LET THERE BE LIGHT: COSMIC PHOTONS PRIOR TO THE MICROWAVE BACKGROUND *

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(Received December 6, 2005)

Cosmological photons as relics from the decoupling era in the childhood of the Universe were predicted in 1948 and detected in 1965. However, light has played a role in the history of cosmology at a much earlier date, first in a speculative sense and later in a more scientific context. The paper offers an incomplete survey of some of these early attempts to integrate light into cosmology. Of particular interest is a paper of 1945, written by J.B.S. Haldane, which includes what is probably the first suggestion of a radiation-dominated early Universe.

PACS numbers: 01.65.+g, 14.70.Ph

It is generally accepted that modern cosmology rests observationally on two momentous discoveries, the expansion of the Universe, which dates from the late 1920s, and the cosmic microwave background from the mid-1960s. As far as detection is concerned, the insight that the Universe is filled with a dilute, cold radiation goes back to the celebrated and Nobel-prize rewarded experiment of Arnold Penzias and Robert Wilson in 1964–65. On the other hand, it is well known that the existence of a cosmic background radiation was predicted as early as 1948, first by Ralph Alpher and Robert Herman, two of the pioneers of early-big-bang cosmology [1].

The cosmic background radiation left over from the original decoupling era made its entrance into cosmology in a letter to the journal *Nature* of November 13, 1948. In this letter, Alpher and Herman argued that the earliest phase of the Universe was dominated by radiation rather than matter, and they calculated that the energy density of what they explicitly referred to as "the background radiation" would decrease rapidly with time, namely as $1/t^2$. By means of the Stefan–Boltzmann law they found the temperature of the cosmic blackbody radiation to vary as $1/\sqrt{t}$. Whereas originally the

* Presented at The Centenary of the Photon Conference, 30 August 2005, Warsaw, Poland.

photon gas dominated the Universe, today, after several billions of years of expansion, the temperature of the photon gas would be "about 5 K" — so cold and imperceptible that Alpher and Herman believed that it might not be possible to distinguish it from starlight. They did not mention explicitly that the radiation would be in the microwave range, but this follows directly from the other of the classical laws of radiation, Wien's displacement law.

Alpher and Herman's prediction was truly remarkable, and the subsequent history was no less remarkable, not least because the prediction made no impact at all on the community of physicists and astronomers. The result was that it was repeated independently in 1965 by Robert Dicke and James Peebles [2], who at first were unaware of the earlier prediction of Alpher and Herman. The events around the 1965 discovery are complex, but rather than dealing with this and the subsequent development of the cosmic microwave background radiation, I shall take a brief look at earlier and less well-known events, that is, call attention to some cases where light was discussed in a cosmological context before the Alpher–Herman prediction of 1948.

A good starting point may be the opening verses of The Old Testament, where we are told that God commanded light to come into existence (*Fiat lux*) on the very first day, even before the waters were divided and the material world had been created. During the Middle Ages, this was a problem that occupied the best minds of the theologians and natural philosophers, for how could there be light in a Universe that did not yet exist? One of the many prominent philosophers who reflected on this important problem and related problems of light was Robert Grosseteste, the first Chancellor of the University of Oxford who is today known particularly for his important works in optics. In the 1220s, Grosseteste wrote two cosmological treatises, *De luce* and *De motu corporali et luce*, in which he constructed a cosmology of light [3]. The Universe, he said, was originally created by God in the form of a point of light in a primeval, transparent and dimensionless form of matter; the light instantaneously propagated itself into an expanding sphere, thereby giving rise to spatial dimensions and eventually, by means of light emanating inwards from the expanding light sphere, to the celestial spheres of Aristotelian cosmology. Grosseteste described the essence of his cosmogony as follows:

"I hold that the first form of a body is ... light (*lux*), which as it multiplies itself and expands without the body of matter moving with it, makes its passage instantaneously through the transparent medium and is not motion but a state of change. But, indeed, when light is expanding itself in different directions it is incorporated with matter, if the body of matter extends with it, and it makes a rarefaction or augmentation of matter ... . From this it is clear that corporeal motion is a multiplicative power of light, and this is a corporeal and natural appetite."

Grosseteste's light-cosmogony was of course speculative, but it was an attempt at a naturalistic explanation of the origin of the Universe in so far as it did not rely on miracles or other divine intervention. It is also worth to point out that the scenario has a curious (if of course superficial) similarity to modern accounts of the radiation-dominated expanding Universe.

More than 600 years later, in 1848, the American author Edgar Allan Poe, better known as the inventor of the modern crime and detective novel, gave a lecture in New York on "The Cosmogony of the Universe", and on the basis of this he composed a long poem called *Heureka*. In spite of having no scientific training, Poe had a wide knowledge of astronomical literature and sought to support his cosmogonical scenario with scientific arguments. In *Heureka*, he imagined that the Universe arose from the explosion of a singular state of matter in "one instantaneous flash" [4]. From the explosion of the undifferentiated primordial atom followed the entire history of the Universe: First the fragments would be diffused by means of radiation in such a way as to fill space homogeneously, and eventually they would form the celestial bodies by gravitational attraction. Poe had philosophical as well as scientific reasons to picture his Universe as consisting of only a finite number of stars populating an infinite space. Thus he argued that the distance to the stars most far away was so immense that no light rays from them had yet been able to reach the earth. This was an original solution to Olbers' paradox that made sense because Poe's Universe had come into being a finite time ago.

The next time that photons explicitly entered the cosmic scene was in the late 1920s, when Robert Millikan and his collaborators concluded from cosmic radiation data that the mysterious cosmic rays consisted of distinct bands of energy, corresponding to photons of distinct energy ranges. Millikan believed that the cosmic-ray high energy photons resulted from the building up in the cosmos of nuclei of the chemical elements — they were, as he phrased it, "the birth cries of the elements" [5]. His photons were cosmological in the sense that supposedly they were generated all over in space, but they did not relate to any particular era of the history of the Universe. Indeed, Millikan believed that the Universe was eternally regenerating and thus without a proper, unidirectional history; it had no beginning and no end. In any case, Millikan's cosmological theory was shortlived, as the data on which it relied were soon contradicted by Arthur Compton's improved experiments which proved that the cosmic rays were of a corpuscular nature, not consisting of photons but of charged particles.

Millikan's view of the cosmos was indebted to the ideas of the Chicago astronomer William MacMillan, who, like Millikan, favoured a kind of stationary or steady-state Universe and consequently resisted the idea of the expanding Universe. In 1932, MacMillan suggested a "tired-light" hypothesis according to which the photons lost energy on their travels through space, and in this way he could account for the redshift-distance relation without assuming the galaxies to fly apart. The energy might either disappear in space and reappear in the shape of material particles, or "if the energy which has evaporated from the photon continues to exist as radiant energy, there should exist an abundance of radiation of very low frequency" [6]. However, MacMillan admitted that there was no evidence of such radiation — he could not anticipate that some three decades later such evidence would be found.

The photons that appeared in the works of Millikan, MacMillan and some other cosmologists in the early part of the 20th century were not related to a definite period in the cosmic past, such as envisaged in the later big bang theory. Yet photons of such cosmological origin can be found even before the Alpher–Herman prediction and the nuclear-physical big bang tradition initiated by George Gamow in the years following the end of World War II. As early as March 1930, at a time when the notion of an expanding Universe was brand new, the American relativist and cosmologist Richard Tolman suggested that what caused the expansion was a conversion of matter into radiation [7]. Tolman's point was that the annihilation of matter — at the time meaning transformation of protons and electrons into photons — necessarily led to a non-static Universe in which there is a redshift rather than a blueshift. A somewhat similar assumption had also been vaguely entertained by Georges Lemaître in his classical paper of 1927, which ended with a speculation that "the expansion has been set up by the radiation itself" [8].

Today the cosmological theory of the British astrophysicist Edward Arthur Milne is almost forgotten, but in the period from about 1935 to the late 1940s his unorthodox version of big bang theory, based on what he called kinematic relativity, was well known and hotly debated. According to Milne, the Universe was in a state of uniform expansion, corresponding to an age equal to the Hubble time, and it had started its expansion from a space-time singularity a few billion years ago. Among those who were fascinated by Milne's theory was J.B.S. Haldane, the eminent evolutionary biologist, who had an interest in cosmological speculations and found in Milne's cosmology a Universe that appealed to his ideological preferences. In early 1945 Haldane published a grand and speculative hypothesis of his own, based on Milne's theory and therefore occasionally known as the Haldane–Milne hypothesis [8, 9].

Haldane suggested that there would at any time exist a maximum size of photons, with a wavelength proportional to the cosmic era (given by $\lambda = ct$) and thus a minimum frequency of the order $1/t$. Going far back in time, photons would therefore have enormous frequencies and energies; at the time

$t = 10^{-92}$ sec, the smallest photons would have had an energy corresponding to the mass of a galaxy. Haldane thus pictured the Universe as originating from one or a few such superphotons of incredibly large energy, and sketched from this assumption the entire evolutionary history of matter and life. As to the origin of these superphotons, he suggested that they might have been "primordial constituents of the Universe". Interestingly, in the course of his wild speculations he was led to suggest that "at a sufficiently early date most of the mass of the Universe, or all of it, may have been radiation rather than matter". This may have been the first time a radiation-dominated early Universe was suggested, although in a context entirely different from that of Alpher and Herman three years later.

In conclusion, light (whether described as photons or not) has played a role in cosmological thought before the modern radiation-dominated early Universe was introduced by Alpher, Herman and Gamow in 1948. The concept of cosmological photons can thus be traced back in time longer than what is usually assumed. Several other papers relevant to the topic could be mentioned, such as a paper on illuminated spacetime that Ludwik Silberstein wrote shortly before Hubble's announcement of the expansion of the Universe. Silberstein was impressed by the huge amounts of radiation energy emitted by the stars and galaxies over a timespan of two billion years, which he estimated to correspond to 800,000 sun-masses. He therefore suggested that light ought to play a capital role in cosmological research [10].

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