Emission-line profiles from model nova shells

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1 INTRODUCTION

Classical novae are semidetached systems containing a main-sequence dwarf and a white dwarf. The outburst is the result of a thermonuclear runaway in matter accreted from the main-sequence star on to the white-dwarf surface. This results in a large increase in brightness of the systems (~15 mag) and the ejection of ~10^{-4}M_{\odot} of material at velocities of a few hundred to several thousand kilometres per second (Bode & Evans 1989). This matter takes the form of an expanding shell which is often not smooth or spherically symmetric. Observations of old classical novae in which the shells are spatially resolved (Slavin, O’Brien & Dunlop 1995; Gill & O’Brien 1998) reveal clumpy ejecta with a variety of structures including prolate shells with equatorial and polar rings or polar caps. Similar structures have also been suggested on the basis of spatially unresolved spectroscopy taken nearer to outburst (e.g. Hutchings 1972; Solf 1983). The shaping of the shell may be the result of several mechanisms including the interaction of the outflow from the white dwarf with the secondary, the rotation of the white dwarf and any significant white-dwarf magnetic field. Hence, investigation of the structure of the shell can provide useful information on the nature of the binary system itself.

The interaction of the outflow with the secondary has been modelled using 2.5-dimensional hydrodynamic simulations by Lloyd, O’Brien & Bode (1997, hereafter LOB97) and Porter, O’Brien & Bode (1998, hereafter POB98). Synthetic images derived from the results of these simulations produce banded shells similar to those seen in observations. However, these are 2-dimensional projections of a 3-dimensional object. In reality the only information on the third dimension is provided from spectroscopic determinations of line-of-sight velocities. Most information is obtained if these are spatially resolved but as novae generally fade rapidly, many spectra are taken at early times when the shell cannot be resolved.

If we make the simple assumption that the ejection is spherically symmetric, then with the velocity of ejection (v) measured in km s^{-1}, the distance of the nova (d) in pc and the time since ejection (t) in yr, then the angular radius of the shell on the sky (θ) in arcsec is given by \(θ = 0.21v d / t\). For a canonical classical-nova outburst with speed of ejection 1000 km s^{-1} at a distance 1 kpc then it takes about 5 yr for the ejecta to get to a radius of 1 arcsec which is about the limit of resolving the shell from the bright central source from the ground. A radius of 5 arcsec would allow some determination of structure (e.g. rings) but would take approximately 24 yr. A slow nova with ejection at 300 km s^{-1} and again at a distance of 1 kpc would take 16 yr to get to a radius of 1 arcsec and 79 yr to get to a radius of 5 arcsec.

If we go on to assume the shell to be smoothly expanding at a constant velocity then we can make some simple estimates of the variation of the brightness of the shell with time. If the emission coefficient is proportional to the square of the gas density then we can say that the total emission from the shell with constant density \(ρ\) has intensity \(I \propto ρ^2V\), where \(V\) is the volume of the emitting material. If the shell is thin then the volume varies with time as \(V \propto t^3\). The density varies as \(ρ \propto V^{-1} \propto t^{-3}\) and so \(I \propto t^{-5}\). Therefore the intensity of the shell with these simple assumptions is seen to quickly die away. If we assume that the shell becomes broken up or clumped then the volume increases with time more slowly leading to a slower decline in brightness of the shell. However, if the shell is illuminated by the photoionizing radiation field from the central source then this too can be expected to fade with time.

It is therefore easy to see why there are relatively few bright spatially well-resolved classical-nova shells available for observation. Consequently, it is important to consider what information can be extracted from spatially unresolved observations taken soon after outburst when the nova is still bright, in particular the determination of line profiles.

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In this paper we calculate emission-line profiles from several model classical-nova shells. These include generic ellipsoidal shells with a variety of equatorial/tropical ring features but also the hydrodynamical models of LOB97 and POB98. We assume that the emission is optically thin and simply proportional to the square of gas density. For each case the calculated line profile is shown for a range of inclination angles. Finally, we present a recent example of a spatially unresolved spectrum of a classical nova and make comparisons with our theoretical line profiles.

\section{LINE-PROFILE CALCULATION}

The emission profile code takes as input a 2-dimensional grid in polar coordinates of density and \( r, \theta, \phi \) momenta for the model shell. This is then used to generate a velocity cube appropriate to some angle of inclination with two spatial dimensions corresponding to the plane of the sky and one dimension corresponding to velocity along a line of sight orthogonal to this plane. The input is in polar coordinates as this is the most convenient system for hydrodynamical modelling of these objects. This cube can then be collapsed in the spatial directions to give a spectrum of the source or collapsed in the spectral direction to give an image. It is also possible to generate synthetic long-slit spectra of the shells by taking a slice through the cube.

The line-of-sight velocity is calculated for each element of the 3-dimensional spherical grid formed by rotation about the polar symmetry axis and reflection about the plane orthogonal to this axis. Emission, assumed to be proportional to the volume and the square of the density, is added into the appropriate bin in the velocity cube.

\section{RESULTS}

For all models, results are shown for the inclination angles of 0°, 30°, 60° and 90° when defined in the usual manner (inclination of 0° when the system is viewed along the polar symmetry axis). The synthetic images are shown next to their corresponding line profiles. In the grey-scale used to represent the images the range is kept the same within each figure in order to show any variation resulting from changing inclination angle.

\subsection{Simple models}

With the code it is possible to input simple models of shells for comparison with observational data. The first model shown is that of a smooth ellipsoidal shell (major to minor axis ratio 1.33) with enhancements of double the background shell density in the form of equatorial and tropical rings. The velocity field is \((v_r, v_{\theta}, v_{\phi}) = (\text{const} \times r, 0, 0)\). The shell semimajor axis covers 750 cells with a shell thickness of 50 cells.

The resulting images and line profiles are shown in Fig. 1. Also presented in Fig. 2 is a decomposition of the profile into the components contributed by each element of the model shell for the case of inclination angle 60°. Each ring produces a saddle-shaped profile with two distinct peaks – the equatorial ring is symmetrically placed about the rest wavelength whilst the tropical rings are offset to either side. The prolate ellipsoidal shell itself

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{simple_model}
\caption{Components contributing to the total spectrum for Fig. 1 for an inclination angle of 60°.}
\end{figure}
provides an underlying spectrum that peaks at the rest wavelength if viewed at inclination 0° and dips in the centre if viewed at 90°. Overall the spectrum displays between 3 (viewed at 0°) and 6 peaks (30°–60°) superimposed on a broad profile.

Various authors have referred to the possible presence of polar caps rather than rings. For completeness we also present a model that is the same as the previous model except that the density is enhanced by a factor of 2 at latitudes above and below the positions of the tropical rings in the previous model. The results are shown in Fig. 3. There are clear differences between the cap and the ring spectra for a given inclination angle, which in principle may allow cap shells to be distinguished from ring shells by comparison with observation. These differences result from the ‘filling-in’ of additional velocity phase space corresponding to the polar caps. Clearly this extra emission appears in the final spectrum at velocity ranges that are a function of inclination.

3.2 Hydrodynamical models

LOB97 produced a series of hydrodynamical models of classical-nova shells by examining the effects of the underlying binary system on the shaping of ejecta from the nova. The outburst took the form of a wind with secular increasing velocity that flows past the secondary, which in turn transfers energy and angular momentum into the envelope from its orbit. The mass-loss rate was kept constant at all times. Different speed classes (Payne-Gaposchkin 1964) of classical novae were modelled by varying the velocity of the ejection, the masses of the primary and secondary and their orbital parameters to follow observed values. The novae were modelled using a 2.5-dimensional Godunov scheme due to Falle (1991) which allows φ velocities to be non-zero whilst restricting the flow to be axisymmetric. The models produced the general features of classical nova shells although they tended to be oblate whereas observations have shown that classical-nova shells are prolate.

POB98 followed on from the models of LOB97 by also considering the effects of the envelope of accreted matter on the white dwarf having significant rotation. They started from LOB97’s model 2 and allowed the envelope of the white dwarf to rotate at a fraction f of the break-up speed prior to outburst – values of

Figure 3. Images and calculated line profiles for a simple ellipsoidal shell with an equatorial ring and polar caps of enhanced brightness. Displayed with inclination angles of 0°, 30°, 60° and 90°.

Figure 4. Calculated images and line profiles for Lloyd et al. (1997) Run 1 model. Results are displayed for inclination angles of 0°, 30°, 60° and 90°.
Figure 5. Calculated images and line profiles for Lloyd et al. (1997) Run 2 model. Results are displayed for inclination angles of 0°, 30°, 60° and 90°.

Figure 6. Calculated images and line profiles for Lloyd et al. (1997) Run 3 model. Results are displayed for inclination angles of 0°, 30°, 60° and 90°.

Figure 7. Calculated images and line profiles for Lloyd et al. (1997) Run 4 model. Results are displayed for inclination angles of 0°, 30°, 60° and 90°.
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In the simulations the wind was not turned off and hence the central regions contain a medium with $r_{1/2} = r_{2}$. As intensities are taken to be proportional to the square of the density for any element of the grid then the spectra are dominated by the top-hat profile from this wind. For times when optically thin spectra can be measured for classical-nova shells ejection has usually ended and so the densities and momenta for each radial bin are set to zero out to a radius where the density stops decreasing. This has the effect of removing the central wind without affecting the emission from the shell.

As previously stated, the hydrodynamical models allow $v_\theta$ and $v_\phi$ to be non-zero. This is required for the simulations to accurately model the shaping of the shell via the interaction of the ejecta with the secondary. Indeed, $v_\theta$ and/or $v_\phi$ may be significant in the inner parts of the simulation where the shell is shaped. Owing to conservation of specific angular momentum, by the time the ejecta have travelled a significant distance away from the central system (as in the models shown here) $v_\theta$ and $v_\phi$ are negligible compared with $v_r$. Although the $v_\theta$ and $v_\phi$ components are still used to generate the results, they have negligible effect on the final line profiles.

The results for the models of LOB97 are shown in Figs 4–7. The results for the models of POB98 are shown in Figs 8 and 9. The profiles resulting from these simulations bear a strong resemblance to those from the simple equatorial/tropical ring model described above, except that they do not commonly produce a strong equatorial ring and hence they often display only four obvious peaks rather than six. The lack of strong equatorial ring features was identified by LOB97 and POB98 as an unsolved problem with these simulations.

4 DISCUSSION

It is important to consider how these synthetic-spectra line profiles compare with observations of real classical novae. V705 Cas (Nova Cas 1993) was discovered by Kanatsu, Matsue and Shimane (Nakano 1993) on 1993 December 7. It took 64 d to decline two magnitudes from maximum and 90 d to fade by three magnitudes (Mason et al. 1998) classifying it as a moderately fast
Emission-line profiles of V705 Cas taken on 1996 August 3 for Figure 10.

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H

2

been corrected for heliocentric motion and a systemic velocity of 4861.3, [N

40 km s

b

B3
B2
B1
R1
R2
R3
Mean

Table 1. Measured radial velocities for peaks in the V705 Cas spectra for Hβ λ4861.3, [NII]a λ6549, [NII]b λ6584, [OIII]a λ4959 and [OIII]b λ5007. All profiles have been scaled to the same peak intensity and have been corrected for heliocentric motion and a systemic velocity of about zero velocity.

The velocities are all quoted in km s

1 and have been corrected for forbidden lines. This figure is then subtracted from the raw velocities for each line leading to revised velocities (indicated by an asterisk) presented in the second half of the table along with the mean velocity for each feature. The peaks clearly lie symmetrically about zero velocity.

Table 1. Measured radial velocities for peaks in the V705 Cas spectra for Hβ λ4861.3, [NII]a λ6549, [NII]b λ6584, [OIII]a λ4959 and [OIII]b λ5007.

The velocities are all quoted in km s

1 and have been corrected for heliocentric motion and a systemic velocity of −40 km s

nova (Payne-Gaposchkin 1964). At about day 70 it entered a DQ Her type minimum, reaching minimum at about day 100. This indicates a dust-forming phase.

The observations of V705 Cas were performed on the night of 1996 August 3 with the 4.2-m William Herschel Telescope on La Palma in the Canary Islands. The ISIS spectrograph was used in conjunction with the R1200B and R1200R gratings giving a spectral resolution of 0.82 Å (two pixels) equivalent to 50 km s

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classical-nova shells being enhanced in [N II] emission the authors argue that these enhancements might be best explained by variations in ionization rather than density. This implies it may be possible to produce an equatorial ring in the observations without a corresponding density enhancement and our simple \( dI \propto \rho^2 \, dV \) assumption may be invalid. We are currently developing improved models in which account is taken of possible aspherical photoionizing radiation fields.

The simplest way to produce a six-peaked structure in a classical-nova-shell line profile is to assume the ejecta is in the form of an inclined ellipsoidal shell with enhancements in equatorial and tropical rings. Two peaks will be seen from each of the three rings, with minimum and maximum velocity arising from the furthest and nearest parts of the rings along the line of sight. The velocities of these six peaks can be reduced down to three characteristic velocities owing to the symmetry of the shell – \( v_1 \), the maximum line-of-sight velocity from the equatorial ring, and \( v_2 \) and \( v_3 \), the maximum and minimum line-of-sight velocities from one of the tropical rings. It can be shown (Gill 1999) that for a given ellipticity of shell \( e \) (defined as the polar to equatorial axis ratio) with tropical rings at latitude \( \phi \) (from the equatorial plane), equatorial ejection speed \( v_{eq} \) from the centre of the shell, all seen at an inclination angle \( i \), then \( i \), \( \phi \) and \( v_{eq} \) are given by

\[
\tan(i) = e \left( \frac{v_2 - v_1}{v_2 + v_1} \right) \left( \frac{2v_1}{v_2 - v_1} \right)^2 - 1 \],
\]

(1)

\[
\cos(\phi) = e^2 \left( \frac{2v_1}{v_2 - v_1} \right)^2 - e^2 + 1 \],
\]

(2)

\[
v_{eq} = \frac{v_1}{e} \left[ 1 - \frac{(v_2 + v_3)^2}{4v_1^2} + \frac{e^2}{e^2 + 1} \right]^{1/2}.
\]

(3)

If the average of the red and blue mean peak velocities of V705 Cas (see Table 1) are taken to be measures of \((v_1, v_2, v_3)\) with \( v_1 \) corresponding to R2* then we obtain the first set of solutions for \( i \), \( \phi \) and \( v_{eq} \) presented in Table 2. Only solutions for prolate shells have been produced as there are no classical-nova shells that are known to be oblate. Usually there would be two sets of solutions to this problem once the apparent equatorial ring velocity \( v_1 \) has been assigned as one can associate either B1* or R1* with R3* as peaks from the same tropical ring. In this particular case associating B1* with R3* is not allowed as the difference in velocity of these features would be more than the difference in velocity of the two equatorial ring peaks. This would imply that the diameter of the tropical ring be greater than that of the equatorial ring which is not possible for a simple ellipsoidal shell.

If Table 1 is examined more closely, one can see that the values of B2* and R2* are systematically higher for the two [N II] lines than those for H\( \beta \) and the [O III] doublet. There are many possible reasons for this including simple effects such as the heights of the equatorial ring being different for the [N II] emission than for the other lines. If the [N II] apparent equatorial velocities are used rather than the mean peak velocities then the solution for B1* with R3* being generated from the same tropical ring is now valid. The two possible sets of solutions for the average of the [N II] line profile velocities are also shown in Table 2.

It is also possible to calculate the maximum line-of-sight velocity of the ellipsoidal shell, \( v_{\text{max}} \), which is given by

\[
v_{\text{max}} = \left[ \frac{4v_1^2(v_2 + v_3)}{4v_1^2 - (v_2 - v_3)^2} \right]^{1/2}.
\]

(4)

Perhaps surprisingly, this is independent of the ellipticity and so for assumed values of \((v_1, v_2, v_3)\) a unique solution to \( v_{\text{max}} \) can be found. The calculated values of \( v_{\text{max}} \) are shown at the bottom of Table 2. The maximum velocity of 1330 km s\(^{-1}\) for the final set of solutions is larger than any velocities seen in Fig. 10. Combining this with the low values of \( i \) and \( \phi \) this seems an unlikely true solution for the morphology of V705 Cas. Furthermore only the very fastest novae (Payne-Gaposchkin 1964) result in ejection velocities of more than 1000 km s\(^{-1}\). V705 Cas was classified as moderately fast where ejection velocities are more of the order of the \( v_{\text{max}} \) derived for the other two solutions. Our simple models of

**Table 2.** Solutions to the inclination angle \( i \), latitude of the tropical rings \( \phi \) (measured from the equatorial plane) and equatorial-ring speed \( v_{eq} \) for ellipticities \( e \) (ratio of polar to equatorial axes) varying from 1.0 to 2.0 for the line profiles of V705 Cas as shown in Fig. 10 and Table 1.

<table>
<thead>
<tr>
<th>( e )</th>
<th>( i )</th>
<th>( \phi )</th>
<th>( v_{eq} )</th>
<th>( e )</th>
<th>( \phi )</th>
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All velocities are quoted in km s\(^{-1}\) and all angles in degrees. The three sets of solutions represent, from left, the mean peak velocities with peaks R1* and R3* being produced in the same tropical ring (there are no solutions for B1* and R3* being produced in the same ring), the [N II] equatorial peak velocity with a set of tropical peaks R1* and R3* and the [N II] equatorial peak velocity with a set of tropical peaks B1* and R3* respectively.

ellipsoids with equatorial and tropical rings (Fig. 1) do not generate line profiles with high velocity wings as seen in the observations. This makes it difficult to decide which of the other two sets of solutions may be more likely to be the true solution. However, both use \( R_1^* \) and \( R_3^* \) as the minimum and maximum line-of-sight velocities from one of the tropical rings. Between these two solutions a low inclination angle seems to be favoured \((\sim 30^\circ \pm 35^\circ)\) which is expected as there must be enough of an angle between the pole of the system and the plane of the sky to shift the maximum line-of-sight velocity of the tropical ring to a higher value than that of the equatorial ring. The inclination is also limited by the \( R_1^* \) velocity such that this value be less than the value of the observed equatorial ring velocity.

Although this approach is an exact solution, one must be aware that the velocities used are those of the positions of the peaks in the spectra rather than the maximum line-of-sight velocities which are the values used in the formulae. The peak positions will generally lie at a slightly lower velocity, the value of which is dependent on several factors including the thickness of the rings, the thickness of the shell and the shapes of any underlying profiles. However, these formulae should still be useful tools in inspecting line-profile models as they can rule out extreme cases of what would otherwise appear reasonable fits to the data.

For novae that are known to be eclipsing the inclination angle can be limited to \( i \approx 80^\circ \). Unfortunately, if the synthetic profiles for all of the models where \( i = 90^\circ \) are examined, then one can see that for each model this is the angle where least information on the shell structure can be derived from the line profiles. However, it would still be possible to distinguish between, for example, polar-cap and polar-ring structures.

5 CONCLUSIONS

We have calculated optically thin emission-line profiles for various models of classical-nova shells at various inclination angles. These results show that beyond suggesting the basic structure of the shell we are still not normally able to derive the details on the basis of this spectrum alone. Similar profiles can be produced by models with different inclination angles, ellipticities and positions of tropical rings. In fact the identification of a particular peak with a tropical or equatorial ring changes as these parameters change. Nevertheless, we have provided a detailed analysis of the line profiles obtained from spatially unresolved observations of the shell of V705 Cas, which demonstrate both the potential and limitations of such analyses.

We have also demonstrated that existing numerical models of nova shells, in particular those of LOB97 and POB98, fail to reproduce the equatorial-ring features clearly seen in observations. We are currently investigating models for the emission resulting from illumination of structured shells by an aspherical radiation field, which we believe may reproduce this feature without the need for a density enhancement.

The shell of V705 Cas is scheduled to be imaged in a Hubble Space Telescope snapshot survey in \( H_\alpha + [N\,\text{ii}], [N\,\text{ii}] \) and \([O\,\text{iii}] \). It should then be possible to attribute spectral features described in this paper to those seen in the image of the shell. As we hope to have demonstrated in this paper, it is important to obtain both good spectra and images to resolve the true nature of classical-nova shells.

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