MODEL ATMOSPHERES FOR NOVA DURING THE EARLY STAGES

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Abstract

We present the first continuum and line blanketed models for expanding photospheres of novae in the early stages of their outbursts. The expanding envelopes are characterized by a very slow increase of density with decreasing radius which leads to very large geometrical extensions and large temperature differences between the inner and outer parts of the line forming regions. The spectra show a large IR excess and a small Balmer jump which may be either in absorption or in emission. For the parameters considered ($T_{\text{eff}} = 10^4, 1.5 \times 10^4$, and $2 \times 10^4$ K, $R(\tau_{\text{abs}} = 1) = 10^{11}$ cm, $\rho_{\text{out}} = 2 \times 10^{-15}$ g cm$^{-3}$, $M = 10M_\odot y^{-1}$, expansion velocity of $v = 500$ km s$^{-1}$ at $\tau_{\text{abs}} = 1$ and solar composition), most lines are in absorption. The effects of changes in the abundances of the heavy elements on the emergent spectra is discussed.

I. Introduction

The best determinations at the present time of the abundances in novae ejecta have been obtained from analyses of the emission line fluxes obtained late in the outburst. These analyses use standard techniques developed for studying the emission lines in planetary nebulae. However, there exist numerous IUE spectra of novae obtained very early in the outburst that have never been analyzed because the tools to do the analysis did not exist until recently. There is a great deal of information about the novae outburst contained within these data and it is our purpose to begin the analysis of these spectra using a new non-grey, spherical stellar atmosphere program that was developed specifically for this purpose. The abundances in the ejecta can be determined from spectral syntheses of the energy distributions and line fluxes observed in the IUE spectra during the early phases of the nova. These results are completely independent of the abundances obtained from nebular emission line analyses. This will be an important check on both techniques. In addition, there are novae in the archives that formed dust and by combining...
the results from both techniques, we will obtain abundance information before and after dust formation and possibly determine the composition of the dust. Furthermore, model atmosphere analyses of the IUE spectra will allow us to determine the energy distributions of novae and obtain global parameters like the effective temperature, velocity and density distribution, and the radius of the expanding material as a function of time. These data will both improve our knowledge of the energy budget of the nova outburst and constrain the hydrodynamic calculations.

One of the input parameters to the code is the density distribution. In this paper we will use the hydrodynamic simulations to obtain the density distribution and any deviations between the theoretical atmospheres and the observations will be useful in constraining the theory. This is especially true of the observations which indicate the existence of large inhomogeneities in the expanding material. Finally, the atmospheric calculations provide the opacity as a function of frequency and depth. These data can be used to obtain opacities that will be used in the hydrodynamic simulations and indicate the mechanism by which material is ejected during the late stages of the outburst. The problem of the 'expansion opacity' is so complicated that we think that only detailed atmospheric models which include the particular lines (and in great number) can provide an acceptable approximation to this problem.

There are many spectroscopic features of the evolution of novae that are still unexplained and, in addition, there are strong lines in the ultraviolet that have yet to be identified. These problems are compounded because the techniques developed to analyze normal stars, whose atmospheres are in hydrostatic equilibrium, can hardly be used on novae since novae atmospheres have very different density and temperature structures from normal stars.

Therefore, in order to analyze the expanding atmospheres of novae, we have developed new methods that are appropriate to their structure. We present here our first results for blanketed, expanding, model atmospheres and calculate synthetic spectra for novae during their early stages. These atmospheres will ultimately allow detailed analyses of the observed energy distributions and improve the accuracy of the elemental abundances determined from the observations. We note that this method is completely independent of the method normally used to determine elemental abundances in novae: nebular analysis of the emission lines at late stages in the outburst. Comparison of the results, by applying both methods of analysis to the same nova, will provide a unique and important check on each technique.

The atmospheric models are based on the idea (Bath and Shaviv, 1976) that, during the early phases, the outer layers of novae in outburst behave like steady-state, spherical, expanding winds. Energy distributions based on this idea were calculated by Harkness (1983). However, his calculations were restricted to the continuum and the radial temperature distributions were kept fixed, i.e., he did not iterate to fulfil the energy equation. He was able to demonstrate the effects of the very low density in the outer layers which resulted in a dominance of scattering and a very large geometrical extension. However, because of the limitations mentioned, the calculated energy distributions cannot be used for spectroscopic analyses. No additional atmospheric modeling of this type for novae is known to us.
In the next Section we list the assumptions made and outline the methods used for construction of our models. Since these atmospheres are very different, not only from normal stars but also from supernovae, several general properties are presented and discussed in Section II. In Section III we present synthetic spectra and Chapter IV is devoted to a discussion. We end with Section V which describes future improvements that are planned to treat the problems of novae.

II. Model Assumptions

Following the discussion of Bath and Shaviv (1976), we consider nova photospheres to be spherical and stationary configurations. Therefore, we assume that all time dependent terms in the hydrodynamics and in the radiative transfer equation can be neglected and all quantities depend only upon the radial coordinate (except for the specific intensity of the radiation field which depends, in addition, on the angle to the normal direction). These assumptions seem to be justified since the hydrodynamic time scale is much longer than the time scales for photon escape and for the establishment of excitation and ionization equilibria. In addition we assume radiative equilibrium in the Lagrangian frame, so that energy is transported only by radiation. Using the results from hydrodynamic calculations of the consequences of thermonuclear runaways in accreted envelopes on white dwarf stars, we assume that the density varies according to a power law, \( \rho \propto r^{-n} \), and the expansion velocity is given by, \( v = M/4\pi r^2 \rho \), with \( M \) being the mass loss rate. We stress that the parameters for the models presented here were taken from the hydrodynamic simulations and were not adjusted to fit the observed spectra.

We expect that departures from local thermodynamic equilibrium (LTE) are important in nova photospheres because of the low densities in the expanding shell. Therefore, we take non-LTE effects of the important species H I, Mg II and CaII self-consistently into account in the model construction, i.e. in the radiative transfer equation and the ionization equilibria.

The early spectra of novae show a large number of lines in the UV range. It is clear that proper models of nova photospheres must include line blanketing of a large number of UV lines to reproduce the observed spectra. Furthermore, for abundance determinations we have to use single lines and need to know the dependence of the line profiles on the elemental abundances. For this reason we include in the model construction and the computation of the synthetic spectra approximately \( 10^5 \) metal UV lines in addition to the NLTE lines.

The models are characterized by the following parameters:

(i) A reference radius \( R \), which refers to the radius where either the optical depth in absorption at 5000\( \text{Å} \) is unity or the optical depth in extinction at 5000\( \text{Å} \) is unity.

(ii) An effective temperature \( T_{\text{eff}} \), which is defined by means of the luminosity, \( L \), and the reference radius \( T_{\text{eff}} = (L/4\pi R^2 \sigma)^{1/4} \) where \( \sigma = \) is the Stefan’s constant).

(iii) A density parameter, \( n \).

(iv) A mass loss rate, \( \dot{M} \).
(v) The density, $\rho_{\text{out}}$, at the outer edge.
(vi) The line scattering parameter (defined below),
(vii) The elemental abundances.

As a consequence of the extremely slow increase of density with decreasing radius in nova atmospheres, the density $\rho_{\text{out}}$ is an important parameter in contrast to the situation in compact atmospheres or even supernovae and red giant photospheres. Actually, nova atmosphere are the most extended objects and consequently spherical effects are extremely large.

III Model Construction

For the calculation of the models and the synthetic spectra we follow the same philosophy as for supernovae photospheres (Hauschildt et al. 1989, 1990; Hauschildt, 1991). According to our model assumptions, we have to solve the combined radiative transfer, radiative equilibrium and rate equations for an expanding shell with a given density law (which replaces the hydrodynamic equations). For an accurate description of the line blanketing, we have to solve the radiative transfer equation for a large number of wavelength points (usually we used more than 1700 wavelength points). The use of the complete linearization method (Auer and Mihalas, 1969) is not feasible because the CPU time for this method scales with the cube of the number of wavelength points. Consequently, we use a combination of a Newton–Raphson iteration for the temperature structure and a fixed point iteration scheme for the departures from LTE. This scheme scales only linearly with the number of wavelength points and the number of iterations required for convergence is relatively small.

In each iteration cycle, we first solve self-consistently for the density distribution by integrating

$$\frac{d\tau_{\text{std}}}{dr} = -(\kappa_{\text{std}} + \sigma_{\text{std}})$$

on a prescribed optical depth grid $\tau_{\text{std}}$ (with the temperature structure $T(\tau_{\text{std}})$ and the run of the NLTE variables given from the previous model iteration) and by iterating for the radius so that

$$r(\tau_{\text{std}} = 1) = R$$

is fulfilled. In eq. (1), $r$ denotes the radial coordinate, $\kappa_{\text{std}}$ the absorption coefficient and $\sigma_{\text{std}}$ the scattering coefficient at 5000Å. The solution of eqs. (1) and (2) gives the run of the gas pressure with optical depth. The density is given by the density law.

From the radiative transfer equation in the comoving frame (see Mihalas and Weibel-Mihalas, 1984, page 434)

$$\gamma(\mu + \beta)(1 - \mu^2)^{\frac{1}{2}} \left[ \frac{(1 + \beta \mu)}{r} \right] \gamma^2(\mu + \beta) \frac{\partial \rho}{\partial r} - \frac{\partial}{\partial \rho} \left\{ \left\{ \frac{\partial \rho}{\partial \rho} \right\} ^2 + \gamma^2 \mu(\mu + \beta) \frac{\partial \rho}{\partial T} \right\} I$$

$$+ \gamma \left\{ \frac{2 + \beta(3 - \mu^2)}{r} + \gamma^2(1 + \mu^2 + 2 \beta \mu) \frac{\partial \rho}{\partial T} \right\} I$$

$$= \eta - \chi I$$
we obtain the Lagrangian frame specific intensities $I$. In eq. (3), $r$ is the radius, $\mu$ the cosine of the angle between a ray and the direction normal to the surface, $\nu$ the frequency, $I = I(r, \mu, \nu)$ denotes the specific intensity at radius $r$ and frequency $\nu$ in direction $\arccos\mu$ in the Lagrangian frame. The matter velocity $v(r)$ is measured in units of the speed of light $c$: $\beta(r) = v(r)/c$ and $\gamma$ is given by $\gamma(r) = 1/\sqrt{1-\beta^2}$. The sources of radiation present in the matter are described by $\eta = \eta(r, \nu)$, and $\chi = \chi(r, \nu)$ denotes the extinction coefficient. $\eta$ contains contributions of scattering terms proportional to the mean intensity $J$ of the form $\sigma J$ which are explicitly treated in the radiative transfer. The derived radiation fields incorporate all relativistic effects, in particular advection and aberration, which are important even for the velocity range considered here (Hauschildt et al., 1991).

The temperature distribution is iterated so as to fulfil the energy equation

$$\int_0^\infty \kappa_\lambda (B_\lambda - J_\lambda) d\lambda = 0, \quad (4)$$

where $B_\lambda$ denotes the Planck function, or the equivalent condition for the wavelength integrated Eddington flux $H = \int_0^\infty \int_{-1}^1 \mu I_\mu d\mu dl$ which satisfies the equation

$$\frac{\partial^2 H}{\partial r^2} + \beta \frac{\partial r^2 J}{\partial r} + \frac{\beta}{r} J r^2 (J - K) + \frac{\gamma^2 \partial \beta}{\partial r} J r^2 (J + 2K + 2\beta H) = 0. \quad (5)$$

The numerical procedure of the solution of eqs. 3–5 is based on the Discrete-Ordinate-Matrix-Exponential (DOME) method (Schmidt and Wehrse, 1987) for fast expanding configurations (Hauschildt and Wehrse, 1991).

The level populations for H (10 levels), Ca (1 level for the neutral, 5 for the singly ionized, 1 for the doubly ionized species) and Mg (1 level for the neutral, 3 for the singly ionized, 1 for the doubly ionized species) are obtained from the NLTE rate equations whereas for the additional species level populations according to the Boltzmann statistics of the local kinetic temperature are assumed. The ionization equilibrium is solved for the NLTE species and the ionization stages I–III of He, C, N, O, Si, S, Fe, Al, Na, K, Ti, Sc, Mn and Cr.

In the continuous opacity the bound-free and free-free transitions of all important absorbers, as well as Rayleigh and Thomson scattering, are taken into account with the cross-sections as compiled by Mathiesen (1984).

In order to derive consistent values of the radiation field and the departure coefficients $b_i \equiv n_i/n_i^*$, where $n_i$ and $n_i^*$ denote the LTE and LTE occupation numbers of the levels treated in NLTE, we use the equivalent-two-level-atom (ETLA) method (Mihalas, 1978) to compute the NLTE line source function and iterate for the $b_i$. All permitted transitions of the NLTE species (55 transitions for H I, 2 lines for Mg II and 5 lines for CaII) are treated in this way.

About $10^8$ lines, which are estimated to be the strongest for the particular temperatures and pressures in the list of Kurucz and Peytremann
(1975), are included in models with line blanketing. In order not to neglect the scattering of photons, we divide the line extinction coefficient $\kappa_l$ into a fraction $\alpha \kappa_l$ that describes the absorption processes and a fraction $(1-\alpha)\kappa_l$ that refers to the scattering. We take the same value of $\alpha$ for all metal lines and consider it to be a free parameter. The number of lines used in the calculation is checked every iteration and properly adjusted. Also, the number of lines used in the calculation is based on the predicted intensity at predetermined optical depths. We checked this approximation as well and verified that the results do not depend on the particular criteria applied.

Typically, for a line blanketed, NLTE-model we use 50 depth points spaced logarithmically between $\tau_{\text{std}} = 10^{-6}$ and $\tau_{\text{std}} = 10^4$, 4 angles per a half-sphere distributed according to a Lobatto scheme, and about 1800 wavelength points between $\lambda = 20\,\text{Å}$ and $\lambda = 10^7\,\text{Å}$. Depending on the initial stratification, 10 to 15 iterations are required to satisfy the energy condition to better than 0.1% and for the same accuracy in the departure coefficients.

IV. General Properties of Nova Photospheres

The density exponent, $n$, in nova photospheres is only $\sim 2 \ldots 3$ (Starrfield, 1989, Bath and Shaviv 1976), as compared to $n \sim 5 \ldots 12$ for the atmospheres of SNe II. This has a number of important consequences:

(i) nova photospheres are far more geometrically extended than those of any other object known to us so that the curvature term in the transfer equation is of great importance and radii determined from observations in different ways may differ by large amounts (cf. Baschek et al., 1991);

(ii) the densities are so low that, in large parts of the atmosphere, electron scattering is the main source of opacity and photons generated from thermal emission at rather large depths can reach the surface (possibly after a number of scatterings). A particular consequence of this property is the large difference between the color and the effective temperatures.

(iii) the mass $M_{\text{visible}}$ from which photons can escape (that part of the atmosphere directly visible to an outside observer) may be rather large.

(iv) the temperature distributions are characterized by optically thin (in absorption) outer parts in which the temperature $T \propto r^{-1/2}$ (as a consequence of the geometrical dilution) and inner parts where the temperature rises very fast. This important result implies that the ionization conditions vary extremely in nova photospheres and that we can have a large number of ionization stages present simultaneously in the spectrum. In addition, in several models the outer temperature is low enough, so that molecules and perhaps even dust can form in the outer layers as is observed. Our equation of state does not include the possibility of dust and so is the radiative transfer. We note that the observation of multiple ionization stages in novae spectra is one of the important diagnostics of these spectra and its cause has been, heretofore, unexplained;

(v) an appreciable part of the matter receding from the observer (i.e matter which is on the "backside") can actually been seen in the quite extended red wings of strong lines.

(vi) the are strong departures from LTE, but the temperature structure is dominated by the UV lines.
(vii) the are very strong effects of line blanketing due to the velocity differences inside the atmosphere.

V. Synthetic Spectra - First Examples

We try to simulate actual nova envelopes the parameters of which are given in table 1. The parameters were derived from hydrodynamic simulations and no effort was made to change them and obtain a better fit. The observed spectra is the one from the nova PW Vul. The data was taken by Starrfield.

Table 1
Models for PW Vul

<table>
<thead>
<tr>
<th>Model</th>
<th>$L/L_{\odot}$</th>
<th>$T_{eff}(K)$</th>
<th>$R_{out}(cm)$</th>
<th>$\dot{M} (M_{\odot}/yr)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N10</td>
<td>$2 \times 10^4$</td>
<td>$10^4$</td>
<td>$2.50 \times 10^{14}$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>N25</td>
<td>$2 \times 10^4$</td>
<td>$2.5 \times 10^4$</td>
<td>$3.13 \times 10^{14}$</td>
<td>$1.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>N30</td>
<td>$2 \times 10^4$</td>
<td>$3.05 \times 10^4$</td>
<td>$4.65 \times 10^{14}$</td>
<td>$6.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Figure 1a shows the UV part of the nova spectra on August 5, 1984. The fit is with model N10. Note that certain parts of the spectra are over exposed and hence the comparison in these parts is meaningless. We note the following: the slopes in the range 1600-1800Å agrees quite well. The model predicts vanishing continuum between 1370-1570Å as observed. The strength of the wide features near 1350Å and 1520Å are not reproduced. Figure 1b shows the second part of the UV at the same date and compared with the same model. The general trend of the continuum is quite well reproduced as well as some of the lines. Note that the large discrepancies are where the plate is over exposed.

Figures 2a and 2b compare the data for September 30th, 1984. The comparison is now with two models. First we note that none of the model provides good agreement, however, the models seem to border the variations in the observed spectra. Since the models are not that different in their parameters, we see the sensitivity of the modelling to the details.

VII. Discussion

The spectra presented here have been calculated using the assumptions of radiative equilibrium and solar composition which are both questionable for this particular novae. We note that during the explosion it seems reasonable that shocks can form and heat the outer layers by non-radiative processes. It is also clear that most novae show strong evidence for enhanced abundances of the C, N, O, Ne, Mg elements (Truran and Livio 1986; Starrfield 1989, Sparks et al. 1987).

Model atmospheres, such as those presented here, make a quantitative interpretation of early novae spectra possible for the first time. An extensive program of comparing observed and computed spectra is presently under way by our group. However, it is also evident that in the future the following improvements will have to be introduced: (i) A full NLTE treatment of ions like HeI, HeII, CII, CIII, NI, NII, NIII, FeII, FeIII, etc. which will improve the accuracy of abundances derived from subordinate transitions and from lines which are formed very close to the surface;
(ii) Spatially resolved images of nova envelopes often show significant deviations from spherical symmetry so that 2 or even 3 dimensional modeling of the density, temperature, and radiation fields may eventually be required. Such modeling is certainly feasible by means of powerful present day computers (see, for example, Stenholm et al. 1989) and should be tried. On the other hand, it is not clear to what extent unique values for nova parameters can be derived so that many fundamental aspects may have to be discussed again in order to fully understand the results;

(iii) Both direct images and high resolution spectra (Krautter, 1988) demonstrate that nova shells are in most cases not as homogeneous as assumed in the models but that, instead, there are inhomogeneities (knots, blobs etc.) of very different scales and contrasts. Therefore, a statistical treatment would be most appropriate. A straightforward generalization of the approach developed by Gierens et al. (1986) should not only give a better representation of reality but, in addition, it should be possible to obtain the information contained in the local minima and maxima of line profiles and to have much improved estimates of the errors in the derived parameters.

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References
Mathiesen, R. Photo Cross Sections for Stellar Atmosphere Calculations - Compilation of References and Data, Inst. of Theoret. Astrophys. Univ. of Oslo, Publ. Series NNo.1
Figure 1. Comparison between the observed spectra of PW Vul and the present models on August 5th, 1984. The observations were carried out by Starrfield. The details of the model are given in table 1. Figure 1a shows the range 1300-1900 Å while figure 1b shows the range 2600-3200 Å.
Figure 2. The same as figure 1 but for September 30th, 1984.