ON THE NATURE OF MASER SOURCES IN INFRARED STARS

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Abstract. Supergiant infrared stars with OH maser emissions, like NML Cyg, VY CMa, and VX Sgr, are discussed assuming a model consisting of a star with a photospheric temperature of about 2000 K and a radius of $R \sim 2 \times 10^{14}$ cm surrounded by a gas and dust shell. A possible similarity with OH Miras is mentioned.

Some Mira-variable IR stars, and M supergiants emit in the 1612-, 1665-, 1667-MHz lines of OH and the 22235-MHz line of H_2O. The interferometry of OH/IR stars NML Cyg, VY CMa, VX Sgr (Davies *et al.*, 1972; Masheder *et al.*, 1973) has revealed a complex spatial structure of single components of the 1612-MHz OH maser emission. The aim of the present paper is to suggest a possible mechanism of formation of maser condensations (i.e., single structures) in IR stars and to analyze the interferometric results. Also, a model of OH/IR stars is considered and microwave spectra and pumping mechanisms are discussed.

As a rule, the OH maser radio spectrum consists of two broad features, from 10 to 50 km s^{-1} apart in radial velocity. In supergiants, the features which are at the velocity of the star (for red-shifted ones) are usually situated at the periphery of the maser region; the features at more negative velocities (blue-shifted) are inside it. The H_2O maser radio lines are in general more intense inside OH structures, coinciding very closely in velocity with the main 1665- and 1667-MHz lines.

The models of OH/IR stars, as well as of supergiants, have been often discussed (Hyland *et al.*, 1969; Litvak, 1969a; Herbig, 1970; Davies *et al.*, 1972; Dickinson *et al.*, 1973). We shall adopt a model similar to that proposed by Masheder *et al.* (1973). In this model, in the case of a supergiant, a star with a photospheric temperature $T \sim 1800$–2600 K and with a radius $R \sim 2 \times 10^{14}$ cm is surrounded by a gas and dust shell. A shock is propagating in the shell with a velocity of 10–50 km s^{-1}. Apparently, shocks travel through the shell many times.

It is shown that thermal instability may serve as a mechanism for the formation of the maser sources associated with Mira variables and late-type supergiants. Thermal instability develops behind shock fronts crossing the atmospheres of these stars. A similar mechanism was proposed by Burdjuzha and Ruzmaikina (1974) for galactic maser sources near compact H II regions. The condition serving as a criterion for the development of thermal instability in a cooling medium, leading to the development of temperature and density inhomogeneities in which the pressure remains unperturbed, is

Sherwood and Plaut (eds.), Variable Stars and Stellar Evolution, 175–177.

$$\left(\frac{\partial L}{\partial T}\right)_P - \frac{L}{T} < 0,$$

where L is the specific cooling function in erg gm^{-1} s^{-1}.

In the process of cooling the matter compressed at a constant pressure behind the shock front, the perturbations grow as

$$\left(\frac{\delta n}{n}\right) \approx \frac{T_1}{T} \exp\left\{\int_{T_1}^{T} \left(\frac{\partial \ln L}{\partial T}\right)_P \mathrm{d}T\right\}.$$

The main cooling agents are O^+ ions (at 10^4 K) and Fe^+ and Si^+ ions which are excited by electrons and, at lower temperatures, by neutral atoms. Also, the Boltzmann-populated levels may contribute to cooling as well as H_2 molecules at $T \sim 10^3$ K. We shall not reproduce the bulky formulae for the cooling function; note only, that an approximation is

$$L \approx nT^{\alpha}$$

where $0 < \alpha < 1$. In this case, the temperature in the shock front does not significantly exceed 10^4 K, and only the dissociation of molecules occurs. The molecular hydrogen is the main cooling agent of the matter. Thermal instability develops in the temperature range where the dissociation of molecules is effective. The mechanism of thermal instability is due to the fact that the number of cooling molecules is increasing when the temperature is decreasing (Ruzmaikina, 1972; Yoneyama, 1973). The minimum size, l_c, of the clouds that can form due to thermal instability is determined by the thermal conductivity of the matter; in our case it is $\sim 10^{12}$ cm.

In the spectra of M supergiants (NML Cyg, VY CMa, VX Sgr), the structures of the main OH lines and H_2O features lie in a radial velocity scale inside 1612-MHz features which suggests different spatial structure. Such a difference may be engendered by different pumping mechanisms. All maser radio lines seem to be pumped by infrared radiation, of differing wavelengths however, and, most important, of different required linewidths of the pumping IR lines. This demand may influence the spatial distribution of maser features; e.g., the 1612-MHz maser can exist only in that region of the shell where the Doppler (kinetic + turbulent) temperature is rather low, $T < 3000$ K, and the thermalization is insignificant. The maser radio lines are pumped by IR radiation with $\lambda \sim 2.8\ \mu$ for the 1612-MHz features (Litvak, 1969b; Litvak and Dickinson, 1972), $\lambda \sim 53.3\ \mu$ and 34.6μ for the 1667 and 1665-MHz features (Burdjuzha and Varshalovich, 1973; Burdjuzha, 1973), and $\lambda \sim 2.7\ \mu$ and $6\ \mu$ for the 22235-MHz H_2O maser features (Litvak, 1969a, 1971). For the pumping of main lines, it is necessary that the Doppler temperature exceeds ~ 500 K. Such conditions are normal behind the shock front where the temperature is higher and microscopic turbulence evidently should take place. For maser amplification of OH main features, thermalization is minor up to $n_H \sim 10^7$ to 10^8 cm^{-3}. From these restrictions on the Doppler linewidth of the pumping IR lines, one can try to distribute spatially maser structures in IR stars.

The 1612-MHz features of OH both red-shifted and blue-shifted are situated before the front of the shock wave which passes over the shell, in contrast to the 1665, 1667- and 22235-MHz features which are probably situated just behind the shock front. The red-shifted features are located at the periphery in the undisturbed zone of the shell. The blue-shifted features are positioned near the front zone and their velocities practically coincide with the shock wave velocity. We suggest that this distribution can explain a number of features in OH and H_2O maser spectra. The blue-shifted 1612-MHz features lie spatially inside the red-shifted features as they are situated nearer to the stellar photosphere. A similar OH feature distribution has been suggested by Dickinson and Chaisson (1973). The picture described is somewhat endorsed by the observed duplicity (10–50 km s^{-1}) of some metallic lines in the Mira star spectra (Adams, 1941). Also, some peculiarities of the microwave spectrum can be explained. Steep outer edges of the 1612-MHz spectrum and a smooth decrease in the internal part of the spectrum determine the feature distribution and restriction on the Doppler temperature.

If this picture is correct for OH/IR supergiants, then an analogous (or similar) fine spatial structure should exist and be observable in many OH Mira variable stars.

To conclude, note that from the estimates of the rotational momentum of the shell and because of the possible multiple shock waves in the shells of the supergiants NML Cyg, VY CMa, and VX Sgr, the hypothesis that these objects are in a protostellar stage becomes very attractive.

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DISCUSSION

L. A. Pustil'nik: How were the effects of the magnetic field considered during the thermal instability?

V. V. Burdjuzha: The influence of the magnetic field was not considered in this paper. However, in a previous paper we showed that these effects have no large influence on the thermal instability in the interstellar matter.