NOVAE AT MAXIMUM LIGHT: THEY CAN BE COOL!

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INTRODUCTION

Novae generally are considered to be “hot” objects, showing ‘effective’ temperatures of 10,000K and higher at maximum in the optical. However, Nova DQ Her 1934 was a very slow nova that displayed strong CN band absorption for a short time around maximum light. The presence of CN, which dissociates at ≈ 5000 K, shows that an expanding nova shell can evolve to very low temperatures. A previous study by Sneden & Lambert (1975) analyzed the early spectra and indicated that $^{13}$C was probably enriched when compared to a solar composition.

We have now computed synthetic spectra for novae with low effective temperatures to investigate the structure of the expanding envelope and the formation of the spectrum for this type of cool nova. Our spherically symmetric, expanding, stellar atmospheres include a solution of the Lagrangian frame radiative transfer equation, line, and molecular band blanketing. We discuss the properties of the atmospheres and the synthetic spectra for Novae with low ‘effective’ temperatures.

Our models (Hauschildt et al. 1992, 1994) show the following characteristic features: (1) a very large extension of the atmosphere - typically the relative radial extension of the line and continuum forming layers is about 100, (2) large departures from LTE, (3) very large temperature gradients throughout the envelope - the electron temperatures, for a model with $T_{\text{eff}} = 6,500$ K, range from 1,100 K to 50,000 K, (4) therefore, both molecules and higher ionization stages of various elements are simultaneously present in the atmosphere and the spectrum, (5) the UV spectra are dominated by line-blanketing, in particular by the Fe II-curtain, (6) some of the observed “emission lines” are merely “holes in the iron-curtain”, and (7) molecular absorption bands are prominent in the cooler model atmospheres.

NOVA MODEL ATMOSPHERES

Model Assumptions
Our basic model assumptions are as follows: (i) steady state, i.e., $\partial/\partial t \equiv 0$, (ii) power law density, i.e., $\rho(r) \propto r^{-n}$, (iii) constant mass loss rate, $\dot{M} \equiv \text{const.}$,
with respect to time and radius, (iv) radiative equilibrium in the Lagrangian frame, (v) full non-LTE treatment of H I (10 levels), He I (11 levels), He II (10 levels), Na I (3 levels), Mg II (3 levels), and Ca II (5 levels), (vi) non-LTE equation of state including LTE occupation numbers for up to 26 ionization stages of 40 elements and up to 100 molecules (treated consistently with the non-LTE species), and (vii) all relevant molecular bands (JOLA approximation), b-f, f-f and b-b transitions are included (b-f, f-f: Mathisen 1984; b-b: ~ 42 million lines of Kurucz 1993; molecules: Allard 1993).

Model Parameters
The most important model parameters are (i) the reference radius $R$, which refers to the radius where either the optical depth in absorption or extinction at 5000Å is unity, (ii) the 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 Stefan’s constant), (iii) the density parameter, $n_s$, ($\rho(q) \propto r^{-n}$), (iv) the maximum expansion velocity, $v_\infty$, (v) the density, $\rho_{\text{out}}$, at the outer edge of the envelope, (vi) the metal line threshold ratio, $\Gamma$, (vii) the albedo for line scattering (LTE metal lines only, here set to 0.95), (viii) the element abundances. For more details of the model construction see Hauschildt et al. (1992, 1994).

RESULTS
We find that molecular bands dominate the synthetic spectra in the cooler atmospheres, with increasing effective temperature, however, atomic and ionic lines become more and more important. The optical and infrared spectra are very sensitive to abundance changes of CNO due to the presence of molecular bands. This is because the relative abundances of molecules such as, CN, CH$_4$, C$_3$, CO, and CO$_2$ depend strongly on the relative abundances of C, N, and O. In the line forming regions of cooler models we find that only resonance lines of neutral or singly ionized elements are important, in addition to the molecular bands. The number of important atomic and ionic lines, i.e., lines that have central extinction coefficients of more than $10^{-4}$ when compared to the local continuum, is about 50,000 to 100,000, much less than the typical 1,000,000 lines found to be important in nova atmospheres with higher “effective” temperatures.

Of particular interest is the molecular structure of cool nova atmospheres. The formation of molecules starts at relatively low temperatures because of the very low pressures in the extended envelope. However, the largest “effective” temperatures of the nova atmospheres which show significant amounts of molecules in the line forming regions are about 8000 to 9000 K.

In order to form significant amounts of CN, as observed in Nova DQ Her 1934, the abundances of C, N, and O must be significantly different than in the solar mixture. In nova model atmospheres with solar abundances, the relative fraction of CN molecules never rises above $\approx 10^{-6}$ (by number) which is probably too small to explain the CN features. However, in those atmosphere models in which we enhanced the abundances of C and N by a factor of 100 and the abundance of O by a factor of 10 (by number relative to the solar abundances), the relative fraction of CN is increased to $10^{-3}$. This results in very strong molecular band absorption by CN and other molecules, much stronger than
found in the model atmospheres with solar abundances. In some models we
found that the infrared bands of CO could be in emission, as was observed in
nova V842 Cen (Krautter 1993, private communication).

CONCLUSIONS

Line and molecular band blanketing is a dominant factor in understanding and
interpreting early spectra of cool novae. Non-LTE effects in nova atmospheres
are large and very important due to the large radial extension and the huge
temperature gradient in the photosphere. In order to find a significant abun-
dance of CN in the atmosphere, the relative abundances of C, N, and O must be
significantly different when compared to the solar mixture. The abundance of
the CN molecule in the nova atmosphere with enhanced CNO abundances has
a maximum around “effective” temperatures of about 7000K. Due to the huge
temperature gradient present in the line forming region, the electron tempera-
tures are much lower (∼ 4000 K), as found in the work of Sneden & Lambert
(1975). The presence of CN may already indicate a non-solar mixture of C, N,
and O. The high sensitivity of the optical spectrum of cool novae to molecule
formation make them very promising objects for accurate abundance determi-
nations. Isotopic abundances can also be derived by analyzing these spectra.
Therefore, observations of this rare class of novae are very important for testing
the TNR theory of the nova outburst.

ACKNOWLEDGMENTS

We are grateful to G.C. Anupama, E. Baron, L. Ensman, S. Shore, H. Störzer,
and M. Wagner for valuable discussions. This work was sponsored, in parts, by
a NASA LTSA grant to ASU.

REFERENCES

Allard, F. 1993, private communication
Hauschildt, P. H., Starrfield, S., Austin, S., Wagner, R.M., Shore, S.N., & Son-
Kurucz, R.L. 1993, (CDROM1), private communication
Mathisen, R. 1984, Photo Cross-sections for Stellar Atmosphere Calculations —
Compilation of References and Data, Inst. of Theoret. Astrophys., Univ.
of Oslo, Publ. Series No. 1