IONIZATION IN NOVA ATMOSPHERES

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ABSTRACT

Calculations on the expansion of novae shells are presented, from which the degree of ionization is obtained using a simplified form of a non-LTE ionization equation. From this, estimates of the time of vanishing of the Balmer absorption spectrum can be made.

Key words: novae shell, ionization, expansion.

Atmospheres of novae are strictly speaking not in a steady state. However, relaxation effects are not observed before the later nebular stage. Therefore the development of a nova shell may be understood as a sequence of different extended atmospheres of the type discussed in this colloquium.

The nova phenomenon varies considerably in amplitude, time scale, and light curve details, but it is possible to reduce the data to an average nova by using the time t_3 (the interval between maximum brightness and $m_{max} + 3\overset{m}{.}0$) as a time unit. A nova that followed the average rather closely, and which is appropriate for an investigation because the absolute intensities of emission lines were measured, is DK Lac 1950. It will be used here as an example.

During the first phases from 0.1 t_3 to about 6 t_3 the magnitude m of this star was strongly correlated to T_S (radiation temperature) as well as to the spectral type (intensities of absorption and emission lines). Hence it was possible to eliminate the effects of light and temperature fluctuations and of secondary eruptions. We disregard here the dif-

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ferent components of the diffuse enhanced spectra and the Orion spectrum because they belong to the secondary processes or originate in masses of gas, which are negligible compared with the main shell.

The principal spectrum showed an increase of radial velocity from about 800 to 1300 km/sec during the absorption line stage and a nearly constant value in the later development. An estimate shows that the observed RV changes cannot be interpreted as accelerations. Instead we have to assume that velocities between certain limits were present all the time, and that the measured line shift is due to a motion of the effective layer of absorption. Each substantial atmospheric element had a constant outward velocity between v_{min} and v_{max}.

The basic model is a shell with radius and geometrical depth increasing linearly with time. Hence the density of each substantial element decreases with r^{-3}, and the velocity field is

$$v(r,t) = r/t-t_o \ ,$$

t_o being the time of the initial magnitude rise.

During the stages with forbidden lines, N_e, the electron density, can be found from the intensities of these lines. According to a well-known theory, we have, for instance, for [0 III],

$$\frac{\text{intensity } (N_1 + N_2)}{\text{intensity } (\lambda\ 4363)} = f(N_e, T_e)$$

with a given function f. Unfortunately f has a form that forbids the solution for N_e and T_e of two such equations for different ions, with a reasonable accuracy. However, because of the "thermostatic" action of the forbidden transitions, an electron temperature of about 10000°K during the whole period can be accepted. The corresponding N_e, proportional to N (total density) is well defined and changes as $(t-t_o)^{-3}$. Using the hydrodynamic force equation,

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial r} = k \approx 0 \ ,$$

and the equation of continuity,

$$\frac{\partial N}{\partial t} + \frac{1}{r^2} \frac{\partial (N\ v\ r^2)}{\partial r} = 0,$$

it is very easy to verify that the observed relations

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agree and that the density field is given by

$$N(r,t) = \frac{N_o}{(t-t_o)^2 r} \quad .$$

The principal shell crossed a radius R during an interval of time,

$$\Delta t = R\left(\frac{1}{v_{min}} - \frac{1}{v_{max}}\right)$$

and that gives Δt in the range of 10^1 to 10^2 min, if R is of the order of the solar radius. The corresponding density is of the order of 10^{20} atoms/cm^3. The nova phenomenon started with a short time "explosion" of a layer not very far below the original photosphere.

We return to the problem of the formation of the spectra of different excitation. The computation of the population of atomic or ionic levels from the steady state equations

$$\frac{d\ N(\chi_i)}{d\ t} = 0$$

is rather complicated. So we use the first approximation for the equation of ionization under non-LTE conditions

$$\frac{N^{(n)}N_e}{N^{(n-1)}} = \frac{2\ B^{(n)}}{B^{(n-1)}}\ K\ W\ T_s(T_e)^{1/2} e^{-\chi_n/kT_s} \quad .$$

The dilution factor is $W \sim (R_*/2r)^2 e^{-\tau}$ where τ is the optical depth between the photosphere and a point at distance r. This is to be combined with the definition of $d\tau$

$$d\tau = (1-x)\varepsilon N(r)\ \bar{a}\ dr,$$

where

$$x = N^{(n)}/\sum_n N^{(n)} \quad .$$

Here $\bar{a}$ is the absorption coefficient averaged over ν from the series limit to infinity. It is convenient to write $\bar{a}$ = 0.5 a(series limit), which can be

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verified a posteriori. ε is the abundance of the element investigated. This differential equation has been solved numerically for $\tau(r)$ and $x(r)$, using arbitrary $N(r)$. Of course, the Strömgren theory of ionization zones is the special case N = const, $\varepsilon = 1$.

Under certain conditions, which are fulfilled in many cases, x changes rapidly from 1 to 0 at a distance, r_s. These "Strömgren radii," if of finite size, are very sensitive to T_s: a small change in temperature makes r_s jump through the whole main shell and then causes a very quick spectral change with $m(T_s)$. The motion of r_s for hydrogen through the shell explains the width and the radial velocities of the Balmer lines. At first, the whole shell belongs to the H I region, and the lines are very wide (width corresponding to $v_{max} - v_{min}$), with RV $\sim 0.5\ (v_{max} + v_{min})$. Since r_s increases faster than r_{max}, the effective center of the absorptions moves to v_{max}, the width becoming normal. When $r_s = r_{max}$, the whole of the shell belongs to the H II region and the Balmer apsorptions vanish from the spectrum. Using T_s from different observations (spectrophotometry of continuum and Zanstra methods) and adjusting the parameter N_o to give the correct absolute intensities of the hydrogen emissions, it was possible to predict the times of disappearance of the He I, O I, N II, [N II] and [O III] emissions sometimes within a few days. The main source of uncertainty is the still inadequate information on T_s.

It can be shown that the condition for a change of spectral type, r_s equal to the average shell radius, is fulfilled for specific T_s, independently of time, if the degree of ionization follows the temperature without delay. Only in the later nebular stage, when the electron density is below the predicted limiting value of $N_e = 10^{7.6}$, a delay of one day or more between temperature changes and the appearance and disappearance of the nebular lines $N_{1,2}$ has been observed.

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DISCUSSION

Osterbrock: Are the time-dependent effects of the finite rate of emission of ionizing radiation by the nova important to your problems?

Wellmann: The retardation of the ionization changes did not occur before $4.t_3$, that is in the later nebular stage, and was observed mainly in [O III].

Nussbaumer: I want to give two warnings: (1) Atomic data: Seaton's group has recalculated some of the [O III] collision cross sections. Changes in some of these are important. For all interpretational work where cross sections or oscillator strengths are used it is worthwhile to make sure that you have the latest calculations. (2) Line widths: Combined effects of radial velocities and temperature gradients may influence the line widths considerably. Suppose a radial expansion but unique temperature, then you have the normal Doppler broadening. Now suppose a radial drop in temperature sets in and increases the abundance of your ion. The displaced line component will then be more intense than the undisplaced component. Thus the radial drop in temperature produces a line width that makes you believe in a temperature increase.

Wellmann: Every time Seaton's group has published new values of the cross sections, we have repeated our calculations for the forbidden lines. Fortunately the fundamental result has not changed very much. But there is another difficulty. The relations between N_e and T_e for different forbidden lines should give a unique solution for electron density N_e and electron temperature T_e. But we don't find such a solution. It may be that this effect is due to inaccurate cross sections.

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