On propagation of electromagnetic and gravitational waves in the expanding Universe

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Abstract. The purpose of this study was to obtain an equation for the propagation time of electromagnetic and gravitational waves in the expanding Universe. The velocity of electromagnetic waves propagation depends on the velocity of the interstellar medium in the observer's frame of reference. Gravitational radiation interacts weakly with the substance, so electromagnetic and gravitational waves propagate from a remote astrophysical object to the terrestrial observer at different time. Gravitational waves registration enables the inverse problem solution - by the difference in arrival time of electromagnetic and gravitational-wave signal, we can determine the characteristics of the emitting area of the astrophysical object.

The propagation time of electromagnetic radiation depends on the result of superposition of the source electromagnetic wave and secondary waves arising from the interaction between the primary wave and moving atoms of the medium.

Moving off the emitting astrophysical object from the observer leads to Doppler shift of frequency radiation in an expanding area, which is related to the movement of the space area where the object is located [1].

The spread of electromagnetic radiation in the interstellar medium of the expanding Universe will lead to a further time delay in light signals propagation.

We obtain an equation for electromagnetic wave propagation taking into consideration movements of the interstellar medium. Consider Robertson-Walker metric [2]

$$d\tau^2 = dt^2 - R^2(t)\left\{\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 sin^2\theta d\varphi^2\right\}. \tag{1}$$

Here r, θ, φ, t are the coordinates, $R(t)$ is the cosmological scale factor, k is the spatial curvature, $R(t) = R_0/c$, R_0 is the common distance.

The equation for propagation of electromagnetic and gravitational-wave signal along the radial direction can be obtained from (1) when $d\theta = d\varphi = 0$

$$d\tau^2 = dt^2 - R^2(t)\left\{\frac{dr^2}{1-kr^2}\right\} = 0. \tag{2}$$

The expression for the invariant proper time is given by [3]

$$d\tau^2 = (1-\beta_e^2)dt^2, \tag{3}$$

where $\beta_e = v/c$, v is the group velocity of electromagnetic waves, c is the speed of light in vacuum.

If we equate this expression to the element of Robertson-Walker length (2), we obtain

$$\int_{t_1}^{t_0} \frac{dt}{R(t)} = \int_0^{r_1} \frac{1}{\beta_e(r,t)} \frac{dr}{\sqrt{1-kr^2}}. \tag{4}$$

Here t_1, t_0 are the moments of radiation and registration time, measured from the singular state, r_1 is dimensionless distance to the source of space radiation in the Earth's ISO. Before the

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integral on the right, the positive sign is chosen, which corresponds to the phase of the Universe expansion.

Since the cosmological expansion can be slowed down with time, the group velocity of the electromagnetic wave depends on t.

The dependence of the relative velocity of the interstellar medium on the coordinate along the light propagation path concerning the terrestrial observer, has the form

$$\beta_n(r,t) = \frac{\dot{R}(t)}{cR(t)}(r - r_1), \tag{5}$$

where r is the current radial coordinate. The parameter R with $k = 1$ can be characterized as the Universe radius. In the point of time $t = 0$ the radius $R = 0$, so the current time t_0 is the time measured from this singularity, and it can be called the age of the Universe.

The relative velocity of moving off the emitting astrophysical object without taking into account the speed of the object in the local area of expanding space equals

$$\beta(t) = -r_1 \frac{\dot{R}(t)}{cR(t)}\,. \tag{6}$$

In the expanding Universe any kind of $R(t)$ at the expansion stage will increase the difference $t_0 - t_1$. This will lead to the same time delay of the light and gravitational signal arrival.

To estimate the effect of the interstellar medium motion, let us consider the properties of the integral on the right in (4).

Consider i - medium layer when the motion of the interstellar medium is directed opposite the wave vector of the electromagnetic wave. The phase velocity of radiation propagation in a moving medium can be found from the solution of the dispersion equation [4]. We introduce the following symbols:

$$y_i^{-2} = 1 - \beta_{in}^2, \qquad k_i = \varepsilon_i\mu_i - 1, \qquad \beta_{in} = \frac{u_{in}}{c}, \qquad \beta = \frac{V}{c}.$$

Here, the values u_{in} characterize normal and tangential velocity components, ε_i, μ_i are dielectric and magnetic permeability of i layer in the observer's ISO, V is the velocity of the radiation source motion in the observer's ISO, c is the velocity of a plane monochromatic electromagnetic wave in vacuum.

Consider the case when $\beta = 0$ for i - layer of the medium, when the interstellar medium motion is directed opposite the wave vector of the electromagnetic wave. For a terrestrial observer the phase velocity of electromagnetic wave propagation in the i - moving medium layer corresponds to

$$v_i = c\frac{1 - k_i\gamma_i^2\beta_{in}^2}{-k_i\gamma_i^2\beta_{in} + \sqrt{1 + k_i}}\,. \tag{7}$$

Assuming the function $v(r)$ to be continues for the signal propagation time, from (4) we obtain

$$\int_{t_1}^{t_0} \frac{dt}{R(t)} = \int_0^{r_1} \frac{-k_i y_i^2\beta_{in} + \sqrt{1 + k_i}}{1 - k_i y_i^2\beta_{in}^2}\frac{dr}{\sqrt{1 - kr^2}}\,. \tag{8}$$

As the interaction of gravitational radiation with the medium is negligibly small, the propagation time of a gravitational-wave signal will also be determined by (8), but when $\beta_e(r,t) = 1$.

Registration of relic cosmological gravitational waves would make it possible to determine the dependence of the scale factor on the time $R(t)$ [5].

Analysis of the integral equation kernel shows that the interstellar medium and the emitting area medium of the star can make a substantial contribution to the effect of time delay of light propagation.

We can also take into account that $n = \sqrt{\varepsilon\mu} = n(r,t)$ is the refractive index of the inter-galactic medium and it depends on t, as in the expanding Universe the medium density changes with time.

Registration of gravitational waves could help to solve the inverse problem - according to the time difference in arrival of the electromagnetic and gravitational-wave signal, we can determine the characteristics of the emitting area of the astrophysical object.

Let us deal with the experiment when we measure the registration time of SN1987A burst of radiation by means of neutrino and gravitational-wave detectors. With the help of spaced detectors [6, 7] used in this experiment, we measured an abnormally long signal registration time delay. The burst was registered by the gravitational antennas in Maryland and Rome, as well as by the neutrino detector in Monte Blanco, which is bound to Greenwich Mean Time. Detector reading is correlated for 2 hours with a 1.1 second signal lag recorded by the neutrino detector.

The measured registration time delay of a signal propagating with the speed of light in a vacuum in any ISO is a consequence of different propagation velocity of the neutrino and gravitational signals. From the above analysis, we make a conclusion that the determination of the cosmological distance must take into account the effect of the light propagation delay in a moving medium.

References

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