THE EXTRA-GALACTIC BACKGROUND LIGHT: A MODERN VERSION OF OLBERS' PARADOX

(Or: Why the Space Between Galaxies is Dark)

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Abstract. A non-technical discussion is given of the energy density E of the extra-galactic background light. The fact that E is small means that the space between galaxies is dark, which is a modern version of a classical problem in astronomy known as Olbers' paradox. It is seen that the order of magnitude of E is fixed by the order of magnitude of the lifetime of the galaxies, as pointed out by Harrison; but that the expansion of the Universe can affect E by a smaller factor, typically about 2. These comments should help to end persistent confusion about the effects of the lifetime of the galaxies and the expansion of the Universe on the darkness of the night sky. It is hoped that Olbers' so-called paradox can now rest in peace.

1. Introduction

Galaxies emit optical photons into the space between them, creating a field of radiation called the extra-galactic background light (EBL). The energy density E of the EBL is small, which means that the space between the galaxies is dark. The value of E has in recent years become a parameter of increasing interest in astrophysics, because it is a parameter that contains information not only about the galaxies as they are at present but also about the galaxies as they were in the remote past. To illustrate this, consider the photons of the EBL near the Milky Way. Some of these were emitted by nearby galaxies quite recently. But some were emitted by very distant galaxies which, due to the finite speed of light, means that they were emitted in the remote past. In fact, the EBL near the Milky Way contains photons that were emitted at all times from the present back to the epoch when the galaxies were formed, of order 10^{10} yr ago. Thus, the value of E is a kind of measure of the whole history of the light-producing properties of galaxies. And the fact that E is small allows certain constraints to be set on that history.

Understanding the small value of E for the EBL is in many respects similar to resolving a problem of classical astronomy dating from 1826 called Olbers' paradox (see Jaki, 1967, 1969, for historical accounts). This paradox, which like all such is only a paradox in the sense that humans sometimes have trouble understanding the Universe, can be formulated loosely as follows. In a Universe which is static and of infinite age, and where the galaxies have constant luminosities and are distributed uniformly in Euclidean space, the accumulated light should be so intense as to make the night sky bright, rather than dark as observed.

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There has been considerable confusion through the years as to why the energy density of the EBL is small and why Olbers' paradox is resolved. It was realized quite early on that the expansion of the Universe and the finite lifetime of the galaxies are the two most plausible explanations (e.g., Bondi, 1960), but there was no demonstration of which was the more important. For a long while, it was tacitly assumed that the expansion of the Universe is the main factor involved. For photons emitted from galaxies that recede from each other have their number density reduced by the increasing-volume effect and their energy reduced by the redshift or Doppler effect. But it was pointed out by Harrison (1964, 1965) that this is not the main factor, even though the expansion does tend to lower E over that for the static base. Harrison showed that the main factor is the finite lifetime of the galaxies. For this *time* determines the *size* of that portion of the Universe from which photons can be received (it is a sphere with a radius of order 10^{10} light years). The volume of that portion, in combination with the average separation of the galaxies, determines the number of galaxies from which photons can be received. And that number determines in turn the intensity of the background light. A detailed calculation shows that the intensity is actually quite low. Thus, *it is the finite lifetime of the galaxies, in combination with their large average separation, which resolves the problem of the bright night sky.* But while Harrison was correct in pointing out that this was the real crux of the matter, confusion still persisted about whether or not the expansion could have a significant effect. In particular, it was argued by Layzer (1966) that the expansion could be significant under certain circumstances. Harrison (1974, 1977, 1980, 1981) in subsequent years continued to try to get the idea across that it is the lifetime of the galaxies rather than the expansion of the Universe that is the main factor in the darkness of the night sky. But while he is undoubtedly correct, confusion still persists, even among authors of astronomy texts. A survey in 1985 of recently published books shows two kinds of confusion. Firstly, some people still wrongly identify the expansion as the main factor. Secondly, some people correctly identify the lifetime of the galaxies as the main factor, but then mention expansion as another factor, without saying anything about the relative sizes of the two.

In what follows, an attempt will be made to cut through this confusion by giving a discussion of the energy density E of the EBL that is non-technical. By the latter phrase is is meant that the discussion will use Newtonian as opposed to Einsteinian physics, and that all non-essential details (of which there are many) will be omitted. The derivations of important results will be made using models that are believed to be more readily understood than others in the literature. The following discussion of the energy density of the EBL may be simple, but this is justified by the fact that the topic is fundamental yet so affected by confusion that many workers appear not to appreciate its true nature. It will be seen that the order of magnitude of E is fixed by the order of magnitude of the lifetime of the galaxies; but that the expansion of the Universe can affect E by a smaller factor, typically about 2.

2. The Extra-Galactic Background Light

To see how the energy density E of the EBL is affected by the lifetime of the galaxies and the expansion of the Universe, it is instructive to calculate E for the static case and the expanding case, and then compare them.

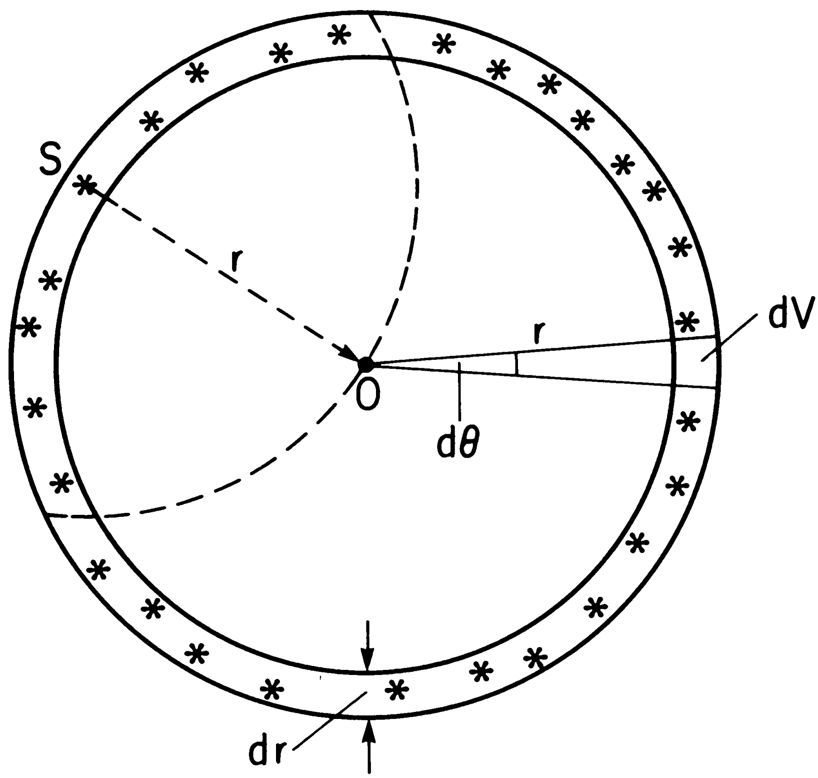

Fig. 1 To illustrate the EBL in a static, Newtonian universe.

The value of E in a static, Newtonian universe can be calculated using Figure 1. An observer O receives light from sources (galaxies) distributed uniformly in space. For the sake of clarity, only those sources in a spherical shell of radius r and thickness dr are illustrated. A typical source S has a luminosity L erg s^{-1}, and radiates isotropically. The spherical wavefront centered on S and passing through O has area $4\pi r^2$, so the intensity (flux) of the light emitted by S that is received by O is $i = L/4\pi r^2$ erg cm^{-2} s^{-1}. If there are n sources per unit volume in space, the number of sources in the shell illustrated is $4\pi r^2 n\,\mathrm{d}r$. Multiplying this number by i gives the intensity at O due to all the sources in the shell as $\mathrm{d}I = Ln\,\mathrm{d}r$. Summing up the contributions from all shells out to some radius r gives the total intensity at O as $I = Lnr$. Light travels at speed c, so in this last expression $r = ct$. Here, t is the time since the light was emitted by the most distant sources visible to O. If the sources came into existence a finite time ago, then t is also that time. In practice, this means that t is the lifetime or age of the galaxies. Thus, $I = Lnct$ where t is of order 10^{10} yr. This result is the same as the static limit of a result for expanding, relativistic universe models derived by Whitrow and Yallop (1964, p. 311). The energy density E is just I/c or $E = Lnt$ erg cm^{-3}.

It is convenient to express this result in a slightly different form. If the average density of matter in the form of galaxies is ρ and the average mass of a galaxy is m, then $n = \rho/m$. Thus $E = L\rho t/m$. This illustrates an interesting point. If galaxies should turn out to be 10 times more massive than their visible parts imply (which seems increasingly plausible) then *m and* ρ would need scaling up by a factor 10, but E would remain the same. This means that the value of E is unaffected by uncertainties in the masses of galaxies, a property which makes E a parameter of special interest in galactic astrophysics. However, this topic will not be discussed further here, and henceforth ρ will be taken to be the density of luminous matter unless otherwise stated. The last expression for E can now be expressed in another form by introducing $\varepsilon = L/m$. This is the rate of energy production, or power, per unit mass. In terms of this, the energy density is

$$E = \varepsilon \rho t. \tag{1}$$

This result is the same as the static limit of a result for expanding, relativistic universe models derived by Harrison (1965, p. 1). The full result of Harrison will be quoted below, but for the present let (1) be evaluated for a reasonable choice of parameters. Since most of the luminous matter in the Universe is in the form of stars, data for the Sun can be used to give $\varepsilon = L_\odot/M_\odot \simeq 2$ erg s^{-1} g^{-1} approximately. The other parameters may be taken to be $\rho = 1 \times 10^{-31}$ g cm^{-3} and $t = 1 \times 10^{10}$ yr $\simeq 3 \times 10^{17}$ s. Then by Equation (1), $E \simeq 6 \times 10^{-14}$ erg cm^{-3}. This value of E is quite small: it corresponds to about 20 optical photons in a box 10 cm on a side.

The value of E in an expanding universe described by Einstein's theory of general relativity was first calculated by Whitrow and Yallop (1964). They considered a model in which galaxies are distributed uniformly in space and increase their distances from each other in proportion to a power p of the time. For such a model, the intensity of the light received by a typical observer is $I = Lnct/(1 + p)$, where the symbols here have the same meanings as above and t is of order 10^{10} yr. The energy density E, again, is just I/c. The expression for I in an expanding universe differs from the expression for I in a static universe only by the factor $(1 + p)$. However, an examination of the work of Whitrow and Yallop shows that I (expanding) cannot be derived from a simple analysis like that given above for I (static). In fact I (expanding) is fortuitously simple, in the sense that it results from a long and complicated calculation. This latter involves some concepts which are essentially relativistic, such as that of luminosity distance in Einstein's theory (see McVittie, 1965). Thus, if it is desired to give a non-technical discussion of the EBL, expressions for I and E cannot be derived but must be quoted from work like that of Whitrow and Yallop (1964). A similar comment applies to the work of Harrison (1965), who finds that in an expanding universe

$$E = \frac{\varepsilon \rho t}{(1 + p)}. \tag{2}$$

This can be compared to the result for a static universe, Equation (1) above. Since cosmological observations indicate that p is close to unity, it is seen that expansion reduces the value of E by about a factor 2 over the static case.

From either (1) or (2), it is clear that the order of magnitude of E is fixed by the order of magnitude of the lifetime of the galaxies, and that the expansion of the Universe affects E by a smaller factor of order unity.

This conclusion is confirmed by more detailed calculations of E done on a computer. Such calculations have been carried out by Stabell and Wesson (1980) and extended by Valle (1983). In the latter work, E was calculated for models which were static and expanding but where the galaxies existed for the same period. The calculations were done for uniform models in Einstein's theory of general relativity, but with more realistic behaviours for the expansion than the simple power law assumed above. The results depend somewhat on the precise model, but typical values of $E(\text{expanding})/E(\text{static})$ are in the range 0.65–0.70, with a value of 0.48 for the model named after Milne that may be regarded as delimiting the class of acceptable models (Valle, 1983, p. 28). Stabell and Wesson and Valle also studied the effect on E of allowing the luminosities of galaxies to change with time. But while this alters the value of $E(\text{expanding})/E(\text{static})$ somewhat for a given model, it does not alter the overall conclusion: expansion reduces the energy density by a factor that is typically about 2.

Absorption is another factor, not included in either (1) or (2), which could reduce the value of E (Whitrow and Yallop, 1965; Valle, 1983). Light which travels great distances may be absorbed by gas and dust located either in intergalactic space or in intervening galaxies. The former is difficult to assess due to lack of data; but the latter may be assessed by considering an observer who views the distant universe and calculating how much of his field of view is blocked by intervening galaxies.

Referring to Figure 1, let it be assumed that an observer O has a telescope with a field of view $d\theta$ which is small. At distance r from O, the volume dV of space sampled by the telescope can be approximated as a box of sides $r\,d\theta$, $r\,d\theta$, and dr, so $dV = r^2\,d\theta^2\,dr$. This volume contains $dN = n\,dV = nr^2\,d\theta^2\,dr$ galaxies. The total number of galaxies in the field of view out to some distance r is $N = nr^3\,d\theta^2/3$, or $N = \rho r^3\,d\theta^2/3m$ in terms of the average density of matter in the form of galaxies and the average mass of a galaxy. If the telescope samples the Universe out to the maximum feasible distance $r = ct$, then $N = \rho c^3 t^3\,d\theta^2/3m$. It is instructive before proceeding to use this last expression to evaluate N for the real universe. Take $\rho = 1 \times 10^{-31}\ \text{g cm}^{-3}$, $t = 1 \times 10^{10}\ \text{yr} \simeq 3 \times 10^{17}\ \text{s}$, $d\theta = 1\ \text{degree} \simeq 0.017$ radians and $m = 1 \times 10^{10}\ M_\odot \simeq$ $\simeq 2 \times 10^{43}$ g. Then the number of galaxies is $N \simeq 4 \times 10^5$. This means that the telescope receives photons from many distant galaxies, provided they are not blocked along the way. To see if this is the case, let a galaxy be modelled as a thin disk of radius R and area πR^2. As seen through the telescope, some of the galaxies will be face on, some edge on, and some tilted at angles inbetween. Introducing a factor $\frac{1}{2}$ to allow for this, the area in the field of view occupied by galaxies is $A_1 = \pi R^2 N/2$. The mean area of the field of view itself can be approximated by a square of sides $(r/2)\,d\theta$, where the mean viewing distance $r/2$ has been taken, so the mean viewing area is $A_2 = r^2\,d\theta^2/4$. There will be *no* significant blocking by galaxies of the field of view of the telescope if $A_1 \ll A_2$. Substituting into this inequality from above and assuming the maximum feasible viewing distance $r = ct$, it becomes

$$\frac{2\pi\rho ct R^2}{3m} \ll 1 \,. \tag{3}$$

This expression (which is actually independant of the field of view of the telescope) has been derived on the basis of a very simple model, but is nevertheless expected to be fairly accurate. It can be evaluated using $R = 10$ kpc $\simeq 3 \times 10^{22}$ cm and other data as above. It then reads $0.08 \ll 1$. The condition for no significant blocking is therefore satisfied: only about 8% of the light from distant galaxies encounters intervening galaxies.

The diminution in intensity of the light from distant galaxies will actually be less than the blocking percentage, because in general not all of the light which encounters an intervening galaxy will be absorbed. Thus, absorption appears to be only a minor effect. However, this conclusion might be altered if galaxies should turn out to be 10 times larger in mass and size than their visible parts imply. For in that case, (3) shows that while the extra factor cancels out of ρ and m, it is still present in R. This raises the left-hand side of Equation (3) by 10^2, so the condition for no significant blocking is not satisfied. The conclusion drawn above therefore needs to be qualified: the intensity of the EBL is not significantly reduced by absorption due to galaxies, provided these latter have conventional sizes.

Attempts to detect the EBL using telescopes have so far not succeeded. This may at first seem strange. But it should be recalled that although there are many distant galaxies in the field of view of a large telescope (see above), their integrated light is very weak. In fact, the EBL is swamped by light from non-galactic sources, such as the Earth, the Solar System, and the Milky Way. In order to identify the EBL, light from these other sources has to be discounted, and this is a task fraught with problems. Due to its inherent weakness and the problems of identifying it among other things, the only useful data on the EBL available at present are limits.

The best upper limit on the intensity of the EBL was set by Dube *et al.* (1977, 1979), who tried to detect it directly by making observations at a wavelength of 5100 Å using two ground-based telescopes. A lower limit on its intensity can be obtained from work of Toller (1983), who tabulated intensities that correspond to smearing out the light from galaxies not too far from the Milky Way over the volumes they occupy. These two limits, and others like them, are usually discussed in terms of the S_{10} unit (see the Appendix for a discussion of this unit and limits on the EBL). This is the intensity corresponding to one tenth-magnitude star per square degree. In terms of this unit, the upper and lower limits for the EBL are 3.4 S_{10} and 0.5 S_{10}, respectively. In principle, it is possible to transform these observational data from S_{10} units to erg cm^{-3}, and so compare them with theoretical results on E like those derived above. In practice, this is a problematical procedure (see the Appendix). But it can be stated that the observational limits just quoted are not in overt conflict with the theoretical calculations.

Once the EBL is detected observationally, presumably at a level in the range 0.5–3.4 S_{10}, it will provide an important cosmological tool. For while its intensity depends mainly on the lifetime of the galaxies and the expansion of the Universe, it can also be affected by other factors such as absorption (see above) and possible changes in the luminosities of galaxies through time. However, the study of these subjects depends on a firm detection of the EBL, which in turn depends on a better way of observing it, perhaps from space.

3. Conclusion

In a static, uniform Universe the energy density of the extra-galactic background light is determined by the power and average density of luminous matter, and by the lifetime of that matter, which in practice means the lifetime of the galaxies. In an expanding universe, the energy density is reduced, but only by a factor of about 2. This can be seen by a comparison of Equations (1) and (2) above. Absorption does not significantly reduce the EBL, unless there are large amounts of intergalactic matter or unless galaxies are much larger than they appear to be. An observational detection of the EBL would be of considerable importance for galactic astrophysics and cosmology.

The major conclusion is that Harrison's argument is confirmed. It is the finite lifetime of the galaxies, in combination with their large average separation, that is the main reason why the space between galaxies is dark.

These comments should help to end persistent confusion about the effects of the lifetime of the galaxies and the expansion of the Universe on the darkness of the night sky. To help forestall more confusion, it may be permissable to make two remarks about a subject that many workers apparently feel obliged to mention in introductory accounts of astronomy, namely Olbers' paradox. *First*, it should be stated bluntly that Olbers' paradox is obsolete. The preconditions on which it was originally formulated are now known to be false; and the modern study of the dark night sky involves different physics and goes under a different name (the EBL). The appropriate place for Olbers' paradox is the history of astronomy, and its place in accounts of modern astrophysics should be taken by the EBL. *Second*, it should be emphasised that any discussion of the dark night sky, under whatever name, has to be approached with great care at the introductory level. For while Equation (1) above and the effect of the lifetime of the galaxies can be treated using Newtonian physics, Equation (2) and the effect of the expansion of the Universe can only be treated properly using relativity. The best approach would appear to be one of comparison of the two effects; and they should be viewed as complementary rather than competitive.

For the foregoing reasons, it is devoutly to be wished that Olbers' paradox can now rest in peace.

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Appendix

There is considerable confusion in the literature about the S_{10} unit and how limits on the EBL measured in these units should be employed. Dube *et al.* (1977, 1979) used an S_{10} unit which at a wavelength of 5100 Å is equivalent to 7.55×10^{-6} erg cm^{-2} s^{-1} steradian^{-1}. They failed to detect the EBL at 5100 Å, and in their first article quoted a value for it of $1.0 \pm 1.2\ S_{10}$. In their second article they quoted an upper limit for it at the 90% confidence level of $3.4\ S_{10}$. Toller (1983) used an S_{10} unit which at a wavelength of 4400 Å is equivalent to 1.2×10^{-9} erg cm^{-2} s^{-1} steradian^{-1} Å^{-1}. He reviewed certain observational data which indicate a lower limit for the EBL of about $0.5\ S_{10}$. However, all observational data on the EBL refer to its intensity at a certain wavelength. And these data are not exactly transformable into values of E as employed in the main text and in theoretical articles (e.g., those of Whitrow and Yallop, 1964; and Harrison, 1965), since E as employed there refers to the intensity integrated over all wavelengths. A rough comparison between observational and theoretical data may be made by transforming between the two using factors of 4π (steradians), c (the speed of light) and the wavelength. But this procedure is of course open to doubt, especially since the spectrum of the EBL is unknown. This procedure was, despite is roughness, adopted by Stabell and Wesson (1980), who compared their theoretical data with an observational upper limit on the EBL, which latter they took as $1.2\ S_{10}$ following the first article by Dube *et al.* (1977). However, a more exact procedure is that of Valle (1983) who made theoretical calculations at a certain wavelength, and compared these with an observational upper limit on the EBL at 5100 Å, which latter he took as $3.4\ S_{10}$ following the second article by Dube *et al.* Valle (1983, p. 65) found theoretical values for the intensity of the EBL in expanding models with constant-luminosity galaxies of 0.5–0.6 S_{10},which do not conflict with either the observational upper limit or the lower limit.

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