On the Localization of Emission Line Region in Mira Stars

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New evidence is obtained that hydrogen emission lines as well as metallic ones originate below the molecular absorption layers in Mira stars.

The time scale t_c of gas cooling behind a shock front propagating through the stellar atmosphere when the gas temperature tends to its preshock value T_0 equal to 2800–3000 K corresponding to the molecular layers, is calculated as a function of temperature T at the final stage. This calculation shows that the gas does not have sufficient time to be cooled to its preshock state. So, T_0 should be greater than the temperature of the molecular layers.

This result agrees with the spectra of Mira-like stars available in the literature. The emission lines show a complex structure with asymmetric or multi-component profiles because of molecular line absorption.

1 Introduction

Mira-like stars belong to a class of long-period pulsating variables on the Asymptotic Giant Branch stage [1]. They pulsate with the largest visible amplitude greater than 2.5 mag and the longest period of about some hundred days. The Miras have complex spectra including molecular absorption bands (TiO and VO), absorption lines of metals (Ca, Fe, Ti, V), and strong emission lines of hydrogen and some metals (MgI, MgII, FeI, FeII and others). The emission lines are observed during approximately $70-80\%$ of time: they appear before the luminosity maximum and disappear after the luminosity minimum.

Gorbatskii [2] suggested a shock wave model (similar to that of Cepheids) to explain the emission lines in the spectra of Mira variables. In solving the problem of the shock wave in Mira's atmosphere, one usually considers the regions in which the radiation is mainly formed. These regions are rapidly cooled on the timescale of less than a day. Less attention was paid to further cooling of the gas to the preshock temperature, but estimating the time required for complete relaxation of the gas may be important.

It is shown below that the radiative cooling rate of the gas declines at low temperatures and the cooling time can exceed a half of the period.

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2 Cooling timescale

Let us consider the process of gas cooling in the final stage when the gas temperature T (electron temperature is nearly equal to temperature of atoms and ions) tends to the preshock value T_{bg} (see [3] for more details).

At this stage the main processes are photorecombination, free-free transitions, electron-collisional excitation. The ionization state is determined by photoprocesses as the contribution of electron-collisional ionization to the electron density at the gas temperature of 5000 K is far less than the contribution of photoprocesses at the photosphere temperature of 3000 K. The energy gain due to photoionization and energy losses due to recombination cancel each other out. Thus, the cooling is determined by electron collisions and bremsstrahlung.

In general terms, the equation for the temperature in the final stage of cooling may be written as follows:

$$\frac{dT}{dt} = \Phi\left(\varphi_{ff}(T), Q_{ex}(T)\right) = \Phi(T), \tag{1}$$

where $\varphi_{ff}(T)$ is the contribution of bremsstrahlung, $Q_{ex}(T)$ is that of collisional excitation.

The right side of Eq. (1), designated by $\Phi(T)$, is a function of temperature T under the conditions of quasi-stationary ionization. Consequently, the cooling timescale can be calculated as the integral

$$t(T_{\text{beg}}, T_{\text{fin}}) = \int\limits_{T_{\text{fin}}}^{T_{\text{beg}}} \frac{dT}{\Phi(T)}, \tag{2}$$

where T_{beg} is the temperature from the interval 4000–5000 K at which the integration begins. The timescale t is determined by the final temperature T_{fin}.

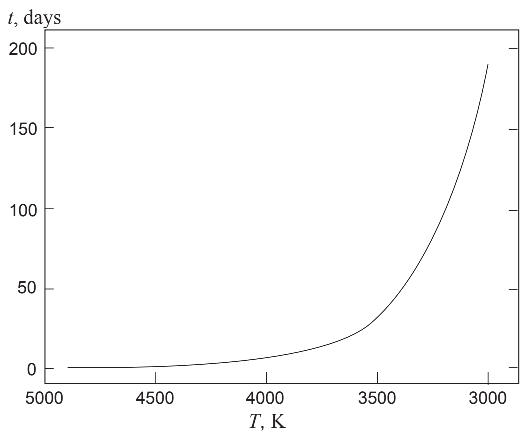

Figure 1: The cooling time as a function of the final temperature T_{fin}.

Some results of our calculations are presented in Fig. 1. As can be seen, the gas is rapidly cooled to a temperature of order of 3700–3500 K, but the rate of cooling significantly decreases for $T_{\rm fin}$ below 3500 K. So, the time of cooling to the temperature equal to 3000 K is approximately 200 days, and that to the temperature of 2800 K is even much more.

It is clear from Table 1 that the cooling time exceeds a half of the period for the majority of Mira variables. Therefore, the gas does not have time to return to the undisturbed value of the temperature. This means that the shock wave passes through the regions under the layer of molecular gas. This fact should be manifested in the spectra of Miras.

Table 1: Typical periods of Mira variables

Star	Period, days	Star	Period, days
o Cet	332	S CrB	360
U Her	406	R Aql	284
S Car	150	RS Vir	354
T Her	165	R Leo	310
T Col	150	R Hya	389

3 Information on emission-line profiles

Let us compare the results of calculations with the observational data. Spectra of Mira variables suitable for analyzing the structure of emission lines were published in [4]–[7].

Gillet et al. [4] studied the Hα profile in the spectra of *o* Cet from the maximum ($\phi \sim -0.05$) to the minimum ($\phi \sim 0.60$). The Hα line has complex structure: there are blue- and red-shifted components. The blue-shifted component has 4 components during about a quarter of period (till $\phi \sim 0.23$): three absorption lines are observed against the emission profile. After the phase $\phi \sim 0.23$, the absorption lines are not separated, but the blue-shifted component has an asymmetric profile. The red-shifted component appears in the spectrum after the phase $\phi \sim 0.14$ and also has an asymmetric shape. These features of the Hα line are associated with the absorption band (γ system) of TiO.

Other papers include emission profiles of Balmer series (Hα–H12) and metal lines (MgI, MgII, FeI, FeII, SiI, MnI) for different Miras. All the profiles demonstrate an asymmetric shape. This is attributed to the effect of scattering by atoms and molecules and absorbing by molecules, mainly TiO.

Thus, emission lines are influenced by atomic and molecular absorption. In this case, the shock wave motion should occur in the layers located below the molecular one. Such a model of Mira's atmosphere is shown in Fig. 2.

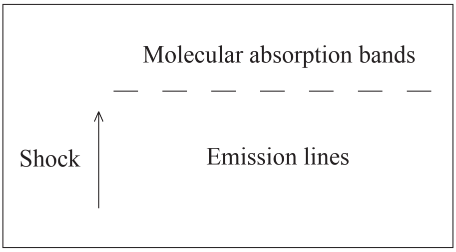

Figure 2: Model of Mira's atmosphere.

4 Conclusion

The problem of cooling of the gas behind the shock front in Mira variables was considered. The cooling time of the gas was calculated as a function of the final temperature and was compared to the typical periods of Mira stars. For most Miras, the cooling time is more than a half of the period, so the gas does not have time to cool down to the unperturbed temperature. In this case, the shock wave should propagate under the layers where molecular absorption bands are formed. This conclusion is confirmed by the available high-resolution optical spectra which show the influence of molecular bands on the emission line profiles.

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