Of fundamental electrodynamics and astrophysics

MAXWELL's equations are well established for phenomena on laboratory and terrestrial scales, but there are other electrodynamic theories, as yet indistinguishable on such scales from Maxwell's theory, that have significantly different consequences for phenomena on an astronomical scale. For example, extensive magnetic fields are possible in the Universe[1] because of the general absence of magnetic monopoles. Parker[1] considered the abundance of magnetic monopoles that would neutralise or dissipate the magnetic fields of the Earth, Sun and the Galaxy, and deduced for the number density of free magnetic monopoles upper limits that are more stringent than those deduced from laboratory and terrestrial data.

Another example of electromagnetic equations that might be relevant to the description of astrophysical phenomena are the Proca equations, which may be interpreted in terms of a non-zero photon rest mass. A consequence of the Proca equations is that static electric and magnetic fields in free space decay exponentially with distance from the source: for phenomena on scales comparable with or exceeding the characteristic length for decay, the description provided by the Proca equations departs from that provided by the Maxwell equations. In static space–time the Proca equations, like the Maxwell equations, predict that electromagnetic waves propagate with fixed frequency; contrary to what has been claimed[2,3], the Proca equations do not form a basis for the 'tired-light' interpretation of the cosmological redshift.

Laboratory and terrestrial experiments have determined[4] that the photon rest mass, m, is less than about 3×10^{-48} g; astrophysical considerations have led to an improvement by about four and a half orders of magnitude[5]. Here, we obtain an upper limit on m from consideration of the Proca equations and the mass of the Galaxy.

The Proca equations show that $(\mathbf{E}^2+\mathbf{H}^2+\mu^2\varphi^2+\mu^2\mathbf{A}^2)/8\pi$ can be interpreted as the energy density of the electromagnetic field[4]; $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic fields, φ and $\mathbf{A}$ are the scalar and vector potentials and $\mu^{-1} = h/2\pi mc$, where μ^{-1} is the reduced Compton wavelength of the photon, h is Planck's constant and c is the relativistic limiting speed. If ρ denotes an upper limit on the mean mass density of matter and energy in all forms that could exist in a region of space in which a magnetic field is observed, the $\mu^2\mathbf{A}^2/8\pi c^2 \lesssim \rho$. The relationship $\mathbf{H} = \Delta \times \mathbf{A}$ shows that $|\mathbf{A}| \sim |\mathbf{H}|L$ where, for an approximately uniform magnetic field, L is of the order of the smallest dimension. Thus, the above inequality leads to

$$\mu^2 \lesssim 8\pi\rho c^2/\mathbf{H}^2L^2 \tag{1}$$

The Galactic magnetic field in the vicinity of the Sun has been observed[6] to have a strength of about 2×10^{-6} gauss and is approximately uniform over a distance of at least 300 pc, so that in the Galactic disk L may be estimated as greater than about 10^{20} cm. The masses of galaxies may be estimated from their rates of differential rotation and from the orbital velocities of binary systems; it has been deduced[7] that for many galaxies the mass exceeds the total mass of known stars by an order of magnitude. The mass of the Galaxy is often quoted[8] at about $10^{11}M_\odot$ so that $10^{12}M_\odot$ is a conservative upper limit on the mass of the Galactic disk. Thus, using the dimensions given by Allen[8], $\rho \lesssim 10^{-21}$ g cm^{-3} for the Galactic disk. Assuming that the interstellar magnetic field in the vicinity of the Sun is typical of magnetic fields of the Galactic disk, equation (1), with $|\mathbf{H}| \sim 2\times10^{-6}$ gauss, $L \gtrsim 10^{20}$ cm and $\rho \lesssim 10^{-21}$ g cm^{-3}, leads to $\mu \lesssim 3\times10^{-14}$ cm^{-1}, corresponding to $m \lesssim 10^{-51}$ g. This limit is not far from the best available upper limit[5] of 10^{-55} g.

In interstellar space the energy densities resulting from radiation from stars, turbulent gas motions, universal background radiation and cosmic rays are all of a similar order of magnitude to the Maxwellian energy density. $\mathbf{H}^2/8\pi$, associated with the magnetic field[8]; if $m \sim 10^{-52}$ g, then the energy density $\mu^2\mathbf{A}^2/8\pi$ exceeds these energy densities by 11 or more orders of magnitude. It may well be that the upper limit of 10^{-52} g could be improved by consideration of the possible sources of the energy density, $\mu^2\mathbf{A}^2/8\pi$, associated with large scale magnetic fields and of instabilities that may result from this energy density. Conversely, it is worth bearing in mind that large energy densities associated with large scale magnetic fields and a non-zero photon rest mass could be significant in some astrophysical processes.

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1 Parker, E. N., *Astrophys., J.*, **160**, 383–404 (1970).
2 Yourgrau, W., and Woodward, J. F., *Acta phys. hung.*, **30**, 323–329 (1971).
3 Weinstein, D. H., and Keeney, J., *Nature*, **247**, 140 (1974).
4 Goldhaber, A. S., and Nieto, M. M., *Rev. mod. Phys.*, **43**, 277–296 (1971).
5 Byrne, J. C., and Burman, R. R., *J. Phys., A*, **6**, L12–L14 (1973).
6 Manchester, R. N., *Astrophys., J.*, **188**, 637–644 (1974).
7 Einasto, J., Kaasik, A., and Saar, E., *Nature*, **250**, 309–310 (1974).
8 Allen, C. W., *Astrophysical Quantities*, 3rd ed. (Athlone Press, London, 1973).

Oblique rotators in binary systems

RADIO pulsar PSR1913+16, which has a period of about 59 ms, has been identified as a member of a binary system[1]. The X-ray 'oscillars' HerX-1 and CenX-3, which are also members of binary systems, are not radio pulsars. (I use the word 'oscillars' to distinguish these objects from pulsars, which maintain their periodicity much more accurately). These facts, together with the 34-d periodicity[2,3] of HerX-1 and the lack of this periodicity in CenX-3, can be explained by using the rotating neutron star hypothesis for the compact object in all of these systems. As is common in pulsar theories, I assume that rotating neutron stars are oblique rotators, that they have magnetic fields and that the magnetic axes are not along the axes of rotation.

An oblique rotator, with a magnetic field, B, a period of rotation, P, and radius, R, gives out low frequency radiation with energy[4]:

$$E \simeq 10^{-28}B^2R^6/P^4 \text{erg s}^{-1}$$

Using $B \sim 10^{12}$ gauss, R $\sim 10^6$ cm and a period, P, of 59 ms, PSR1913+16 gives out about 5×10^{37} erg s^{-1} of low frequency radiation. This is quite close to the Eddington limit and can equal it with only a slight variation of B or R. Radiation of this intensity opens the equipotential lines near the first Lagrangian point[5], and accretion of matter from the binary companion is thus prevented. The radio emission, which is attributed to a polar phenomenon[6] can, therefore, occur without interference from accreting matter. The lack of accretion prevents PSR1913+16 from becoming an X-ray oscillar like HerX-1 or CenX-3. On the other hand, PSR1913+16 could be an X-ray pulsar like NP0532, but with considerably smaller flux.

HerX-1 has an X-ray periodicity of 1.24 s and if this is attributable to the rotation period of the neutron star, the low frequency radiation emitted is about 5×10^{31} ergs s^{-1}. CenX-3 has a period of 4.8 s and gives out about 2×10^{29} erg s^{-1}.