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Classification of nova spectra

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Abstract. The evolution of the optical spectrum of a nova outburst is described. The classification schemes used to classify novae based on the outburst spectral features and their evolution are discussed.

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1. Introduction

Novae are interacting binary systems with a white dwarf primary and a 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, and the main sequence secondary is filling its Roche-lobe. The white dwarf accretes hydrogen rich matter from the secondary as a result of mass transfer via Roche-lobe overflow. The accreted matter forms an accretion disc around the white dwarf. As more matter is constantly accreted, 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). 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 an optically thick wind, as discrete shells, or as a combination of both.

Nova explosions are observed as a sudden brightening of the star by several magnitudes, followed by a decline. A nova outburst leads to the ejection of the accreted matter alone, without disrupting the binary system, leading to a resumption of the accretion process. Repeated outbursts are hence possible in these binary systems. Those

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systems that have had only one recorded nova outburst are termed as Classical Novae, while the systems that have recorded more than one nova outburst with a recurrence period ranging from a few years to a few decades are termed as Recurrent Novae.

Novae are classified into different speed classes depending on the time taken to decline by two magnitudes from outburst maximum (t_2), or by three magnitudes from outburst maximum (t_3). 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).

2. 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.

2.1 Evolution of outburst spectra

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 are described below.

Pre-maximum spectrum: The spectrum during the pre-maximum phase is that of an optically thick, cooling ejecta, with blue shifted absorption lines indicating expansion of the material.

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 aborption 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 II, Na II, Fe II, N, He and O.

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 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 now a mixture of the principal and diffuse enhanced system, 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 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 system occurs at $\Delta m \sim 2.7$. 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. The lines are generally structured.

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. This phase is marked by the presence of high ionization lines such as the auroral, nebular forbidden lines, and high excitation coronal lines. The high excitation lines gradually fade and in the post-nova phase the spectrum is dominated by that of the accretion disc.

3. Spectral classification

The spectra of different novae appear quite diverse. However, Williams (1992) grouped them based on common characteristics in this seemingly diverse ensemble. The classification of novae is based on their outburst spectra in the optical. All novae are dominated by the strong hydrogen Balmer 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. It is found that all novae spectra either have lines due to Fe II or due to He/N as the strongest non-Balmer lines during the early phases. Hence, novae can be classified into two broad groups, the "Fe II" and the "He/N" class (Williams 1992). However, as we shall see in the following, there are a few novae that fall in between the two classes and are termed "hybrid" novae.

3.1 Fe II class

The strongest non-Balmer lines during the early phases in this class are due to Fe II. The early phase spectra show pronounced P-Cygni absorption, with velocities < 2500 km s^{-1}. Low ionization transitions are seen during this phase. Novae belonging to the Fe II class are generally the moderately fast to the slow novae, with the 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.

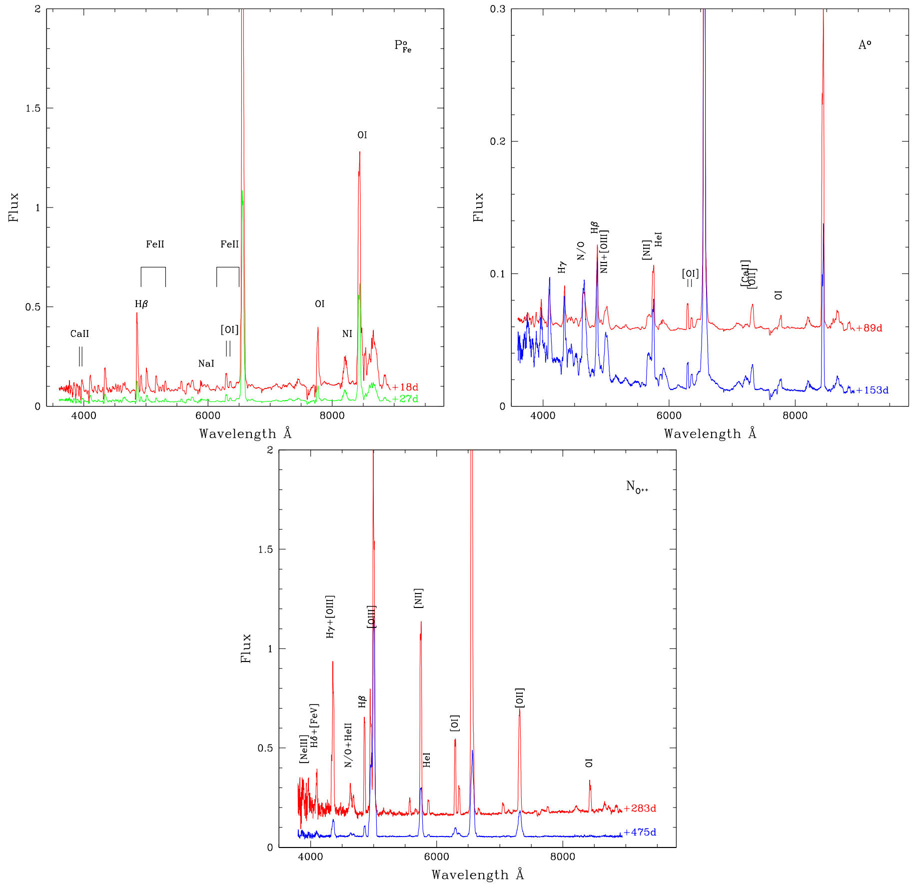

Figure 1. Spectral evolution of nova V2362 Cygni, an example of the "Fe ii" class of novae.

The dominant ejection mechanism for this class of novae appears to be wind ejection. Fig. 1 shows the spectral evolution of nova V2362 Cygni that belongs to the "Fe ii" class.

3.2 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 "Feii" class, and P-Cygni absorptions are either weak or absent. The lines are generally broad, indicating high 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.

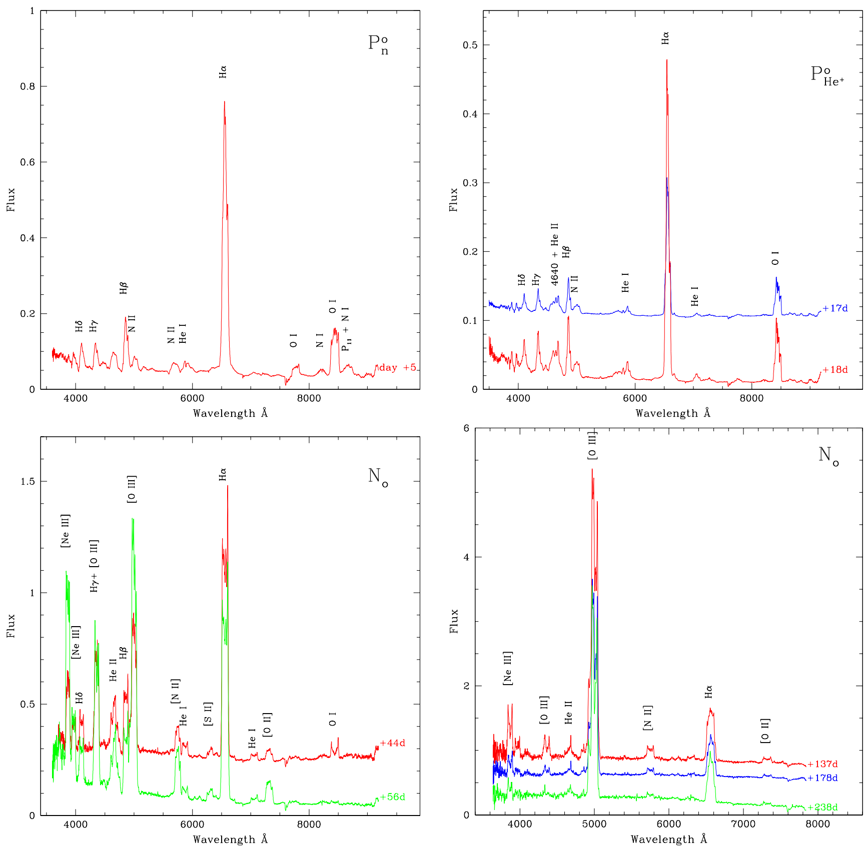

Figure 2. Spectral evolution of nova V2491 Cygni, an example of the "He/N" class of novae. Note thefaster evolution compared to the "Fe ii" class.

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. Fig. 2 shows the spectral evolution of the He/N nova V2491 Cygni.

3.3 Hybrid novae

The hybrid novae are those systems that change their spectral class from "Feii" to "He/N" during the early 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 "Feii" class. The line profiles indicate ejection of matter via a weak wind as well as shell ejection. Fig. 3 shows an example of a hybrid nova.

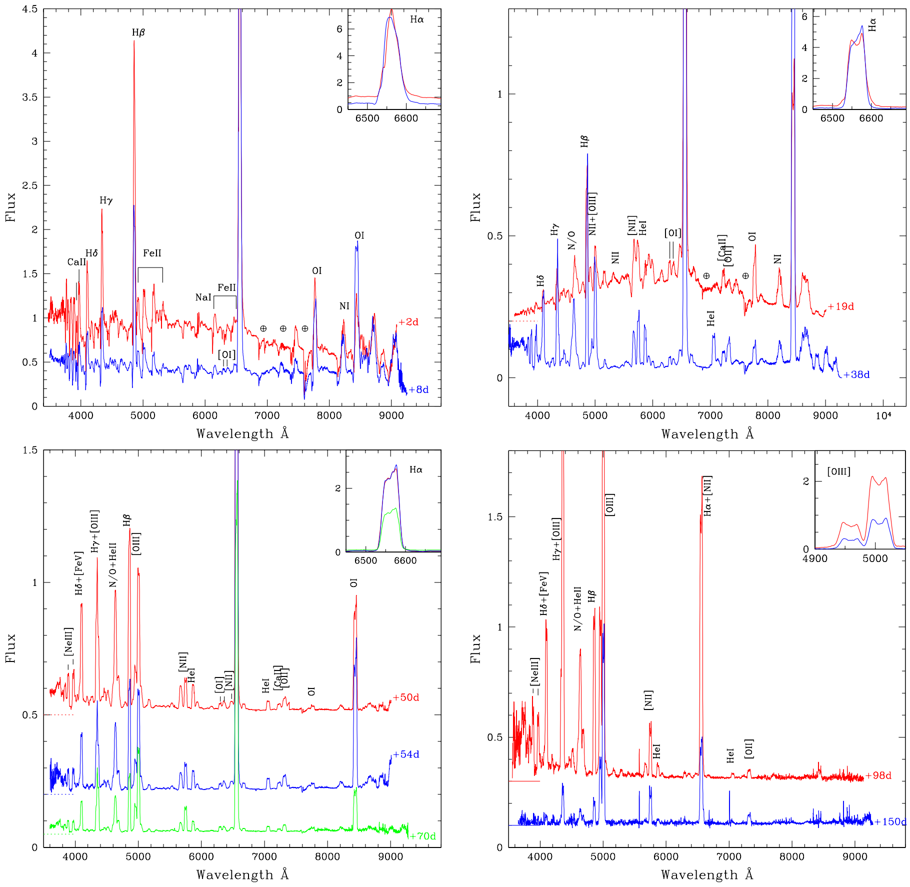

Figure 3. Spectral evolution of nova V5114 Sgr, and example of the "Hybrid" class of novae. Note the change from an "Fe II" class to "He/N" class during the early phases.

4. The Tololo classification scheme

Williams et al. (1991) devised a physical basis to describe the outburst spectral evolution, generally referred to as the Tololo Classification Scheme. 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.
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. For example, in the case of "Fe II" novae, this phase would be represented by P_{fe}, while in the case of "He/N" novae this phase would be P_{he}, or P_N.
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.
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.
6. If the OI 8446 Å line is present and prominent, it is represented an 'o' in the superscript, irrespective of the phase.

The various phases of the outburst evolution according to the above scheme are marked for the spectra in Figs 1, 2 and 3.

5. Summary

The classification schemes of nova outburst spectra are based on the non-Balmer emission lines. The classes or phases under these schemes provide information about various physical parameters such as radiation field and mean gas density, and also clues to the nature of the white dwarf primary. Nova spectra also provide clues about the ejection mechanism, whether wind or shell ejection. A detailed knowledge about the ejection mechanism is however, quite complex in the nova outburst. Although the classification schemes mentioned here have been in existence for over two decades, an extensive database of novae spectra, and an automated spectral classification method is still unavailable. It is of extreme importance to develop a database of novae spectra, along with their classification. Such a database and an automated classifiation method will prove extremely useful in the identification of novae in the upcoming large spectroscopic surveys.

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