Final-week Report(24th June - 29th August)

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August 29, 2016

Abstract

The period of two months was utilized mainly in understanding the basic concepts of novae,Cataclysmic Variables, classification of the spectra of such novae and formation and evolution of close binary systems in the universe along with reviewing the observational characteristics of classical novae in the optical region. Analysis has been done on the spectra obtained with the 2m Himalayan Chandra Telescope (HCT) and necessary readings have been tabulated. Images have also been provided to support the theoretical concepts.

1. Introduction

This project is associated with interactive binary systems found in the universe.

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 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 large amount of energy. 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, and ejection of matter.

Matter is ejected either in the form of discrete shell(s), an optically thick wind, or as a 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. This is the fundamental difference between a nova explosion and a supernova explosion. In a supernova, the binary system is completely destroyed in a catastrophic explosion. The accretion process of the nova 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)**.

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.

This project limits the discussion and observational studies of novae to the optical region.

2. Light curves and classes

A classification system for nova light curves is as follows :

- S - Smooth light curves
- P - Plateaus
- D - Dust dips
- C - Cusp-shaped secondary maxima
- O - Quasi-sinusoidal oscillations
- F - Flat-topped light curves

- J - Jitters or flares

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, or by three magnitudes from outburst maximum.

The light curve evolution of all novae, in general, follow the following sequence. 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.

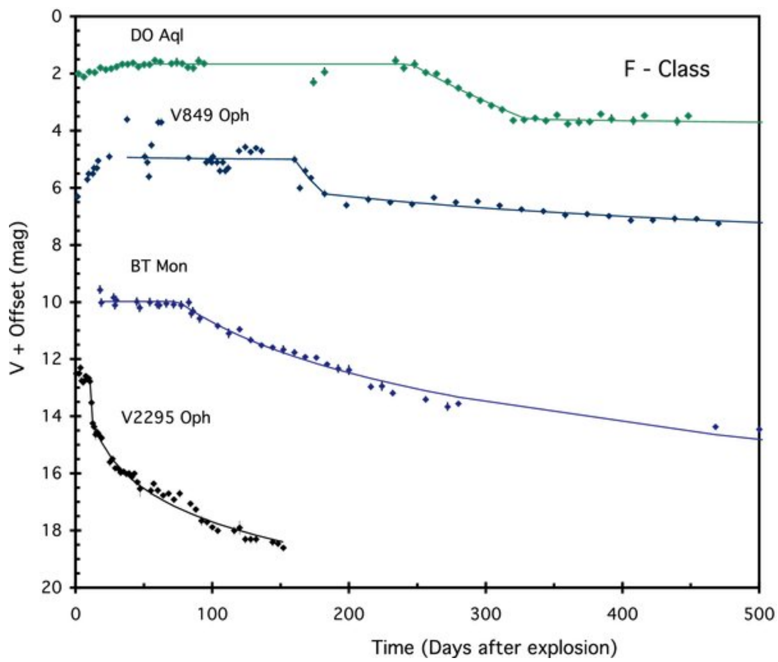

Figure 1: Illustration of light curve classes.

3. 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. 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 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. The evolution from the pre-maximum all the way to the late phase spectra was mentioned in the previous report. These concepts will now be explained in depth.

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: The principal spectrum occurs close to visual maximum. At maximum, the spectrum is characterized by strong absorption 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.

Diffuse enhanced spectrum: 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. In the later phases of this stage, the lines often split into narrow components.

Orion system: 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 at least as much as the diffuse enhanced system. 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. The emission lines are generally structured during the Orion phase.

Nebular and post-nova phase: 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 decreases as it expands. 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

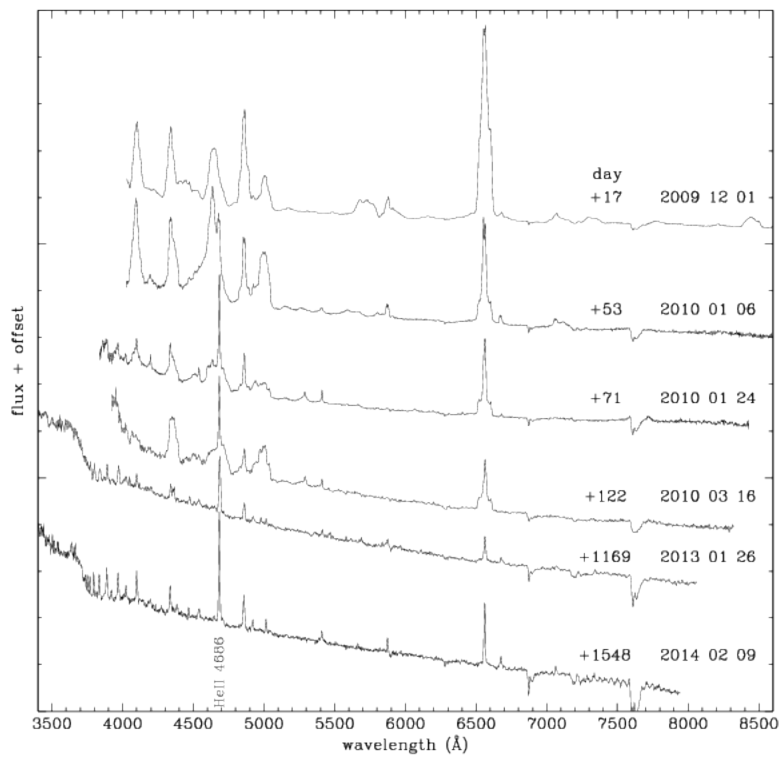

Figure 2: The narrow and moving HeII lines in nova KT Eridani recorded during the spectroscopic evolution of nova outburst.

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.

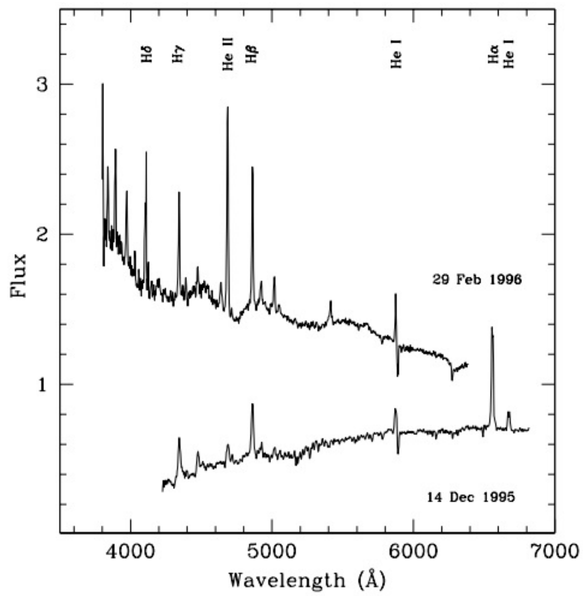

Figure 3: The old nova GK Per just before (14 December 1995) and during (29 February 1996) its dwarf nova outburst.

4. 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 variability 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.

Nova GK Per (1901) (Figure 3) 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.

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. A well studied, and long lasting nova shell is that of GK Per. Imaging of the nebular shell of GK Per in the [NII] and [OIII] 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. Optical images in the H line also reveal the presence of a bipolar nebula, which is a remnant of an evolutionary mass loss event during the born-again AGB phase of the white dwarf.

5. Nova models

5.1 Parametric and one-dimensional models

Different approaches have been adopted to date in the modeling of nova explosions. A first category includes parameterized one-zone models, in which the envelopes history relies on the time evolution of the temperature and density in a single layer (usually, the envelope base). Such thermodynamic quantities are often calculated by means of semi-analytic models, or occasionally correspond to T-profiles directly extracted from hydrodynamic simulations.
This approach was widely used in the past to overcome the strong time limitations that arose when large nuclear reaction networks were coupled to computationally intensive numerical codes. More recently, it has also been used as a feasible tool to estimate the impact of nuclear uncertainties on the final nova yields. This often requires thousands of calculations that are still prohibitive with hy-

drodynamic codes. This approach requires a decision regarding how material is mixed between individual layers, since nova envelopes become fully convective close to the peak of the outburst.

A second, somewhat improved approach relies on semi-analytic models directly coupled to a nuclear reaction network. The models assumes a fully convective envelope in hydrostatic equilibrium. Therefore, key aspects of the evolution, such as the way convection settles, extends throughout the envelope and recedes from its surface, are completely ignored. So far, the state-of-the-art in nova nucleosynthesis relies on 1D hydrodynamic models. The underlying assumption of any 1D model is spherical symmetry.
This simplifying hypothesis demands that the explosion must occur simultaneously along a spherical shell.

5.2 Multidimensional models

Despite many observational features that characterize the nova phenomenon being successfully reproduced by hydrodynamic simulations under the assumption of spherical symmetry, certain aspects like the way in which a thermonuclear runaway sets in and propagates, or the treatment of convective transport clearly require a multidimensional approach.
Even though multidimensional models are necessary ,they are extremely time consuming and the handful of 2D and 3D simulations performed to date assumed reduced computational domains (i.e., a box containing a small fraction of the overall star) as well as limited nuclear reaction networks. Indeed, only a handful of isotopes (from H to F) have been considered in all previous multidimensional nova simulations, to approximately account for the energetics of the explosion. Hence, no reliable nucleosynthesis predictions can be inferred from these studies.

6. Recent developments in studying novae

Recent developments in computer science are now providing modelers with the required capabilities to study novae in a truly multidimensional framework. Pioneering 2D and 3D simulations are beginning to shed light into the nova mixing problem and detailed multidimensional simulations of the expansion and ejection stages are likely to become available soon.

Moreover, the emergence of high-energy astrophysics with spaceborne observatories has opened new windows to observe novae, from a new perspective. Detection of unambiguous gamma ray signatures from a close enough event would provide unprecedented constraints on the predicted nucleosynthesis accompanying nova outbursts.

Cosmochemistry, in turn, is helping in the analysis of tiny pieces of stardust embedded in primitive meteorites, giving clues on the processes operating in novae.

Finally, nuclear physicists are determining reaction rates at (or close to) stellar energies, through combined efforts with stable and/or radioactive ion beams and theoretical modeling, at the required precision for nova explosions. Soon, all nuclear interactions of interest for novae would have been determined experimentally.

Illustrations of a 3D computer model that accurately simulates the formation and life cycle of a nova are given below. The model was applied to the U Scorpii nova and the effects of various model parameters on the nova evolution from accretion to explosion were studied.

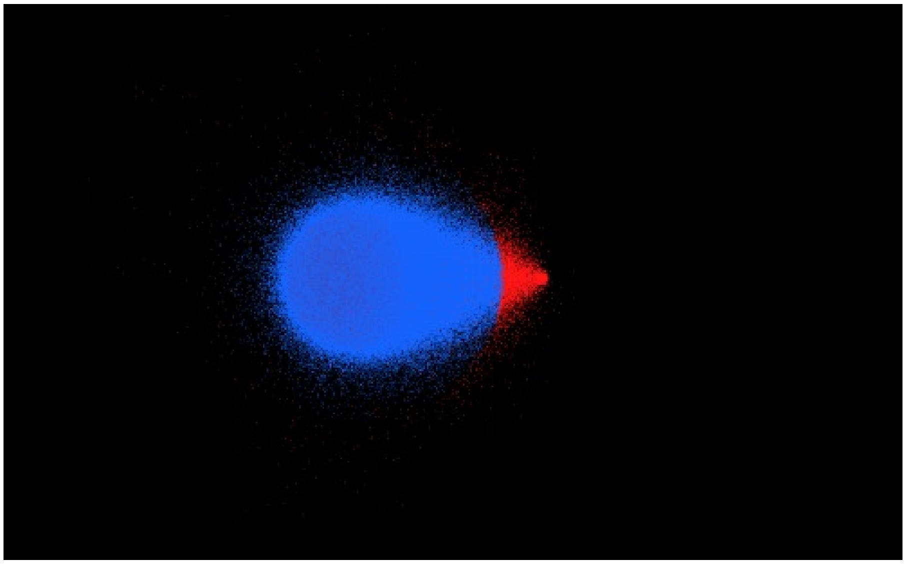

Figure 4: Nova U Scorpii before explosion.

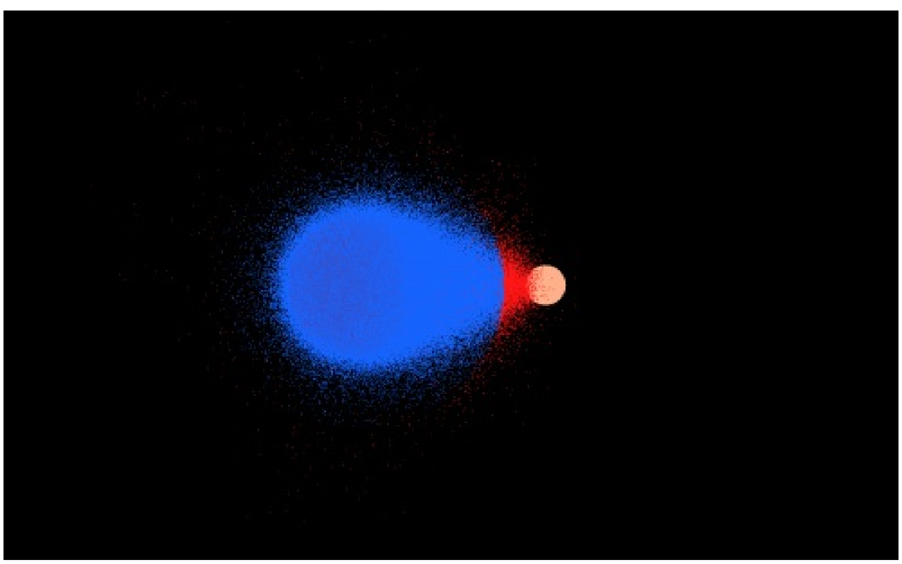

Figure 5: Nova U Scorpii 100 seconds after explosion.

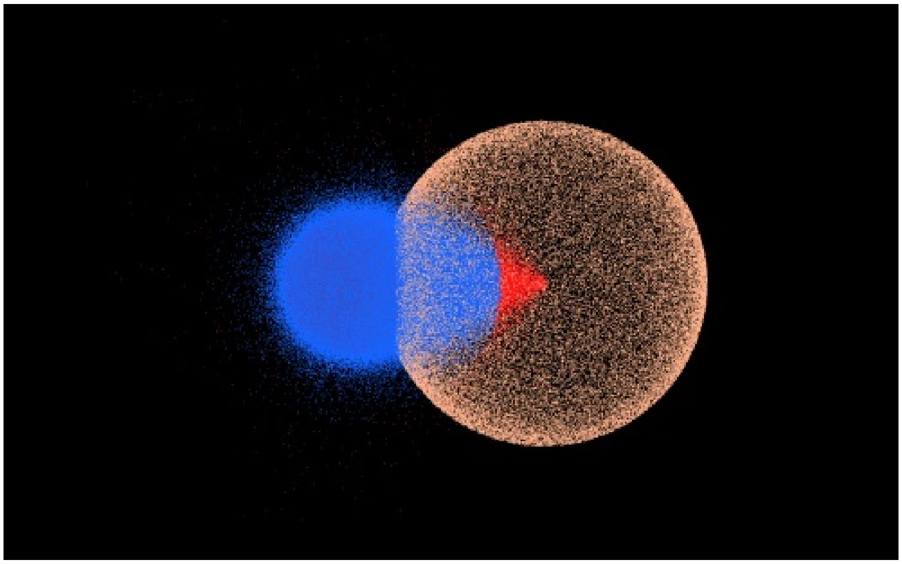

Figure 6: Nova U Scorpii 14 minutes after explosion.

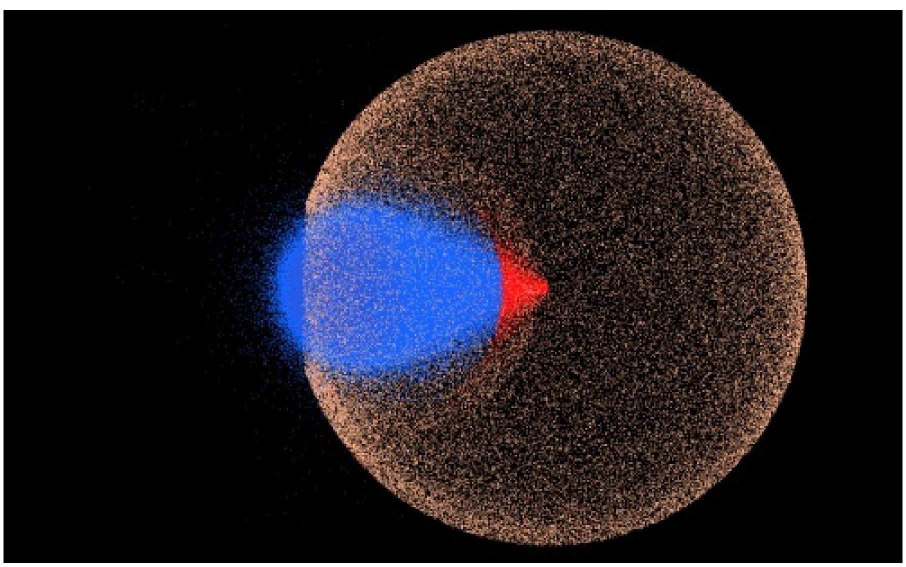

Figure 7: Nova U Scorpii 22 minutes after explosion.

7. Data Analysis of V339 Delphini

In this project, analysis was done on the spectra obtained of the nova V339 Delphini that occurred in 2013.

V339 Delphini is a bright nova star in the constellation Delphinus. It was discovered on 14 August 2013 by amateur astronomer Koichi Itagaki in Japan and confirmed by the Liverpool Telescope on La Palma. The nova appeared with a magnitude 6.8 when it was discovered and peaked at magnitude 4.3 on 16 August 2013.

What we've seen so far

Nova Del 2013 is a very fast classical nova. Its nova-nature was confirmed while it was still rising through the presence of optical emission lines of hydrogen typically seen in novae. V339 Del is another member of the recently-discovered class of novae that show gamma-ray emission, something discovered to occur only recently; gamma rays were first detected in V339 Del by the Fermi satellite on August 18 (day 4). The nova quickly reached peak and remained near this plateau state for a few days, but began its decline on August 20 (day 6).

Its luminosity and spectral evolution since then has matched those of typical novae. The eruption begins with a bright, optically thick fireball, which begins to slowly cool after maximum light. At some point, this fireball cools (and fades in brightness) enough that the emission lines from the ejecta dominate the luminosity of the nova; this is the point where you see the first break in the V339 Del light curve around September 3 (day 20). Over the next few weeks, the system continues to cool and the emission lines fade more slowly than the continuum emission. X-rays were first detected on September 19 (day 36), which is a sign that the density of X-ray absorbing gas around the white dwarf is beginning to dissipate. The X-ray light rose steadily coinciding with much faster optical decline, a sign that the material responsible for the emission lines is also starting to dissipate and fade.

Around October 9 (day 55) there was a large jump in X-rays, and on October 19 (day 65), AAVSO observations show a flattening of the optical light curve. As of October 24 (day 70), the nova is now a very bright X-ray "supersoft source", indicating that the environment around the nova's white dwarf primary has cleared enough to let the hot white dwarf shine through at low-energy X-ray wavelengths. V339 Del was seen to be entering the "nebular phase" in which a new series of emission lines characteristic of hot, low-density gas seemed to appear in the early 2014.

7.1 Working

From the spectra of the nova outburst, I was able to plot Gaussian curves for the peaks (for different dates) and was able to identify the elements present by comparing the center wavelength of each peak to the corresponding standard center wavelengths of the elements.

The readings obtained have been tabulated for each date and are shown below:

For each peak, the center wavelength, relative flux and FWHM have been tabulated.

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6562.94	4.94E-10	35.86
4861.46	1.26E-10	22.38
4342.32	3.75E-11	19.82
8444.65	1.03E-10	44.83
7774.44	5.32E-10	38.76

1. del_28aug

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6563.27	7.33E-11	28.68
4861.32	1.62E-11	17.12
4339.77	5.33E-12	15.09
8445.78	2.02E-11	38.49
7773.87	4.42E-12	28.02

2. del_04sept

Figure 8:

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6563.37	8.27E-11	30.13
4859.84	2.00E-11	16.91
4339.66	9.10E-12	19.04
4100.06	5.73E-12	15.36
8444.97	2.28E-11	36.41
7772.44	4.85E-12	27.4

3. del_05sept

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6561.86	1.92E-10	28.29
4860.44	4.54E-11	17.48
4340.03	1.52E-11	15.00
4100.36	1.15E-11	15.89
8446.85	5.37E-11	32.54
7774.21	8.80E-12	27.24

4. del_10sept

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6564.1	5.51E-10	26.19
4861.97	6.69E-11	18.88
4344.93	2.79E-11	20.41
4099.85	2.43E-11	25.94
8445.81	2.44E-10	29.11
7774.56	1.00E-11	25.95

5. del_30sept

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6563.24	1.84E-10	28.38
4861.11	2.94E-11	25.19
4344.85	1.83E-11	29.73
4099.86	1.72E-11	27.09
4636.61	1.62E-11	30.17
8446.53	6.01E-11	25.85

6. del_07oct

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6564.35	1.82E-10	32.48
4860.16	2.28E-11	27.03
4100.04	1.17E-11	26.32
4639.61	1.26E-11	29.01
8448.6	4.65E-11	30.82

7. del_14oct

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6561.21	7.43E-11	35.74
4100.09	6.15E-12	25.99
8447.07	8.61E-12	36.95

8. del_30oct

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6565.98	6.80E-11	39.43
4860.96	1.29E-11	30.5
4100.04	7.23E-12	28.43
8439.85	5.98E-12	38.92

9. del_06nov

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
6562.2	1.03E-10	33.28
4862.36	4.20E-11	27.65
4099.62	4.31E-11	25.43
8447.39	4.41E-12	35.81

10. del_24nov

CENTER WAVELENGTH	RELATIVE FLUX	GFWHM
4855.49	6.46E-11	24.29
6558.42	1.11E-10	37.95

11. del_13mar

From the tabulated readings above, the following emission lines were identified :

- Hα - Center wavelength - 6563
- Hβ - Center wavelength - 4861
- Hγ - Center wavelength - 4340
- NIII - Center wavelength - 4097, 4103, 4640
- OI - Center wavelength - 8446, 7774

The following images are the different stages of the spectra during the nova outburst. The peaks have been referenced with Gaussian curves. In doing so, we obtain the relative flux values and the center wavelengths.

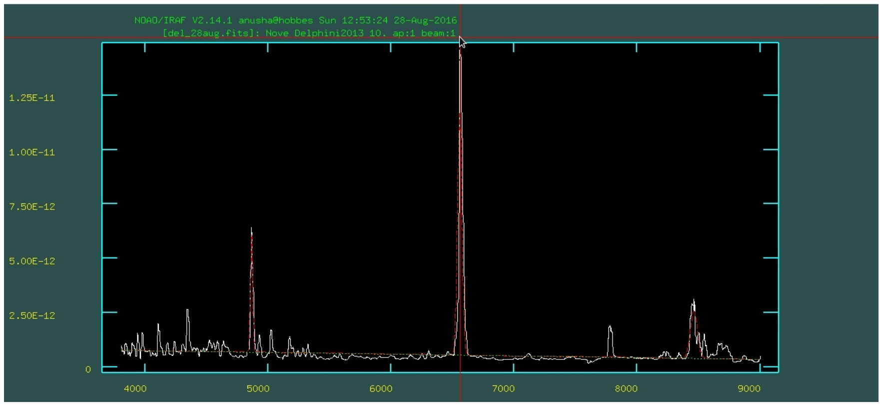

Figure 9: del-28aug

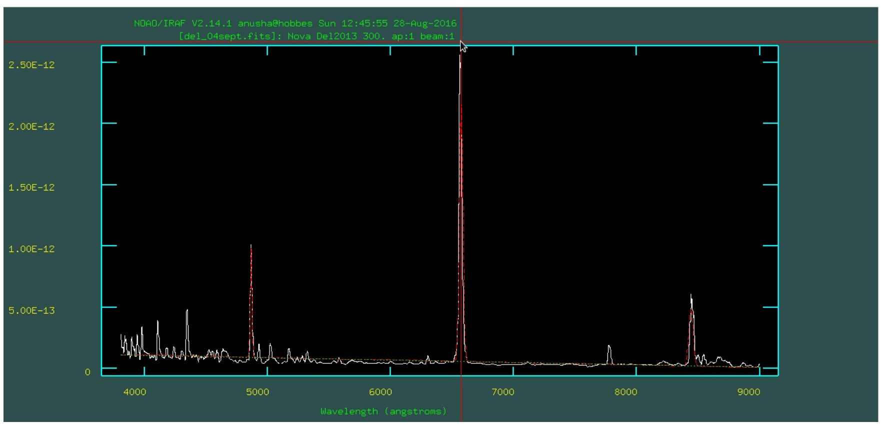

Figure 10: del-04sept

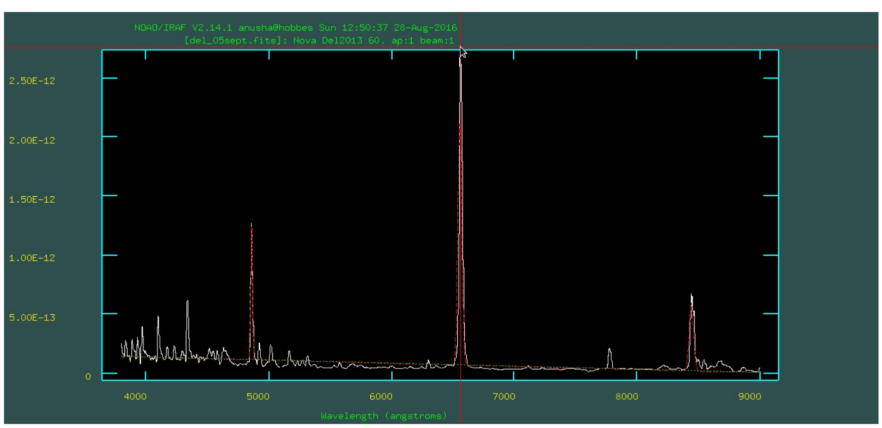

Figure 11: del-05sept

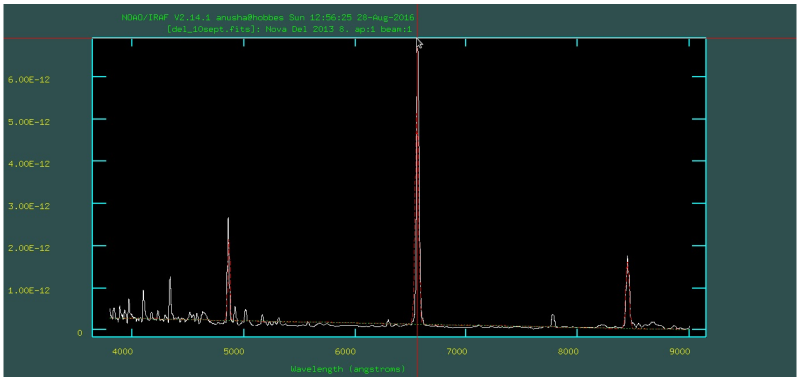

Figure 12: del-10sept

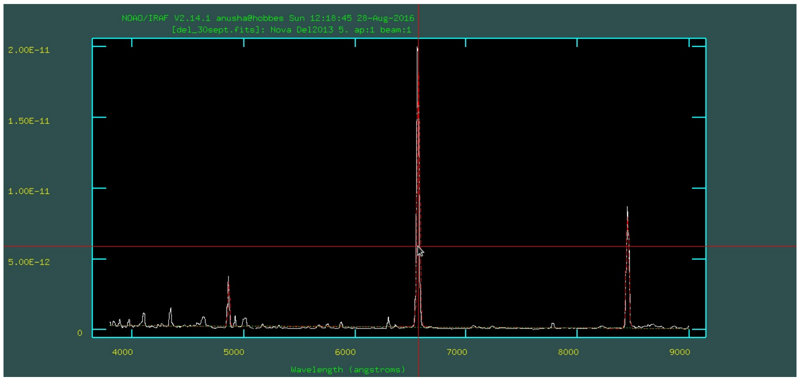

Figure 13: del-30sept

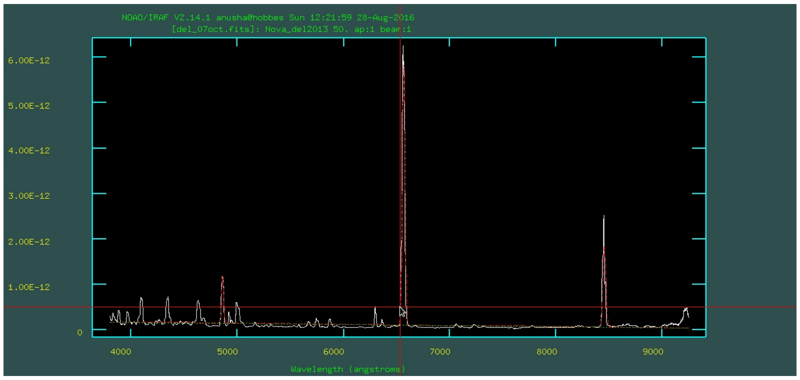

Figure 14: del-07oct

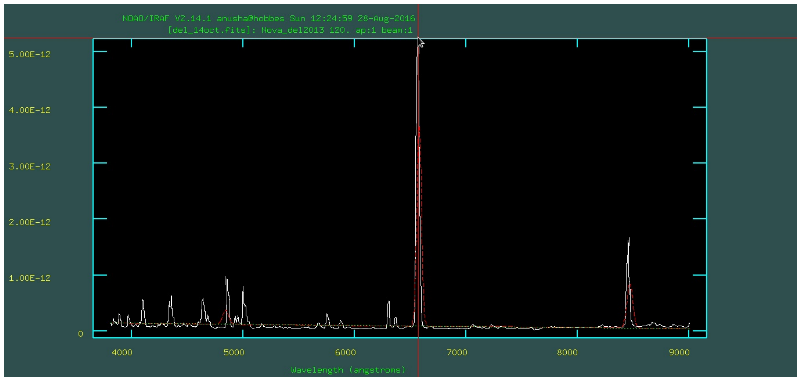

Figure 15: del-14oct

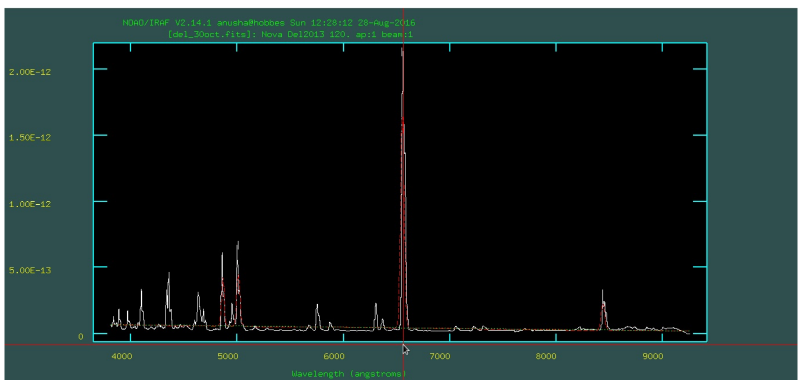

Figure 16: del-30oct

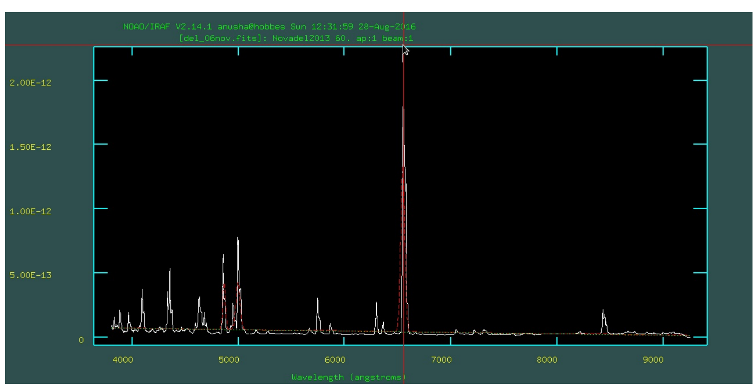

Figure 17: del-06nov

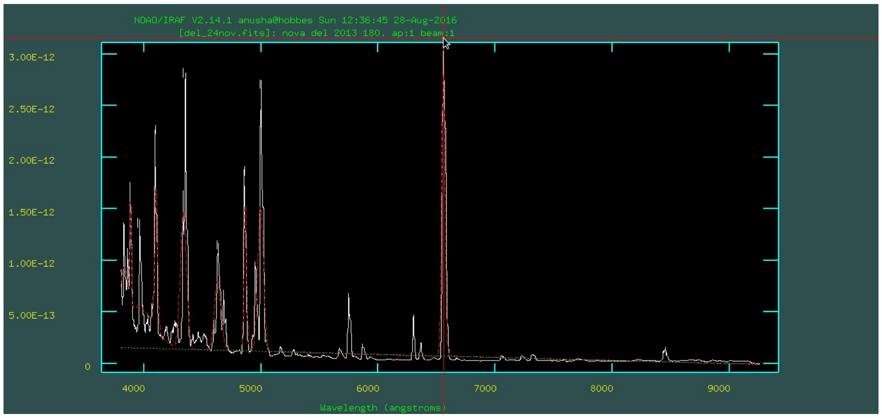

Figure 18: del-24nov

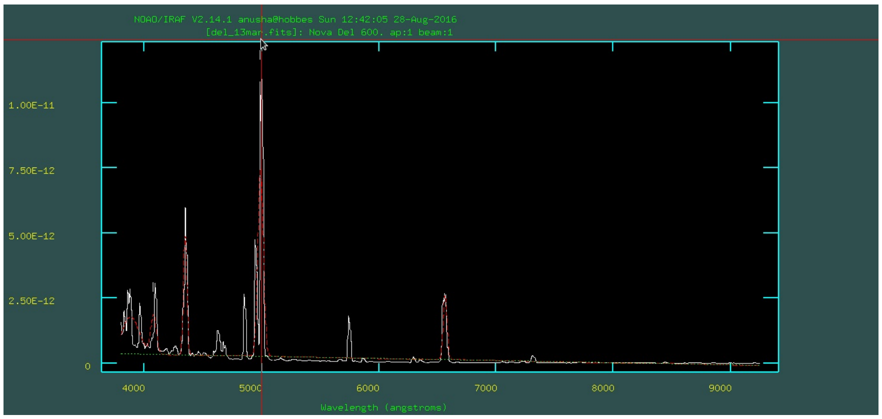

Figure 19: del-13mar

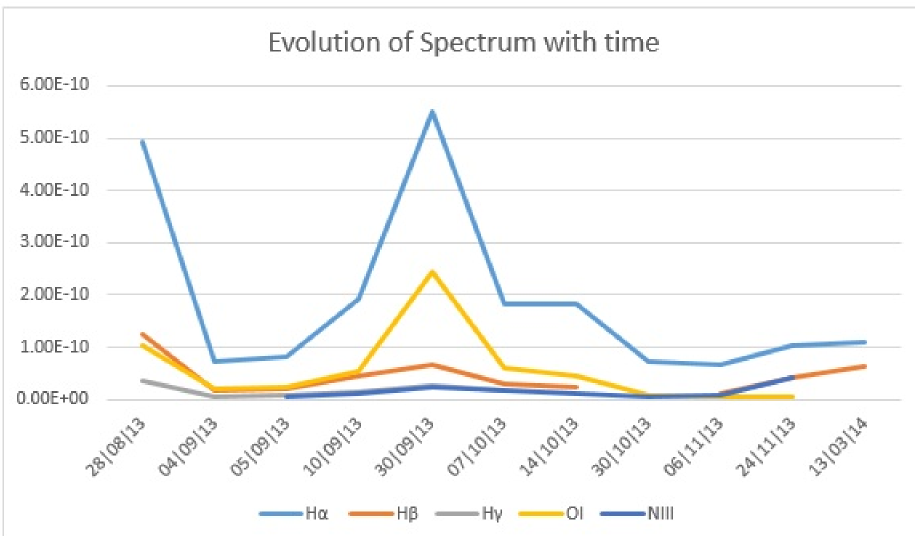

Figure 20: Changes observed in the spectrum as it evolved with time have been plotted on a graph of Relative Flux versus Time(Dates observed) for different elements.

8. Conclusion

During the period of first four weeks, extensive reading was carried out to gain insight into the definition, classification, formation, evolution and general working of novae and in particularly, classical novae.During the next four weeks, analysis was done on actual data. I worked on the spectroscopic observation of V339 Delphini which is a classical nova whose explosion took place in August 2013. I have tabulated the necessary readings and identified the different emission lines that were present. Images that show the evolution step by step have been provided. In conclusion, a graph has been plotted to observe the evolution of spectrum with time with respect to the emission lines present in the nova outburst.

9. Acknowledgement

I would like to thank my Guide, Dr.G.C.Anupama for guiding me throughout this Research Fellowship and providing me with the necessary help to undertake this project. I would also like to thank the PhD students working under Dr.G.C.Anupama for their help and support. Many topics in this report have been written with the help of the books, "Classical Novae by Bode and Evans" and "Physical Universe: An introduction to Astronomy by Frank H.Shu" and the Review Articles "Optical studies of Novae by G.C.Anupama and U.S.Kamath" and "Classical nova explosions - hydrodynamics and nucleosynthesis by J.Jose".