V. Concluding Remarks and Future Prospects

Nova outbursts are understood to take place in interacting binary systems where a white dwarf accretes matter from the Roche-lobe filling secondary through an accretion disc. When a critical amount of matter is accreted, thermonuclear runaway reactions take place on the surface of the white dwarf. The result of the injection of the energy released over such a short duration is the ejection of the envelope (see Starrfield 1989). As the envelope expands, in some cases, there is a nucleation of dust particles. The envelope interacts with the ambient medium which may simply contain the interstellar matter, or also the matter lost through slow wind by the secondary, the matter ejected at the previous outbursts, or even the matter ejected during a previous planetary nebula phase that gave birth to the white dwarf. In some cases the nebula may provide perceptible angular disc many years after the outburst. When the envelope has expanded out, it becomes easier to study all the components of the central system. Observations of outburst and quiescence through all the available windows of electromagnetic radiation — both ground-based as well as satellite-borne — add the vital information needed to construct a more detailed account of the above scenario.

In this chapter specific problems under the general context of the nature and evolution of a nova system are described. In each area the contribution of the present study is summarized, and prospects for the future brought out.

1. The Nova System

Though the interacting binary model of novae is universally accepted, detailed models are available only for a few systems. In particular, one requires the estimates of the mass and composition of the white dwarf, the characteristics of the secondary, the mass transfer rate, the structure of the accretion disc, the composition of the mass transferred, the mass-loss rate from the secondary in the form of steady wind, etc. Indeed, it has even been suggested the primary in some recurrent novae is a main sequence star instead of a white dwarf. In the following, individual components are focused upon.

The primary

A direct evidence for the white dwarf can be obtained only from observations in the
far ultraviolet, after the short-wavelength turnover of the accretion disc spectrum. Even there it would be difficult to detect it at the mean distance to novae. Recombination lines from the nova envelopes during outburst and the accretion disc at quiescence have been used in the present work to determine the temperature and radius of the source of photoionization.

The temperature of the central source in RS Oph increased from $3 \times 10^4$ K early in outburst to $3.6 \times 10^5$ K at later epochs. The radius decreased from 9 $R_\odot$ to 0.03 $R_\odot$ during the same period. Thinning out of the inner envelope until the central source becomes bare is thus seen. A similar analysis was not possible at quiescence due to a large contribution to the Balmer lines from the envelope of the cool component. High-resolution observations of the line profiles at different orbital phases will help separation of the emission lines arising in the accretion disc. This can lead to an estimate of the characteristics of the primary. In the case of T CrB the emission lines certainly arise from a region around primary. However, large variations in their strength suggest some non-steady processes are taking place around the primary. Hence no attempt was made here to obtain the characteristics of the primary. More detailed observations are needed before a physical model can be constructed. The central source of Nova Sct 1989 had a temperature of $8.7 \times 10^4$ K and radius of 2.8 $R_\odot$, 77 days after outburst. This is identified with the hot white dwarf with an optically thick envelope just as in the case of RS Oph in outburst. Temperature estimates of $1.3 \times 10^5$ K for the white dwarf in GK Per and $5.8 \times 10^5$ K for the one in T Pyx have been derived, based on the hydrogen and helium emission lines present in the quiescence spectra. The corresponding radii of the white dwarfs are 0.01 $R_\odot$ in the case of GK Per for an assumed distance of 470 pc, and $\ll 0.01$ $R_\odot$ for T Pyx for an assumed distance of 2.2 kpc.

The temperature determination is affected by the following assumptions. (i) The white dwarf is the only source of ionizing radiation. In fact, the boundary layer and the inner regions of the accretion disc may also contribute significantly. The spectral shape of the total ionizing radiation may hence depart from the assumed blackbody radiation. (ii) The line forming region is radiation bound. If not, the H-ionizing radiation would escape preferentially, resulting in a higher estimate of temperature. (iii) Significant contribution to the emission lines may arise from the outer regions of an optically thick accretion disc or from the secondary without irradiation from the white dwarf. The estimate for T Pyx is specifically affected by (ii) as seen from the very low value of the derived radius.
The estimate of radius depends on temperature, and is hence affected by the above uncertainties. In addition, it is also affected by the following factors. (i) The line-emitting region is not spherically symmetric about the central source, and does not intercept all the radiation emitted by it. It appears reasonable to assume that it intercepts about 1 percent of the radiation. The radius varies inversely as the square-root of the fraction intercepted. (ii) The derived radius is proportional to the assumed distance.

The above uncertainties permit only the conclusions that the source of ionization has the dimensions \( R_* \sim 0.01 \, R_\odot \) and the temperature \( T_* \sim 10^5 \, \text{K} \) consistent with those of a white dwarf, for RS Oph in late outburst, and GK Per and T Pyx in quiescence. Estimates of the temperature and size of the primary was not possible based on the quiescence observations of RS Oph and T CrB due to uncertainties in the model of line forming region. It should be noted that because of a large separation of binary components in these systems the accreted matter has a large specific angular momentum. This fact would complicate the structure of the inner regions of the accretion disc. The estimates for RS Oph based on outburst observations, however, support the idea that the primary is a white dwarf rather than a bloated main sequence star as suggested by Livio, Truran & Webbink (1986). Better estimates can be obtained only from multiwavelength observations and detailed modelling of the continuum and line emission. Such a study is feasible with the best facilities available on and around the globe.

Though a theoretical relation is available between the mass and radius of a white dwarf (Chandrasekhar 1967), the uncertainties in the radius do not permit an accurate estimation of the mass. It is hence necessary to obtain the mass function from spectroscopic orbits and obtain the mass of the white dwarf using estimates for the mass \( M_2 \) of the secondary, and the inclination \( i \) of the system to the line of sight. Such studies are feasible with medium and large optical telescopes. The available information suggests that the mass of the white dwarf is \( > 0.73 \, M_\odot \) in GK Per and possibly \( \sim 1.4 \, M_\odot \) in the recurrent novae. These estimates are considerably uncertain due to an uncertainty in \( M_2 \) and \( i \). Detailed spectroscopic monitoring and modelling can improve the estimates. It is necessary to determine and refine spectroscopic orbits of these systems. Orbits of the emission-line components need to be studied using detailed line profiles (see Selvelli 1989).

The secondary

Based on the spectrophotometric data during quiescence, it has been shown here
that the secondaries of RS Oph, T CrB and GK Per are of spectral types M1III, M4III and K0-2IV respectively. Though these determinations do not differ appreciably from the values in literature, the present study has brought out the importance of subtracting out the accretion disc spectrum before the methods of quantitative spectroscopy are employed. All the above systems have evolved secondaries that are bright enough to be observed easily in the red spectrum. The secondary of T Pyx, on the other hand, does not contribute much to the optical spectrum, and is hence not an evolved star. Future attempts at its identification should depend on spectroscopy extending to the near infrared. Our understanding of the secondaries of nova systems in general would be improved considerably from their near-infrared spectroscopy.

The accretion disc and mass transfer rate

The theory of physically thin and optically thick steady accretion discs is sufficiently well developed for a comparison of the observed continuous spectrum. The continuum can be fit well by \( f_\nu \propto \nu^{-1/3} \) or \( f_\lambda \propto \lambda^{-2.33} \) power laws (see King 1989). It was possible to obtain good fits for RS Oph and GK Per. The observed fluxes in erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\) are \(10^{-3.55}\lambda^{-2.33}\) for RS Oph and \(10^{-5.02}\lambda^{-2.33}\) for GK Per, with \(\lambda\) expressed in Å units. It is, in principle, possible to obtain a fit for T Pyx, except for the poor signal-to-noise ratio of the present data. Telescopes of aperture greater than 1 m are thus necessary. In the case of T CrB the secondary is much brighter than the accretion disc in the optical region and hence it would be necessary to use the ultraviolet data.

The accretion disc spectrum has turnovers in the ultraviolet due to the finite inner radius of the disc, and in the infrared due to the finite outer radius. With the available ultraviolet data for GK Per, it was possible to determine the inner radius as \(10^9\) cm; similarly, with the available infrared data for RS Oph, it was possible to determine the outer radius \(\sim 10^{12}\) cm. The \(\lambda^{-1}\) ultraviolet spectrum of T CrB suggests the high frequency turnover. The very blue colours of T Pyx suggest that the low frequency turnover is in the blue region of the spectrum itself because of the compact size of the disc. Clearly, it would be rewarding to observe the accretion discs from far ultraviolet to the infrared.

The absolute spectrum of the accretion disc is determined by the product of mass of the white dwarf and the mass accretion rate (Webbink et al. 1987). Since the white dwarf mass has a narrow range, the mass transfer rate can be estimated if the distance to the nova can be determined (see §3 below). Mass transfer rates of
$\sim 10^{-6}$, $\sim 10^{-7}$, $\sim 10^{-8}$ and $\sim 10^{-10}$ $M_\odot$ yr$^{-1}$ are estimated for RS Oph, T CrB, T Pyx and GK Per respectively.

Based on the hydrogen and helium line ratios in the spectra of GK Per and T Pyx, it is estimated that the helium abundance is $\text{He}/\text{H} \leq 0.24$ in the accretion discs of these systems. An absorption feature due to O I 7774 Å has been identified in the accretion disc of RS Oph. Detailed model atmospheres of accretion discs are necessary in order to compare these observations, as also of emission line regions of the accretion discs.

The current understanding of the accretion disc is limited to the continuum spectrum of the optically thick discs, and the emission lines from optically thin discs. These ideas are used in the present study. The course of the theoretical studies are taking the direction of modelling absorption lines in optically thick discs that are optically thin to the lines while optically thick to the continuum (Smak 1990). Models of extended atmospheres of accretion discs are likely to become available in near future, and a better comparison of observed profiles of lines in emission and absorption would then be possible. Such studies are also necessary in an attempt to obtain better estimates of the characteristics of the primary.

Spectroscopic studies of dwarf-nova-like outbursts of novae in quiescence will also improve our knowledge of the nature of accretion discs and mass transfer rate since such an outburst is powered by accretion disc instabilities. However, such studies necessarily depend on the efforts of discovery and dissemination of information.

The binary orbit

Spectroscopic orbits are available for GK Per, RS Oph and T CrB. A binary period has been inferred for T Pyx from photometric observations. Fairly good spectral resolution is required for a determination of spectroscopic orbits. Such observations require medium to large size telescopes, and sustained effort in the case of long-period systems such as RS Oph and T CrB.

The absorption line orbits refer to the secondary, whereas at least a part of the emission line is centred around the primary. The orbit of the primary can be determined only after a separation of the emission line component belonging to it. Both the orbits, and an estimate of the inclination of the orbit $i$ to the line of sight are needed before an estimate of the masses of individual orbits can be made. Available methods of determination of $i$ are very inaccurate, in the absence
of eclipses. An accurate model of the orbital phase dependent variations of the continuum spectrum and emission lines can constrain the possible range of \( i \). Such variations have been reported in the H\( \alpha \) line from T CrB in the present work. The emission is peaked around phases 0.53 and 0.93. It is important to monitor such variations using a linear detector at good spectral resolution, and also to look for interrelationship between the variations of different lines and the ultraviolet continuum.

**Secular variations in the spectra**

Long-term variations in the mass transfer rate and in the structure of accretion disc are useful for understanding the cyclic evolution scenario of novae. The class of recurrent novae particularly offer a possibility of observing a complete cycle over a reasonable span of decades. The present investigation has revealed a \( \sim 2400 \) day variation in the H\( \alpha \) flux from T CrB. This variation may either be related to the secular changes in the accretion disc — which require to be monitored in the ultraviolet, or in the secondary — such as pulsations, or both. A major fraction of our data is based on photographic spectra with poor photometric accuracy. A linear detector and photometric skies are called for. It is also important to observe the spectrum from the ultraviolet to the infrared.

**The ejecta**

Observations of the ejecta of a nova explosion in the form of a resolved nebula have manifold interests. The abundances of light elements can be accurately determined by spectroscopic observations of the nebula. Once the nebulosity is resolved, one may look for abundance variations in the nebula — an input yet to enter the models of an outburst. An indication of spatial variations in N/O abundance ratio has been brought out here in the case of GK Per in §III.4.1. It appears that the equatorial plane has an excess of oxygen. Similar indications are also present in T Pyx (§IV.3.1). Spectroscopic confirmation requires large aperture telescopes.

Angular expansion of the shell, together with spectroscopic expansion velocities determined during the outburst provide an accurate estimate for the distance to the nova. A 'nebular parallax' of 1-2 kpc has been determined for T Pyx (§IV.3.1). The expansion was, however, marginally detected over a baseline of 3 years in time. Further monitoring is thus necessary. The use of space telescopes would not only cut down the requirement on the baseline in time, but also the reduced background would enable the identification of individual shells ejected in the past outbursts.
Such an attempt was made by Seitter (1987) from ground-based observations.

In the case of GK Per, the ejected shell is interacting with the remnant of an old planetary nebula (Bode et al. 1987; Seaquist et al. 1989). The densities in the ambient circumstellar matter in the immediate neighbourhood of the ejecta are higher in the polar region than in the equatorial region. A distance of 470 pc based on early observations was used to determine the initial velocities and decelerations in the equatorial and polar regions using the measured proper motions of knots in the ejecta. The initial velocity was lower in the equatorial regions (~ 1100 km s\(^{-1}\)) in comparison with the polar regions (~ 1500 km s\(^{-1}\)). The higher density ambient medium has decelerated the polar regions more (12.8 km s\(^{-1}\) yr\(^{-1}\)) than the equatorial region (1.5 km s\(^{-1}\) yr\(^{-1}\)). The ratio of the equatorial to polar velocity (0.73) is comparable to that deduced for the shell of DQ Her (0.67) based on its images. The shell of DQ Her is expanding relatively freely in the interstellar medium. The observations of structure, expansion parallax and kinematics can be made for a large number of arcsecond size nova shells using space telescopes, and from ground based telescopes using interferometric methods such as speckle interferometry.

It is possible to construct a kinematic model of the ejected shell based on the line profiles observed during the late stages of outburst. An example is provided here in the case of LW Ser (§III.2.3) based on the H\(\alpha\) line profile. The model consists of an equatorial ring and polar cones similar to the ones observed in DQ Her and HR Del among other novae. The optical depth effects were probably still present in the H\(\alpha\) profile. However, it was not possible to obtain either the observations of H\(\alpha\) at later epochs, or of fainter forbidden lines at corresponding epoch, using the 102 cm reflector and the photographic plate. The capabilities have certainly improved since then and it is easier now to obtain more accurate data on novae of similar brightness.

An instance of interaction of the ejecta with high density ambient medium is also provided by the coronal lines in the outburst spectra of recurrent novae. These are produced in a region shocked by the expansion of the envelope into the stellar wind of the secondary. Temperature of ~ 10\(^6\) K has been estimated for the shocked region of the ejecta of RS Oph using a few coronal lines in the optical region (§IV.1.1.3). The shocked region is likely to contain regions of differing temperature and densities. Rayleigh–Taylor instabilities may even cause condensations in the shell. A detailed model of such inhomogeneities can be made from the observations.
of a large number of coronal lines from the ultraviolet to the infrared. Different regions of the ejecta could be ionized to differing degrees. One should use various density and temperature sensitive line ratios to construct a detailed model.

2. The Outburst

The spectra of novae during outburst are the most complicated to interpret. Studies are hence generally restricted to the determination of expansion velocities based on P-Cygni absorption features, qualitative description of the emission line spectra at different times, and a comparison of the spectral evolution with that of a standard nova (§1.1.2). The major hurdles are the high densities, large expansion velocities, non-steady-state evolution, and the variations in the characteristics of the energy source. Synthetic spectra need to be constructed similar to the ones used for supernovae (cf. Branch 1990), in order to improve our understanding of the spectral evolution.

Recent models of recombination lines produced in high-density environments and high optical depth conditions (§III.1) have enabled a qualitative inference of physical conditions in Nova Sct 1989 and RS Oph 1985. In particular, it was found that the density varied as $3.2 \times 10^{11} t_d^{-2.02} \text{ cm}^{-3}$ in Nova Sct and $8.36 \times 10^{12} t_d^{-2.26} \text{ cm}^{-3}$ in RS Oph, where $t_d$ is the time measured in days since outburst. The total mass of the shell was estimated as $3.5 \times 10^{-5} M_\odot$ for Nova Sct, and $3.1 \times 10^{-6} M_\odot$ for RS Oph.

The derived mass in the case of Nova Sct increased directly with time. This has been explained as an effect of decreasing optical depth that allows one to see deeper into the envelope. Another contributing factor could be the fact that the outer part of the envelope could initially be neutral and the ionization front moves into it as the optical depth of the inner region to Lyman continuum decreases. In the case of RS Oph, the derived mass decreased as $t_d^{-0.3}$. Since the envelope mass is lower in RS Oph than in Nova Sct 1989, and also since RS Oph was observed at epochs later than those of Nova Sct 1989, the mass of its shell should remain constant in time. It has been assumed that the volume of the shell of Nova Sct increased as $t_d^2$ corresponding to free expansion. In the case of RS Oph, the volume was assumed to increase as $t_d^2$ corresponding to adiabatic expansion as the shell is interacting with circumstellar matter. The restriction on the constancy of mass suggests that volume varied as $t_d^{2.6}$, i.e. intermediate between free expansion and
adiabatic expansion. It was possible to obtain the above information because of the availability of recombination line emissivities in high density conditions (Hummer & Storey 1987). However, considerable amount of uncertainty is introduced by the effect of high optical depth in Balmer lines. Detailed photoionization models have been employed in the analysis of emission lines in DQ Her by Matrin (1989). Similar models need to be constructed for other novae also.

In the case of RS Oph, a helium abundance of He/H= 0.16 is estimated, which implies moderate enrichment. He abundances could not be determined in the slow novae LW Ser and Nova Sct 1989 since considerable amount of He is in neutral form. Detailed models of the envelope would be needed before an abundance determination can be made at corresponding stages of the light curve. Abundances are best estimated during the nebular stage when the envelope is like a photoionized nebula though not of perceptible angular size. The systems are normally faint at this stage, and require moderate aperture telescopes for detailed spectroscopy.

The moderately slow novae LW Ser and Nova Sct 1989 exhibit spectral evolution that compares well with other novae of similar speed class. The principal, diffuse enhanced and Orion absorptions at $\sim -750$ km s$^{-1}$, $\sim -1300$ km s$^{-1}$, and $\sim -1800$ km s$^{-1}$ could be identified in LW Ser, whereas only one system — probably diffuse enhanced — at $-1300$ km s$^{-1}$ could be identified in Nova Sct 1989. The principal system had apparently weakened by the time of our early observations. Both these novae are characterized by oscillations in the light curve near maximum. In the case of Nova Sct 1989, the oscillations are more clearly seen as continuum variations rather than variations in the emission lines. The oscillations thus indicate variations in the photospheric radius, indicating inhomogeneities in the shell. Detailed models are required in this direction.

The spectral evolution of the fast nova RS Oph is similar to its past outbursts. The narrowing down of emission lines as the envelope is decelerated by interaction with the circumstellar matter is clearly seen. More continuous spectrophotometric monitoring than presented here are essential for all novae to induce motivation for theoretical modelling.

3. Interstellar Extinction and Distance

Most of the discussion in §1 and §2 above depends on the ability to deredden the observed spectrum. Interstellar colour excess of $E(B - V) = 0.5$ and 0.4 have been
estimated for LW Ser and Nova Sct 1989 respectively, based on a comparison of the colours with other novae with known extinction. These estimates are not as accurate as the value available for RS Oph based on ultraviolet and radio observations. Such observations, as also the spectrophotometric observations of the ejecta beyond the nebular stage are necessary for an accurate estimation of extinction.

Whenever absolute fluxes are needed, the estimate of distance becomes important. The most accurate distances are obtained from the infrared and radio expansion parallaxes, and also from the angular size of the expanding nebulosity. An alternative is to study the interstellar extinction, or the 21 cm column density as a function of distance in the direction of the nova. All these methods are equally difficult and require assured time on sensitive telescopes.

Our best estimates of interstellar extinction and distances to LW Ser and Nova Sct 1989 suggest that they are underluminous compared to other novae of similar speed class by 1–2 mag. The interstellar extinction is not likely to be much higher than that estimated, since these novae would rise above the galactic plane in a few kpc. This leaves the possibility that the maxima of these novae were missed, and were 1–2 mag higher than recorded.

At present one depends largely on amateurs for discovery and follow up of the early light curves of novae. Dedicated surveys and immediate photometric and spectroscopic follow up of Galactic novae are desirable. More sensitive surveys in the nearby galaxies like the Magellanic Clouds and M31 should also be carried out, along with spectroscopic follow up on large telescopes. A ten-fold increase of the sample of novae with spectroscopic observations is likely to reveal intrinsic differences in novae of different luminosities in a given speed class.