The Extragalactic Infrared Background and its Cosmological Implications
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Introductory Remarks

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Abstract. I review the assumptions and observations that motivate the concept of the extragalactic cosmic background radiation, and the issues of energy accounts and star formation history as a function of galaxy morphological type that figure in the interpretation of the measurements of the extragalactic infrared background.

1. Fundamental Assumptions

It is useful to begin by recalling the basic assumptions and observations that lead us to the concept of the extragalactic cosmic background radiation, as opposed to radiation surface brightness that may be some highly variable function of position and direction.

Deep counts of objects detected at a broad range of wavelengths, from gamma-ray sources to radio galaxies, are close to isotropic across the sky. It is an excellent bet therefore that the integrated radiation from observed sources plus those too faint to be detectable as individual objects also is quite isotropic. This allows us to think of the local extragalactic radiation background as a function of one variable, the radiation energy density u_ν per interval of frequency ν. The fluctuations around the mean as a function of position in the sky are important too, as a measure of large-scale structure, but u_ν is the center of attention in these Proceedings.

The argument for large-scale homogeneity — against a universe with a radial density gradient and us at the center — is less direct but I think persuasive; my review of the considerations is in Peebles (1993). If we are persuaded then we conclude that, within our Hubble length, space is filled with a near uniform sea of radiation with spectral energy density u_ν: the cosmic extragalactic background radiation.

If the propagation of the radiation is described by a metric theory then it satisfies the Liouville or brightness theorem. If the metric describes a homogeneous isotropic spacetime then the geometry is fixed by the expansion factor $a(t)$, a function of the proper world time t alone, together with the radius of curvature $a(t)R$ of sections of constant time, where the comoving radius R is a constant. In this spacetime the radiation energy density $u(t) = \int d\nu\, u_\nu$ integrated over frequency at time t is an integral over the history of production and absorption of radiation,

$$u(t) = \int^t dt'\, j(t')\, (a(t')/a(t))^4. \tag{1}$$

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At tine t' the net rate of production of radiation (emitted minus absorbed) per unit proper volume is $j(t')$, and $j(t')\,(a(t')/a(t))^3$ is the rate of production of energy per comoving volume normalized to the time t of observation. The remaining factor in the integrand, $a(t')/a(t) = (1+z)^{-1}$, where z is the redshift at the epoch t' observed at time t, represents energy lost due to the cosmological redshift.

If spacetime were static, a independent of time, equation (1) says j could not have been constant: there would have to have been a characteristic time at which star formation commenced. The point, associated with the name Olbers, is not often mentioned now; an edifying discussion is to be found in Bondi (1960). In the classical steady state cosmology (which also is well described by Bondi) the universe is expanding, $a \propto e^{Ht}$, where H is Hubble's constant. This makes the integral converge even when j is constant, stars forming at a fixed mean rate per physical volume back to the indefinitely remote past. But we know now this is not a viable picture: Cowie and Lilly describe in these Proceedings observations of galaxies and an intergalactic medium at high redshift that are distinctly different from what is observed nearby; the more youthful appearance of objects at high redshift agrees with the interpretation that they are seen closer to the time when the structure we see started forming. In the general relativistic Friedmann-Lemaître model with a classical stress-energy tensor that satisfies $\rho + 3p > 0$ the integral in equation (1) has to have a lower limit, at the singular start of expansion at $a(t) = 0$. In the eternal inflation scenario (Linde 1990) this unsatisfactory situation is relieved by the return to a steady state philosophy: the lower limit to the integral extends back along our world line to the remote past.

2. Cosmic Energy Densities

Let us consider now the interpretation of the radiation background under the standard relativistic cosmology. Evolution after inflation — or whatever produced the initial conditions for the present state of our expanding universe — was accompanied by exchanges of energy among different forms. An accounting of the integrated results of the transactions at the present epoch offers a measure of cosmic evolution, and in particular it informs our interpretation of the infrared background.

The estimates in Table 1 are expressed in units of the Einstein-de Sitter value, $\rho_c = 3H_o^2/(8\pi G)$, at Hubble constant $H_o = 70 \pm 10$ km s^{-1} Mpc^{-1}. That is, these numbers are contributions to the cosmological density parameter. The first set of numbers, labeled primeval, are thought to have been fixed by physical processes operating in the early universe, well before stars and galaxies started forming; the second set are estimates of the effects of the formation and evolution of structure on scales ranging from clusters of galaxies down to star remnants.

The accounting in this table accepts the evidence for a Friedmann-Lemaître model that is close to cosmologically flat, the stress-energy tensor being dominated by a term that acts like Einstein's cosmological constant, Λ. The next most important term appears to be some form of nonbaryonic dark matter. The baryon density in the third line agrees with the theory of the origin of the light elements in the early universe, with the fluctuation spectrum of the 3 K thermal background radiation — within reasonable-looking uncertainties (e.g., Hu et al. 2000) — and with the observational constraints on the baryon budget (Fukugita, Hogan, & Peebles 1998). The baryon entry seems secure to 30% or so, a truly remarkable advance. It is a measure of the state of our subject that the two largest entries are conjectural. The evidence for low pressure dark matter at about the density indicated in the table is compelling if we accept general relativity theory (and hence the inverse square law for gravity); the evidence for Λ or its near operational equivalent is strong if we accept the adiabatic CDM model for structure formation. Work in progress promises to establish more tests of general relativity theory applied on the scale of the Hubble length, of the cosmology, and of the theory of structure formation. The results certainly will be searched for potential insights into the enigmatic leading entries in the table.

Table 1. The Cosmic Energy Account

	Ω
Primeval	
Λ/Quintessence/dark energy	$10^{-0.1\pm0.1}$
low pressure nonbaryonic matter	$10^{-0.75\pm0.25}$
baryons	$10^{-1.3\pm0.1}$
relict neutrinos	$10^{-2.4\pm0.8}$
thermal radiation	$10^{-4.15}$
gravitational binding energy	$\sim -10^{-6}$
Products of Structure Formation	
gravitational binding energy:	
relativistic	$\sim -10^{-5.4}\epsilon$
stars	$\sim -10^{-7.8}$
galaxies	$\sim -10^{-8.3}$
nuclear binding energy:	
helium	$-10^{-5.6\pm0.5}$
heavy elements	$-10^{-5.9\pm0.3}$
X / gamma radiation	$\sim 10^{-8.5}$
optical/near ir radiation	$\sim 10^{-6}$
far ir/sub-mm radiation	$\sim 10^{-6}$

The entry for relict neutrinos that broke thermal equilibrium with the background radiation at $z \sim 10^{10}$ assumes the tau neutrino mass is no smaller than 0.03 eV, from atmospheric neutrinos (Super-Kamiokande Collaboration 2000), and no larger than about 1 eV, to avoid undue effect on structure formation (Klypin et al. 1993). The accepted provenance of the 3 K thermal radiation and its related neutrinos — entropy originating near the end of inflation — is conjectural. The observed peak in the angular fluctuation spectrum of this radiation, at the length scale set by decoupling at $z \sim 1000$, is good evidence this radiation is primeval, present well before the observed stars and galaxies could have started forming.

The meaning of the last of the primeval entries is illustrated by the comparison of two Friedmann-Lemaître models, both containing only cold dark matter particles with the same particle mass, and with the same comoving radius of curvature measured relative to the mean distance between particles. In one model the mass distribution is close to homogeneous; in the other model primeval curvature fluctuations have placed most of the dark matter in gravitationally bound nonrelativistic halos. At a given mean particle number density the mean mass density is smaller in the latter model by the amount of the mean halo gravitational binding energy: the sum of the kinetic energy of proper motion of the particles relative to the general expansion and the gravitational potential energy relative to a homogeneous mass distribution. Thus, when the particle number densities are the same, the physical radii of curvature are the same in the two models, and the expansion rate, from the relativistic expression $(\dot{a}/a)^2 = 8\pi G\rho/3 \pm 1/(aR)^2$, is lower in the model with halos. This gravitational binding energy in the model with halos is primeval in the sense that it is a consequence of the gravitational growth of structure out of given initial conditions; there is no energy transaction when the halos collapse to form bound systems. We have good evidence that this gravitational growth of structure is responsible for the large-scale structure of our universe; most dramatic is the consistency of the angular fluctuation spectrum of the 3 K background with the simple adiabatic CDM model for the gravitational instability picture (e.g., Hu et al. 2000 and references therein). In this CDM model radiation pressure suppresses the growth of density fluctuations on scales less than the matter-radiation Jeans length at decoupling, ~ 10 Mpc, lowering the binding energy, and the dissipation of the small-scale pressure waves adds a little entropy. The number in the table for the primeval gravitational binding energy assumes that matter at the sum of the mass densities in the second and third entries has rms peculiar velocity comparable to that of the Local Group relative to the 3 K background, ~ 600 km s^{-1}.

Many have commented on the small differences of values of successive entries in this first group, which may in part reflect the anthropic consideration that these parameters can be adjusted so we could not have been here to measure them, may in part result from physical relations to be discovered, and may in part be pure coincidence. Similar remarks apply to the second group of entries, of course.

The first entry in this second group is based on the contribution to the density parameter by the mass bound in compact nuclei of galaxies (from the review by Fabian 2000). If these objects are relativistic black holes, mass may flow into them without the emission of energy in radiation or jets. For our purpose this accretion without emission represents an exchange of small particles for large ones, both gravitationally bound to the massive halos of galaxies, and it has no effect on the accounting in Table 1. The same applies to the kinetic energy of a jet that is dissipated within the galaxy. The factor ϵ in the table is the mean fraction of energy in radiation and jets that has left the gravitationally bound halos within which these compact objects live.

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Most of the baryons are thought to be in intragroup and intracluster plasma, distributed in about the same way as the dark matter. The gravitational binding energy per unit mass consequently is about the same, and, as we have noted, in the adiabatic CDM model this primeval binding energy appeared without transfer of energy to some other form. The dominant energy exchange in this component of the baryons may be the thermal bremsstrahlung and emission line X-ray radiation from intracluster plasma; less important transactions include the energy exchanges due to galactic winds and the energy exchanges between baryons and dark matter via fluctuations in the gravitational potential.

The formation of baryon-rich spheroids and disks of galaxies requires about the same dissipative production of binding energy per unit mass as does star formation. Here too one can think of subdominant energy transactions: magnetic fields produced by galaxy dynamos and then blown out with the galactic winds, and escaping cosmic rays. The largest transaction likely was the contribution to the cosmic background radiation.

The entry for the binding energy in atomic nuclei heavier than helium is from Fukugita (2000); it uses the baryon budget of Fukugita, Hogan, & Peebles (1998) at $H_o = 70$ km s^{-1} Mpc^{-1}, and assumes the heavy element abundance is ~ 0.4 times Solar in the intracluster plasma and ~ 0.1 times Solar in the intragroup plasma. The production of helium in stars assumes the ratio of production of helium and heavier elements is $1 \lesssim \Delta Y/\Delta Z \lesssim 4$.

The energies in the optical/near ir and far ir/submillimeter extragalactic radiation backgrounds are taken from Pei, Fall, & Hauser (1999). These measurements, and their interpretations, are the subject of these Proceedings; a few comments suggested by the entries in Table 1 will be noted here.

The optical extragalactic background at $\lambda \sim$5000 Å likely is dominated by starlight from low redshift, because the spectra of most galaxies decrease toward the ultraviolet. If so, this background is not sensitive to the parameters of the cosmological model, but it is of considerable importance to cosmology as a test for stars in the extreme outer halos of galaxies or in objects with effective radii or surface brightnesses too small to be included in galaxy counts (Arp 1965; Peebles 1971). The measurement of the extragalactic contribution to the light of the night sky has a long history (e.g., Dube, Wickes, & Wilkinson 1979; Bernstein, Freedman, & Madore 2000). It shows we have not grossly underestimated the density of starlight, but further advances in the measurements will be followed with interest.

The estimate of the energy released by star formation is less than the upper bound on the background radiation between the optical/near ir and far ir/submillimeter peaks, not an observationally promising situation.

The energy released during dissipative contraction to the central baryon-dominated parts of the galaxies could make an interesting contribution to the X-ray background. The contribution by spheroids depends on the mode of formation, whether by dissipative contraction of plasma followed by star formation or by near dissipationless merging of dense star clusters. Wyse (1999) reviews the observational considerations on which might be closer to what happened. If the latter, and if the star cluster building blocks had small individual escape velocities, the radiation accompanying the dissipative assembly of the star clusters could be lost in the UV/optical background. Disks likely formed by dissipative settling, and might be a significant source for the soft X-ray background.

The energy density in the X-ray background is three orders of magnitude down from the estimate of the energy density in black holes in galactic nuclei. Fabian (2000), Hasinger (2000) and others note that even with the $1+z$ redshift dimming (eq. [1]), and a low radiation efficiency, ϵ, there is an ample budget for significant contributions by AGNs to the optical and submillimeter backgrounds.

About half the extragalactic B-band background radiation comes from the disks of spiral galaxies. The dust in disks absorbs a substantial fraction of the starlight, so the contribution to the energy density in the submillimeter radiation background from starlight absorbed and reradiated by dust would be expected to be comparable to the contribution to the optical/near infrared radiation by unabsorbed starlight. This is in line with the background measurements discussed by Hauser and others at this meeting. The entry for the binding energy in atomic nuclei is comparable to the measured energy in the infrared background. And with Pettini's (1999) calibration, the time integral of the observed star formation history agrees with the present mass density in stars. These three results could be taken to suggest we are getting close to a reconciliation of our accounts. There are some complications to consider, however, as discussed next.

3. Star Formation Histories

Michael Fall and Piero Madau discuss in these Proceedings an important observational and conceptual advance, the establishment of a global star formation history. This history can be compared to the record of the evolution of heavy element abundances, and to the resulting extragalactic infrared background. I will present reasons for thinking complications in the history may require a generalization of the star formation history to a function of two variables, world time and environment. The latter might have just three values: normal $L \sim L_*$ galaxy bulges, galaxy disks, and everywhere else. Even with this simple second parameter the assembly of useful observational constraints would be a messy project, but it may be necessary for concordance in the interpretation of a more sophisticated version of Table 1.

To begin, suppose we choose cosmological parameters (and the range of values now under popular discussion is not that broad) so as to fix the world time t as a function of redshift. Then the Madau plot (Pei & Fall 1995; Madau et al. 1996) — the observed star formation rate dM_*/dt per unit comoving volume as a function of redshift — could be replotted as the product $t\,dM_*/dt$ as a function of $\log t$ (or, what is equivalent, $z\,(dM_*/dt)\,(dt/dz)$ against $\log z$). The motivation is the same as for the representation of the energy density of the extragalactic background as $\nu u_\nu = \lambda u_\lambda$: in a semi-logarithmic plot the area under the curve is the contribution to the integral over the independent variable per logarithmic interval of the variable. That is, this way to represent the star formation history gives us a picture of when there were significant contributions to the net mass in stars. One would see that about half the observed star formation was relatively recent, at redshift $z < 1$. Where are these young stars? The answer may well be complicated; I will mention two simple possibilities.

First, the star formation observed at $z < 1$ might be concentrated somewhere other than in the normal textbook galaxies. Maybe this has something to do with the enigmatic fading faint blue galaxy population; we don't know where they ended up either. In this scenario most stars may have formed at $z < 1$ and produced most of the metals and most of the extragalactic infrared radiation. But by assumption the extragalactic infrared background would have no direct relation to the origin and evolution of the populations of normal galaxies.

A second scenario is that most of the stars that formed at $z < 1$ end up in normal $L \sim L_*$ galaxies. Then the evidence as I understand it is that these stars would have to be subdominant additions to the predominantly older star populations. We might recall that this evidence includes these four points:

a. About two thirds of the star mass in the high surface density $L \gtrsim L_*$ galaxies is in spheroids. The evidence I have been hearing is that most of these spheroid star populations are a good deal older than $z \sim 1$.

b. Galaxy counts as a function of redshift at $z \lesssim 1$ are consistent with near passive evolution of the star populations already present at $z = 1$.

c. It seems to be agreed that the present population of normal $L \gtrsim L_*$ galaxies by and large were in place, with near familiar morphologies, and close to the present-day comoving number densities, at $z = 1$.

d. The normal-looking $L \sim L_*$ spirals and ellipticals observed at $z \sim 1$ are close to the Tully-Fisher and fundamental plane dynamical relations, after correction for passive evolution, consistent with the idea that these are full-grown textbook galaxies.

I think we must conclude that in this scenario the observed star formation history does not include the main event: the bulk of the star formation would have to be off scale to larger redshift, or maybe present at the redshift range of the Madau plot but heavily obscured by dust and in concentrations small enough to have avoided too many SCUBA detections.

We have a constraint on this hypothetical "main event" from the production of heavy elements. Pei, Fall, & Hauser (1999) estimate that the observed star formation rate integrated from high redshift to $z \sim 2.5$ is about enough to account for the observed accumulation of mass in heavy elements at this redshift, while Pettini (1999) and Pagel (1999) argue that the observed mass in heavy elements at $z \sim 2.5$ may actually be significantly less than what might have been expected from the seen amount of star formation up to this epoch. Under the former estimate the "main event" requires a special conjecture: we have to suppose the heavy elements associated with the substantial early star formation are hidden, perhaps in dense clouds. Under the latter estimate heavy elements have to be hidden at $z \sim 2.5$, so it would not be such a great stretch to imagine the heavy elements associated with the "main event" are hidden too. Advances in the subtle analysis of the constraints on the star formation history, including the relation between star formation and heavy element production, will be fascinating to follow.

4. Concluding Remarks

It has been widely and properly noted that we have significant observational evidence that galaxies as we know them formed recently, at $z \lesssim 1$: the energy in the infrared extragalactic background, without large redshift dimming, is comparable to the binding energy of the heavy elements in normal $L \gtrsim L_*$ galaxies, and the time integral of the seen star formation rate, which implies most stars are young, agrees with the seen mass in stars. But, I have argued, other lines of evidence indicate the cohort of stars and their heavy elements that formed at $z < 1$ had to have ended up somewhere other than the high surface brightness parts of normal galaxies, or else are subdominant additions to the normal galaxies. True coincidences happen, of course: we have a sensible case for similar contributions to the submillimeter background by two quite different sources — the radiation from stars and from AGNs — with quite different fractions processed through dust.

The lesson is that untangling the relations among the extragalactic radiation background, the histories of star formation in different environments, and the accumulations of stars and heavy elements, is likely to be a complicated operation. This is hardly surprising, considering that we live in a complicated universe. But the suite of observational evidence in hand is rich, rapidly growing, and fascinating to see sorted out.

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Discussion

Jim Felten: Please expand on your point about giants, dwarfs, and voids. Isn't it possible that the dwarfs form part-way into the voids (to respect some required formation condition) but then act like mass points and migrate into the filaments, where more mass is? Isn't there time for that?

Jim Peebles: Yes, it seems easy to imagine that gravity cleared the voids and mixed together the originally segregated giants and dwarfs. But in the numerical CDM simulations I have seen there remain in the voids at $z = 0$ significant numbers of dark mass halos that would seem to be suitable homes for dwarf galaxies, contrary to what is observed.

Felten: Perhaps someone here who is more expert than I would speak up about the "Madau curve". I thought there were results from HST indicating that the curve is wrong – that the star formation does not drop off at high red shifts z.

Peebles: The observed star formation rate dM_*/dt may be close to constant at $z > 1$. But then the integral $\int dt\, dM_*/dt$ is dominated by low redshift, where the universe spends most of the time. That's why I think it would be helpful to see $t\, dM_*/dt$ plotted as a function of $\log t$.

Ned Wright: I have two comments: 1) The measurements in the near infrared and optical are quite a bit (2 to 3 times) larger than the lower limits from source counts. 2) The total power in the Primack et al. ΛCDM model (with a Salpeter initial mass function scaled to fit the data) is 0.1 times the Cosmic Microwave Background, which definitely raises a problem about energy sources.

Peebles: If there were excess light in the measured optical and near infrared background, the first sources I would consider are the low surface brightness outer parts of the galaxies. If light were missing in the models, I would look for the early generations of stars that seem to be missing from the observed global star formation history.

Leonid Ozernoy: The contributions from Λ/quintessence and dark matter to Ω change differently as functions of cosmological time. Unless the present epoch is special, what makes the current values of Ω_Λ and Ω_{DM} of the same order of magnitude?

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Peebles: I wish we knew! The easy answer used to be that we live in an Einstein-de Sitter universe, with $\Omega_\Lambda = 0$, but that has become very difficult to reconcile with the observations. So I think we have to learn to live with a coincidence, that we have come on the scene as the Universe is making the transition from matter-dominated expansion.

Vera Rubin: A comment – the Kelson plot of the fundamental plane was for a cluster at $z = 0.3$. Keck observations of spirals at $z \sim 1.0$ by Nicole Vogt show only passive evolution of the Tully-Fisher relation from $z = 1$ to the present. Question: If the Madau plot rose beyond $z = 3$, would this conflict with any data?

Peebles: Thank you for the comment; the evidence for near passive evolution at $z < 1$ is impressive and surely important. Concerning your question, I am not the one to assess the observational basis for the Madau plot!

Bernard Pagel: It has been shown by Pettini and by me (astro-ph/9911204) that the integrated star formation up to $z \sim 2$ implies much more metals than seen in absorption-line systems at that red shift.

Peebles: We have the "missing metals" problem you and Max Pettini pointed out, and an "unseen metals" problem: If the metal-rich spheroid stars really are old, they formed out of metal-rich gas clouds at high redshift that are not in the known classes of absorbers. Maybe the two problems are related. In any case they illustrate the subtlety of the heavy element account.

Michael Rowan-Robinson: Even with a flat star-formation history from $z = 1$ to 5, it is still true that about half the stars were formed after $z = 1$. However, this does not necessarily conflict with the fact that the fundamental plane for ellipticals shows only passive evolution to $z \sim 1$, since most stars made to date are in spirals and gas-rich galaxies, and in low-mass rather than L_* galaxies.

Peebles: I understand the $L \sim L_*$ spirals also tend to exhibit close to passive evolution at $z < 1$, and so conclude that most stars made to date in the high surface brightness $L \sim L_*$ galaxies formed at $z > 1$. Where are most of the stars that formed at $z < 1$? I presume they are in low mass and low surface brightness objects of the sort you mention.

Charley Lineweaver: Did you say that half of all stars ever formed, formed at $z < 1$ or that half of the stars we see at $z = 0$ formed at $z < 1$? On what data is this statement based?

Peebles: I suspect the numbers are too uncertain for the distinction you mention. I base the statement on the Madau plot of the rate of star formation, dM_*/dt, as a function of redshift z. And as I said, my reading of the evidence is that this misses a substantial fraction of the star formation at $z > 1$.

Martin Harwit: The Madau plot tends to be misleading, because the time available at high red shifts is very brief – few stars are formed. If one increases the early star formation rate, the early abundance of heavy chemical elements would have to rise, which does not seem consistent with observations.

Peebles: Your first comment explains why I would prefer to look at a plot of $t dM_*/dt$ as a function of $\log t$. I think people agree that the stars in massive spheroids formed at redshift well above unity, and that the evidence for near passive evolution of spirals suggests a good fraction of the stars in spirals formed

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at $z > 1$ too. If this were so, there would have to have been regions with high heavy element abundance at high redshift. Perhaps they are obscured by dust.