperature as its radius decreases at constant bolometric luminosity, coupled with a decrease in density in the envelope (Williams 1990). For a nova emitting close to Eddington luminosity for 1 $M_\odot$, the temperature is given by

$$T_{\rm rad} \approx 9 \times 10^4 \left(\frac{R}{R_\odot}\right)^{-1/2} \mathrm{K}. \qquad \ldots (1)$$

The observational evidence for such a relationship can be obtained from the observed continuum flux corrected for nebular emission and emission line flux from the nebula as first shown by Anupama *et al.* (1992).

Though the excitation conditions of the spectrum are similar to the first approximation, there indeed are differences which became apparent as the number of novae observed spectroscopically using the CCDs increased. Some novae have shown coronal line emission in the late stages of evolution. In some cases the coronal lines can arise due to the interaction of the nova ejecta with the ambient medium (e.g. RS Ophiuchi: Anupama & Prabhu 1989). However, there are cases where there are strong indications that the coronal lines are due to radiative ionization. The special evolution of different novae can be understood better in the ($T_{\rm rad}$, n_e) plane. The mass of ejected shell is an important factor influencing the evolution though the nature of white dwarf and the abundances in the accreted matter are probably the basic factors. Figure 1 shows schematically the probable evolutionary tracks of different novae.

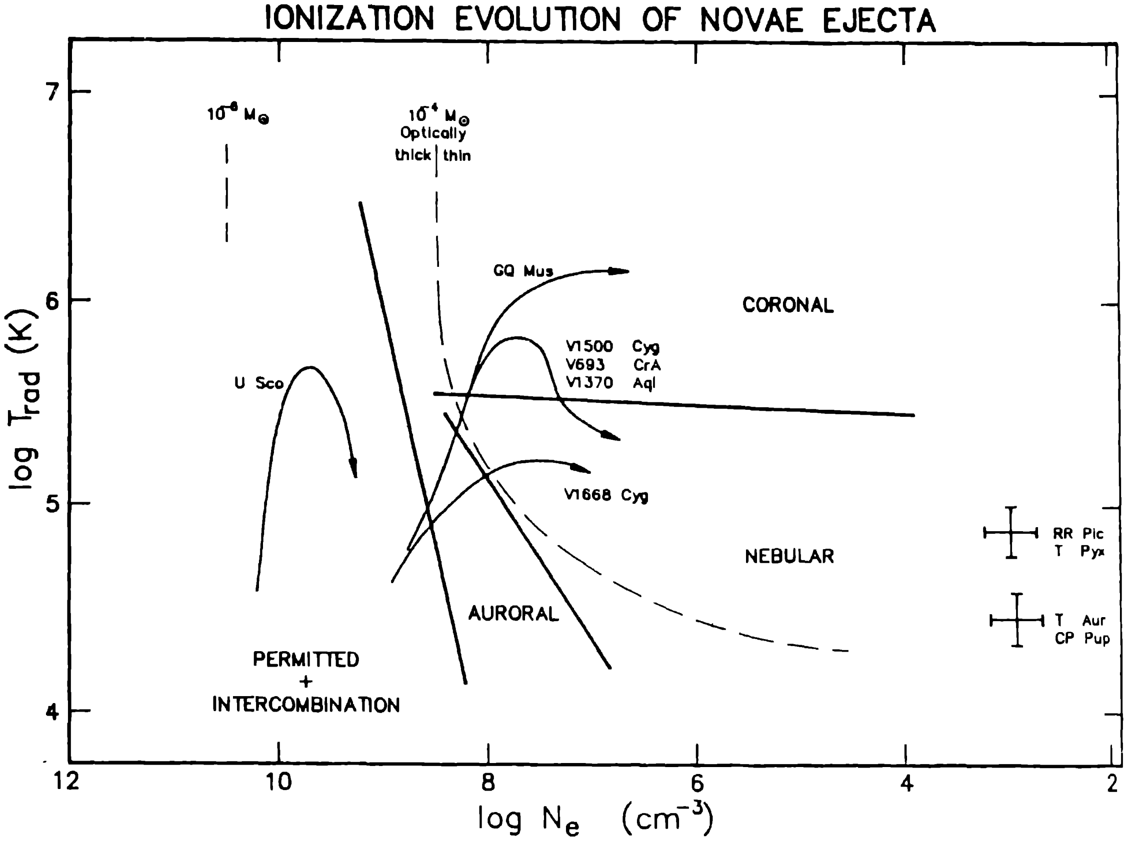

Figure 1. Schematic representation of evolution of nova ejecta in terms of ionization and the emission spectrum (reproduced from Williams 1990).

First order modelling of nova shells during the outburst is now becoming tractable with CCD spectrophotometric data and theory of line formation in higher density material. The main uncertainty is due to the fact that the forbidden line diagnostic of density is not possible during the early phase of high densities. An estimate of N_e and mass of the ionized shell can be made from the Balmer line fluxes if the filling factor and the volume are known. The volume can be computed from the expansion velocity measured from P-Cygni absoption features during the early phases and from emission line widths during the late phases. Spectrophotometric monitoring from outburst to late nebular stage, continuing into the quiescent stage is hence of great interest.

There was a good number of novae reaching comfortable brightness at maximum during 1991-92. Of these, Nova Puppis 1991 and Nova Cygni 1992 have been monitored well using the 1- and 2.3-m telescopes at Kavalur. Nova Cygni was observed at 3 epochs in 1992 March, April and May using VBT and at two epochs, in 1992 March and 1993 January using 1-m reflector. The monitoring will continue when the object becomes available again in

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1993 March. Both these novae, together with Nova Herculis 1991 which was also observed fairly extensively, belong to the class of novae in which the white dwarf appears to be ONeMg type. The spectra of these novae are characterized by the unusual strength of emission lines of these elements and also of high excitation and ionization lines. Spectra of Nova Cygni are shown in figure 2.

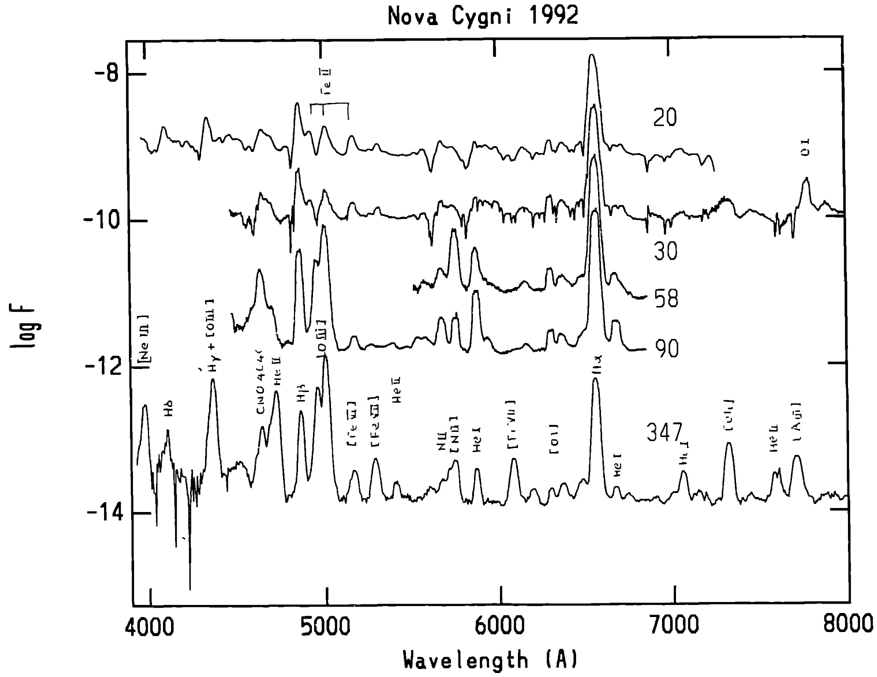

Figure 2. Spectra of Nova Cygni 1992 obtained at 20, 30, 58, 90 and 347 days since outburst. The first and the last spectra were obtained using the 1-m reflector whereas the remaining ones are from the 2.3-m reflector. Ordinates are log F_λ (erg cm^{-2} s^{-1} Å^{-1}) + constant where the values of constant are 2.0, 1.5, 1.0, 0.5 and 0.0 for the spectra in chronological order.

Once the spectra are corrected for interstellar reddening [$E(B-V) = 0.31$ in the case of nova Cygni], one can use the continuum fluxes and the Balmer emission fluxes to check the (R, $T_{\rm rad}$) relationship. It is found that the theoretical relationship is obeyed only if one assumes that a fraction of ionizing radiation escapes the nebula, with this fraction increasing with time. This assumption is supported by the structure of nova shells seen at later stages which shows that they do not form a fully enclosed shell around the central source, but have equatorial rings and polar caps. As the envelope expands, the low-density region in between the structure becomes optically thin to ionizing radiation. The structure itself may consist of clumps and thus at the very late stages an additional fraction of ionizing radiation can escape through the regions between the clumps. The diagnostic diagram of Anupama *et al.* is shown in figure 3 in the case of Nova Cygni 1992. The continuum flux on day 347 is an upper limit since the nebular emission has not been subtracted out. This will have the effect of overestimating the radius and underestimating the temperature. It is seen from the figure that the covering fraction reduced considerably from ~1 before 90 days from maximum to a value of 0.003 by day 347. It is also seen that the radiation temperature crossed 10^5 K. The Zanstra temperature determined from He lines indicates that the temperature could have been even higher : 4×10^5 K. The ionization in Nova Cygni 1992 reached [Fe VII] with some indication of [Fe X]

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6374 Å line blending with [O I] 6363 Å. The lines due to [Fe XI] and [Fe XIV] which are strong in solar corona and in recurrent novae are absent. Hence the ionization is very likely due to hard radiation from the white dwarf, rather than shock ionization as in recurrent novae.

The nova ejecta can be envisaged to be formed by mass loss at constant velocity, decreasing as t^{-2} where t is the time in days since the outburst. The density in such a shell also decreases as t^{-2}. Balmer line fluxes from the shell vary as the emitting volume V times the square of density, i.e., t^{-1}. The fluxes from Nova Cygni till day 90 agree with such a relationship. Once the mass loss ceases, the shell expands freely and the density and consequently the Balmer line flux decrease as t^{-3}. This is shown for Nova Cygni in figure 4. Using the Balmer line fluxes and assuming a filling factor ϕ one can compute the electron density (which scales as $\phi^{-0.5}$) and mass of ionized envelope (which scales as $\phi^{0.5}$). The estimated values are listed in table 1 for an assumed value of $\phi = 0.1$. The mass of ionized shell increases initially due to high optical depth in Lyman continuum which leaves part of the shell neutral. As the entire shell is ionized it reaches a constant value of ~5×10^{-4} $M_{\odot}$. It appears that the assumption of a constant filling factor through time is valid; the shell expands homologously. The decease in covering fraction with time would then imply that the shell is clumpy and increasing portions of clumps get optically thin to Lyman radiation with time.

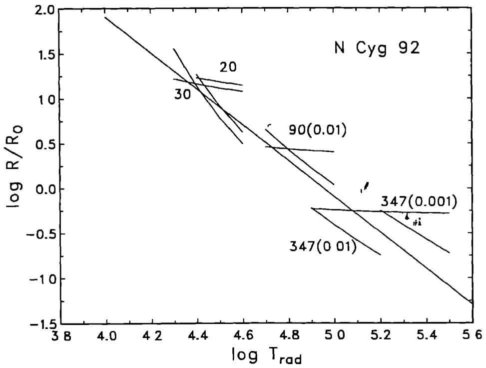

Figure 3. The loci of continuum fluxes (at 5450 Å) corrected for nebular emission (nearly horizontal curves), and Hβ emission line fluxes (steeper curves) due to a blackbody source of radius R (in $R_{\odot}$) at temperature $T_{\rm rad}$ (K) for Nova Cygni 1992. The numbers correspond to days since outburst maximum with assumed covering fraction in paranthesis when it is different from unity. The theoretical line (equation (1)) is shown as a straight line. The continuum flux on day 347 is an upper limit since it has not been corrected for nebular emission.

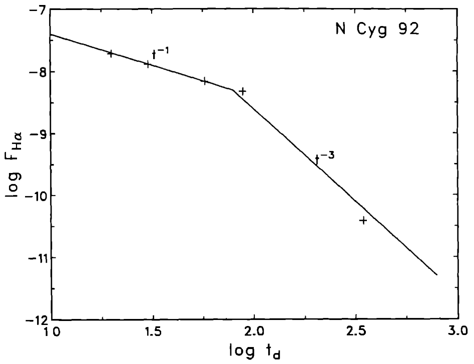

Figure 4. The decrease of Hα flux with time. The crosses represent observed fluxes and the two segments of straight lines the curves t^{-1} and t^{-3} passing through these points.

As the nova shell begins to thin down, the structure starts becoming apparent. This will be noticeable in emission line profiles. There are very few novae which have detectable surface brightness of the shell when it has expanded sufficiently to show the structure in images. Hence the emission line profiles are very useful in understanding the nature of a majority of nova shells. We show in figure 5 the Hα and Hβ profiles of Nova Herculis 1991 during its nebular phase. The structure of profiles is similar in both the lines. The various peaks in such profiles are generally identified with edges of equatorial rings or polar caps

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Table 1. Envelope of Nova Cygni 1991

t_d day	n_e 10^8 cm^{-3}	M_H 10^{-5} $M_\odot$	T_e [O I] K
20	6.9	1.1	5170
30	3.0	1.6	4870
58	1.0	3.8	6820
90	0.44	5.7	6210
347	0.006	5.0	10000*

*Based on [O III] line ratio and figure 3.

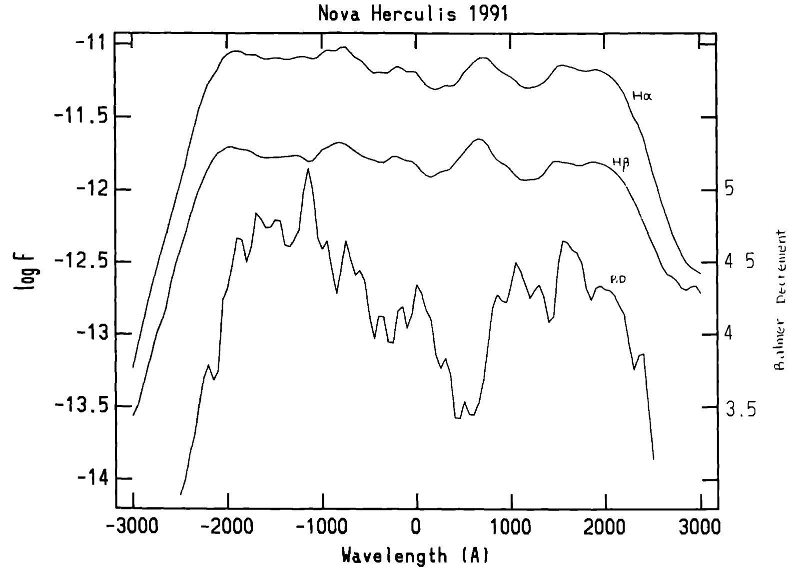

Figure 5. The Hα and Hβ profiles of Nova Herculis 1991 observed with the VBT on 1991 April 4. The ratio BD = Hα/Hβ is shown on a linear scale marked at right.

(see Prabhu 1977a; Prabhu & Anupama 1987). As shown in the figure, the Balmer decrement, or the ratio of the two profiles varies considerably across the profile. This can be an important input towards reconstruction of the geometry of the shell based on emission line profiles. Comparison with other lines such as He I, [O III] etc. will yield information on the physical conditions in different parts of the shell.

Nova Ophiuchi 1991 and Nova Sagittarii 1992, the other two novae monitored with the VBT, belonged to the slower class of novae which do not reach as bright absolute luminosities as the fast novae. The early spectrum of Nova Ophiuchi is compared in figure 6 with that of Nova Cygni. Clear differences are evident in terms of characteristic strength of Fe II lines in slow novae. These novae belong to the class of moderately fast novae such as Nova Sagittarii 1977 (Prabhu 1977b) and LW Serpentis 1978 (Prabhu & Anupama 1987) in contrast to the very fast novae N Her 91, N Pup 91 and N Cyg 92, which are similar to nova V1500 Cygni 1975 (Prabhu 1977a).

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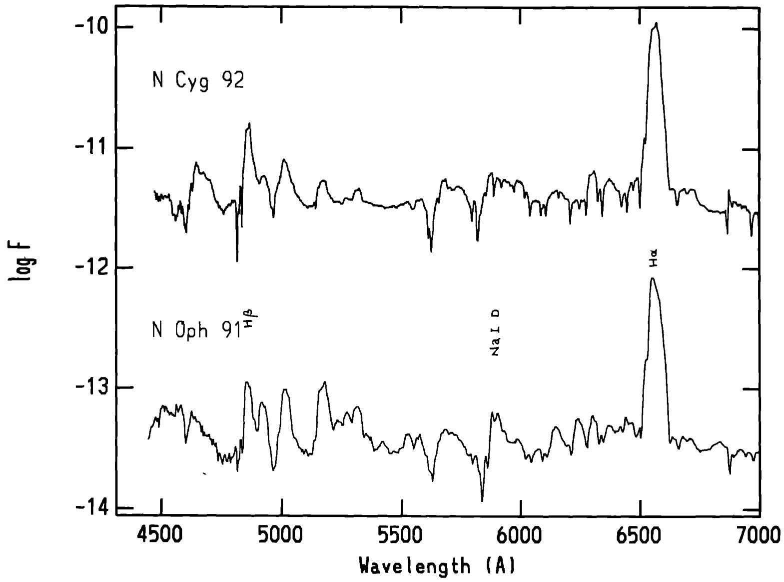

Figure 6. The spectrum of Nova Ophiuchi 1991 obtained with the VBT on 1991 April 27 is compared with that of Nova Cygni 1992 obtained on 1992 March 21. The strongest lines are Balmer lines of hydrogen, many lines of Fe II, and Na I D.

Unfortunately no recurrent nova has had an outburst during the last two years. The outburst of T Pyxidis is imminent. Some of the recurrent novae like U Scorpii (Prabhu & Shylaja 1979) and V3890 Sagittarii (Anupama & Sethi 1993) are fast and require quick adjustment of telescope time in order to be observed.

3. Novae in quiescence

Twelve postnovae brighter than 16 mag are bright enough to be observed with the VBT at Cassegrain with the present limitations of instrumentation. Of these, only three—GK Persei, V603 Aquilae and HR Delphini are bright enough to be observed during grey periods. GK Persei 1901 is a well-observed postnova with resolved shell (Anupama & Prabhu 1993). The postnova exhibits dwarf nova activity during quiescence and hence has been of great importance to modelling of novae in between outbursts. Continuous monitoring of this nova is hence of interest, and is being carried out with both the telescopes at VBO.

Out of the seven recurrent novae with outburst periods of few to several decades, four are within the reach of VBT spectroscopy. Two of these—T Coronae Borealis and RS Ophiuchi—are bright enough to be observed even close to full moon. They are being monitored with both the telescopes. Long-term monitoring can bring out secular and periodic changes in spectra (Anupama & Prabhu 1991) which are of interest in understanding the cause of such small interoutburst periods compared to classical novae. A fainter recurrent nova—T Pyxidis—has been observed in 1991 when a few dark nights had become available. This nova, which was at the limit of 1-m reflector (Anupama 1990) has been recorded fairly easily at the VBT.

The observations of novae at quiescence help in obtaining the physical characteristics of the secondary and the accretion disc. The study of accretion disc during quiescence helps

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in estimting the mass transfer rate which is crucial to our understanding of the trigger for the nova phenomenon in general and for identifying the differences between the classical and recurrent novae (see Anupama 1990 on RS Oph and Anupama & Prabhu 1993 on GK Per).

4. Supernovae in outburst

Extragalactic supernovae are being observed spectroscopically from VBO since 1980. Of 10 supernovae observed so far, the bright supernova in the LMC was followed in great detail using the 1-m and 0.75-m reflectors despite its low elevation over the southern sky. Others were observed sparsely close to the maximum light. Table 2 lists all the supernovae observed so far.

Table 2. Supernovae observed from VBO

Supernova	Galaxy	Type	Reference
1980K	NGC 6946	II	Prabhu (1981)
1980N	NGC 1316	Ia	Prabhu (1981)
1983G	NGC 4753	Ia	Prabhu (1983)
1983N	NGC 5236	Ib	Prabhu (1985)
1984A	NGC 4419	Ia	Unpublished
1986G	NGC 5128	Ia	Unpublished
1987A	LMC	IIp	Ashoka *et al.* (1987); Anupama *et al.* (1988); Rao (1988); Prabhu (1991)
1989B	NGC 3627	Ia	Prabhu & Krishnamurthi (1990)
1991T	NGC 4527	Ia	Unpublished
1991AA	Anon.	Ia	Unpublished
1992A	NGC 1380	Ia	Unpublished

As this article is going to press, SN 1993J in M 81 is being observed extensively using both 1- and 2.3-m telescopes.

SN 1991T and SN 1991AA were observed with both the telescopes at VBO, using the VBT during the bright moon period and 1-m reflector during the dark moon. The spectra are shown in figure 7. The first spectrum of SN 1991T was obtained close to its maximum around 11 mag. Though the spectrum closely resembles Type Ia, the characteristic feature at 6150 Å is very weak. In fact, earlier spectra did not show this feature at all and thus the supernova is peculiar (cf., Filippenko *et al.* 1992). The spectrum on May 12 resembles post-maximum type Ia spectra better. The interstellar Na I D absorption due to the host galaxy NGC 4527 is seen in the spectra at a redshift of 1700 km s^{-1}. The spectra shown in the figure are averages of 3 half-hour exposures in the case of VBT data and of 2 half-hour exposures in the case of 1-m reflector. Longer exposures were needed in the case of the VBT reflector to achieve desired signal-to-noise ratio in the presence of strong moonlight background.

SN 1991AA was a much fainter supernova in an anonymous galaxy with a redshift of 3300 km s^{-1}. It was discovered at magnitude ~ 16 on May 7, but brightened by about 1.5 mag on June 1. Spectra were recorded with 1-m reflector on May 12, and with the VBT on

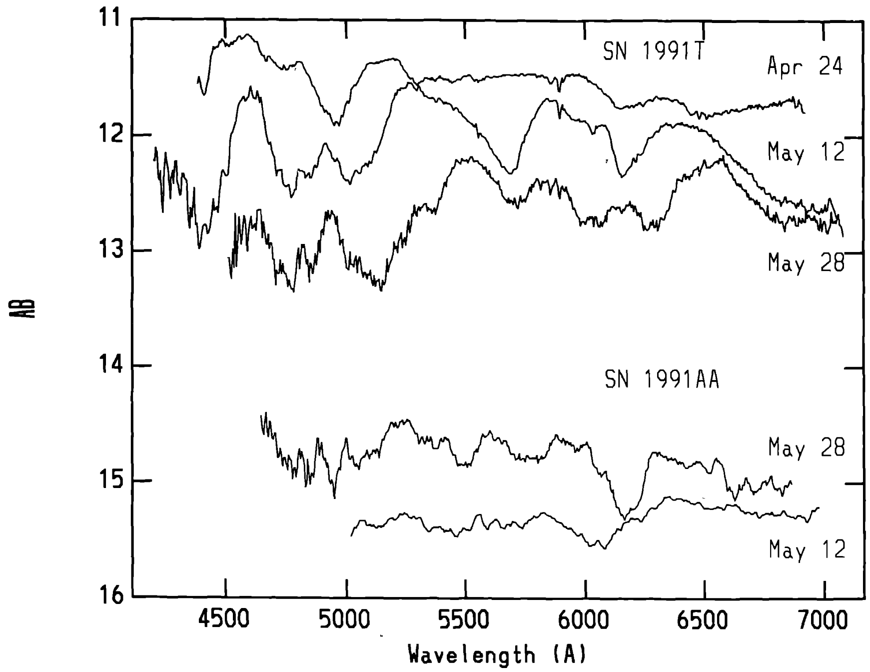

Figure 7. Spectra of SN 1991T and SN 1991AA. Observations on 1991 April 24 and May 28 used the VBT whereas those on May 12 are from 1-m reflector.

May 28 (see figure 7). The signal-to-noise ratio was very poor in the case of the spectrum from 1-m reflector and hence it has been heavily smoothed. The prominent feature is the characteristic 6150 Å absorption which appears to be considerably blueshifted. It resembles that of SN 1990N in this respect (Filippenko *et al.* 1992). The feature moves redward with time which is a characteristic feature of Type Ia supernovae. Intrinsic differences among Type Ia supernovae are characterized by the speed of velocity evolution of this feature (Pskovskii 1977; Branch 1981; Prabhu & Krishnamurthi 1990).

VBT observations of both these supernovae have been important contributions since they were observed close to full moon when most other telescopes in the world do not look at supernovae.

5. Future prospects

We have summarized in the preceding sections many programmes which have been undertaken at VBO on spectroscopy of novae and supernovae. Several of these could not be completed to the extent desireable due to many factors. First, the weather at Kavalur is not excellent and the number of clear nights are limited. There has been a tough competition for these nights. For example, only three nights (and moonlit ones) could be made available for this project at VBT during the first trimester of 1993. Secondly, a part of the allotted time has been unused due to problems related to the telescope and instrument. Finally, the efficiency of data collection itself can stand improvement permitting much more observations to be carried out during the allotted time. Some of the immediate needs of observers were discussed during the second VBT Workshop in 1990 April (Prabhu 1990), a part of which has already been implemented. I summarize here the current needs for intermediate and low-resolution spectroscopy.

Telescope performance : The performance of the telescope has improved considerably during the past few years. The pointing was not excellent this year, and fresh determination of pointing parameters may improve the performance. Improving the least count of RA display will also be necessary in order to set faint objects quickly. There has been some doubt on whether the dome shutters were partially obstructing the telescope aperture during observations. If automatic dome positioning—of which the first trials have already been done—wins the confidence of observers, this doubt will be alleviated. Additionally, aperature spectrophotometry requires offset guiding capability which is lacking at present. This need will be met with the fabrication of Cassegrain Acquisition and Guiding Unit which is in its early stages of development.

Spectrograph performance : The Boller & Chivens spectrograph belongs to the older generation of spectrographs which is known to be not very efficient. It was suggested that the efficiency of the spectrograph can be improved by reducing the beam convergence. However, this would increase the image size and hence loss at the slit. Providing a larger aperture camera before making the instrument available at VBT has improved the efficiency to some extent. The current limitation is due to poor efficiency of gratings which are two decades old, and their small size. New gratings need to be acquired; it would be useful if modifications can be made to the spectrograph so that it can hold a larger grating.

The improvements suggested above will not bring the spectrograph at par with the new designs that have come up in the literature following the availability of detectors with photometric capability. Thus it would be highly desireable to acquire/develop a faint object prime-focus spectrograph and also a Cassegrain spectrograph of modern design, desireably with multiobject capability.

Detector performance : There are two CCD systems available at the VBT with nearly identical chips, dewars and controllers acquired from Astromed Inc., UK. One of these is owned by TIFR/IUCAA and the other by IIA. The data acquisition software and hardware, and also regular maintenance of the systems is due to the engineering group at IIA. The performance of this system has not been as trouble-free as the Photometrics system at 1-m reflector (Prabhu 1991b). However, the experience with this system has helped the engineering group at IIA in acquiring the capability of maintaining CCD systems and also in the in-house development of dewar and controller which are in advanced stage at present. The system has behaved better this year. The data handling time and effort may be considerably reduced by the end of this season. The performance of the dewar is considerably improved, yet the tendency of frosting at the window persists. One also obtains a large number of low-intensity high count events which are more difficult to remove during analysis than the smaller number of high intensity cosmic ray events. The bias shows considerable variation during the night and often significant variation during the readout time. There is no row-by-row overscan possibility at present.

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References

Anupama G. C., 1990, Ph. D. Thesis, Bangalore University.

Anupama G. C., Duerbeck H. W., Prabhu T. P., Jain S. K. 1992, A&A, 263, 87

Anupama G.C., Prabhu T. P., 1989, JAA, 10, 237.

Anupama G.C., Prabhu T. P., 1991 MNRAS, 253, 605.

Anupama G.C., Prabhu T. P., 1993, MNRAS, 263, 335.

Anupama G.C., Sethi S. 1993, Preprint.

Anupama G.C., *et al.* 1988, Vistas Astr., 261, 265.

Ashoka B. N. *et al.* 1987, JAA, 8, 195.

Branch D. 1981, ApJ, 248, 1076.

Filippenko A. V. *et al.*. 1992, ApJ, 384, L15.

Harkness R. P., Wheeler J. C., 1990, in : Supernovae, ed. A. G. Petschek, Springer-Verlag, p. 1.

McLaughlin D. B., 1960, in : Stellar Atmospheres, ed. J. L. Greenstein, Chicago Univ. Press, p. 585.

Prabhu T. P., 1977a, KOB A, 2, 75.

Prabhu T. P., 1977b, BASI, 5, 79.

Prabhu T. P., 1981 BASI, 9, 60.

Prabhu T. P., 1983, BASI, 11, 240.

Prabhu T. P., 1985, BASI, 13, 68.

Prabhu T. P., 1990, VBT News, No. 4, 2.

Prabhu T. P., 1991a, in : Supernovae and Stellar Evolution, eds. A. Ray & T Velusamy, World Scientific Singapore, p. 109.

Prabhu T. P., 1991b, VBT News, No. 8&9, 1.

Prabhu T. P., Anupama G. C., 1987, JAA, 8, 369.

Prabhu T. P., Krishnamurthi A. 1990, A&A, 232, 75.

Prabhu T. P., Shylaja B. S. 1979, KOB A, 2, 213.

Pskovaskii Yu. P. 1977, Soviet Astr., 21, 675.

Rao N. K. 1988, KOB, 10, 25.

Starrfield S. 1989, in : Classical Novae, eds M. F. Bode & A. Evans, John Wiley, p. 39.

Williams R. E., 1990, in : IAU Coll. 122, Physics of Classical Novae, eds. A. Cassatella & R. Viotti, Springer, Berlin, p. 215.

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