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Optical studies of novae

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Abstract. We review the observational characteristics of classical and recurrent novae in the optical region, in the context of observational programmes carried out using telescopes at the Vainu Bappu Observatory (VBO) and the Indian Astronomical Observatory (IAO) of the Indian Institute of Astrophysics. The article discusses the different classes of novae, based on either their outburst light curve properties, or their spectral development. Also provided is a brief discussion on the quiescence properties of novae.

Keywords : classical novae – recurrent novae – cataclysmic variables – optical spectroscopy – optical photometry

1. Introduction

Novae form a part of the broad class of binary stars, having a similar configuration, called cataclysmic variables. These are interacting binary systems consisting of a white dwarf primary and a Roche-lobe filling main sequence K-M type secondary. The white dwarf is generally accepted to be a carbon-oxygen (CO) or an oxygen-neon (ONe) white dwarf. The white dwarf accretes hydrogen rich matter from the secondary via an accretion disc as a result of mass transfer. With time, the semi-degenerate nature of the white dwarf surface causes a build up of pressure and temperature at the base of the accretion disc. At a critical temperature and pressure, hydrogen burning sets in, which soon builds up to a thermonuclear runaway (TNR) reaction that releases a huge amount of energy (e.g. Starrfield et al. 2008; Yaron et al. 2005; Starrfield 2012; this Volume; José 2012; this Volume). The energy released is imparted to the accretion disc, causing the disc to expand and be ejected from the system. A nova explosion thus occurs, accompanied by the release of energy in the range 10^{38} – 10^{40} ergs, and ejection of matter with velocities > 500 km s^{-1}. Matter is ejected either in the form of discrete shell(s), an optically thick wind, or as a

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combination of both. A nova outburst leads to the ejection of the accreted matter and disruption of the accretion disc, but does not affect the binary system substantially. The accretion process resumes within a matter of weeks. Hence, repeated outbursts are possible in these binary systems. A system that has had only one recorded nova outburst is termed as a Classical Nova (CN), while the one with more than one recorded nova outburst is termed as a Recurrent Nova (RN). Recurrence periods range from a few years (U Sco) to a few decades (IM Nor). Archival records have helped to detect previously unknown outbursts of RNe (e.g. Pagnotta et al. 2009; Schaefer 2010).

There are ten known Galactic RNe, and a few more suspected ones, while two are known in the Large Magellanic Cloud and a few suspected systems in M31. RNe display considerable heterogeneity as a group. They can be broadly grouped into (a) long period binaries: systems with giant secondaries, and (b) short period binaries: systems with main sequence, or slightly evolved secondaries. Recent reviews on the properties of RNe can be found in Anupama (2008a) and Schaefer (2010). Some RNe could be potential progenitors of type Ia supernovae.

Much of our understanding of the nova systems has been obtained from the optical observations of these objects, both at outburst and quiescence. While multi-wavelength observations of these systems have augmented and enhanced these studies, optical observations still remain central to detailed studies of novae.

We review in this article the general observational characteristics of the nova phenomenon, limiting our discussions to the optical region. We begin this article with a brief introduction to nova studies at the Indian Institute of Astrophysics (IIA). The classification of novae based on their light curve and spectrum are discussed, and also the generic properties of individual classes. In most of our discussions, we use, as examples the novae that have been observed by us using the observing facilities of the IIA.

The reader is referred to other articles in this Volume for a multi-wavelength perspective of novae.

2. IIA nova programme

HR Del (1967) was one of the first novae to be spectroscopically observed from the Kodaikanal Observatory, IIA, in the "recent historical" times (Doss, Bhatnagar & Natarajan 1972). This was followed by the observations of several novae, for e.g. V1500 Cyg (Prabhu 1977), LW Ser (Prabhu & Anupama 1987), and the 1979 outburst of the recurrent nova U Sco (Shylaja & Prabhu 1979), all using the 1.02m telescope at the Vainu Bappu Observatory (VBO). The 2.34m Vainu Bappu Telescope (VBT) at VBO and the 2m Himalayan Chandra Telescope (HCT) at IAO were / are being used for nova observations, subsequent to their commissioning in 1986 and 2001 respectively. A variety of instruments were used over the years as the observing capabilities were periodically enhanced. Some novae studied in detail include the 1985 and 2006 outbursts of the recurrent nova RS Oph (Anupama & Prabhu 1989; Anupama 2008b; Anupama et al., in preparation), V443 Sct (Anupama et al. 1992), V1425 Aql (Kamath et al. 1997), V1494 Aql (Kamath et al. 2005), the 1999 and 2010 outbursts of the recurrent nova U Sco (Anupama & Dewangan 2000; Anupama et al., in preparation). RNe are also being monitored during their inter-outburst quiescence. A detailed study of the RNe with giant secondaries (Anupama & Mikołajewska 1998) during quiescence clearly established the presence of a hot, massive white dwarf in these systems.

The optical studies of novae at outburst and quiescence have been extended to studies in the low radio frequency regions also, using the Giant Meter-wave Radio Telescope (GMRT). Some details of these studies are provided in the article by Kantharia (2012) in this Volume.

3. Light curves and classes

A nova explosion, which causes the sudden brightening of the star by several magnitudes, is followed by a decline, which could be either smooth or irregular. The overall timescale of a nova outburst is described by the "speed class". The early works by McLaughlin divided the light curves into "fast" and "slow", while Payne-Gaposchkin made five finer divisions depending on the time taken to decline by two magnitudes from outburst maximum (t_2), or by three magnitudes from outburst maximum (t_3) (Payne-Gaposchkin 1957 and references therein). The various speed classes are very fast ($t_2 < 10$ days); fast ($t_2 = 11 - 25$ days); moderately fast ($t_2 = 26 - 80$ days); slow ($t_2 = 81 - 150$ days) and very slow ($t_2 = 150 - 250$ days).

The light curve evolution of all novae, in general, follow the following sequence (McLaughlin 1960, Warner 1989). The initial brightening from the pre-nova level to two magnitudes below maximum takes place within two to three days. Many novae show a pause, a pre-maximum halt, around this phase. The nova then brightens to maximum (optical) over a period of one or two days for fast novae and upto several weeks for the slowest. The duration of the maximum phase is of the order of hours for fast novae and a few days in slow novae. Although the light curves of different novae are broadly similar, there exist several differences in the evolution of individual novae. While the early decline is generally smooth, minor or major irregularities are seen in some, especially the slower ones. At about three magnitudes below maximum, the nova enters the 'transition phase', a phase when novae show their greatest diversity in the light curve evolution. Some show large-scale quasi-periodic oscillations, whereas others enter into a deep minimum phase lasting a few months (due to dust formation), while some others have a smooth transition phase without any noticeable peculiarity. The final decline to the post-nova phase progresses steadily from the end of the transition phase.

The measures of nova light curve properties have been restricted to an estimate of the peak magnitude and rate of decline. The potential use of novae as standard candles based on the Maximum-Magnitude-Rate of Decline (MMRD) relationship has been explored by several astronomers (e.g. Livio 1992 and references therein). Studies correlating the light curve properties to nova outburst parameters are limited to a few. For instance, Hachisu & Kato (2006) propose a universal decline law, in which they show nova light curves can be fit by broken power laws, with different slopes for the early and late phases. They suggest the mass of the white dwarf to

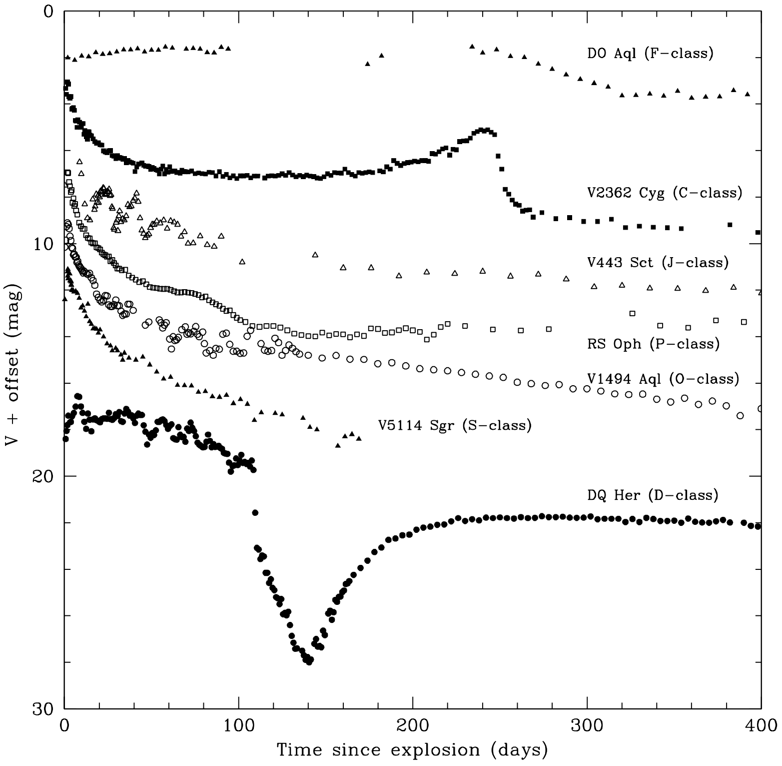

Figure 1. Illustration of light curve classes. Each light curve shows the distinct features of its class.

be closely correlated to the time of the break in the power law slope. Time resolved photometry of several novae during decline have revealed short term variations. These variations, are found to be due to re-formation of the accretion disc, or due to the rotation of the magnetic white dwarf, or orbital motion.

Duerbeck (1981) made the first attempt to classify nova light curves based on their shape and speed. In recent times, in an attempt to measure light curve properties, Strope et al. (2010) have made a detailed study of nova light curves. Based on the shape and t_3 of 93 well-sampled light curves, they provide a classification system for nova light curves. Seven different classes are identified, with the following designations: “S” for smooth light curves, “P” for plateaus, “D” for dust dips, “C” for cusp-shaped secondary maxima, “O” for quasi-sinusoidal oscillations superposed on an otherwise smooth decline, “F” for flat-topped light curves and “J” for jitters or flares superposed on the decline. The classification consists of the single letter (describing shape), followed by the t_3 value in parentheses. Fig. 1 illustrates the light curves of all the seven classes. The binned magnitudes provided by Strope et al. have been used to generate the light curve of each nova chosen to illustrate the class.

4. The evolution of the outburst spectrum

The spectrum of a nova system, following its outburst, shows clear signatures of an expanding material, as well as a TNR reaction and is influenced by the evolution of the photosphere, wind, and surface nuclear reactions, all of which are related (Williams 1992). During the initial stages, when the ionization levels are low, the spectrum is dominated by permitted, recombination lines. The ionization levels increase with time as the layers closer to the ionizing source (central WD) are revealed as the ejecta expand. Forbidden and high ionization emission lines are seen at this stage. As the nova approaches its post-outburst quiescence phase, the ionization levels decrease once again.

The evolution of the outburst spectrum broadly follows the light curve evolution, as was first described in detail by McLaughlin (1960). The evolution from the pre-maximum all the way to the late phase spectra are described below. For a more detailed and multi-wavelength perspective of the evolution, the reader is referred to the article of Shore (2012; this Volume).

Pre-maximum spectrum: The pre-maximum is the first stage of the expansion. The spectrum during this phase is characterized by strong continuum and blue-shifted absorption lines. Emission lines are comparatively weak. This phase of the nova outburst is a period of uniform expansion of an optically thick, cooling ejecta.

Principal spectrum ($\Delta m \sim 0.6$): The principal spectrum occurs close to visual maximum. At maximum, the spectrum is characterized by strong absorption lines and resembles A-F supergiants with enhanced CNO lines. The absorption lines indicate velocities that are larger than that seen during the pre-maximum phase, and are correlated with the speed class. At, or immediately after maximum, an emission-line component appears in the principal spectrum. The strongest lines are due to H, Ca ɪɪ, Fe ɪɪ, N, He and O. Emission lines due to [O ɪ] are seen, indicating the presence of a neutral zone.

Diffuse enhanced spectrum ($\Delta m \sim 1.2$): This is the third absorption system, with broad diffuse absorption lines of species similar to those in the principal system, but with velocities that are almost twice those of the principal system. The absorptions reach a maximum at $\Delta m \sim 2$, when the lines show P-Cygni profiles with broad emissions of the diffuse enhanced system underlying those of the principal spectrum. In the later phases of this stage, the lines often split into narrow components.

Orion system ($\Delta m \sim 2.1$): The nova spectrum, which is already a mixture of the principal and diffuse enhanced systems, is further complicated by the presence of yet another absorption system, the Orion system. The absorption lines are diffuse, with velocities that are atleast as much

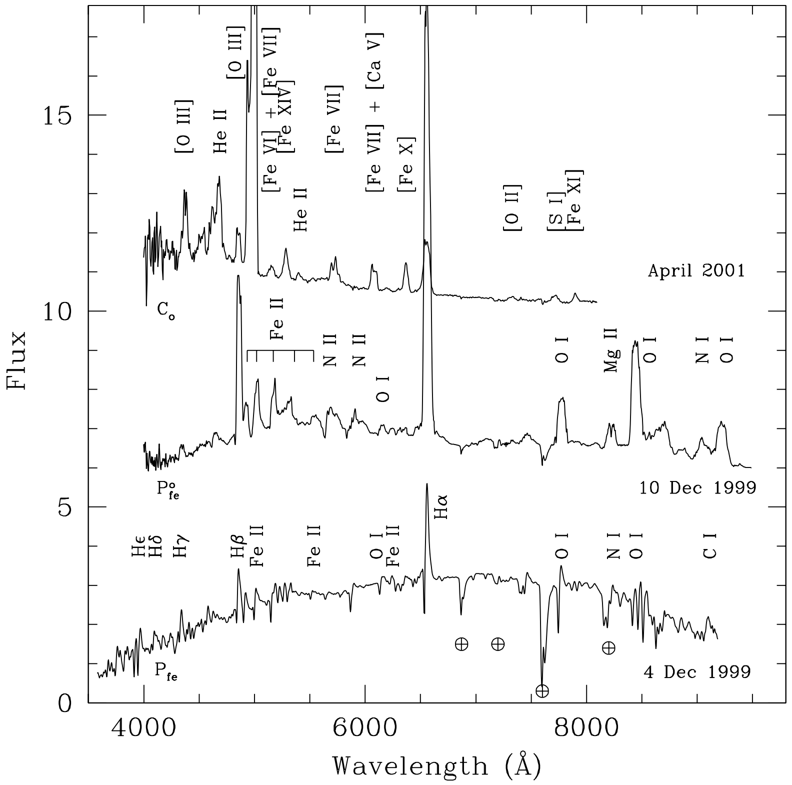

Figure 2. The evolutionary sequence of nova V1494 Aql showing the change from a permitted to coronal spectrum as labelled on the left side of each spectrum. Dates of observations are labelled on the right side of each spectrum. Prominent lines are labelled.

as the diffuse enhanced system. The absorption systems remain diffuse until they disappear at $\Delta m \sim 3.2$, when the nova enters the transition phase. The maximum of this absorption system occurs at $\Delta m \sim 2.7$, and is accompanied by the emergence of N III absorptions. The excitation and ionization levels increase with time all through the Orion system, and the emission line component also increases in strength as the absorption component disappears. There are distinctive stages in the development of the Orion emission during which particular species become exceptionally strong. A typical example is the nitrogen flaring, which appears at $\Delta m \sim 3.0$ due to blending of lines of the N III multiplet at 4640 Å, and other N II and N III lines. The emission lines are generally structured during the Orion phase.

Nebular and post-nova phase ($\Delta m \sim 4.4$): The nebular phase is the final stage of the nova outburst before the nova enters its post-nova quiescence phase. The spectrum during this phase evolves towards one that resembles those of nebular regions. The density in the ejecta steadily

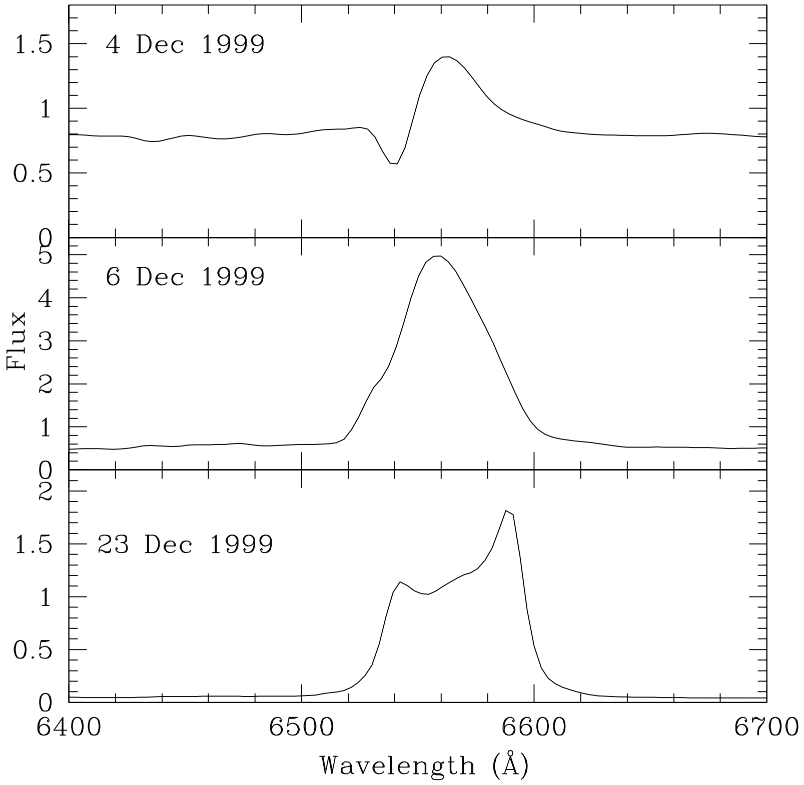

Figure 3. The Hα profile of nova V1494 Aql showing the change from a thick wind (top) to a polar-ring geometry (bottom) (Figure adapted from Kamath et al. 2005).

decreases as it expands. The pseudo-photosphere steadily moves inwards, closer to the central ionizing source, increasing the ionization levels in the ejecta. This phase is marked by the presence of high ionization lines such as the auroral, nebular forbidden lines, and high excitation coronal lines, with their line strengths steadily increasing relative to the permitted lines. The width of the emission lines indicates a velocity that is the same as that of the principal absorption system. The high excitation lines gradually fade and, in the post-nova phase, the spectrum is dominated by that of the accretion disc.

The spectral evolution described above is illustrated in Fig. 2, which shows the evolution of the nova V1494 Aql (Kamath et al. 2005). V1494 Aql was a bright nova, reaching a visual magnitude of $\sim$ 4 mag on 1999 December 3.4. With a decline rate of t_2 = 6.6 days, it can be classified as a fast nova. The light curve (Fig. 1) showed oscillations during decline, classifying the nova as O(6), according to the classification scheme of Strope et al. The spectrum of 1999 December 4 corresponds to the near-maximum, fireball phase of the explosion. Lines due to

Hydrogen Balmer series, right up to Balmer 21, are seen at this phase, along with several lines of O I. All these lines show a P-Cygni profile, a clear signature of the outflowing optically thick wind. Numerous lines of Fe II, N I, Mg I and C I are also present, although the P-Cygni profiles of some of them are not apparent due to blending with adjacent lines. The absorption components of some lines, such as the Ca II IR triplet, are much stronger than the emission component. The expansion velocities, indicated by the absorption minima lie in the range of 1000 – 1500 km s^1. The spectrum of 1999 December 10 is that of the early decline phase, where the P-Cygni absorption component is either weak, or absent. The emission lines show a rounded peak, with a hint of structure, indicative of an optically thin wind. The spectrum of 2001 April, obtained nearly 500 days after the outburst maximum is clearly that of a nova in the nebular phase. In addition to the strong nebular lines, highly ionized, coronal iron lines are seen in the spectrum. While the coronal lines show sharp, single-peaked profiles, the nebular lines are double peaked and show a structure similar to that of the Balmer lines (Fig. 3 shows the evolution of the Hα line profile). This suggests that the coronal lines could be arising in a region different from that of the nebular and other permitted lines, and that the nova ejecta consists of warm ($T \sim 10^4$ K), dense clouds, embedded in a hot ($T \sim 10^6$ K), tenuous gas. The two phases are photoionized by the hard white dwarf continuum, and the warm phase is further photoionized by the free-free continuum generated in the hot gas (Kamath et al. 2005). A non-uniform temperature and density structure in the shell is required to explain the observed range of ionization.

5. The Tololo classification system

Williams et al. (1991) devised a physical basis to describe the outburst spectral evolution, generally referred to as the Tololo Classification System. This scheme defines phases in evolution in terms of the characteristics of the stronger emission lines. These phases are related to the physical conditions in the shell through the ionizing radiation field and mean gas density. Hence, the classification provides an insight to the physical conditions in the nova ejecta as the outburst evolves with time. The main points describing this scheme are (following Williams et al.):

1. The spectrum is classified as belonging to either phase C, P, A, or N, with subclasses under each class being defined by the strongest species present.
2. Phase C (coronal): A spectrum is considered to be in the coronal phase C if, irrespective of all other line strengths, [Fe x] 6374 Å line is present and stronger than [Fe VII] 6087.
3. Phase P (permitted): If the spectrum is not in phase C, then it can be classified as in the permitted phase P if the strongest non-Balmer line is a permitted line. The species of this permitted line is mentioned in the subscript and defines the subclass. If the strongest non-Balmer lines are due to Fe II multiplets, this phase would be represented by P_{fe}. Likewise, if the strongest non-Balmer lines are due to nitrogen, it would be P_n. In the case of the strongest non-Balmer being due to helium, the permitted phase could either be P_{he}, or P_{he^+}, depending on whether He I lines are stronger, or the He II line 4686 is stronger.
4. Phase A (auroral): If the spectrum is not in phase C, it is considered to be in the auroral line

phase whenever any auroral forbidden line has flux higher than the strongest non-Balmer permitted lines, irrespective of the strengths of other nebular lines. The subclass is based on the strongest non-Balmer and non-auroral line in the spectrum.

5. Phase N (nebular): The spectrum is considered to be in the nebular phase N if it is in neither phase C nor phase A, and the strongest non-Balmer line is a forbidden nebular transition. The subclass is based on the strongest nebular line in the spectrum.
6. If the O I 8446 Å line is present and prominent (stronger than Hβ), it is represented by an 'o' in the superscript, irrespective of the phase.

Fig. 2 illustrates the spectral evolution of a nova (V1494) from the permitted (P) phase to the nebular/coronal (C) phase.

6. Spectral classification

The spectra of different novae appear quite diverse. However, Williams (1992) grouped them based on common characteristics in this seemingly diverse ensemble. This classification of novae is based on their outburst optical spectra obtained very close to the maximum. All novae are dominated by the strong hydrogen Balmer emission lines. Hence, classification is best done using the strongest non-Balmer lines present in the optical spectrum during the first few days following an outburst. Quite commonly these lines are due to Fe II or helium and/or nitrogen (see Fig. 4). Novae are thus classified into two broad groups, the "Fe II" and the "He/N" class (Williams 1992). There are a few novae that fall in between the two classes and are termed "hybrid" novae.

Fe II class

The strongest non-Balmer lines during the early phases in this class are due to Fe II, and novae belonging to this type would be classified as P_{fe} in the Tololo classification system. The early phase spectra show pronounced P-Cygni absorption, with velocities < 2500 km s^{-1}. Low ionization transitions, such as Na I, O I, Mg I, Ca II, are seen during this phase. Novae belonging to the Fe II class are generally the moderately fast to the slow novae, with their spectra evolving over timescales of weeks. The early nebular phase spectrum is dominated by low ionization auroral lines, while some Fe II novae develop strong [Ne III] lines. The line profiles indicate that the dominant ejection mechanism for this class of novae to be wind ejection, although shell ejection cannot be ruled out.

Nova V1494 Aql (discussed earlier) belongs to the "Fe II" class. Another example of the Fe II class shown here is that of nova V2362 Cygni, a fast nova belonging to the C(26) light curve class. Fig. 5 shows the spectrum of this nova during the early decline P_{fe}, the auroral A_n and the nebular N_o phases. The FWHM velocity at all the phases shown here was $\sim$ 1300 km s^{-1}. The spectral evolution of V2362 Cygni went through all the absorption systems described earlier

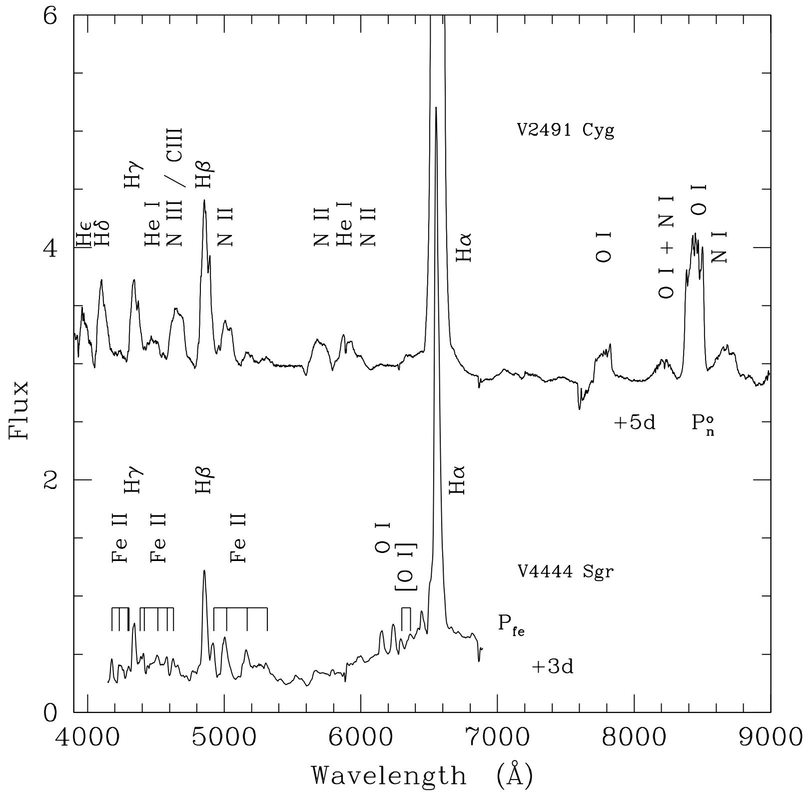

Figure 4. Early phase spectrum of an Fe II nova (V4444 Sgr, +3d; bottom) and a He/N nova (V2491 Cyg, +5d; top) illustrating the differences between the two types. Some prominent emission lines are labelled. The spectral classification according to the Tololo scheme is marked for each spectrum.

(Munari et al. 2008), and behaved like a typical "Fe II" classical nova. However, around a 100 days after outburst, well into its decline phase, V2362 Cygni underwent a re-brightening (see Fig. 1). The spectrum during this phase is dominated by lines due to nitrogen and oxygen (Munari et al. 2008). Absorption systems, similar to that seen during the principal and diffuse enhanced phases were seen in the Hα line.

He/N class

The strongest non-Balmer lines in this class are either the helium (He I/He II) or the nitrogen (N II /N III) lines. The excitation levels in this class of novae are found to be higher than the "Fe II" class, and P-Cygni absorptions are either weak or absent. The lines are generally broad, indicating high

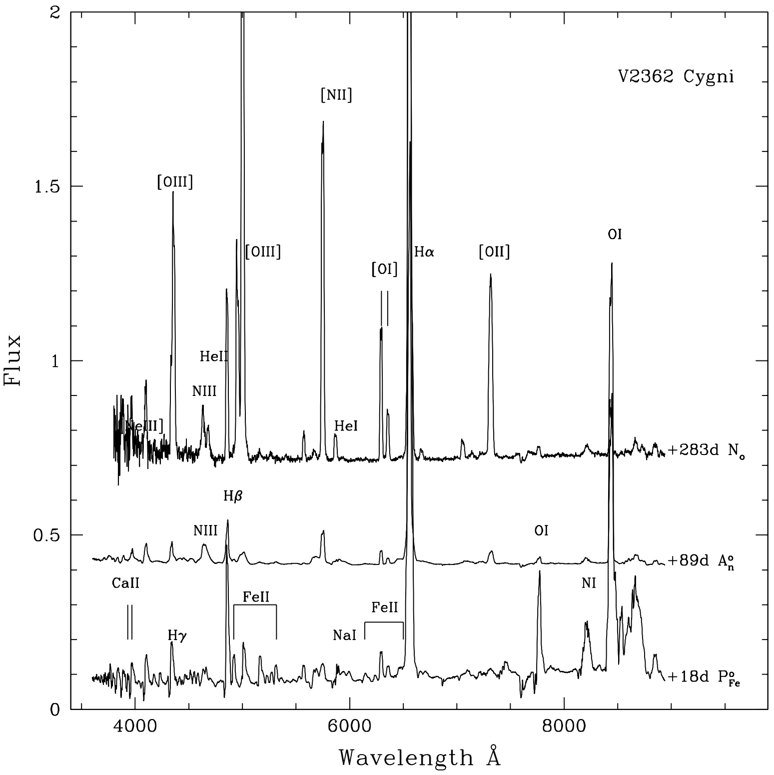

Figure 5. Spectra of V2362 Cygni, an Fe ii nova, during the early decline (+18d), auroral (+89s) and nebular (+283d) phases. Some prominent emission lines are labelled. The spectral classification according to the Tololo scheme is given for each epoch.

expansion velocities, with the velocity being as high as 10,000 km s^{-1} in some cases. The line profiles are boxy and structured indicating shell ejection. The "He/N" novae generally belong to the very fast and fast class of novae, and also show a faster spectral evolution, indicative of a mass ejection lower than that of the "Fe ii" class.

The nebular phase spectrum is quite diverse. Some novae develop high excitation coronal lines, while some do not show any forbidden lines during the nebular phase. Yet other novae show strong Ne iii forbidden lines. These are also termed as Ne novae and are presumed to have an ONe white dwarf.

The evolution of a "He/N" class of nova is illustrated by that of nova V2491 Cygni in Fig. 6. V2491 Cygni was a fast nova (t_3 = 16d) that showed a re-brightening by about 0.5 mag, about 10 days after maximum. The re-brightening phase reached a maximum around 15 days

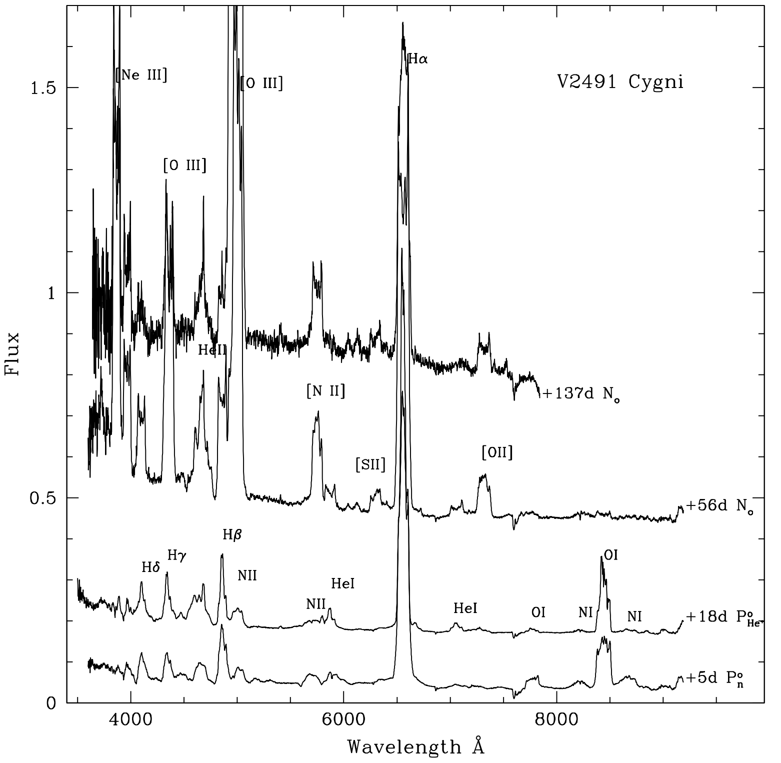

Figure 6. Spectra of V2491 Cygni, a He/N nova, during the early post-maximum (+5d), early decline (+18d) and nebular (+56d, +137d) phases. Some prominent emission lines are labelled. The spectral classification according to the Tololo scheme is given for each phase.

after maximum, and had a rapid decline before the light curve followed a smooth decline at later phases. V2491 hence has a light curve classification of C(16).

The early spectrum of V2491 Cygni showed strong hydrogen Balmer lines. The other prominent lines were those due to O I, He I and N I, N II. The FWHM of the emission lines indicated an average velocity ~ 5000 km s^{-1}. In the phase immediately after the re-brightening the line widths showed a narrowing, with the average FWHM velocity being 3000 km s^{-1}. He I lines showed an increase in strength, while the strength of nitrogen lines decreased. O I 7774 Å also decreased, while O I 8446 A continued to remain bright, with its strength more than that of Hβ. He II 4686 was also strong, blended with the 4640 feature. The nova had entered its nebular phase by day 56, with forbidden lines dominating the spectrum. The FWHM of the line widths indicated a velocity ~5200 km s^{-1}, similar to that seen during the early phases. All emission lines showed a multiple peaked flat top profile. An interesting feature to be noted in the late nebular phase (137d) is the presence of narrow (~500 km s^{-1}) emission line of He II 4686. This narrow feature could probably be from the re-formed accretion disc (Page et al. 2010). This nova developed strong [Ne III] lines during its nebular phase, indicating the presence of an ONe white dwarf. No coronal lines were detected in the nebular phase, even around 200 days past maximum. A detailed study of the evolution of this nova is presented by Munari et al. (2011).

Hybrid novae

The hybrid novae, also termed Fe II*b* are those systems that change their spectral class from "Fe II" to "He/N" during the permitted lines phase, before the forbidden lines appear. Some novae belonging to this class show evidence for simultaneous emission from both components. The line widths indicate higher velocity compared to the "Fe II" class. The line profiles indicate ejection of matter via a weak wind as well as shell ejection.

The evolution of an Fe II*b* nova is illustrated by that of nova V5114 Sgr (Fig. 7), a moderately fast (t_3 = 21d) nova with a smooth decline – light curve class S(21). The early spectrum (day 2), in addition to the hydrogen Balmer lines, showed lines due to Ca II, Na I, O I and Fe II. Two absorptions were detected in the P-Cygni profiles, at −900 km s^{-1} and −1200 km s^{-1}. The spectrum was found to be typical of the Fe II class. The spectrum, however, showed an evolution that is not typical of an Fe II class, in the sense that the Fe II lines faded quite rapidly, and the spectrum was dominated by helium and nitrogen lines, typical of that seen in the "He/N" class. Thus the spectrum had evolved from an "Fe II" class to a "He/N" class. No coronal lines were seen in the nebular phase in the optical, even around 200 days past maximum, while coronal lines were present in the near-IR (Lynch et al. 2004a).

Helium novae

In addition to the nova classes described above, a new species of novae that are hydrogen deficient have been discovered. Nova V445 Pup 2000 was the first such nova to be discovered. The early spectra (Fig. 8) indicated the nova to be unusual in not having any hydrogen lines. The early spectra were dominated by numerous emission lines arising from Fe II, Na I, C II and He I (Kamath & Anupama 2002a; Iijima & Nakanishi 2008). Several lines of N I, C I and Mg II were also present. Spectra obtained about three years after the explosion (Woudt & Steeghs 2005; Lynch et al. 2004b) showed the emission lines of He I, [O I], [O II], and [O III], but no H I line. The emission lines of highly ionized ions, such as He II, [Ca V], or [Fe VII], were not detected (Woudt & Steeghs 2005). Despite unusual spectral behaviour, the light curve was not very different from the normal novae. V445 Pup was found to be a slow nova (t_3 ~ 240d) that developed dust – light curve class D(240).

We have described here the various light curve types of a nova phenomenon, the spectral classes and their evolution. While the spectral evolution follows the light curve generically, no

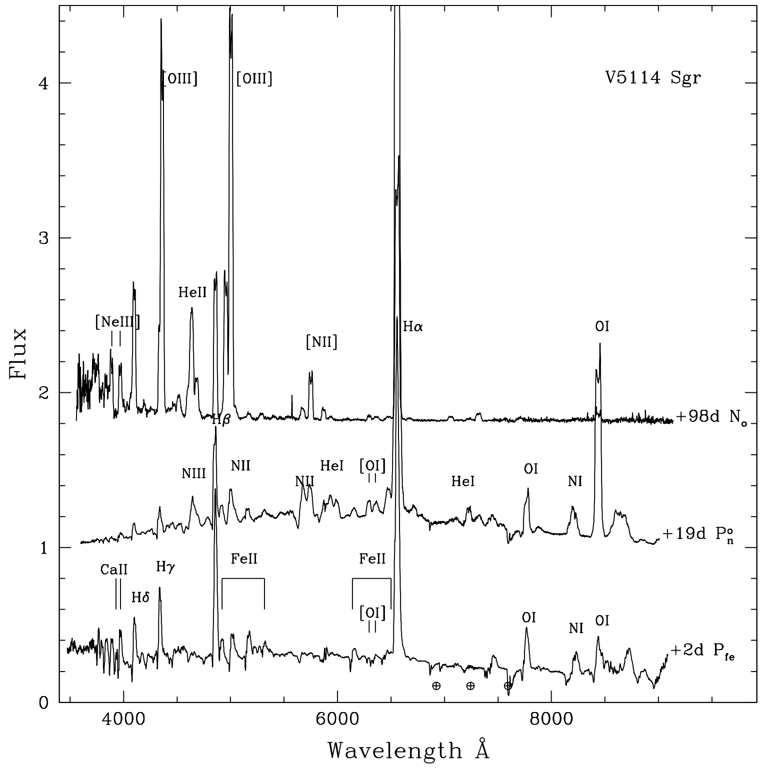

Figure 7. Spectra of V5114 Sgr, a He/N nova, during the early post-maximum (+2d), early decline (+19d) and nebular (+98d) phases. Some prominent emission lines are labelled. Note the change in the spectrum from Fe II class on day 2 to He/N class by day 19. The spectral classification according to the Tololo scheme is given for each phase.

correlation is seen with the light curve shape and the spectral type of the nova. For example, both V2362 Cyg (Fe II class) and V2491 Cyg ("He/N" class) show a re-brightening in their light curve. The reason for this re-brightening is not very clear. Hachisu & Kato (2009) suggested the re-brightening as being due to magnetic activity of the white dwarf. However, no evidence was found for the presence of a magnetic white dwarf in V2491 Cygni (Page et al. 2010). In the case of V2362 Cyg, evidence for the emergence of a pseudo-photosphere was found from the optical and infrared observations (Arai et al. 2010; Munari et al. 2008), with the fading post re-brightening being caused by the slowly shrinking photosphere. The spectrum during this phase was more akin to that of the "He/N" class. V2491 Cyg showed a marginal decrease in the emission line widths during this phase, but no change in the spectral type. An increase in the X-ray flux was seen at the same time as the optical re-brightening (Page et al. 2010), indicating a possible correlation. X-ray observations also indicated the re-formation of the accretion beyond

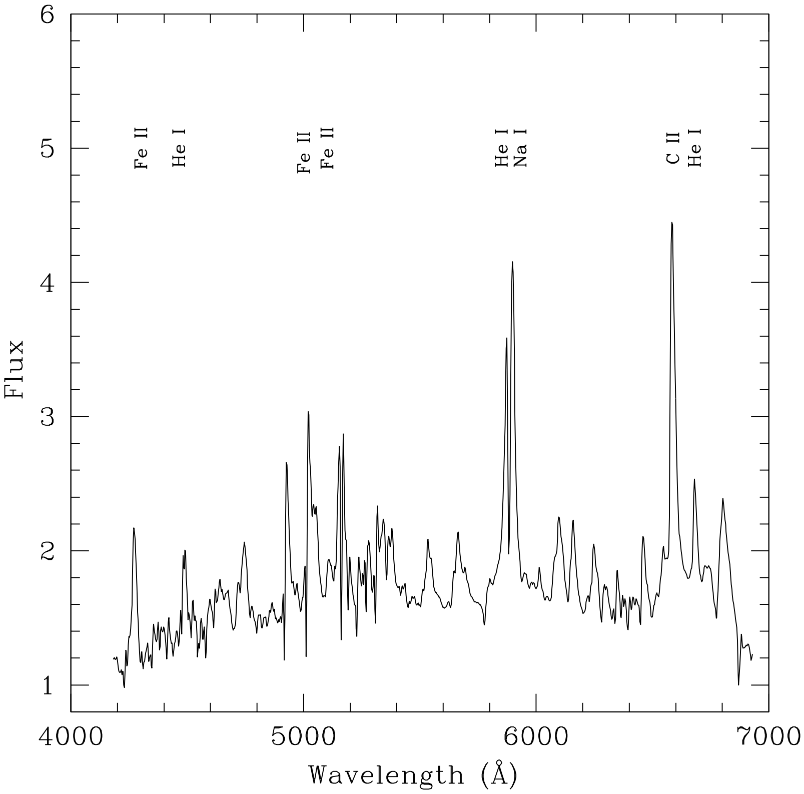

Figure 8. Early outburst spectra of the helium nova V445 Pup. Some prominent lines are labelled.

day 57, while the optical spectrum obtained in the late nebular phase showed very narrow He II 4686 Å line, which could be from the newly formed accretion disc. This illustrates the need for multi-wavelength, dense temporal coverage at all phases of a nova outburst.

7. Novae at quiescence

Quiescent novae often do not receive similar attention as outbursting novae, probably because the timescale of their evolution takes years or decades. However, such studies are crucial to understand the long-term evolution of novae and the inter-class relationship amongst the cataclysmic variables. Differences between quiescent novae arise out of the differences seen during outburst, and are seen in their spectra (Kamath 2008). The fading away of nebular and coronal lines points to the exhaustion of quiescently burning fuel on the white dwarf and thus to the turn-off of a nova.

Several novae show light curve variability during their post-outburst quiescence. This vari-

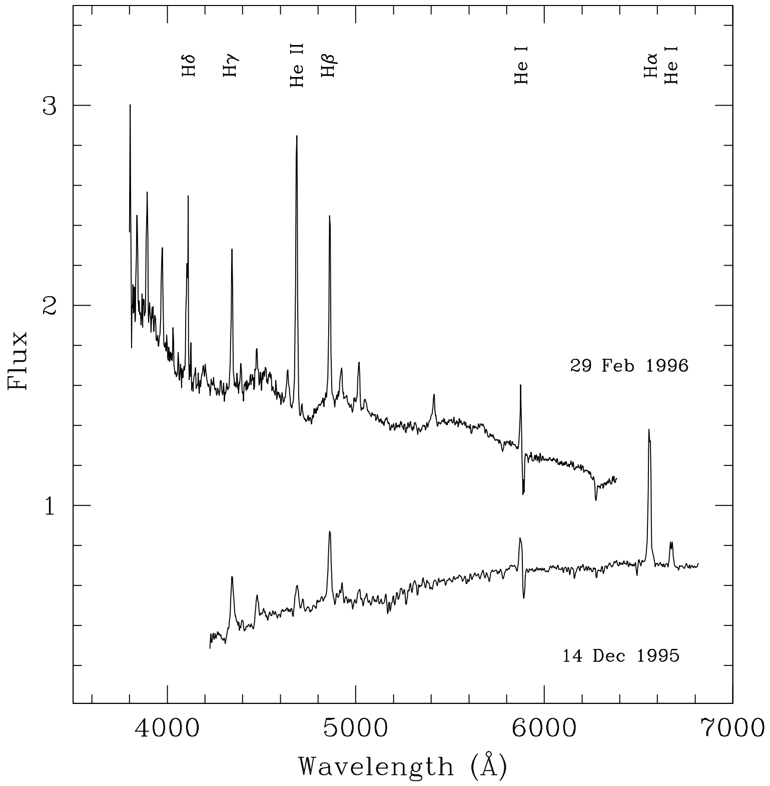

Figure 9. The old nova GK Per just before (14 December 1995) and during (29 February 1996) its dwarf nova outburst.

ability could be due to several reasons, the most common ones being due to the orbital motion, rotation of the white dwarf, which could be magnetic, and flickering due to accretion. Several classical novae also exhibit dwarf nova outbursts, which causes an increase in the magnitude by almost 2-3 magnitudes. These accretion induced outbursts are generally quasi-periodic. Nova GK Per (1901) is a well studied example of a classical nova showing dwarf nova outbursts in its post-nova phase. The dwarf nova outbursts in this system occur with quasi-periodic intervals ranging from 900 to 1340 days. It has done so since 1948, 47 years after its nova outburst. Spectra obtained during its quiescence and two dwarf nova outbursts in 1996 and 1999 have shown considerable variations in the structure and fluxes of emission lines, particularly the Balmer lines (Kamath & Anupama 2002b). Fig. 9 illustrates the spectral differences in the quiescence spectrum of GK Per during a ‘normal’ quiescence and during a dwarf nova outburst.

Many past novae do not have easily identifiable quiescent counterparts. The candidates can be identified based on their blue colours and Hα brightness. Spectra can confirm the identification.

Kamath (2009) has identified a possible candidate for the old nova KT Mon. Based on unfiltered images, Kamath, Ashok & Anupama (2008) have given two possible quiescent candidates of nova V4444 Sgr. Non-detections are also important because they can be used to set limits on the nova outburst amplitude and consequently on the outburst energy.

The old nova IV Cep, which erupted in 1971, had magnitudes of B = 18.63, V = 17.35 and R = 16.89 in October 2005. This was found to be fainter by 1.6 magnitudes in B and more than 0.9 magnitudes in V and R since the observations of Szkody (1994) obtained 17 years after outburst. Periods ranging from 1.1 to 5.08 hours were found from our V band data obtained on two nights in June and July 2008. However, this needs to be confirmed using extended data runs. Hα emission, presumably from the accretion disc, is seen in spectra obtained in 2006 and 2007. [1]

Under favourable circumstances, it is possible to observe the expanding shell from the nova outburst several years after the event. Distance to the nova can be determined from size of the shell and its expansion velocity (e.g. HR Del: Slavin et al. 1994; Harman & O'Brien 2003). A well studied, and long lasting nova shell is that of GK Per. Imaging of the nebular shell of GK Per in the [N II] and [O III] emission lines over several years indicate the evolution of the shell, and also indicate the nova ejecta has had a shock interaction with its environment that harbors an old planetary nebula (Seaquist et al. 1989 and references therein; Anupama & Prabhu 1993; Slavin et al. 1995; Lawrence et al. 1995; Anupama & Kantharia 2005). Optical images in the Hα line also reveal the presence of a bipolar nebula (Tweedy 1995; Bode et al. 2004; Anupama & Kantharia 2005), which is a remnant of an evolutionary mass loss event during the 'born-again' AGB phase of the white dwarf.

8. Recurrent novae

The spectral evolution of recurrent novae indicate they may be grouped under three classes: the T CrB/RS Oph class, the U Sco class and the T Pyx class.

The T CrB class of RNe are systems that have an M giant secondary, with orbital periods ~ several hundred days (long period binaries). At quiescence, these systems are very similar to the symbiotic binaries. The members of this group are fairly homogeneous in their outburst and quiescence properties. The outburst spectrum of this group is characterized by broad emission lines (V_{exp} ~4000 km s^{-1}) that narrow with time (e.g. Anupama & Prabhu 1989; Anupama 2008b). The early phase spectra show permitted lines, followed by the presence of intense coronal and other high excitation lines that develop when the nova has faded by 2-3 magnitudes from maximum, and fade as the nova enters the nebular phase. The narrowing of the emission line widths and the development of intense coronal lines are well explained by the interaction of the nova material with the red giant wind material. The development of the optical spectrum is largely similar during all outbursts. The 2006 outburst of RS Oph has been extremely well studied in all

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[1] This work was done by Catharine J. Wu, New Mexico State University at IIA under the Indo-US International Research Experience for Students (IRES) Programme in 2008.

wavebands (e.g. Bode et al. 2006; Sokoloski et al. 2006; Das et al. 2006; Evans et al. 2007a,b; Osborne et al. 2011; Eyres et al. 2009; Kantharia et al. 2007).

The optical spectrum at quiescence is dominated by that of the giant secondary, with emission lines due to H I and He I superposed. Fe II, Ca II and O I 8446 Å lines are also present, except in T CrB. He II lines are weak or absent (e.g. Anupama & Mikołajewska 1999).

The members of the U Sco class are very fast nova systems, with very similar outburst properties. They belong to the short period binaries, with a slightly evolved secondary. U Sco is the most well studied member of this group, with its most recent, outburst in 2010 being extremely well monitored. The outburst spectra are characterized by extremely broad emission lines due to hydrogen Balmer, N III, C III and He I lines with initial FWZI velocities of $\sim$ 10000 km s^{-1} (e.g. Munari et al. 1999; Anupama & Dewangan 2000; Yamanaka et al. 2010; Diaz et al. 2010; Kafka & Williams 2011; Banerjee et al. 2010; Anupama et al., in preparation). The spectra indicate a rapid increase in the ionization levels, however, unlike in RS Oph, no coronal lines are seen in the U Sco systems. The nebular spectrum shows the presence of broad [O III] and [N II] lines, and weak Balmer lines.

The quiescence spectrum of the U Sco group is dominated by He II lines (e.g. Hanes 1985; Duerbeck et al. 1993), with hydrogen lines either absent or weak. U Sco has a K2 subgiant secondary (e.g. Kahabka et al. 1999; Anupama & Dewangan 2000; Schaefer 2010), while the orbital periods of V394 CrA and V2487 Oph indicate the presence of an evolved secondary in these systems also.

The T Pyx class are all slow novae, with t_3 ranging from 36–80 days. The outburst spectral development is however very similar in all three systems. Early spectra show lines due to H I, Fe II, N III and O I with P Cygni absorptions with velocities ranging from $\sim 800 - 2500$ km s^{-1}. The spectral development is very similar to classical novae. Early spectra are similar to the Fe II class, and changes to the He/N class, similar to the hybrid novae. The 2011 outburst of T Pyxidis, that was discovered well before maximum, indicated the nova to have a He/N spectrum in the pre-maximum phase, that developed into an Fe II type around the maximum phase (Shore et al. 2011). The spectrum reverted to the He/N type once again during the early decline.

The properties of T Pyx, CI Aql and IM Nor are quite different at quiescence. T Pyx and IM Nor have orbital periods that are similar to classical novae (Mennickent & Honneycutt 1995; Uthas et al. 2010). T Pyx is the only recurrent nova with a shell that has a slow expansion velocity with thousands of discrete knots (e.g. Duerbeck & Seitter 1979; Shara et al. 1997). CI Aql is an eclipsing binary with a quiescence spectrum that is very different from nova systems. The spectrum shows weak emission lines due to He II, C III-N III complex on a reddened spectrum. Hydrogen Balmer lines are in absorption or absent (e.g. Anupama 2008a), similar to shell stars. Spectra suggest a K-M secondary, while the orbital period suggest the secondary is evolved.

The near-maximum phase outburst spectra of RS Oph (2006), U Sco (2010) and T Pyx (2011) are shown in Fig. 10. Note the differences in the spectra as described above.

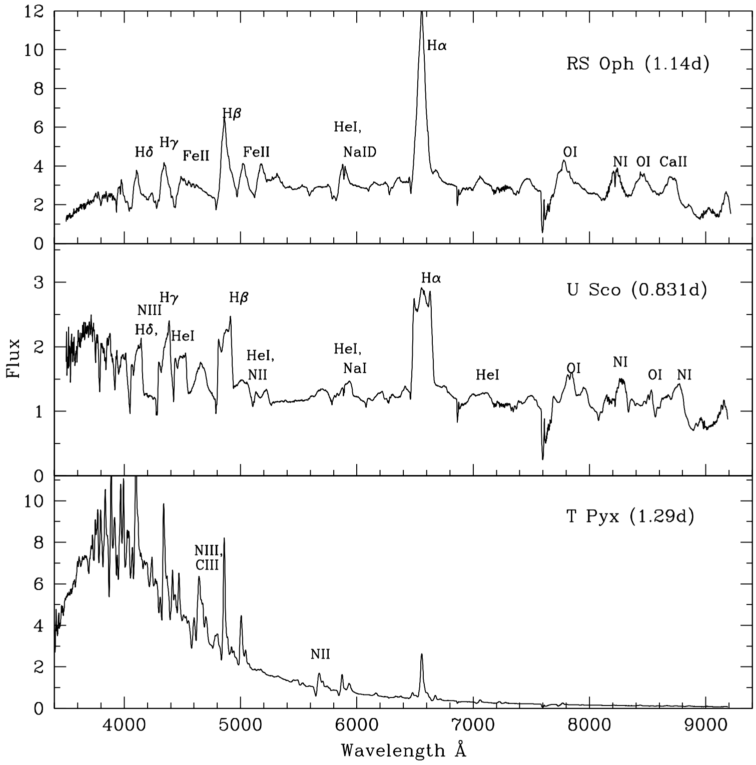

Figure 10. Early outburst spectra of the recurrent novae RS Oph 2006 (top), U Sco 2010 (middle) and T Pyx 2011 (bottom). The prominent emission lines are labelled.

9. Physical parameters

A detailed study of the evolution of the spectrum as the nova evolves through its various phases provides information about the physical conditions in the nova ejecta. The emergence of the lines of various species and ionization levels and their relative fluxes provide direct information on the temperature, density and optical depth conditions in the ejecta, as well as the temperature of the central ionizing source, the hot white dwarf. Emission line fluxes, corrected for extinction, enable us to determine physical conditions in the ejecta. The line profiles, and the evolution of their structure can be used to obtain the geometry of the ejecta (Shore 2012; this Volume). While detailed photoionization models applied to multiwavelength spectra provide the most comprehensive information about the temperature, density and elemental abundances, emission line diagnostics used for studies of other objects such as planetary nebulae, H ii regions, AGNs, etc (Osterbrock & Ferland 2005) can also be applied to understand the physical conditions in novae.

Table 1. Deductions from optical observations of novae.

Parameter	Estimates
He I 5876/4471	$E_{\mathrm{B-V}}$
Balmer and Paschen series	$E_{\mathrm{B-V}}$
Colour index and MMRD relation	$E_{\mathrm{B-V}}$
[O I] 5577/6300	Temperature of neutral zone
Hα, Hβ fluxes and velocity	ejecta mass (hydrogen)
He I 4471, 5876, 6678 and He II 4686 fluxes	Helium abundance
Hydrogen and He I line ratios	Zanstra temperature of the central source
[O I] 6300, 6363	Neutral Oxygen mass
[O III] Nebular line ratio	Temperature of ionized zone
Velocity and line profile evolution	Geometry of the ejecta, interaction with environment
Light curve shape and spectral evolution	mode of ejection of matter, WD mass and type

The most useful line ratios are [O III] 4959+5007/4363; [O III] 4959+5007/[Ne III] 3869 and [O III] (4959+5007)/He I 5876 (Starrfield 1988). The use of these line ratios are however, only possible during the nebular phase. Further, they also provide information only about the nebular phase. During the initial outburst stages when the densities in the line forming regions are relatively high, the [O I] 5577/6300 Å line ratio can be used to estimate the temperature (of the neutral zone) using the relation (Martin 1989)

$$[\mathrm{O\,I}]\,5577/6300 = 43\exp\left(-2.58\times10^4/T_e\right).$$

Electron densities may also be estimated from the recombination lines using the relation

$$f_\lambda = \epsilon_\nu n_e n_A V/d^2$$

if an estimate of the line emitting volume V can be made. Here, f_λ is the observed flux in the emission line, ϵ_ν the emissivity, n_e and n_A are the electron and ionic densities and d is the distance to the nova. The volume of the shell may be computed from spectroscopically determined expansion velocities v_{exp} as $V = \frac{4}{3}\pi(v_{\mathrm{exp}}t)^3\phi$, where t is the time since outburst, $v_{\mathrm{exp}}t$ is the radius of the shell and ϕ is the filling factor, which can be estimated from line profile evolution. (Shore 2012; this Volume).

Hydrogen Balmer lines are the most commonly used recombination lines. During early phases of the outburst when matter is radiation bound and the density is high, optical depth in Lyman and Balmer series is high. Under high optical depth conditions, self absorption becomes important and normal Case B condition cannot be employed. Under such conditions, the effect of high optical depths have to be incorporated. The He I, He II and H recombination lines can be used to estimate the helium abundance.

In Table 1 we summarize the parameters that can be deducted from optical observations.

10. Summary

We have provided in this article a general overview of the observational properties of classical and recurrent novae in the optical region. We provide a description of the nova light curve classes, and also describe the evolution of the outburst spectrum, and its classification through the various outburst phases. Recent studies of novae indicate the need for simultaneous, or nearly simultaneous multi-wavelength observations in order to obtain a comprehensive understanding of the nova phenomenon. Optical studies form a vital link in the all important multi-wavelength studies. It is also important to study the outburst at various stages, including the post-outburst quiescence. While a sparse coverage may provide the broad picture, dense temporal coverage is required to understand the details, and also provide important inputs to the outburst models.

Intensive observational programmes, even with modest sized telescopes, provide a wealth of information that go a long way in understanding the nova phenomenon.

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