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A NEW INTERPRETATION OF THE FEATURE OF SIO MASER SPECTRA ASSOCIATED WITH M–TYPE STAR

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ABSTRACT

There exists a systematic redshift of spectra ($v = 1,2;\ J = 1-0$) of SiO masers associated with a number of late–type M stars. On the contrary, the redshift is rather small for the spectra ($v = 1;\ J = 2-1$). The latter is approximately symmetrical with respect to the star. For the above, no good interpretation has been given up to now. A new redshift mechanism of SiO spectra, the mechanism of radiation frequency shift, has been derived here from the interaction between the radiation field of the star and the energy levels of the maser. Detailed calculations show that, under the influence of the radiation field of the star, the redshift of the SiO spectra ($J = 1-0$) is more substantial than that of the spectra (J=2-1). This is consistent with the result of the observation, and shows that the non–kinematic effect of the spectra is non negligible for the SiO maser of the star.

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1. INTRODUCTION

The SiO maser has recently been observed, and is particularly common in the envelope of the late–type M giants. According to the observation of high resolution VLBI, the emission area of the SiO maser is located near the star at several radii. Both the strong radiation field of the star and the complex mass movement cause variations of the profile of the SiO spectrum. But there exists some regularity. The spectra ($v = 1,2;\ J = 1-0$) redshift systematically. The redshift velocity of some sources even exceeds the terminal expanding velocity of the envelope. These features have not been interpreted so far.

The SiO masers, which come from the red giant and Orion A, have been observed and studied for a long time by Lane [1] and Nyman [2]. They have discovered that, for SiO masers associated with M stars, the spectra ($v = 1,2;\ J = 1-0$) have similar structure of velocity. Most of them have obvious redshift. Statistical results show that the amount of redshift is approximately 2.7 ± 1.0 km/s. For the star χC_{yg}, the spectra are smoothly blueshifted, but χC_{yg} is not a M star. If we disregard this star, the statistical result shows that the redshift of the spectrum ($v = 1,2;\ J = 1-0$) is approximately 3.0 ± 1.4 km/s, but that of ($J = 2-1$) is only 1.5 ± 1.7 km/s. The value obtained by Nyman is 1.1 km/s, so we notice that the velocity distribution of spectra (j = 2-1) is symmetric with respect to the star, considering that the uncertainty of the velocity of the star is approximately 1.0 km/s.

A possible interpretation of the above behaviour is that the SiO maser ($v = 1;\ J = 2-1$) comes from a steady envelope far from the star, so that its frequency spectrum is symmetric with respect to the velocity of the star. But the SiO maser ($v = 2-1;\ J = 1-0$) is very near the star, where the gas goes back to the star, so the spectra should be redshift, since the radiation at the back of the star is sheltered. This interpretation will oblige us to invert the levels of v=1; $J = 1-0$ and $v = 2;\ J = 1-0$ simultaneously, but this is difficult to understand. The result calculated by Langer and Watson proves [3] that corresponding masers for $v = 1,\ J = 1-0$ and for $v = 2;\ J = 1-0$ come from different areas, whereas both the masers $v = 1;\ J = 1-0$ and $v = 1;\ J = 2-1$ come from the same area, they are far from the star compared to the masers $v = 2;\ J = 1-0$. In addition, the gradient of radial velocity near the star is large. The SiO maser seems to have tangent amplification in order to obtain gain of maser large enough. At least, it will be amplified partially tangentially [4]. Then the maser should have stationary velocity, which is approximately the velocity of the star. Therefore it is necessary to put forward a new mechanism to interpret the redshift of the SiO maser. It is not quite satisfactory to interpret the SiO maser by using only the kinematics of the envelope of the star, and other physical processes must be considered. This paper focusses on the special properties of the SiO maser associated with late–type M star. A new mechanism of the redshift of the SiO maser, based on the interaction between the radiation of the star and the levels of the molecule has been derived. The calculation shows that this mechanism can provide the required amount of redshift. It should be an important origin for the tangential amplification of the SiO maser. The calculation also presents that there exists, under the effect of the radiative field of the star, a redshift for $J = 1-0$ (43GHz) stronger than that for $J = 2-1$

(86GHz). Since this redshift is caused by the radiative field of the star, it depends substantially on the geometric dilution factor.

The mechanism mentioned in this paper will be too weak to account for the interstellar SiO masers, since they are located far away from the sources, whereas for circumstellar SiO masers, this mechanism cannot be neglected.

2. THE RADIATION FREQUENCY SHIFT OF SIO MOLECULAR LEVELS

Suppose that there are two unperturbed levels of the molecules SiO, E_m and E_n, see Fig.1. The interval is $E_m - E_n - \hbar\omega_0$. When it is radiated by some external radiation, the levels will shift. According to the quantum field theory, they will become, in second order approximation, separately [5]:

$$E'_m = E_m + \frac{|H'_{mn}|^2}{\hbar(\omega_0 - \omega)} \tag{1}$$

$$E'_n = E_n + \frac{|H'_{mn}|^2}{\hbar(\omega - \omega_0)} \tag{2}$$

When $\omega > \omega_0$, the level separation will decrease. But when $\omega \rightarrow \omega_0$, the above formulae will obviously be invalid, since the widths of the levels are omitted. Suppose the width of the upper level is $\hbar\Gamma_m$ and the lower level is the ground state, formula (2) pertaining to the lower level becomes [6]:

$$\begin{aligned} E'_n &= E_n + \frac{|H'_{mn}|^2}{\hbar(\omega - \omega_0) + i\hbar\Gamma_m/2} \\ &= E_n + \frac{|H'_{mn}|^2}{\hbar}\left[\frac{(\omega - \omega_0) - i\Gamma_m/2}{(\omega - \omega_0)^2 + (\Gamma_m/2)^2}\right] \end{aligned} \tag{3}$$

Even though both the upper and lower levels are the excited states, formula (3) is still valid, provided we consider $\hbar\Gamma_m$ as the effective width $\hbar\Gamma$, which relates to both the upper and lower levels. The real part of formula (3) represents the shift of the level, and the imaginary part to the broadening of the level, so the shift of level E_n is

$$\Delta E_n = E'_n - E_n = \frac{|H'_{mn}|^2}{\hbar}\frac{(\omega - \omega_0)}{(\omega - \omega_0)^2 + (\Gamma/2)^2} \tag{4}$$

The interaction energy operator is

$$\hat{H}' = \vec{P} \cdot \vec{E}$$

$\vec{P}$ is the dipole moment of the SiO molecule and $\vec{E}$ is the strength of the external radiative electic field. The thermal radiation is isotropic. In the first order approximation,

$$|H'_{mn}|^2 = P_0^2 \cdot E^2\,. \tag{5}$$

P_0 is molecular permanent dipole moment. We know that the energy density of the radiation field at a distance R from the star is:

$$\begin{aligned} \rho(R,\nu) &= \frac{4\pi}{C}B_\nu(T_{eff}) \cdot W(R) \\ B_\nu &= \frac{2h\nu^3}{c^2}\frac{1}{\exp[h\nu/kT_{eff}] - 1} = \frac{\hbar}{2\pi^2 C^2}\frac{\omega^3}{\exp[\hbar\omega/kT_{eff}] = 1} \end{aligned} \tag{6}$$

T_{eff} is the effective temperature of the surface of the star. $W(R) -(1/4)(R_*/R)^2$ is the geometric dilution factor of the radiation field of the star. According to electrodynamics, the energy density of the radiation field can be written as follows:

$$\rho = E^2/4\pi$$

then

$$E^2 = 4\pi\rho = \frac{8\hbar}{C^3}W(R)\frac{\omega^3}{\exp[\hbar\omega/kT_{eff}] - 1} \tag{7}$$

Substituting (7) and (5) into (4), and considering the external radiation to be continuous, formula (4) becomes an integral. The shift of the energy level is then

$$\Delta E_n = \frac{8P_0^2}{C^3}W(R) \cdot \int \frac{(\omega - \omega_0) \cdot \omega^3}{[\exp(\hbar\omega/kT_{eff}) - 1][(\omega - \omega_0)^2 + (\Gamma/2)^2]}d\omega\,, \tag{8}$$

For the SiO molecule maser ($v = 1,2; J = 1 - 0$ or $2 - 1$), there are two excited levels and they can both suffer level shift. Therefore the total shift of the energy levels will be double that of formula (8). The level shift can also be represented by

$$\begin{aligned} \Delta V &= \frac{\Delta\nu}{\nu_0}C = \frac{2\Delta E_n C}{h\nu_0} \\ &= \frac{32\pi}{\omega_0 hC^2}P_0^2 \cdot W(R) \cdot \int \frac{(\omega - \omega_i) \cdot \omega^3}{[\exp(\hbar\omega/kT_{eff}) - 1][(\omega - \omega_0)^2 + \Gamma/2)^2]}d\omega \end{aligned} \tag{9}$$

where ΔV is the Doppler velocity change.

Several useful molecular constants of the state $X'\Sigma^+$ of the molecule SiO are [7]:

$$r_e = 1.5097\,\text{Å}\,, \alpha_e = 0.00504\ \text{cm}^{-1},\ B_e = 0.7268\ \text{cm}^{-1}$$

From $B_v = B_e - \alpha_e(v + 1/2)$ we can obtain nuclear interdistances,

$$r_1 = 1.5173\ \text{Å}, \quad \text{for state } v = 1;$$

$$r_2 = 1.5280\ \text{Å}, \quad \text{for state } v = 2\,.$$

so that the dipole moments

$$P_{01} = qr = 1.4566 \times 10^{-17}\ CGSE, \text{ for } v = 1,$$

$$F_{02} = qr = 1.4669 \times 10^{-17} CGSE \text{ , for } v = 2 \text{ .}$$

For convenience, we introduce the parameters:

$$x = \omega/\omega_0 \text{ , } y = h\omega_0/k \text{ , } A = (\Gamma/2\omega_0)^2$$

Then formula (9) becomes

$$\Delta V = -\frac{16\pi}{hC^2} P_0^2 \omega_0^2 W(R) \int \frac{(x-1)x^3}{[\exp(yx/T_{eff}) - 1][(x-1)^2 + A]} dx$$

$$= D \cdot W(R) \cdot \int \frac{(x-1) \cdot x^S}{[\exp(yx/T_{ff}) - 1][(x-1)^2 + A]} dx$$

$$D = \frac{32\pi}{hC^2} P_0^2 \cdot \omega_0^2 \qquad (10)$$

We know from calculation and experiment

$$\nu_0 = 4.3122 \times 10^{10}/s, \quad \text{for transition } v = 1; J = 1 - 0,$$

$$\nu_1 = 8.6243 \times 10^{10}/s, \quad \text{for transition } v = 1; J = 2 - 1,$$

$$\nu_0 = 4.2820 \times 10^{10}/s, \quad \text{for transition } v = 2; J = 1 - 0 \text{ .}$$

Substituting the above data, we obtain that

$$A = 5.377 \times 10^{-12}, \ y = 2.07068, \ D = 2.624095 \times 10^{-4}$$

for $v = 1; \ J = 1 - 0$,

$$A = 1.344 \times 10^{-12}, \ y = 4.1416, \ D = 1.049614 \times 10^{-3}$$

for $v = 1; J = 2 - 1$,

$$A = 5.4229 \times 10^{-12}, \quad y = 2.05623, \ D = 2.66126 \times 10^{-4}$$

for $v = 2; \ J = 1 - 0$.

3. RESULTS AND DISCUSSIONS

We have calculated in detail the frequency shift of the SiO maser spectra of several typical late M–stars, and compared it with the results of the observations, see Table 1. The results of the observations come from Lane [1] and Nyman [2]. Effective temperatures of most of the stars come from Ref.[8], and effective temperatures marked "*" are derived from their classification. U Ori has not been listed since its velocity is uncertain.

The theoretical values of ΔV for $W(R) = 0.1736(R = 1.2R_*)$, and $W(R) = 0.111$ $(R = 1.5R_*)$ are given in Table 1. Results show that, on average, the redshifts obtained by our mechanism are consistent with the observations. While R increases, the redshift decreases according to formula (10). An important result of this mechanism is that the SiO spectra ($J = 1 - 0$), no matter what the value v is, have always more red shift than those of $J = 2 - 1$. For instance, when $R = 1.2R_*$, the average redshift of $J = 1 - 0$ is 2.55 km/s, and that of $J = 2 - 1$ is 1.22 km/s: They are most consistent with observational data.

Table 1

Value of Redshift

source	T	v=1 J=1-0			v=1 J=2-1			v=2 J=1-0		
·	(k)	obs. km/s	theor. km/s		obs. km/s	theor. km/s		obs. km/s	theor. km/s	
		R=	1.2R	1.5R		1.2R	1.5R		1.2R	1.5R
R Leo	2776	2.70 [1] 2.00 [2]	2.65	1.68	0.15 [1] 0.00 [2]	1.19	0.76	2.40 [1]	2.74	1.74
W Hya	2693	2.00 [1]	2.44	1.55	1.40 [1]	1.22	0.77	-.60 [1]	2.52	1.60
RCas	2710	3.20 [1] 3.00 [2]	2.48	1.57	1.45 [1] 1.0 [2]	1.23	0.78	3.40 [1]	2.56	1.63
K Tau	2687	2.90 [1]	2.71	1.53	1.75 [1]	1.20	0.76	2.45 [1]	2.51	1.89
0 Cet	2800 *	2.00 [2]	2.78	1.72	0.0 [2]	1.36	0.86	/	2.80	1.78
NML Tau	2600 *	3.00 [2]	2.18	1.39	2.0 [2]	1.09	0.69	/	2.27	1.44
R Aql	2848	/	2.84	1.80	1.0 [2]	1.41	0.90	/	2.94	1.87
T Cep	2749	/	2.58	1.63	2.0 [1]	1.29	0.82	/	2.69	1.70
TX Cam	2619	2.40 [1]	2.24	1.42	2.15 [1]	1.12	0.71	2.55 [1]	2.31	1.47

From formula (8), the frequency shift of the spectrum caused by radiation is directly related to the field intensity of the radiation. So the geometric dilution factor of the field plays an important role. Frequency shift is larger only near the star. There indeed exist observational data for SiO ($J = 1 - 0$) maser spectra which tell that the star is at a distance of $(1 - 2)R_*$ [3],[9].

VLBI observations of SiO masers show that most of them occur in the area very close to the star. Taking the late–type star "R Cas" as an example, interferrometric studies indicate that the SiO maser cluster is in $R \sim 4 \times 10^{13}$ cm. Radius of R Cas is $\sim 3 \times 10^{13}$ cm [10]. Therefore, our mechanism is reasonable. But for the SiO maser source at a distance $R > 1.5R_*$, the redshift of the spectrum (J=1-0) may be caused mainly by kinematic effects. This problem will be discussed in another paper.

Orion is the unique SiO maser in interstellar cloud observed in detail*). Its frequency characteristics are quite different from the above mases associated with late-type M stars. They consist of two simple frequency components, separated by a distance of $10^{15} \sim 3 \times 10^{16}$ cm that can be understood. Because this maser is located from the exciting star IRC2, at a distance of about hundreds of radii of the star, the geometric dilution factor is $\sim 10^{-4}$. There is hardly any radiation frequency shift.

In conclusion, we believe that the mechanism of the radiation frequency shift can become an important mechanism of redshift of the SiO maser.

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*) Recently, the SiO maser activity in the area of W511R52 and SgrB2M65 have been found by using Japanese 45 metres' Minimetre telescope.

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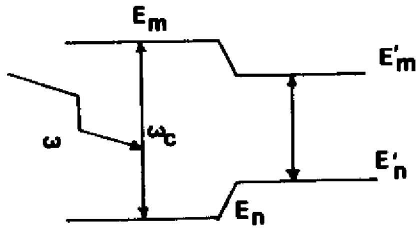

Fig. 1

The radiation frequency shift.