POLARIZATION OF THE OH RADIO-EMISSION

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We give formulae for the polarization parameters and the amplification and attenuation of coefficients of the OH resonance radiation at 1612, 1665, 1667, and 1720 MHz, when the radio waves travel through a medium containing OH radicals with arbitrarily oriented spins for the case when $\Delta\nu_{\mathrm{Dopp}} \gg \Delta\nu_{\mathrm{Zeem}} \gg \gamma$.

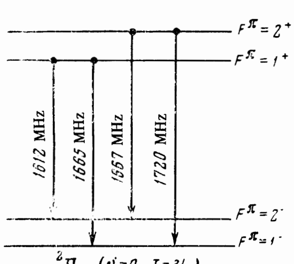
THE cosmic OH radio emission at a wavelength of $\lambda = 18$ cm possesses anomalous peculiarities which indicate the presence of coherent stimulated OH radio emission in the cosmic medium. These are manifested in an extraordinarily high intensity of the emission lines with a very narrow width, an abnormal ratio of the intensities of the multiplet components and an, as a rule, almost complete circular polarization of the components.[1-6]

The present paper deals with the problem of the passage of the resonant radio emission with frequencies 1612, 1665, 1667, and 1720 MHz through a rarefied medium which contains free OH radicals, taking the orientation of the OH spins into account. We shall assume that the populations of the corresponding sublevels of the Λ-doublet of the OH ground state[7] (see figure) are given, that is, we shall not consider the mechanism through which the inverted populations are produced.

We assume that there is a magnetic field in the medium such that 10^{-7} Oe $< H < 10^{-2}$ Oe and such that the magnitude of the Zeeman splitting of the levels considered is much larger than their energy width but much less than the Doppler width of the radio emission lines:

$$\Delta\nu_{\mathrm{Dopp}} \gg \Delta\nu_{\mathrm{Zeem}} \gg \gamma. \tag{1}$$

The system will then be symmetric with respect to the direction of **H** and the component **M** of the spin **F** along the direction of **H** will be a good quantum number. If the excitation of the OH levels is random (collisions with particles or continuous optical pumping) the density matrix characterizing the state of the particles will be diagonal in the energy. Hence, the states of the OH molecule under the conditions considered can be characterized by the populations of the sublevels $R_M(F^\pi)$, where $F^\pi = 1^\pm$ and $2^\pm$ are the spins and symmetries of the four levels of the hyperfine structure of the Λ-doublet of the ground state $^2\Pi_{3/2}(v = 0,\ J = 3/2)$ (see the figure).



In the case when the spins **F** are oriented, the attenuation and amplification coefficients of the resonance radiation, and also the refraction coefficients corresponding to them, will depend in an essential way on the direction of the line of sight and on the character of the polarization.[8,9] In such a medium two waves with orthogonal, in general elliptical, polarizations κ_+ and κ_- with different propagation velocities and different damping (or intensification) can propagate in each direction.

The (attenuation or amplification) transmission coefficients of the resonance radiation $K_\nu^\pm$ corresponding to the polarizations κ_+ and κ_- will be the following ones:

α) for the $\nu = 1612$ MHz line:

$$\frac{K_\alpha^\pm}{k_\alpha} = [1 - e^{-(h\nu/kT)_\alpha}] \mp \frac{3}{4}[\langle M\rangle_{2-} - \langle M\rangle_{1+} e^{-(h\nu/kT)_\alpha}]\cos\vartheta\cos 2\varepsilon_\alpha + \frac{1}{4}\Big[(\langle M^2\rangle_{2-} - 2) - \frac{3}{5}\Big(\langle M^2\rangle_{1+} - \frac{2}{3}\Big) e^{-(h\nu/kT)_\alpha}\Big] \times \Big(1 - 3\sin^2\vartheta\sin^2\Big(\varepsilon_\alpha \pm \frac{\pi}{4}\Big)\Big); \tag{2}$$

β) for the $\nu = 1665$ MHz line:

$$\frac{K_\beta^\pm}{k_\beta} = [1 - e^{-(h\nu/kT)_\beta}] \mp \frac{3}{4}[\langle M\rangle_{1-} + \langle M\rangle_{1+} e^{-(h\nu/kT)_\beta}]\cos\vartheta\cos 2\varepsilon_\beta - \frac{3}{4}\Big[\Big(\langle M^2\rangle_{1-} - \frac{2}{3}\Big) - \Big(\langle M^2\rangle_{1+} - \frac{2}{3}\Big)e^{-(h\nu/kT)_\beta}\Big] \times \Big(1 - 3\sin^2\vartheta\sin^2\Big(\varepsilon_\beta \pm \frac{\pi}{4}\Big)\Big); \tag{3}$$

γ) for the $\nu = 1667$ MHz line:

$$\frac{K_\gamma^\pm}{k_\gamma} = [1 - e^{-(h\nu/kT)_\gamma}] \mp \frac{1}{4}[\langle M\rangle_{2-} + \langle M\rangle_{2+} e^{-(h\nu/kT)_\gamma}]\cos\vartheta\cos 2\varepsilon_\gamma - \frac{1}{4}[(\langle M^2\rangle_{2-} - 2) - (\langle M^2\rangle_{2+} - 2)e^{-(h\nu/kT)_\gamma}] \cdot \Big(1 - 3\sin^2\vartheta\sin^2\Big(\varepsilon_\gamma \pm \frac{\pi}{4}\Big)\Big); \tag{4}$$

δ) for the $\nu = 1720$ MHz line:

$$\frac{K_\delta^\pm}{k_\delta} = [1 - e^{-(h\nu/kT)_\delta}] \pm \frac{3}{4}[\langle M\rangle_{1-} - \langle M\rangle_{2+} e^{-(h\nu/kT)_\delta}]\cos\vartheta\cos 2\varepsilon_\delta + \frac{1}{4}\Big[\frac{3}{5}\Big(\langle M^2\rangle_{1-} - \frac{2}{3}\Big) - (\langle M^2\rangle_{2+} - 2)e^{-(h\nu/kT)_\delta}\Big] \times \Big(1 - 3\sin^2\vartheta\sin^2\Big(\varepsilon_\delta \pm \frac{\pi}{4}\Big)\Big). \tag{5}$$

Here ϑ is the angle between the direction of the line of sight and the field **H**, k_ν the attenuation coefficient ($k_\nu < 0$) of the resonance radiation when the spins are not oriented and when the upper level is not populated while the total population of the lowest level $R(F^{\pi}) = \sum_M R_M(F^{\pi})$ is not changed,

$$\frac{k_\alpha}{k_\gamma}=\frac{1}{9};\quad \frac{k_\delta}{k_\beta}=\frac{1}{5};\quad \frac{k_\alpha}{k_\beta}=\frac{1}{5}\exp\left[\left(\frac{h\nu}{kT}\right)_\alpha-\left(\frac{h\nu}{kT}\right)_\beta\right]. \tag{6}$$

The spin orientation in the states F^{π} is characterized by the average value of the spin component along the direction of **H**,

$$\langle M\rangle_{F^\pi}=\frac{1}{R(F^\pi)}\sum_M M R_M(F^\pi) \tag{7}$$

and the average value of the square of the spin component,

$$\langle M^2\rangle_{F^\pi}=\frac{1}{R(F^\pi)}\sum_M M^2 R_M(F^\pi). \tag{8}$$

When the spins are not oriented $\langle M\rangle = 0$, $\langle M^2\rangle = {}^1/_3 F(F+1)$ so that in Eqs. (2) to (5) all terms depending on the polarization parameter ϵ and on the angle ϑ vanish and

$$K_\nu^+=K_\nu^-=k_\nu(1-e^{-h\nu/kT}). \tag{9}$$

The parameter $e^{-h\nu/kT}$ characterizes the ratio of the average values of the populations in the upper $\tilde{F}^+$ and lower $\tilde{F}^-$ levels:

$$e^{-h\nu/kT}=\frac{\langle R_M(\tilde F^+)\rangle}{\langle R_M(F^-)\rangle}=\frac{R(\tilde F^+)}{2\tilde F+1}:\frac{2F+1}{R(F^-)},$$
$$h\nu=\varepsilon_{\tilde F^+}-\varepsilon_{F^-}. \tag{10}$$

We note that

$$\exp\left[\left(\frac{h\nu}{kT}\right)_\beta-\left(\frac{h\nu}{kT}\right)_\alpha\right]=\exp\left[\left(\frac{h\nu}{kT}\right)_\delta-\left(\frac{h\nu}{kT}\right)_\gamma\right]. \tag{11}$$

The parameter ϵ characterizes the ellipticity of the polarization $\kappa_\pm$, $\cos 2\epsilon = (I_+ - I_-)/(I_+ + I_-)$ is the degree of circular polarization, and $\sin 2\epsilon = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)$ the degree of linear polarization.

For each direction ϑ the value of the parameter ϵ is determined by the following expressions:

α) 1612 MHz line:

$$\operatorname{ctg}2\varepsilon_\alpha=-\frac{2}{3}\frac{\langle M\rangle_{2^-}-\langle M\rangle_{1^+}e^{-(h\nu/kT)_\alpha}}{{}^1/_3(\langle M^2\rangle_{2^-}-2)-{}^1/_5(\langle M^2\rangle_{1^+}-{}^2/_3)e^{-(h\nu/kT)_\alpha}}\frac{\cos\vartheta}{\sin^2\vartheta}; \tag{12}$$

β) 1665 MHz line:

$$\operatorname{ctg}2\varepsilon_\beta=-\frac{2}{3}\frac{\langle M\rangle_{1^-}+\langle M\rangle_{1^+}e^{-(h\nu/kT)_\beta}}{(\langle M^2\rangle_{1^-}-{}^2/_3)-(\langle M^2\rangle_{1^+}-{}^2/_3)e^{-(h\nu/kT)_\beta}}\frac{\cos\vartheta}{\sin^2\vartheta}; \tag{13}$$

γ) 1667 MHz line:

$$\operatorname{ctg}2\varepsilon_\gamma=-\frac{2}{3}\frac{\langle M\rangle_{2^-}+\langle M\rangle_{2^+}e^{-(h\nu/kT)_\gamma}}{(\langle M^2\rangle_{2^-}-2)-(\langle M^2\rangle_{2^+}-2)e^{-(h\nu/kT)_\gamma}}\frac{\cos\vartheta}{\sin^2\vartheta}; \tag{14}$$

δ) 1720 MHz line:

$$\operatorname{ctg}2\varepsilon_\delta=+\frac{2}{3}\frac{\langle M\rangle_{1^-}-\langle M\rangle_{2^+}e^{-(h\nu/kT)_\delta}}{{}^1/_5(\langle M^2\rangle_{1^-}-{}^2/_3)-{}^1/_3(\langle M^2\rangle_{2^+}-2)e^{-(h\nu/kT)_\delta}}\frac{\cos\vartheta}{\sin^2\vartheta} \tag{15}$$

The value $\epsilon = \pm\pi/4$ corresponds to linear polarization. Such a state of polarization will occur, independently of the direction of the line of sight, if

$$\langle M\rangle_{F^-}/\langle M\rangle_{\tilde F^+}=(-)^{F-\tilde F+1}e^{-h\nu/kT}. \tag{16}$$

In particular, if the OH spins are aligned, but not polarized, i.e., the directions parallel and antiparallel to **H** are equivalent, $\langle M\rangle = 0$, but $\langle M^2\rangle \gtrless {}^1/_3F(F+1)$. In the general case for the polarization of the OH spins, purely linear polarization of the radiation will occur only for $\vartheta = 90°$.

The values $\epsilon = 0$ and $\epsilon = \pi/2$ correspond to right-hand and left-hand circular polarization. Such a state of polarization will exist independent of the direction of the light of sight, if

$$\frac{\langle M^2\rangle_{F^-}-{}^1/_3F(F+1)}{\langle M^2\rangle_{\tilde F^+}-{}^1/_3\tilde F(\tilde F+1)}=\frac{2F+1}{2\tilde F+1}e^{-h\nu/kT}. \tag{17}$$

In the general case circular polarization will occur only for $\vartheta = 0$ and $\vartheta = 180°$.

Since the levels of the lowest rotational-vibrational $^2\Pi_{3/2}$ and $^2\Pi_{1/2}$ bands are practically symmetry-degenerate (Λ-doublets), we may expect that states which differ only in symmetry will be excited in the same way through collisions and optical pumping with radiation with a continuous spectrum, i.e., the character and the degree of orientation of the spins in the states F^+ and F^- of the $^2\Pi_{3/2}$ band ($v = 0$, $J = {}^3/_2$) will be very close to each other:

$$\langle M\rangle_{F^+}\approx\langle M\rangle_{F^-},\quad \langle M^2\rangle_{F^+}\approx\langle M^2\rangle_{F^-}. \tag{18}$$

In that case the 1665 and 1667 MHz lines must have almost purely circular polarization, independent of the direction of the line of sight. This situation is also observed experimentally.

When $e^{-h\nu/kT} \approx 1$ the transmission coefficients for the right-hand and left-hand circular polarizations for the transitions at the 1665 and 1667 MHz frequencies will be equal in magnitude, but opposite in sign:

$$K_\nu^\pm(\vartheta)=\pm k_\nu(\langle M\rangle_{F^-}+\langle M\rangle_{F^+})\cos\vartheta, \tag{19}$$

i.e., the radiation with one of the polarizations will be attenuated, while the other one will be amplified so that radiation which is originally unpolarized will obtain a high degree of circular polarization, when passing through such a medium.

Our assumptions about the orientation (polarization) of the OH spins enable us not only to explain the preponderantly circular polarization of the radiation at the frequencies 1665 and 1667 MHz, but also enable us to understand how the ratios of the intensities of the components in the various sub-sources differ enormously and even change sign (absorption instead of emission). This, of course, is explained by the difference in optical thickness and, principally, by differences in the direction of the line of sight and in the degree of orientation of the spins.

The transmission coefficients of the resonance radio emission for different lines of the multiplet are connected with one another. In particular when ϑ is different from 0, 90, or 180° they satisfy (taking their sign into account) the following relations:

$$(K^++K^-)_{1612}+{}^1/_{25}(K^++K^-)_{1665}+{}^1/_9(K^++K^-)_{1667}+(K^++K^-)_{1720}={}^{12}/_{25}k_\beta(1-e^{-(h\nu/kT)_\beta})+{}^4/_9k_\gamma(1-e^{-(h\nu/kT)_\gamma}), \tag{20}$$

$$(K^++K^-)_{1612}-{}^1/_5(K^++K^-)_{1665}-{}^1/_9(K^++K^-)_{1667}+(K^++K^-)_{1720}=(1-{}^3/_2\sin^2\vartheta)\{{}^9/_{25}k_\beta[(\langle M^2\rangle_{1^-}-{}^2/_3)-(\langle M^2\rangle_{1^+}-{}^2/_3)e^{-(h\nu/kT)_\beta}]+{}^1/_9k_\gamma[(\langle M^2\rangle_{2^-}-2)-(\langle M^2\rangle_{2^+}-2)e^{-(h\nu/kT)_\gamma}]\}. \tag{21}$$

For the circularly polarized components the transmission coefficients satisfy the relation

$$(K^+-K^-)_{1612}+{}^1/_5(K^+-K^-)_{1665}-{}^1/_3(K^+-K^-)_{1667}+(K^+-K^-)_{1720}=0. \tag{22}$$

Equations (20), (21), and (22) remain valid for any angle ϑ, if the polarization parameters ϵ are the same for all lines of the multiplet.

If the OH spins are not oriented, we have, independently of the direction of the line of sight

$$K^{+}=K^{-};\quad {}^{1}/_{5}K_{1665}+{}^{1}/_{9}K_{1667}=K_{1612}+K_{1720}. \tag{23}$$

The fact that as a rule Eq. (23) is not found to be satisfied observationally can be caused by an orientation of the OH spins. Of course, that (23) is not satisfied may be connected also with an averaging over the solid angle and over the line of sight.

An orientation of the OH spins may lead to the fact that the transmission coefficient will be positive ($K_\nu > 0$), as can be seen from (2) to (5), i.e., the resonance radiation when passing through the medium may be amplified rather than attenuated, even in the case when the average population of the upper level does not exceed the average population of the lower level, i.e., $e^{-h\nu/kT} \leq 1$.

A number of specific peculiarities of the cosmic OH radio emission can thus be explained by the orientation (polarization) of the OH spins, i.e., by the specific population of the magnetic sub-levels which may occur either as a result of collisions and chemical reactions or as a result of the interaction of the OH with radiation. We emphasize that the propagation through the medium of the polarized resonance radio emission itself must lead to an orientation of the spins of the particles in the medium. The initial polarization of the radio emission may be caused by the compression (or expansion) of the amplifying medium when there is a weak magnetic present which is such that

$$\frac{\Delta\nu_{\text{Zeem}}}{\nu}\sim\frac{dv}{dx}\frac{L}{c} \tag{24}$$

where dv/dx is the velocity gradient, L the size of the amplifying medium, and c the velocity of light.

We note in conclusion that the relations given above which establish a connection between the orientation of the OH spins and the attenuation, and amplification, coefficients, and the polarization of the resonance radio emission which passes through this medium may also be of interest both for radio-astronomy, and for radio-spectroscopy.

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76