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UPPER LIMIT ON THE MEAN MASS DENSITY DUE TO GALAXIES

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ABSTRACT

It is shown that present observations of the brightness of the night sky in the visible fix a useful upper limit to the mean mass density due to luminous matter in the Universe. If the material has a mass-to-luminosity ratio of 20 solar units, this upper limit is four times lower than the density needed to close the universe.

A basic parameter for cosmology is the mean mass density in the Universe. One would particularly like to know whether there is enough mass to close the Universe. With a reciprocal Hubble constant

$$H_0^{-1} = 1 \times 10^{10}\ \mathrm{yr}, \tag{1}$$

the condition given by general relativity for a closed Universe is

$$\rho_0 \geq \rho_c = 1.8 \times 10^{-29}\ \mathrm{gm/cm^3}. \tag{2}$$

It has been known for some time that the mass in ordinary galaxies is inadequate by a factor of about 40 to close the Universe (Oort 1958; van den Bergh 1961; Kiang 1961). However, this was difficult to interpret because, in addition to the uncertain correction for dwarf galaxies and individual stars well outside the recognized limits of the galaxies (cf. Oort 1958; Bondi 1960; Arp 1965; Abell 1965), there were no useful limits on intergalactic matter (see, e.g, the discussion of Klauder, Wheeler, and Willey 1958). Recently the situation has markedly improved. Apparently the missing mass necessary for a closed Universe could not be *uniformly distributed* hydrogen, whether H I (Gunn and Peterson 1965), or H_2 (Field, Solomon, and Wampler 1966). Nor could it be uniformly distributed H II, unless the thermal history of the plasma is chosen with considerable care (Gould and Burbidge 1963; Field and Henry 1964; Rees and Sciama 1966; Weymann 1966). The possibility that the missing mass is present in the form of H I clouds will be discussed by one of us in a subsequent paper (P. J. E. P. 1967). With these greatly improved restrictions on the possible forms of material which might have closed the Universe it is important to consider the second problem: that the mass density in galaxies may be seriously in error because not all the luminous matter was taken into account. The purpose of this paper is to describe an observational limit to the amount of such luminous matter, based on an upper limit to the resulting integrated brightness of the material.

The luminous material is assumed to be uniformly distributed through space on the large-scale average. Then the integrated brightness is given by the formula (McVittie and Wyatt 1959)

$$i(\nu_0,t_0) = \mathfrak{E}(\nu_p)\int_0^{t_0} \frac{c\,dt}{4\pi}\,\frac{\mathfrak{L}\{\nu_0[1+z(t)],t\}}{\mathfrak{L}(\nu_p,t_0)}. \tag{3}$$

Here $i(\nu,t)$ is the energy flux per unit area and time, per steradian, and per unit frequency interval; $\mathfrak{E}(\nu)$ is the total present mean luminosity per unit volume; and $\mathfrak{L}(\nu,t)$ is a mean of the luminosity per galaxy at the epoch t. Each of these three quantities refers to unit frequency interval. The radiation is observed, now, at the proper frequency ν_0.

The luminosity per unit volume $\mathfrak{E}(\nu_p)$ is measured at the proper frequency ν_p where $c/\nu_p = 4300$ Å, since the measurements are based on photographic magnitudes. As usual the redshift $z(t)$ is the fractional increase in wavelength suffered by a photon as it propagates from the epoch t to the present epoch t_0.

Because the luminosity of the galaxies decreases sharply toward the ultraviolet the integrated brightness in the visible part of the spectrum ($\lambda \sim 5000$ Å) is determined almost uniquely by the present values of three things: the mean luminosity per unit volume, the spectrum of the radiation, and the rate (H_0/c) of the Hubble shift toward the ultraviolet as we trace back along a line of sight. Because the time variation of $\mathfrak{L}$ is determined primarily by the changing argument $\nu_0\,[1 + z(t)]$, we can set $\mathfrak{L}\{\nu_0[1 + z(t)], t\} = \mathfrak{L}\{\nu_0[1 + z(t)], t_0\}$ as a first rough approximation to equation (3). Then on changing the variable of integration to $x = \nu_0[1 + z(t)]$, and observing that the redshift of the radiation observed in the visible will be fairly small, we obtain the rough estimate

$$\nu_0 i(\nu_0, t_0) \cong \frac{c}{4\pi H_0} \frac{\mathfrak{E}(\nu_p)}{\mathfrak{L}(\nu_p, t_0)} \int_{\nu_0}^{\infty} \mathfrak{L}(x, t_0)\, dx\,. \tag{4}$$

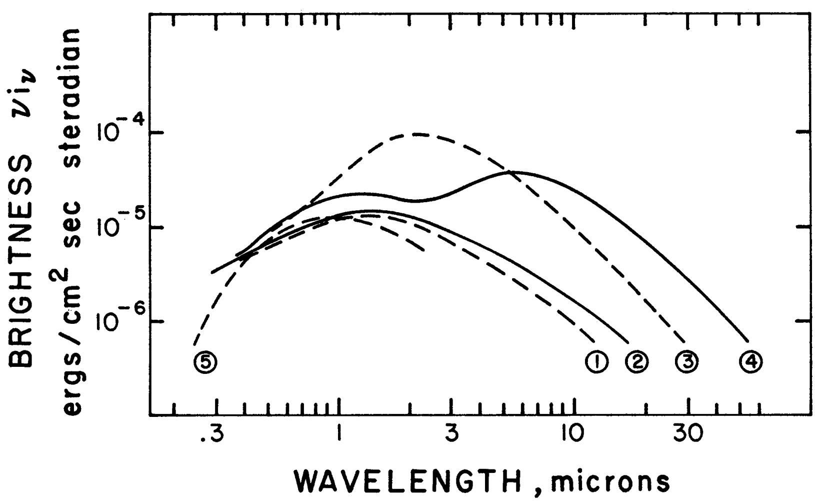

FIG. 1.—Integrated brightness due to the galaxies. The numbers correspond to the models described in the text.

It is interesting that in this approximation $\nu_0 i(\nu_0, t_0)$ is independent of the adopted value of Hubble's constant H_0 (Felten 1966). The mean photographic luminosity per unit volume is taken to be

$$\nu_p \mathfrak{E}(\nu_p) = 3.3 \times 10^8 \nu_p \mathfrak{L}_\odot(\nu_p)/\text{Mpc}^3 = 7.3 \times 10^{41}\ \text{ergs/sec Mpc}^3\,, \tag{5}$$

evaluated at 4300 Å wavelength. In this equation $\mathfrak{L}_\odot(\nu_p)$ is the solar luminosity per frequency interval at this wavelength. The value given by equation (5) is a mean of the three most recent determinations (Oort 1958; van den Bergh 1961; Kiang 1961), each adjusted to the Hubble constant (1). Assuming that the present mean spectrum of the galaxies is the spectrum given by Allen (1963) for our own Galaxy, and using the values given by equations (1) and (5), the approximate formula (4) yields

$$\nu_0 i(\nu_0, t_0) \cong 1.7 \times 10^{-5}\ \text{ergs/cm}^2\ \text{sec sterad}\,, \tag{6}$$

at a 5500 Å wavelength.

More complete model results are shown in Figure 1, which gives the spectrum obtained by numerically integrating equation (3) for the following five models.

1. The mean luminosity and spectrum of the galaxies is time-independent, galaxies are neither created nor destroyed as the Universe expands, and the Universe is just closed (ρ_0 given by the critical value ρ_c in eq. [2]). The spectrum of the radiation from each galaxy is the one given by Allen (1963) for our own Galaxy.

2. The galaxy model is the same as in model (1) and the Universe is open, the present mass density being $\rho_0 = 7 \times 10^{-31}$ gm/cm^3.

3. An evolving model for the galaxies is used, in which the mean luminosity of the galaxies is presently decreasing at the rate of 0.07 mag/10^9 yr, and the wavelength of maximum energy flux of the model presently is increasing at the rate of 1.5 per cent per 10^9 yr. The model, which is described in detail elsewhere (Partridge and Peebles 1967), was chosen to produce the observed abundances of helium and heavy elements in the present state of the Galaxy. The cosmological model is the same as model 1.

4. The evolving model for galaxies in model 3 is used with the open cosmological model, again taking $\rho_0 = 7 \times 10^{-31}$ gm/cm^3.

5. This model was computed by Whitrow and Yallop (1965). A Milne universe is used, and the galaxies are supposed to radiate like black bodies, the present temperature being 6000° K, the temperature decreasing uniformly at the rate of 100° K/10^9 yr, and

TABLE 1

COMPARISON OF COMPUTED BRIGHTNESS WITH OBSERVATIONS

	$\nu_0 i(\nu_0,t_0)$*	$i(\nu_0,t_0)$†
1. Integrated brightness from ordinary galaxies	7 $\times 10^{-6}$	1 3$\times 10^{-20}$
2 Brightness expected if the Universe is closed by matter with $M/L=20$	2 8$\times 10^{-4}$	5 1$\times 10^{-19}$
3 Zodiacal light	9 $\times 10^{-4}$	16 5$\times 10^{-19}$
4 Starlight	2 $\times 10^{-4}$	3 7$\times 10^{-19}$
5 Upper limit to background from depth of Fraunhofer lines	2 3$\times 10^{-4}$	4 2$\times 10^{-19}$
6. Roach and Smith upper limit	7 $\times 10^{-5}$	1 3$\times 10^{-19}$

* Units: ergs cm^{-2} sec^{-1} sterad^{-1}; wavelength λ = 5500 Å.

† Units: ergs cm^{-2} sec^{-1} sterad^{-1} (c/s)$^{-1}$; wavelength λ = 5500 Å

the luminosity variation being fixed by Stephan's law so that the mean luminosity per galaxy presently is decreasing at the rate of 0.07 mag/10^9 yr. This is the curve of Whitrow and Yallop for which absorption is neglected.

It is seen from Figure 1 that, while the infrared brightness varies appreciably with the models used for the galaxies and for the Universe, the background in the visible is very nearly model independent. The total energy density of radiation obtained from curve 1 or 2 agrees well with the value calculated by Harrison (1965), and the spectrum of the curves 1 and 2 agrees with the spectrum calculated by Sandage and Tammann (1965).

In all these models the mean photographic luminosity per unit volume is taken to be the value given by equation (5). With a mean mass-to-light ratio equal to 20 solar units the value given by (5) yields the mass density

$$\rho_g = 4.5 \times 10^{-31} \text{ gm/cm}^3 . \tag{7}$$

The present question is whether the mean emission (5) could be increased so that the density (7) is raised to the cosmologically interesting value (2), without conflicting with the observed brightness of the sky. The situation is summarized in Table 1. The first value given in the table is the computed brightness (from Fig. 1) due to the galaxies assuming the value (5) for the present luminosity per unit volume. The second number is the brightness expected if the mass-to-light ratio is 20 solar units, and the mean density of the luminous material is that required to close the Universe (eq. [2] rather than eq.

[7]). For comparison we have listed the brightness of the zodiacal light perpendicular to the plane of the ecliptic. The brightness was taken to be 130 stars of tenth visual magnitude per square degree (Beggs, Blackwell, Dewhirst, and Wolstencroft 1964*b*), in reasonable agreement with most ground-based measurements of the zodiacal light. There are, however, indications from satellite experiments that the brightness of the zodiacal light may be a factor of 2–3 times lower than this value (Gillett 1966). Also tabulated is the mean brightness of starlight in the direction perpendicular to the plane of the Galaxy. The upper limit on the brightness of the extragalactic light may be placed at a value below the brightness of the zodiacal light, for example, by observing the depth of the Fraunhofer lines in the zodiacal light. An isotropic cosmic background would fill in the Fraunhofer lines. From a comparison with the depth of Fraunhofer lines in the light from moonlit and twilight sky, Beggs *et al.* (1964*a*) placed an upper limit of about 3 per cent on the fractional filling of the Fraunhofer lines in the zodiacal light. The detailed observations were made between elongations of 28° and 37°, where the brightness of the zodiacal light lies in the range $4.5–7.5 \times 10^{-13}$ times the mean solar surface brightness. Using the mean of these two values for the brightness of the zodiacal light, we obtain the upper limit on cosmic light listed in the table.

In a study to be published, F. E. Roach and L. L. Smith attempted to subtract from the light of the night sky the contributions by airglow, zodiacal light, and starlight. In this study the test for extra-galactic light is based on the argument that this light would be strongly attenuated in the direction of the galactic plane. The argument of Roach and Smith apparently safely rules out an extra-galactic brightness as high as 10 $m_v = 10$ stars per square degree. This is the limit (6) listed in the table. This limit implies that if the Universe is closed the missing mass must have a mass-to-light ratio in excess of 80 solar units. The missing mass could not be predominately main-sequence stars with mass-to-light ratio of the order of unity, and the missing mass could not be predominately dwarf irregular galaxies like the Large Magellenic Cloud, for which the mass-to-light ratio is 5 (de Vaucouleurs and de Vaucouleurs 1963), in agreement with Page's (1965) mean value for irregular galaxies.

Since the Roach-Smith limit is a factor of 10 below the brightness of the zodiacal light, it may be well to treat this conclusion with some caution for the moment. In view of its importance it would be most desirable to continue the effort to pierce the veil of the zodiacal light, following the method of Roach and Smith, or perhaps that of Beggs *et al.* (1964*a*), or perhaps in some other fashion.

There remains the possibility that sufficient matter to close the Universe may be present in the form of "dead galaxies" having large mass-to-light ratios. If these galaxies have had an active past, the infrared portion of the curves of Figure 1 will be raised.

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