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THE EFFECT OF MASS ON A FREQUENCY

by

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ABSTRACT

Two experiments are described in which the influence of a mass on the frequency of a spectral line was measured. In the first experiment, the 21 cm line from Taurus A was detected when the sun approached the line of sight. A decrease of the frequency of the line was detected which indicated that the frequency decrease was caused by the presence of the mass. The second experiment confirmed this indication as it showed a decrease of the frequency of a cesium beam oscillator as it was affected by the earth's mass. This effect does not disagree with the observed cosmological red shift and not with other relevant experiments.

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Two known effects can change the frequency of a spectral line: the Doppler effect and the gravitational red shift. Because so much importance is attached to the frequency of lines coming from stars and galaxies, we tried to devise and perform experiments that can disclose further influences on the frequency of a line. This note describes experiments aimed at finding the effect of mass on the frequency of light passing near the mass.

The Taurus A Experiment

During the annual approach (every June) of the radio source Taurus A to the sun, one can measure whether the 21-cm absorption line from Taurus A changes frequency. Such an experiment was performed by us(1), and the results indicate a red shift of the frequency when the optical path approaches the sun. As indicated in Ref. 1, the general theory of relativity predicts a shift in frequency of approximately 0.1 Hz in this case, but the shift found (approximately 150 Hz) is much larger. This experiment was not conclusive because of big error bars and uncertainty concerning the effect of the sun's radio radiation on the receiver.

The Cesium Clock Experiment

If the Taurus A experiment showed a true change in frequency or, in other words, if the frequency decreases when a mass is near the path of the light, such a decrease must manifest itself for an experiment on the surface of the earth.

It is sound logic to assume that if a mass affects the frequency, the effect will be greater the longer the rays are under the influence of the mass. This means that if a well-defined frequency is sent from a station on earth, it is affected by the nearby masses (the earth, the moon, and the sun) as it travels to another station on earth. The receiving station, according to our assumption, will record a frequency $f_o - \Delta f$, where Δf depends on the distance d from the first station. To check the dependence of Δf on d one can move the receiver and measure Δf at each of several locations.

For this experiment we used cesium beam oscillators ($f = 9.1 \times 10^9$ Hz). An oscillator of this type is used at the Naval Observatory, Washington, D.C., for very accurate timekeeping. As no two of these clocks have exactly the same frequency, an electronic comparison between two clocks tells what their frequency difference is. The relative long-term precision of this comparison is better than one part in 10^{13}. Increasing the distance between the two clocks, transmitting the pulses from one clock to the other, one can compare whether their frequency difference changes with distance. The transmitting and receiving system is the Loran C system with the original cesium frequency reduced to 100 KHz. The pulses can be detected hundreds of miles from the transmitter; only ground waves can be detected, and no ionospheric reflections can occur[(2)].

On June 12, 1967, we started comparing at Cape Fear, N.C., a portable cesium clock (called PC9) with the master cesium clock situated at Cape Fear. The comparison of both clocks at the same location provided a calibration and showed that the master clock at Cape Fear was higher in frequency than the portable clock by $\Delta f/f = 6.9 \times 10^{-12}$. Using exactly the same instrumentation we now moved the receiver 566 kilometers from the transmitter (to Washington, D.C.) and found that the difference was only 4.5×10^{-12}. This means that the frequency decreased by 2.5×10^{-12} while traveling the 566 kilometers. To conclude that this decrease actually occurred while the signal was traveling is justified only after carefully checking all other possibilities. The master clock's frequency itself, as monitored by other receivers at several localities during the experiment, did not change. Nothing happened to the portable clock while traveling, as its frequency was monitored by another portable clock and no change in the difference between them was detected. Only if both of them changed their frequency in the same direction and magnitude would this not be a good test. The experiment was repeated by going to Jacksonville, Florida (810 kilometers from Cape Fear).

The results given in Table 1 show that the farther we go the more the frequency decreased. The last column in the table gives the result of a higher precision experiment. In this experiment we used a new improved cesium beam clock (No. 208) which was introduced as a master clock at Cape Fear. Before it was shipped to Cape Fear it was compared with the 140 master clock of the Naval Observatory for two weeks. When at Cape Fear it was monitored in Washington and compared to the 140 for two weeks. The result shows a decrease of frequency of $\Delta f/f = 2.52 \times 10^{-12} \pm 1 \times 10^{-13}$.

Table 1 - Results of the Cesium Clock Experiment

Distance From Master Clock (km)	Red Shift, $-\Delta f/f$	
	Clock PC9	Clock 208
520	$(2.5 \pm 1) \times 10^{-12}$	-
566	$(3 \pm 1) \times 10^{-12}$	$(2.5 \pm 0.1) \times 10^{-12}$
810	$(6 \pm 1) \times 10^{-12}$	-

Neither the Doppler shift nor the gravitational red shift can explain this decrease in frequency. Because there is no relative motion between the receiver and the transmitter, no Doppler effect can occur except for the transverse Doppler effect. As the earth rotates, a point at Cape Fear, N.C., has a lower velocity than a point at Jacksonville, Florida, 520 km south of Cape Fear. The transverse Doppler effect is proportional to $(\Delta v)^2/c^2$ and amounts in our case to $\Delta f/f = 6 \times 10^{-15}$, which is much smaller than what was found. The gravitational red shift also predicts an effect much smaller than the one found. All four locations are at approximately the same gravitational potential; they are all at sea level and thus on the same geoid. (If one wants to use these clocks to measure the gravitational red shift, a transmitter at sea level and a receiver on top of a 10,000-foot mountain will give a shift of only $\Delta f/f = 4 \times 10^{-13}$.)

The frequency shift recorded in this experiment could not be caused by changes of temperature, humidity, or magnetic field. Tests performed show that even larger changes than those that actually occurred did not change the frequency by a measurable amount.

Discussion

Can the oscillator experiment and the Taurus A experiment have the same cause? If we assume that there is a decrease in frequency when electromagnetic waves are traveling near a mass and that the decrease is proportional to the mass M, to the distance traveled X and inversely proportional to the square of distance, then for each point on the path

$$-\Delta f/f = K_1 \frac{MX}{r^2}$$

(where the minus sign means that the change is always a decrease).

For the whole path

$$-\Delta f/f = K_1 M \int_{-\infty}^{\infty} \frac{dX}{r^2} = K_1 M \int_{-\pi/2}^{\pi/2} \frac{d\theta}{a} = 2\ KM\ \pi/2a$$

The constant K_1 (dimensions $\frac{cm}{gr}$) can be determined from the Taurus A experiment

$$\frac{150}{1.4 \times 10^9} = \Delta f/f = K_1 M_S\ \pi/5R_S$$ (M_S, R_S are mass and radius of the sun.)

$$K_1 = (6 \pm 3) \times 10^{-30}\ cm/gr \qquad (3)$$

(The gravitational constant G divided by the square of the velocity of light has the same dimensions and equals to 7.4×10^{-29} thus we can replace K_1 by $K_2\ g/c^2$ where $K_2 = 0.08$.)

If we now calculate the decrease in frequency that should occur in the oscillator experiment on the 566 Km from Cape Fear, N. C. to Washington, D. C.

$$-\Delta f/f = K_1 m \int_0^{566} \frac{dX}{r^2} = \frac{6 \times 10^{-30} \times 6 \times 10^{27}\ \ 5.66 \times 10^7}{(6.37 \times 10^8)^2} =$$

$$= (5 \pm 2.5) \times 10^{-12}$$

m = the earth's mass, r - the earth's radius.

This frequency shift is very close to the 2.5×10^{-12} found in the experiment regarding the accuracy of our experiments.

If the relation $-\Delta f/f = K_1 m \int \frac{dX}{r^2}$ is true there should be a red shift for light coming from a galaxy as it passes by other galaxies. Let us calculate the amount of this red shift and compare it with the cosmological red shift. As every mass, no matter how remote, affects the frequency of a line one has to integrate over all the masses of the universe.

$$-\Delta f/f = K_1 M \int^{\text{all galaxies}} \frac{dn}{r^2}$$

where n is the number of galaxies in the universe, and M the mass of one galaxy. For a close Euclidian universe $n = 4/3\ \pi r^3\ C_1$ (C_1 the density of galaxies). Then for a unit distance the red shift is $-\Delta f/f = 4\ K_1 \pi C_1 M \int_0^{Ro} dr = 4\ K_1 \pi C_1 M R_o$. The total red shift for light that traveled R cm is $-\Delta f/f = 4\ K_1 \pi C_1 M R_o R$. As $C_1 M$ is the density of matter in the universe and is equal to approximately 10^{-31} gr/cm^3 the red shift for a light coming from a galaxy megaparsec away (3×10^{24} cm) is according to the present effect $\Delta f/f = 6 \times 10^{-31} \times 4 \times \pi \times 3 \times 10^{24} \times 10^{28} = 2.2 \times 10^{-8}$ assuming $R_o = 10^{28}$ cm. The cosmological red shift found experimentally is $\Delta f/f = 3.3 \times 10^{-4}$ for megaparsec. Although the present effect is linear with distance as the cosmological red shift is, it can only be responsible for one part in 10^4 of the total effect. Only if one assumes that the radius of the universe Ro is much larger than the observable universe, (or that density of matter is larger), can the present effect explain the cosmological red shift. As it stands now the effect does not disagree with observations.

Two other experiments have to be discussed in view of the present results. Lines emitted from the sun should be red shifted by the gravitational red shift by $\Delta f/f = 2.0 \times 10^{-6}$ and by additional $\Delta f/f = 2.7 \times 10^{-7} \mp 1.3 \times 10^{-7}$ according to the present effect.[4] The experiment[5] shows that this additional effect is within the experimental errors. The radar reflection experiment described by I. I. Shapiro et al.[6] is also within his and our experimental errors. According to the present effect a decrease of frequency of $\Delta f/f = 2.8 \times 10^{-9}$ should occur in addition to the Doppler shift measured. The error quoted in ref. 6 shows Δf of 2Hz out of 1.29×10^{9} Hz $\Delta f/f = 1.5 \times 10^{-9}$. It should be stress that there is a difference between the experiments mentioned in the present note and this last experiment. This radar experiment measures the frequency on a round trip as for the rest of them it is a one way experiment and we do not know apriori if the same relationship holds for the round trip.

References

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