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PROPAGATION OF SHORT ELECTROMAGNETIC PULSES THROUGH NONCONDUCTING MEDIA WITH ELECTRIC AND MAGNETIC DIPOLE CURRENTS

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Propagation of electromagnetic signals through a non-conducting medium with very low density of neutral gas is considered with taking into account both electric and magnetic dipole currents. A new approach based on microscopic description of the medium and analytical solution of Maxwell equations in time domain has been used to solve the problem. The time delay between the signal precursor and its main lobe evaluated may be used for evaluation of either distance to a pulsar for the known medium parameters or those parameters for a given distance to the pulsar.

In the paper, we present some results of our investigations on propagation of EM signals through interstellar medium. The medium is considered within the frame of *microscopic* model using description of hydrogen atom as a combination of electric and magnetic dipoles. Those dipoles produce electric and magnetic dipole currents under the electromagnetic field action that is to be calculated in a self-consistent way. We describe the model under consideration and obtaining of the partial differential equation for one of the EM field components, as well as formulation of initial-boundary value problem for that equation and the method for its solution in time domain.

Propagation of EM waves is governed by Maxwell equations. However, those equations should be modified according to the media properties where EM waves propagate. In the case under consideration, EM signals have to propagate through the medium consisting of atomic hydrogen gas with a very low density. Since the atoms are neutral and signals are supposed to be rather weak they cannot carry an electric monopole current, but only dipole currents. Electric field strength will pull the positive proton and the negative electron slightly apart and produce an electric dipole. A dipole current flows while this pulling apart is in progress and also when the electric field strength drops to zero and the hydrogen atom returns to its original, non-polarized state. Similarly, the hydrogen atom has a magnetic momentum like a little bar magnet. A magnetic field strength will rotate the atoms to make them line up with the field strength. A magnetic dipole current flows while this rotation is in progress and also when the magnetic field strength drops to zero and the magnetic dipoles return to their original random orientation. So, we have to take into account the reaction of the medium onto the action of the EM field of the propagating signal. Conventional approaches to solution of that problem suppose that both intrinsic characteristic time of the media and its relaxation time are much smaller the characteristic time of the EM field variation. Besides, they also suppose performing of space averaging of the EM fields introducing into consideration both electric and magnetic flux densities. Since in our case we have both very low density of the neutral atomic hydrogen and very fast variation of the EM signal fields those methods are not applicable anymore. In order to solve the problem we modify Maxwell equations for "empty space" using both electric and magnetic dipole current densities rather then electric and magnetic flux densities [1]. This implies description of the medium in the frame of *microscopic* approach using representation of a hydrogen atom as a combination of electric and magnetic dipoles. Those dipoles produce *electric and magnetic dipole currents* under the EM field action that is to be calculated in a self-consistent way. Self-consistent system containing both Maxwell equations and equations for the dipole current densities evolution under the EM field action can be written in the following form [1]:

$$-\operatorname{rot}\vec{E} = \mu\frac{\partial\vec{H}}{\partial t} + g_m;\ \ \operatorname{rot}\vec{H} = \varepsilon\frac{\partial\vec{E}}{\partial t} + g_e;\quad \varepsilon\operatorname{div}\vec{H} = \mu\operatorname{div}\vec{H} = 0\ ; \tag{1}$$

$$\begin{aligned} &\vec{g}_e + \tau_{mp}\frac{\partial\vec{g}_e}{\partial t} + \frac{\tau_{mp}}{\tau^2}\int\vec{g}_e dt = \sigma_p\vec{E}\ ;\\ &\vec{g}_m + \tau_{mp}\frac{\partial\vec{g}_m}{\partial t} + \frac{\tau_{mp}}{\tau^2}\int\vec{g}_e dt = 2\sigma_p\vec{H}\ ; \end{aligned} \tag{2}$$

$$\sigma_p = \frac{N_0 e^2 \tau_{mp}}{m};\ s_p = \frac{N_0 q_m^2 \tau_{mp}}{m};\ q_m = \frac{\mu m_{m0}}{2R};$$

where $\vec{E}$ and $\vec{H}$; g_e and g_m; σ and s_p; e and m; m_{m0} and q_m are electric and magnetic fields; dipole electric and magnetic current densities; electric and magnetic dipole current conductances; permittivity and permeability of the vacuum; charge and mass of electron; magnetic dipole moment and fictitious magnet charge, respectively; τ_{mp} and τ are the relaxation time and period of eigen-frequency of the dipoles-oscillator used as the model for atomic hydrogen.

Let consider a planar, transverse electromagnetic (TEM) wave propagating through such medium along the direction y. A TEM planar wave requires

$$E_y = H_y = 0;\ E_x = E_z = E;\ H_x = -H_z = H.$$

With this simplification, the above system of partial integro-differential equations is reduced to the sixth order linear PDE for either electric E or magnetic H field component [1]. In order to investigate propagation of EM signal through the above medium one have to solve initial-boundary-value problem for that equation with the following initial $(t = 0)$

$$E(y,0) = \frac{\partial^n E(y,0)}{\partial t^n} = \int \frac{\partial^2 E}{\partial t^2} dt = \iint \frac{\partial^2 E}{\partial t^2} dt dt' \quad (3)$$
$$n = 1,2,3$$

and boundary $(y = 0)$ conditions:

$$E(\infty,t) = \text{finite};\ E(0,t) = E_0 S(t)(1 - e^{-t/\tau_s}),$$

where $S(t) = \begin{cases} 0, & \text{for } t > 0 \\ 1, & \text{for } t < 0 \end{cases}$.

The above problem is solved [1] by the variables separation method. The solution has the following form:

$$E(y,1) = E_0\left[w(y,t) + e^{-\left(y/L + t/\tau_s\right)}\right], \quad (4)$$

$$w(y,t) = \int_0^\infty \left(\sum_{i=1}^{6} A_i(k) e^{\gamma_i(k)t/\tau_{mp}}\right) \sin(2\pi k y)\, dk,$$

where k is the separation constant; $\gamma(k)$ are six roots of characteristic equation for PDE derived from Eq. (1),(2); $A_i(k)$ are six constants to be determined by six initial conditions (3). The expressions for $L(\tau,\tau')$, $\gamma(k)$ and $A_i(k)$ have an explicit, but rather complicated form and can be found in the monograph [1]. Here we only note that because of the higher symmetry of the modified Maxwell equations (1) we were able to find analytical solutions for the sixth order characteristic equation. This enabled us of both performing of the Eq. (4) integrand analysis as function of k and developing efficient algorithms for numerical evaluation of the electric and magnetic fields of propagating signals.

Solutions of that equation for various combinations of the interstellar medium parameters and initial signal-like E-field distributions are presented in the monograph [1]. Behavior of both signal main lobe and its precursor for various EM signals, such as exponential step function, sinusoidal and rectangular pulses when they are propagating over Billions light years distance are studied in [1].

In particular, time delay between the signal precursor and its main lobe is calculated as function of medium parameters. This may be used for evaluation of either distance to a pulsar for the known medium parameters or those parameters for a given distance to the pulsar.

References

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РАСПРОСТРАНЕНИЕ КОРОТКИХ ИМПУЛЬСОВ ЧЕРЕЗ НЕПРОВОДЯЩИЕ СРЕДЫ С ЭЛЕКТРИЧЕСКИМ И МАГНИТНЫМ ДИПОЛЬНЫМИ ТОКАМИ

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Распространение электромагнитных сигналов через непроводящую среду нейтрального газа с очень низкой плотностью рассмотрено с учетом электрических и магнитных дипольных токов. Для решения этой задачи использован подход, основанный на микроскопическом описании среды и аналитическом решении уравнений Максвелла во временной области. Рассчитанная задержка между предшественником и главным лепестком сигнала может использоваться для оценки либо расстояния до пульсара при известных параметрах среды, либо параметров среды для известного расстояния до пульсара.

РОЗПОВСЮДЖЕННЯ КОРОТКИХ ІМПУЛЬСІВ У СЕРЕДОВИЩАХ З ЕЛЕКТРИЧНИМИ І МАГНІТНИМИ ДИПОЛЬНИМИ СТРУМАМИ

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Розповсюдження електромагнітних сигналів через непровідне середовище нейтрального газу з дуже низькою густиною розглянуте з урахуванням електричних та магнітних дипольних струмів. Для розв'язання цієї задачі використано підхід, що базується на мікроскопічному опису середовища та аналітичному розв'язку рівнянь Максвелла в часовій області. Розрахована затримка між попередником та головною пелюсткою сигналу може використовуватись для оцінки або відстані до пульсара при відомих параметрах середовища, або параметрів середовища для відомої відстані до пульсара.