COSMIC TESTS OF MAXWELL’S EQUATIONS

I: A Photon Rest Mass

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Abstract. Maxwell’s equations are usually assumed for cosmic electrodynamics, although they have not been adequately tested and shown to be applicable. Tradition is the main justification for using them. Other electromagnetic theories exist which are of similar antiquity to Maxwell’s theory; they have been thoroughly tested for laboratory and terrestrial physics and shown to have consequences indistinguishable from Maxwell’s equations for phenomena that occur on these scales. But Maxwell’s equations and the alternative theories can provide fundamentally different descriptions of cosmic phenomena. In this paper we examine the possibility that the photon has a non-zero rest mass. In part II of the series it is intended to examine the evidence for the existence of magnetic monopoles.

Terrestrial experiments have shown that the rest mass \( m \) of the photon is less than \( 3 \times 10^{-48} \text{ g} \), or alternatively that the reduced Compton wavelength \( \lambda_c^{-1} \) is greater than about 10 Earth radii. Maxwell’s equations are a good approximation for phenomena that occur on length scales less than \( \lambda_c^{-1} \), but are a poor approximation for some phenomena that occur on greater length scales. If \( m \neq 0 \), then in free space the speed of light would depend on frequency, and the force between charged particles would have a finite range; but if \( m \leq 3 \times 10^{-48} \text{ g} \) detection of these effects is not feasible. For an observed large scale electromagnetic field, the current density and energy density of the electromagnetic field may be many orders of magnitude greater than the values deduced from Maxwell’s equations, but provided \( \lambda_c^{-1} \) is greater than a few hundred AU, corresponding to \( m \leq 10^{-53} \text{ g} \), dynamical effects of the increased densities on cosmic magnetic fields could be difficult to detect.

1. On Electrodynamics and Astrophysics

Blackett (1947) suggested that the production of a magnetic field by the rotation of a massive body was governed by a new law of nature. This hypothesis is no longer regarded as tenable. Alfvén (1950) commented that if the hypothesis were true, Maxwell’s equations must be supplemented by a term that would be of paramount importance in cosmic physics, and since the arguments in favour of such a term were weak, it was reasonable to maintain the generally accepted view that all common physical laws hold up to lengths and times of order of the age of the Universe. Subsequent workers in the field of cosmic electrodynamics have invariably assumed that Maxwell’s equations were applicable, usually without any consideration of the justification for using them. Here the applicability of Maxwell’s equations to cosmic physics is discussed, and an alternative theory is examined.

Maxwell’s equations are empirical laws. They were deduced from the results of centuries of experimentation and observation. Only the final synthesis by Maxwell, in which he added the displacement current to Ampere’s law, was arrived at by theoretical considerations. The equations so obtained are simple and elegant, and provide a self-
consistent description of electromagnetic phenomena. All predictions based on them, for example Maxwell’s prediction of the existence of electromagnetic waves, have been verified within the precision of the observations. During the century since Maxwell’s synthesis, his equations have been found to provide an accurate and adequate description of the electromagnetic phenomena of the Earth and the laboratory. The quantum mechanical formulation of them provides a good description of electromagnetic phenomena on the smallest length and time scales so far studied in high energy particle physics experiments.

There are many examples in the history of physics and astronomy of empirical relations, thoroughly established over a wide range of conditions, that have subsequently required modification to account for more accurate and extensive data. An example is provided by the empirical laws formulated by Newton to describe the dynamics and gravitational interaction of particles. For two centuries after their formulation, the predictions were in excellent agreement with astronomical observation and terrestrial experiments. But it is now known that Newton’s laws are a poor approximation if the particles have high velocities or if the gravitational interaction is strong. Then Einstein’s modification of Newton’s laws are relevant, and the description so provided is part of the everyday experience of physicists and astronomers.

When a description is sought for phenomena that occur on different time, length or energy scales from the scales for which empirical laws have been verified, the applicability of those laws to the new scales is a topic for experimental and observational test, rather than for assumption. It is often not practicable to devise experimental tests of the applicability of empirical laws to cosmic phenomena since the physical extremes obtained in the laboratory often do not approximate the physical parameters that occur in cosmic phenomena and an experimental test simply verifies the laws to the precision of the experiment for the scale of the experiment.

The question of the applicability of Maxwell’s equations to astrophysics is important. There are a number of electromagnetic theories, each of which could be regarded as a modification of Maxwell’s theory in the sense that the consequences are indistinguishable from Maxwell’s theory on the laboratory and terrestrial scales. But the modified equations have significantly different consequences from Maxwell’s equations for phenomena on cosmic scales. Neither intuition nor custom provide a reliable basis for choosing between rival theories. Examples of such theories are the Proca equations which describe effects of a non-zero photon rest mass and equations that describe effects of magnetically charged particles. Johnson (1972, 1973) and Gaffney (1974) have presented electromagnetic equations that are based on Einstein’s (1945) unified field theory; these equations show significant departures from Maxwell’s equations for phenomena on length scales greater than about $10^{15}$ cm.

One way to find the correct electromagnetic equations for astrophysics is to arbitrarily choose one of the possible theories, work through the consequences and then correlate with observation. In time a sufficient body of work might be built up to decide whether the selected theory provides a good description of the phenomena observed.