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Infrared astronomy and cosmology

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The possible development of infrared astronomy has been a traditional area of concern for cosmologists because, after all, the light from a distant galaxy reaches us red-shifted, in the infrared if the galaxy is far enough away. There is additional interest now generated by the discovery of the cosmic microwave background, radio noise that seems to peak up in the distant infrared (Penzias & Wilson 1965).

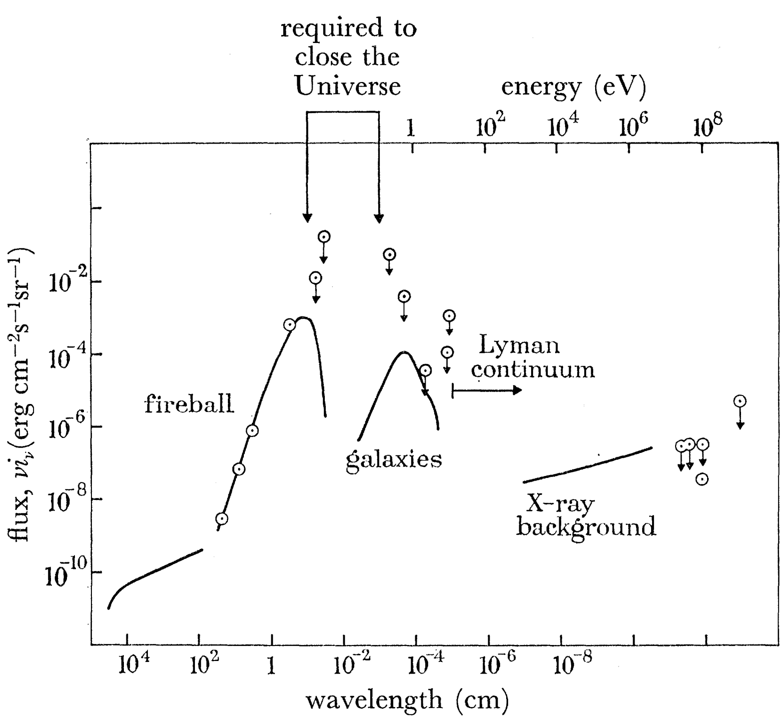

Figure 1. Cosmic electromagnetic radiation.

To show how the infrared observations stand in relation to experiments at other wavelengths, I have plotted in figure 1 some possible observations of extragalactic radiation, and also some upper limits on the intensity of extragalactic radiation. The frequency range in the figure covers most of the spectrum now open to astronomy, from radio waves to γ-rays. To include this broad band, I have plotted the logarithm of the frequency. In the vertical scale I have used the brightness per frequency interval multiplied by the frequency, νi_ν. This is convenient because the integral of νi_ν over the logarithm of ν is just the integrated brightness, which is proportional to the total energy density. Thus the height of the curve in figure 1 is a direct measure of the possible energy content of the Universe in different parts of the electromagnetic spectrum.

At the high-frequency end of the curve I have shown the isotropic X-ray background (Metzger *et al.* 1964). It has been observed at energies ranging from 1 keV to a few MeV. Most experiments at energies higher than this can claim only upper limits, although the curve apparently does break away somewhat at higher energies (Kraushaar *et al.* 1965).

Below about 1 keV energy incident extragalactic radiation would be destroyed in the interstellar gas (by photodissociation followed by radiative recombination to energetic states). The Galaxy apparently is transparent again well below the Lyman limit, 912 Å. Two rocket observations in the ultraviolet are shown on the figure (Byram, Chubb & Friedman 1964).

The point in the visible part of the spectrum is an unpublished estimate by F. E. Roach and L. L. Smith of the possible brightness of extragalactic light, after accounting for the local contribution by stars in our own Galaxy and by the zodiacal light. This upper limit comes rather close to the estimated integrated brightness due to radiation from galaxies (Peebles & Partridge 1967). This does not provide a direct test of theories of the evolution of the Universe or of the galaxies because galaxies do not radiate strongly in the ultraviolet, so the light reaching us in the visible could not have suffered more than a modest red-shift, that is, the light must have been radiated relatively recently. The result is of considerable interest, however, because it shows that people have not grossly underestimated the amount of mass in the Universe that could be in the form of dwarf galaxies or even stars outside the assumed limits of the galaxies.

The integrated infrared radiation does depend on the cosmological model and on the evolution of the galaxies because there can be an appreciable contribution from the highly red-shifted light from very distant galaxies. In figure 1 I have plotted an estimate of the infrared background assuming that the Universe is closed (acceleration parameter $q_0 = \frac{1}{2}$) and assuming that the galaxies were bright enough in the past to have managed to have converted 25 % of their hydrogen to helium (Partridge & Peebles 1967*b*). It is exciting that a recent rocket flight experiment (Harwit, McNutt, Shivanandan & Zajac 1966) yields an upper limit not too far above this computed infrared background.

In the distant infrared is the newly discovered isotropic radiation, which has been interpreted at Princeton as the Primeval Fireball, thermal radiation left over from the early highly contracted state of the Universe, and adiabatically cooled by the expansion of the Universe (see Partridge & Wilkinson 1967 and references contained therein). If this interpretation is correct, and if the Universe truly has been isotropic and homogeneous, then to excellent accuracy this radiation should exhibit a thermal spectrum. So far, the direct measurements all have been on the Rayleigh–Jeans side, while the point based on the spin temperature of interstellar cyanogen is near the peak. Certainly, it would be of considerable interest to have observations shortward of the expected peak of the radiation.

It is evident from figure 1 that, in the frequency range shown, from 10^6 to 10^{26} Hz, far and away the largest possible contribution to the total energy density (hence equivalent mass density) of the Universe is in the infrared. In fact, the curve conceivably rises to the limit shown on the figure, yielding enough energy in the infrared to close the Universe. This notion can be ruled out if it is accepted that the very energetic cosmic ray protons are extragalactic, for the infrared radiation would make the Universe quite opaque on the scale of the Hubble radius for cosmic ray protons above the threshold for photopion production (Dicke & Peebles 1965). Nevertheless, it will be useful to have direct absolute flux observations in the gap between the best available limits in the distant infrared (from spin temperatures of interstellar molecules (Thaddeus & Clauser 1967)) and in the infrared (Harwit *et al.* 1966).

Of very great interest to cosmology is the first point mentioned in this note, the possible observation of the infrared radiation coming from very distant galaxies (Partridge & Peebles 1967*a*, *b*). To estimate the expected magnitude of this effect, one must first arrive at some opinion of when the galaxies formed. To do this, I suppose that a proto-galaxy grows as a perturbation to an initial nearly uniform mass distribution, and, to simplify the computation, I suppose that the developing proto-galaxy is spherically symmetric. One knows that, if the proto-galaxy is non-relativistic ($GM/Rc^2 \ll 1$), the gravitational forces within the system can be described according to the familiar Newtonian theory of gravity, the Universe outside the system contributing only a small tidal stress to the interior (Callan, Dicke & Peebles 1965). Thus, in the spherical model, the radius of the proto-galaxy satisfies the familiar equation

$$\mathrm{d}^2R/\mathrm{d}t^2 = -\tfrac{4}{3}\pi G\rho R. \tag{1}$$

It follows from the solution to this equation that the proto-galaxy reaches the point of maximum expansion, and starts to contract, at the time

$$t_{\mathrm{max.}} = (3\pi/32G\rho_{\mathrm{min.}})^{\frac{1}{2}}, \tag{2}$$

where $\rho_{\mathrm{min.}}$ is the mean density of the proto-galaxy at the point of maximum expansion (Partridge & Peebles 1967*a*).

Judging from the distribution of the stars in the halo of our own Galaxy, the proto-galaxy apparently reached a maximum extent of at least 20 kpc radius. From (2), the Galaxy thus formed at the cosmic time at least

$$t_{\mathrm{max.}} \cong 1{\cdot}5\times10^8\,\mathrm{y}. \tag{3}$$

This corresponds to a red-shift in the range of 10 to 30, depending on the cosmological model (Partridge & Peebles 1967*a*).

The time for free fall of the proto-galaxy down to the disk is also on the order of 10^8 y. It appears that the formation of the disk could not be long delayed beyond this time, for I can think of no way to support the proto-galaxy for a much longer time. The young galaxy must therefore have been very active, because when the disk formed the interstellar heavy element abundances had risen to values comparable to the present 'cosmic' abundances. If we could assume that there was no primeval helium, and that the helium production paralleled the rapid production of heavy elements, we would conclude that about 20 % of the hydrogen was burned to helium and heavy elements in the first 10^8 y of life of the Galaxy. This hydrogen burning corresponds to a luminosity of about 1×10^{47} erg/s for the young Galaxy, about 10^3 times the present luminosity of the Galaxy. Taking the radiating disk of the young Galaxy to be 15 kpc in radius we then find that the surface brightness of the young galaxy would be 1 erg cm^{-2} s^{-1} sr^{-1}. The cosmological red-shift reduces this brightness by the factor $(1+Z)^4$. In the closed cosmological model, with $1+Z \cong 10$, the brightness of the resolved image thus would amount to about 1×10^{-4} erg cm^{-2} s^{-1} sr^{-1}. Although such a young galaxy, observed now at a red-shift $1+Z \cong 10$, would be an enormous distance from us, the Universe is acting something like a magnifying glass—the angular diameter of the image would be 15 sec arc (for a proper diameter of 30 kpc), which could be resolved. The radiation in the young galaxy would originate in massive short-lived stars, the peak intensity being near 1000 Å wavelength, so in the closed cosmological model the radiation would be red-shifted now to about one micron wavelength.

Could one observe these images? There do exist infrared detectors capable of reaching this level of sensitivity. Aside from the obvious problem of making use of this sensitivity in a real astronomical observation, the main question is whether the light from the young galaxies would be obscured by local radiation. The extraterrestrial background would be the zodiacal light, including thermal emission from the interplanetary dust, and starlight in our own Galaxy. This local infrared background appears to be roughly comparable to the computed brightness of the young galaxies (Partridge & Peebles 1967*a*, *b*). However, one is looking for a resolved structure in the infrared background, and a scanning technique would allow one to pull this structure out of the isotropic local background, and out of the contribution from individual stars. The night sky is very much brighter than the expected brightness of the young galaxies, so it is not clear whether or not the experimental test of these ideas must await observations above the atmosphere. In any case, it appears that infrared astronomy might eventually yield some information on how the galaxies formed.

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