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The other backgrounds

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Abstract. The significance of the cosmic microwave background or CMB (3K, thermal, relict, black body, isotropic, etc) radiation in confirming a hot big bang model of the early Universe and in setting precise values of many of the parameters of that model is widely known and has recently been enhanced by the results of three years of operation of the Wilkinson Microwave Anisotropy Probe (WMAP). There are, however, also backgrounds of astrophysical and cosmological significance consisting of photons of other wavelengths, other forms of radiation, particles, and fields. Several predate the discovery of the CMB, while others are relatively recent discoveries. This article explores the history of their predictions and discoveries and their cosmological and astrophysical implications as currently understood.

Keywords : cosmic rays – magnetic fields – gravitational waves – neutrinos – gamma-rays: observations – X-rays: diffuse background – ultraviolet: general – infrared: general – radio continuum: general

1. Introduction and definition

Astrophysical backgrounds are of two types: those arising from truly diffuse emission processes and those that are the sums of sources not yet resolved. The cosmic microwaves (CMB, Penzias and Wilson 1965) and the X-ray background (Giacconi et al. 1962) are the best known relatively pure examples, though, of course, there are also microwaves from sources (a foreground to those studying the CMB) and, at least in principle, diffuse X-rays from hot gas, fields, and particles in intergalactic space. In a few of the cases discussed below, the issue of truly diffuse vs. sum of sources has still not been resolved. And the neutrino and gravitational radiation backgrounds

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are thought to have comparable contributions from both, though at very different wavelengths or energies per particle.

The sky between stars, galaxies and other sources is probably not truly dark in any form of energy, though you might want to claim temporary exceptions for X-rays at the stage when Friedman et al. (1951) had seen one source - the Sun - and nothing else and sporadically for TeV-Pev gamma rays in recent years, because the angular resolution and sensitivity of the detectors have improved more or less in lock step (Aharonian et al. 2006 and previous papers cited therein.) The astronomers of an earlier age seem, however, to have supposed that the moonless night sky could be completely dark in directions away from the planes of the Solar System and Milky Way and in the absence of aurorae, camp fires, fire flies, and all. Simon Newcomb (1907) found that this was not so by visual comparison of the sky toward the North Galactic Pole (seen from the home of A.Graham Bell on Cape Breton Island) with the appearance of the light from various stars blurred by out-of-focus lenses and attenuated by dark glass. He estimated the equivalent of one 5th magnitude star in a circle of diameter 1°, or one 22.8th magnitude star per square arc second in the archaic language modern astronomers still use. Newcomb ought to be credited for this, because he otherwise does not get much good publicity, having been regarded as obstructive in the founding of the American Astronomical Society and as the prototype of the "learned astronomer" of Whitman's poem.

We explore here all of the backgrounds of which I am aware (with three exceptions), beginning with the oldest (cosmic rays), continuing with the other non-photon ones, and ending with photons from hard to soft. The Table summarizes predictions, discoveries, nature and significance of the various entities. "Astrophysical" is short hand for all we know and hope to know about the formation, evolution and death of stars and galaxies and "cosmological" for information about the early Universe and the origins of structure in it.

As for the three exceptions, the first is the CMB. Spring 2006 has certainly been the "season of WMAP". The official summary of implications of the first three years of data from the Wilkinson Microwave Anisotropy Probe is Spergel et al. (2006). I have reviewed the history of CMB pre-discoveries and non-discoveries elsewhere (Trimble 2007). The other two are dark matter and dark energy, for which see Trimble (2005) for a somewhat biased summary of discovery, candidates, and implications.

2. Cosmic rays

The (mostly Galactic) cosmic rays (CRs) are the oldest of the backgrounds, recognized by Geitel (1900), Elster(1900), and Wilson (1900) and shown to be extra-terrestrial by Hess (1911) and Kohlhörster (1913). Credit for demonstrating that they are particles rather than very high energy photons and that the charge is positive has been debated. My favourites are Bothe and Kohlhörster (1929), whose first sentence includes the word "gammastrahlung" and whose last says "korpuskularstrahlen" for the particles, and Johnson (1935) for the charge.

In the same time frame, Walter Baade and Fritz Zwicky (1934) put forward the idea that the underlying energy came from supernova explosions, which they attributed to the collapse of normal stars to neutron stars. Both ideas survive down to the present, though the precise acceleration mechanisms are debated and a second sort of (nuclear) supernova was later identified. Baade and Zwicky supposed that cosmic rays would stream freely out of the Milky Way in less than 10^5 years, so that it required a very large fraction of the 10^{53} ergs available per core collapse to keep up the observed supply of about 1 eV/cm^3. They did not address acceleration, but the "whip crack" picture (in which a given amount of energy is transferred to less and less mass as a shock wave moves outward) would fit with the rest of their paper.

Magnetic acceleration in shocks belongs to Enrico Fermi (1949). You might reasonably have expected Hannes Alfven to have agreed, since the idea of an interstellar magnetic field (next section) was probably first his, except that Alfven seems, as a matter of principle, never to have agreed with anyone. I knew him only quite late in his life, when he could no longer easily carry both a buffet lunch plate and drink across a room and am pleased to report that his teeth, digestion, and mind all remained in excellent condition and that he carried on a cheerful and informative flow of ideas while briskly consuming the same sorts of salads, chicken drumsticks, and such that I had chosen for myself. But the Sun was, by then, known to be a source of energetic particles, and the brief identification of bright radio sources as Galactic "radio stars" (Ryle 1949) sent him off in the direction of stars like the Sun, only much more active as the primary CR source (Alfven 1949). He remarked then that Fermi's idea would probably also work, but was still arguing for something other than diffuse Galactic acceleration at the time of the 1967 IAU Symposium 32 in Nordwijk.

Fermi's accelerating magnetic field would also confine at least the lower energy particles within the Milky Way, greatly reducing the energy needed from each supernova to less than 10^{51} ergs. And, dashing madly down to the present day, we can echo Volk et al. (2005), "We tentatively conclude that Galactic supernova remnants are the source population of Galactic cosmic rays," meaning, they say, the ones up to 10^{15} eV/amu, beyond which the spectrum steepens indicating leakage from the Galaxy, a different source, or something. Thus "low energy" cosmic rays seem to have only astrophysical significance.

The situation changes as you look at higher and higher energies (except for Plaga 1998, who says all cosmic rays are extragalactic). The composition reverts from the domination by heavy nuclei seen at $10^{15}-10^{18}$ eV to mostly protons again, presumably extragalactic, above 3×10^{18} eV (Bird et al. 1993a,b). At first this does not sound like a problem. Our Universe is full of quasars and such, whose photon fluxes indicate that they ought to be able to produce very high energy particles.

The catch is that, to a proton of 10^{20} eV, an innocuous little CMB photon looks like an almighty gamma ray come to smash it out of its path. The first such cosmic ray was reported by Linsley (1963), and its grave difficulty in penetrating more than 100 Mpc or so of CMB photons is called the GZK limit for Greisen (1966), Zatzepin and Kuzmin (1966), though the problem was already known to Zeldovich (1965), for whom it was briefly an argument against a hot big bang. The energy goes mostly into pion production in case you wondered.

The flux at energies in excess of 10^{20} eV is currently in some dispute, though the largest detector array, Auger in Chile, is finding numbers at the low end of the previous range (Cronin 2005), somewhat reducing the transport problem. There would seem to be three possible solutions: the CMB is not cosmic (now entirely out of fashion). There are AGN sources less than 100 Mpc away, for instance 3C273 (Honda and Honda 2004) or colliding clusters of galaxies (Farrar 2005); the evidence in favour of local origin includes correlation of particle arrival directions, but denied by others (Abbasi et al. 2005, based on data from AGASA and Fly's Eye)

Third, and the source of possible cosmological significance, it is possible that the ultra-high energy cosmic rays are actually produced in the halo of the Milky Way by the decay, annihilation, or collisions of dark matter particles, monopoles, topological defects or some such (Sigl et al. 1996; Trimble and Aschwanden 1999; Gelmini and Kusenko 2000). Thus, conceivably, the UHECRs are telling us about the nature of dark matter or some similar cosmological background.

Better measurements of the spectrum of the UHECRs and of the nature of the primary particles (from ratios of muons to photons in extensive air showers, for instance) can be expected from the continued operation of Auger. In the case of alternative two, we will probably be able to deduce the directions to the sources (astrophysically important) or, with alternative three, find out something about dark matter or the seeds for galaxy formation.

3. Magnetic fields

Magnetic fields on the scale of galaxies and clusters present the clearest dichotomy between bottom up (astrophysical) and top down (cosmological) origins. The first objects known to be magnetic were the earth (in 1600, William Gilbert) and the Sun (in 1908, George Ellery Hale), so that early thinking naturally focussed on dynamos and batteries (Biermann 1950). The current observational situation is that magnetic fields are found in every astronomical structure whose formation has involved some gravitational contraction, but that only upper limits, typically a few nG, exist for unconsolidated intercluster regions (Widrow 2002; Vallee 2004; Yamazaki et al. 2005).

Alfven (1943) predicted an interstellar field near 5 μG on the assumption that it would be in energy or pressure balance with the random motions of gas clouds (essentially correct). The discovery process included the recognition of the polarization of starlight when it is scattered by interstellar dust grains (Hall 1949; Hiltner 1949) and the interpretation of that polarization as due to non-spherical dust grains aligned in a field extending along spiral arms (Davis and Greenstein 1951). Independent evidence came from the interpretation of the Galactic radio emission, seen by Jansky (1935) and Reber (1940), as synchrotron emission by cosmis ray electrons, though the issue was again confused by the idea of radio stars as the source (Ryle 1949; Unsold 1949; Shklovski 1952). Indeed just when and by whom synchrotron was understood to be important has been much debated. Key papers are Alfven and Herlofson (1950), Kipenheuer (1950) and Ginzburg (1951).

Hoyle (1958) was among the first to raise the difficult question of the origin of large scale fields, perhaps because he thought he had a solution - self-excitation during matter creation in a steady state Universe (to which a possible 21st century response is, then, well perhaps during baryogenesis in a standard hot big bang Universe). And Fritz Zwicky a decade or so later said that the only answer he could think of was a modification of Genesis, so that the words uttered were "Fiat lux; campusque magneticus." Zeldovich (1964) espoused a secular version of that view.

The alternative is fields produced by self-excited dynamos in stars, active galaxies, and gamma ray bursters, which are then expelled and stirred into interstellar and eventually intracluster gas. In either case, considerable amplification by coherent motions of ionized gas is required. And each hypothesis has at least one major problem: in the bottom up scenario, some way must be found to amplify only long wavelength modes to agree with the kiloparsec and larger scale fields seen in the Milky Way and elsewhere, while in the top-down ("fiat....") picture, the initial seed field of 10^{-19} to 10^{-11} G in various scenarios must come from some early Universe physics that is not very well understood.

The dichotomy has not been resolved in the 20 years since Rees (1987) provided a cogent overview of the origin of cosmic magnetic fields. So, while anthropologists have more or less converged on "out of Africa" for the origin of theoretical astrophysicists and other humans, in this field we find: (1) out of QSOs (Furlanetto and Loeb 2001), (2) out of gamma ray bursts (Gruzinov 2001), (3) out of old radio galaxies (Zweibel 2002), (4) out of domain walls (Forbes and Zhitnitsky 2000), (5) out of non-zero-rest-mass photons during inflation (Prokopec et al. 2002), (6) out of strings (Gasperi et al. 1995). (7) out of inhomogeneous and non-zero lepton number (Dolgov and Grasso 2002), (8) out of symmetry breaking (Ostriker et al. 1986) and undoubtedly many others. Clearly establishing the correctness of any of (4)−(8) would be of considerable cosmological interest. The first three are astrophysical processes, if mysterious ones.

4. Gravitational radiation and neutrinos

For both of these there is the virtual certainty of both numerous astrophysical sources and a cosmological background left from the hot, dense early Universe. All were considered briefly by Zeldovich (1965) in the last major cosmological review written before Penzias and Wilson (1965) announced their result. Also in common is the extreme elusiveness of both sources and continuum.

Gravitational radiation has the longer amd more checkered history. It is a prediction of Einstein's equations of general relativity, though Einstein himself doubted this at one time (a story that is not mine to tell, Kennefick 2005). Indeed "does not exist" papers were still being published in *Physical Review* as late as Scheidegger (1951). The context was that of self-gravitating systems, most simply a point-mass binary pair. Thorne (1987) provides a bit more of the history, describes some possible astrophysical sources, and credits Bondi (1975) with the line of reasoning that persuaded the community that waves would indeed carry energy away from such a system. Weber (1960) began the search for pulses of gravitational radiation from merging compact binary stars, supernova collapses, and such; and we then fast forward to the discovery and analysis of the first binary pulsar, whose orbital evolution is indeed dominated by energy loss in gravitational radiation (Taylor and Weisberg 1982). This counts as indirect detection of predicted radiation in the μHz band. A final merger or free-fall collapse formation of neutron stars and blackholes leads to kHz radiation.

There must be a sum-of-sources background from such systems, as well as from formation and mergers of much more massive black holes in galactic centers, with frequencies ranging from a few kHz down to nHz or less, and we can fast forward again to the present era of large, expensive free-mass interferometers, aimed in the 0.1−10 kHz regime and ongoing calculations of what might be detected. Baker et al. (2006) is a recent one of very many such calculations. Although binary mergers have been the drivers for the construction of the VIRGO, LIGO and other arrays, no actual examples of neutron star plus black hole or double black hole binaries are known, and the case for the much more massive binary black holes in galactic centers also rests on rather indirect evidence (periodic AGN variability, galaxies that look like merger products and still have two nuclei etc), making predicted event rates rather uncertain.

Before going on to truly diffuse backgrounds, it might be worth revisiting analogies with electromagnetic (EM) waves. EM waves are vibrations of an electromagnetic field. But you make them by wiggling charges in a way that leads to, at least, a varying dipole moment. Similarly, gravitational waves are vibrations of space-time geometry, but you make them by wiggling masses with, at least a varying quadrupole moment, preferably very large masses, very fast. On the atomic scale, neutrino production will win by factors of order 10^{10} (Gandelman and Pinyaev 1959).

Of the early work on cosmological gravitational radiation we note only (1) that there are scalar wave solutions in an expanding Universe (Rosen and Taub 1961), and (2) that "alarming phenomena could probably be caused by accelerated expansion" (Schroedinger 1939). This prescient remark from a paper entitled "The proper vibrations of an expanding Universe" enables us to leapfrog over a number of early Universe predictions and land in the midst of inflation, which predicts "nearly scale invariant spectra of scalar (energy density) and tensor (gravitational wave) perturbations" (Boyle et al. 2006).

The scalar perturbations are the temperature or flux variations across the sky that COBE detected in 1991-92 (Smoot et al. 1992) and that have been wallpapered across the literature since the first WMAP report (Bennett et al. 2003). The tensor or gravitational wave ones must be weaker by a factor 10 or more, or we would already have seen them (Spergel et al. 2006). Foreseeable future missions can be expected to reach a tensor/scalar ratio r=0.01 or thereabouts, correct foreground subtraction being at least as much of a problem as sensitivity, as is often the cosmological case (Cooray and Kaplinghat 2007). Why might we care about r? The strength of this non-curl-free part of the CMB fluctuations contains information about the energy scale on which inflation occurred (if it did) and on the equation of state of the Universe during the inflationary epoch (Boyle et al. 2006). A ratio r = 0.01 would be detectable, informative and not entirely unexpected (Boyle et al.)

Neutrinos are just a little less elusive than gravitational radiation, in the sense that two sources (the Sun and supernova 1987A) have been seen. At least for the sources, the broad-brush calculations have also been fairly stable. That a stellar collapse would yield about 10^{53} ergs goes back to Baade and Zwicky (1934), and that most of it should be radiated as neutrinos can be found in the papers of Pontecorvo (1959), Chiu and Morrison (1960), and Gandelman and Pinyaev (1959). The sum of all past SNe in the Universe should be brighter than the forground of atmospheric cosmic ray secondary neutrinos at energies less than 30−40 MeV (Raffelt 2003), and so in principle be detectable.

What flux do you expect? This makes a fine envelope-back calculations of sort traditional astrophysicists rejoice in. Take the 1987A neutrino luminosity between 10 and 40 MeV. Choose a supernova rate (1 SN per 10^{10} $L_\odot$ per century for instance) and the luminosity density of the Universe today ($1-3\times10^{8}$ $L_\odot/\mathrm{Mpc}^3$). Allow something for larger star formation rates in the past, $(1+z)^4$ back to z=2−3 then flat or dropping back by z=6 to the current rate (and, of course, zero at z=30 or so), and integrate. There will be a small prize for the first student reader who does this and comes within a factor, say 10 of my answer. It should also be less than the Super-Kamiodande upper limit (Malek et al. 2002), which actually rules out some of the most optimistic predictions.

Detection of this (unresolved source) background or additional supernovae could have cosmological significance in helping, for instance to establish the correct neutrino mass heirarchy, with the two flavours having the smaller (solar) ΔM^2 either at lower mass (natural) or higher mass (inverted) than the third one that gives rise to the larger, atmospheric, ΔM^2.

Neutrinos up to and perhaps beyond 10^{20} eV could be co-produced with the highest energy cosmic rays and in the GZK processes that stop the propagation of still higher-energy charged particles. They are among the drivers for some planned very large particle detectors like IceCube (the successor to the Antarctic Muon And Neutrino Detector, AMANDA). For some of the details of production, detection and astrophysical implications for active galaxies and neutrino masses and for less standard physics like topological defects and superheavy dark matter, see the papers by Raffelt, Berezinsky, Blasi, and Olinto in Bandiera et al. (2003), or indeed the proceedings of any other recent conference on high energy astrophysics. No such neutrinos have actually yet been detected. In any case, the neutrino background that is the sum of sources will surely have astrophysical significance (for instance as an independent measure of the integrated number of supernovae over the history of the Universe), and in the case of very high energy neutrinos, perhaps also cosmological significance.

Discussions of a neutrino background sea left from processes in the early Universe predate the discovery of the photon sea (Brill and Wheeler 1957; Peres 1960; Smorodinsky and Pontecorvo 1961; Zeldovich and Smorodinsky 1961). All of these address possible very high energy processes (baryon anti-baryon annihilation, pion decay, etc) which would make very high energy neutrinos that might (especially with non-zero rest mass) even today dominate the cosmic mass-energy budget. Weinberg (1962) came closer to current thinking with a shallow degenerate Fermi sea of neutrinos filling the Universe. He pointed out that evidence for rest mass or chemical potential could be sought from the end-point of a Kuri plot if the mass were not too small (it is too small), but he preferred an oscillating or steady state Universe to a single big bang one. Weinberg gave credit for the initial idea of degenerate neutrinos to K.Watson.

The truly cosmological neutrinos are now understood to be a sea with a number density near 100 particles per cubic centimeter (for neutrino + antineutrino of a single flavour). In the past, at sufficiently high density and temperature (but after inflation) these were in thermal equilibrium with the photons (Peebles 1993, p. 160). The equivalent temperature is 1.95K, but a thermal spectrum is preserved only for as long as kT_ν is large compared to the neutrino rest mass. At $kT_\nu=1.66\times10^{-4}$ eV the inequality has probably broken down but not so long ago. For the three known neutrino flavours, the contribution to the mass-energy inventory of the Universe is about 0.1% of the closure density (Fukugita and Peebles 2004).

An experiment called LSND at Los Alamos found a ΔM^2 that can be reconciled with the other two only if there exists a fourth neutrino flavour that was not coupled to the rest of the stuff around during big bang nucleosynthesis. Yes, there could be, we suppose a cosmic sea of them contributing to the dark matter inventory. But really, truly you can find a more promising thesis project than trying to look for a hypothetical sea of sterile particles. In any case Mini-Boone currently in progress at Fermi Lab will probably rule out, or, possibly, confirm the LSND experimental result. Confirmation would obviously be very significant for both cosmology and fundamental physics, but is not widely expected.

5. The highest energy photons

Gamma rays for our purposes come in four very broad bands: (1) those associated with 10^{20} eV cosmic rays and neutrinos (hypothetical), (2) PeV/TeV range (sources known), (3) 100 MeV range and (4) 1 MeV range. Gamma ray astronomy had rather rocky beginnings, with major review papers (Fazio 1967, Hawakawa et al. 1964) before the first non-solar source had been seen. On the other hand, backgrounds in the lower two energy bands were the third and fourth ever seen, after visible light and cosmic rays. The key papers were Kraushaar and Clark (1962), above 50 MeV and Arnold et al, (1962) near 1 MeV.

The higher energy paper reports results from a detector on Explorer XI and data collected between April and September 1961. It contains one of my favourite astronomical sentences, "... the remaining 22 events, which come from a variety of directions in space ....". Arnold et al. collected many more than 22 photons on 27–28 January 1962 with an instrument on Ranger 3, which had been intended to measure gamma radiation from the surface of the moon just before an impact. It missed its target but saw gamma rays from space in a 0.1–2.6 MeV window. Upper limits to sources at GeV, TeV, and even PeV energies already existed at the time of the Fazio review.

Before 1992, there were three extragalactic gamma ray sources, 3C 273, NGC 4151, and Cen A, one each of a quasar, Seyfert, and radio galaxy, not providing much guidance on "typical" types. The inventory expanded rapidly with the launch of COS-B, though the largest class was (and still is) "unidentified", making the Galactic/extragalactic line hard to draw except on the basis of Galactic latitude. After the 1991 launch of the Compton Gamma Ray Observatory, the extragalactic inventory finally extended the number of models (Mattox et al. 1997).

TeV and PeV sources had an even more erratic history, with non-confirmations and detections occuring at about equal rates (Trimble 1993, Sect. 11.2). A new generation of detectors (looking for atmospheric Cerenkov radiation flashes), beginning with Whipple in Arizona, continuing with HEGRA in the Canary Islands and CANGAROO in Australia (see, e.g. paper by Aharonian in Bandiera et al. 2003), and still more recently HESS in Namibia (Aharonian et al. 2005) and MAGIC also in the Canary Islands, has increased the number of extragalactic sources to at least a double handful (Aharonian et al. 2006). All of them have blazar-like characteristics and redshifts less than 0.2.

The majority opinion is that the gamma rays in all of the bands (2−4) that have not yet been resolved into sources, mostly AGNs, are simply the sums of unresolved sources (Strong et al. 2004; Muecke and Pohl 2000; Kazanas and Pearlman 1999; Impey 1996; Stecker et al. 1993; and an arbitrarily large number of other papers). There are, however, still few hold-outs for interpreting some of the gammas as the products of dark matter decays (Elsasser and Mannheim 2005).

It is naturally great fun for theorists to explicate all the ways one might persuade photons to climb to stratospheric energies. (1 PeV is the gravitational potential energy of a microgram in the stratosphere or the kinetic energy of a flea jump.) But, from a cosmological view, the most interesting gamma rays are probably the ones we don't see.

First come gamma rays above about 100 MeV from AGNs more distant than z = 0.2 and drop-offs from power law spectra toward 1 TeV for the closer ones we do see (Aharonian et al. 2006, a rare case where the standard alphabetical order for large collaborations happens to put first someone who does a large fraction of the work; MACHO results from Charles Alcock and his colleagues are another example, though we have occasionally been tempted to adopt a name like Ada Aardvark and try to join the team). What happens to the higher energies and more distant sources? It's those blasted intergalactic photons again (see cosmic rays above), but this time optical, UV, and IR ones, depending on the energy you are looking for. These collide with the most energetic gamma rays and make pairs, degrading the photons to lower energy. We can, thereby, derive an upper limit to the current intergalactic optical-IR energy density, no matter whether it comes from distant first stars and QSOs, local galaxies, or anything else. The limit, $\leq 14 \pm 4$ mW m^{-2} sr^{-1} is very close to what comes just from local known galaxies, a point to which we will return in Sect. 8 (Aharonian et al. 2006).

Second, and closely related, most active galaxies that are known EGRET sources (or would be if they were closer) cannot have spectra extending into the TeV regime, or the degraded photons would yield a background at lower gamma ray energies in excess of measured values (Coppi and Aharonian 1997). It is significant in this respect that BL Lac itself, which is closer to us than the first two TeV AGNs, Mkn421 and 501 is not a strong TeV source.

The third thing we don't see is gamma rays from matter-antimatter annihilation. Steigman (1976) was not the first, and Dudarewicz and Wolfendale (1994) were not the last to point out that this precludes matter anti-matter symmetry in the Universe, even if the volumes occupied by each were comparable with the Hubble radius and even with a Leidenfrost layer of gammas trying to keep the regions separate.

Fourth, we do not see chirps of gamma rays from Hawking evaporation of primordial black holes (PBH). The implication is that either PBHs do not close the Universe (Page and Hawking 1976), Hawking radiation does not occur, or of course, both. Indeed PBHs cannot even be the local Galactic dark matter at any density more than about 0.003 $M_\odot$ pc^{-3} (3% or so of the total) without having chirped at the Cygnus detector (Sinnis 1994).

In summary, then, gamma rays are of considerable astrophysical interest, but they seem to be something of a cosmological washout, except perhaps as dark matter decay or annihilation products and as probes of intergalactic star light.

6. X-rays

The existence of an X-ray background was announced the same year as the gamma ray ones (Giacconi et al. 1962), though the observations, from a rocket, came just a bit later. At the time, major cosmological significance was a real possiblility; for the Universe of 1962 was widely supposed to have a critial density in baryons, most of which had to be between the galaxies. The suggestion that X-rays might be bremsstrahlung from hot intergalactic gas came first from Hoyle (1963) in a steady state context, where density has to be the critical one and heat is available from the creation process. Indeed there was a risk of producing too many X-rays (Gould and Burbidge 1963) for the critical density associated with H=100 km/sec/Mpc.

Two changes modified this conclusion: first, the Hubble constant dropped (which helped because free-free emission scales as $n_e n_p$ or density squared), and second, Gunn and Peterson (1965) found no absorption from intergalactic neutral hydrogen near z=2, setting a lower limit to the temperature of a critical density IGM near 10^6 K. As a result, when Sciama (1971) and Peebles (1971) produced the books that made teaching introductory cosmology a joy for almost the next decade, an X-ray background from intergalactic gas that would tell us the density of the Universe seemed a real possibility.

Then considerations of cosmological nucleosynthesis began driving the baryon density (still thought to be the total) down to what might be accounted for by galaxies and clusters and, if memory serves, the Universe was open for a while. But the firm, final nail in the coffin of hot intergalactic, X-ray emitting gas came from the very precise black body spectrum of the CMB recorded by COBE (Mather et al. 1990) Scattering off the hot electrons would have distorted the spectrum in the direction of pushing photons to shorter wavelengths. But surely, you will say, intergalactic space cannot be an absolute, total vacuum at the 10^{-12} atoms cm^{-3} level required by Gunn and Peterson (1965). There must be at least a bit of diffuse hot gas producing an occasional X-ray photon. Well, perhaps, concur McCammon et al. (2002), though they say, only softward of 1 KeV, and it is mostly lines of ionized oxygen and such (and, since enriched, not real IGM anyhow). Indeed reading Zheng and Davidsen (1995) and Reisenegger and Miralda-Escude (1995) will leave you in doubt about whether we have evidence for truly intergalactic material at any temperature near z=0. Discussion about what it might do in that critical allowed temperature range of 10^5-10^6 K however persists (Perna and Loeb 1998).

What is left is the sum of sources, starting with the AGNs, spotted by the Uhuru satellite and continuing on down to ones still not quite resolved by Chandra and XMM. Indeed you will have been told, by ROSAT and its owners (e.g. Hasinger et al. 1993, 2001 for 1−2 keV) and second hand by me, that the last of the background had finally been resolved more than once. A recent one is 80% by XMM (DeLuca and Molendi 2004). Why do I sound so reluctant to declare victory over the X-rays and go on to Ultraviolet? Three reasons. First, the observers are not entirely in agreement; Loaring et al. (2005) report that only about 50% of the 1−5 keV background is resolved by XMM. Second, and perhaps responsible for the first, the total flux to be accounted for retains a sizable zero-point uncertainty (Campana et al. 2001). And, third, the integrated spectrum at 2−10 keV is good deal harder than local sources (Nandra et al. 2002).

One has, therefore, to invoke a separate population of sources too faint for many to have been resolved and harder than those that have been. This seems to mean moderate redshift, less than spectacular, heavily absorbed (Type 2) AGNs. Well, all right, Sloan Digital has been finding lots of these as optical sources, and Cirano et al. (2005) report the first one with the right X-ray spectrum. But Maineri et al. (2005) and others remain discontent with the situation.

Nevertheless, as we venture onward to longer wavelengths, “sum of sources” and sometimes “sum of sources, but aren’t quite sure which ones” will remain the theme. There will also be some cases of uncertainty about whether anything from outside the Milky Way has been seen.

7. Ultraviolet

UV takes over where X-rays leave off, around 100 eV or 100Å (not quite the same; the useful numbers to remember are leV = 12,400Å = 2.42×10^{14} Hz), and continues longward until the earth’s atmosphere becomes reasonably transparent around 3200Å . As we venture into it, there are four challenges of different sorts; (a) the extremely large opacity of even small amounts of neutral hydrogen near 1216Å (Lyα) and from 912Å down to 100Å , (b) some confusion about what is to be meant by near, far, laboratory, vacuum, and extreme UV (which we will not touch), (c) uncertainty about whether any extragalactic background has been seen so intense 15 years ago that the editors of Annual Reviews of Astronomy and Astrophysics commissioned two competing reviews (Henry 1991; Bowyer 1991), and (d) rapid entanglement with the important cosmological issue of "first lights" and reionization, for which the leading candidate is currently UV shortward of 912Å coming from a first generation of (nearly) metal free stars, so that they are very massive and very hot. The competition is soft X-rays from accretion on black holes of anything from 10 to 10^8 $M_\odot$ (Abel et al. 2002; Rees 2002).

Two ultraviolet backgrounds have been predicted in the past. Weymann (1967) considered bremsstrahlung from a critical density intergalactic medium at a variety of possible temperatures. A warm/hot intergalactic medium (WHIM) is perhaps the most promising phase for the local baryons that are not in galaxies or clusters (Kang et al. 2005; Nicastro et al. 2005), though direct detection of the expected UV remains a challenge (Hurwitz et al. 2005). The second prediction came from Sciama (1990 and earlier papers mentioned there). It is the sort of idea that one would like to have been true. He postulated a large cosmic sea of 28 eV neutrinos with lifetimes like the age of the Universe, each of which would produce a couple of photons slightly harder than 13.6 eV, ionizing the outer parts of galaxies and generally making themselves useful. But careful examination of a couple of nearby clusters of galaxies revealed no excess of ionizing photons in them (Davidsen et al. 1991). Sciama's unexpected sudden death did not give him a chance to reconsider his neutrinos after additional UV data became available.

Curiously, we can be more certain about the extragalactic UV flux at $z \geq 2$ than here and now, because of something called the proximity effect. When absorption lines (especially the Lyα forest) were first discovered in QSO spectra, it was clear that there were more little absorbing clouds at large redshift than at small, except that there was a deficit at redshifts just a smidge less than that of the QSO itself. This was quickly seen to mean that UV from the QSO had ionized the clouds out to some distance and therefore, that the QSO UV was brighter than the general background out to that distance. OK. The redshift range with missing clouds tells you the distance. The QSO UV flux has redshifted to where you can see and measure it, and so calculate how many photons are available to ionize nearby clouds and say, a ha!, the general background must be of that order (Denda and Ikeuchi 1993 and many papers both earlier and later).

Where does that general UV bath come from, and how is it involved in the reionization process? Much of the literature is in preprint and conference proceedings form (e.g. Cooray and Barton 2006), particularly such modifications as will be inspired by the delay in onset of reionization between the first year and three-year results from WHAP (Spergel et al. 2006). But there is a large majority of experts (well, anyhow authors) in favour of star formation in the first galaxies or pre-galaxies starting at $z \sim 15$ and continuing to dominate the last of the reionization near $z=6$, but QSOs dominating the intergalactic flux from $z=2-4$ down to the present (Bolton et al. 2005; Shimasaku et al. 2005; Malkan et al. 2003; Fujita et al. 2003; Meiksin and White 2004; McDonald and Miralda-Escude 2001, and many others). In case you would like an alternative to change with, Oh (2001) derives his reionizing photons from inverse Compton Scattering of CMB photons by relativistic electrons that, in turn came from supernovae in population III.

Thus the diffuse ultraviolet light is, nearly beyond doubt, the sum of many sources (different ones at different epochs) but of cosmological significance in the sense of reionizing baryons, and thereby affecting the formation of structures, especially small ones, because ionized gas cannot easily settle into potential wells less deep than about 30 km s^1.

8. Visible light and near infrared

Optical astronomy is the oldest of all; therefore this background should be the easiest of all to do a good job of measuring. Right? Wrong! The night sky between the stars is not dark (Newcomb 1907). What we see today is, in order of decreasing surface brightness most often artificial light, zodiacal light scattered by dust in the plane of the ecliptic; aurorae and other natural sky light; Galactic starlight, seen directly, reflected, and absorbed and re-emitted, and, last and very much least, extragalactic light, weaker than the Galactic by a factor around 100. This hierarchy leads to the first problem in finding out about the optical/NIR background - you are going to have to look very hard to see it.

Second is that there would seem to be two approaches: either count all the galaxies you can see and add them up, or attempt to look between the galaxies, and discover the two answers don't agree. This brings us to (3), which is an independent handle on the local optical/IR energy density set by the ability of TeV photons to get to us from redshifts of almost 0.2 (Aharonian et al. 2006), given that the high and low energy photons should scatter off each other.

And (4) is the gosh-awful melange of units in which such things can be expressed, whether you are looking for energy densities, luminosity densities, or fluxes received. Henry (1991) likes ev/(eV = cm^2-sec-ster) and magnitudes per square arcsec (the traditional astronomy unit). Bowyer (1991) lays claim to continuum units: photons/(cm^2-sec-ster-A). Lagache et al. (2005) oscillate between W/m^2 and W/(m^2-sr), Hauser and Dwek (2001) prefer nW/(m^2-sr), and elsewhere in the recent literature, W/(Hz-Mpc^3) (Baldry et al. 2005) and $L_\odot/Mpc^3$ (Driver et al. 2005). These last two are local luminosity densities rather than fluxes received at earth, and frankly the only one we can remember is the last, perhaps because, at 10^8 $L_\odot/Mpc^3$ in blue light it hasn't changed for 20 years (Felten 1986 to Driver et al. 2005). Indeed, with proper correction for changes in the Hubble constant, H, Oort's estimate yet another 20 years before was about the same. The implication is, that although dwarf galaxies are very common in the local group, Virgo and so forth, most of the light comes from the few big galaxies. The infrared numbers are larger, 3.6 and 7.0×10^8 $L_\odot/Mpc^3$ in the J and K bands (Eke et al. 2005). Another thing that makes the $L_\odot/Mpc^3$ number easy to remember is that a mass to light ratio of 1000 $M_\odot/L_\odot$ would then just close the Universe!

If you want to compare numbers from different sources, Peebles's (1993) equation 5.152 is useful.

A luminosity density, j, radiating for a time t (H^{-1} for instance) produces an energy density $u \approx jt$, and the equivalent surface brightness, $i = cu/4\pi \approx jct/4\pi$ is the energy flux per unit area and solid angle. The 4π takes care of the 'per unit solid angle' or 'per sr' of various versions.

Here are a few numbers to give a feel for the Universe before we tackle the second and third problems mentioned above: 100 ± 10 mW/m^2-sr all the way from 0.1 to 100μm (Bernstein et al. 2002); 9.43 nW/m^2-sr for visible light (Minowa et al. 2005); 10^{19}W/Hz-Mpc^3 (Baldry et al. 2005) which is a luminosity density. Problem (2) was that you see 2−3 times as much light by looking between the galaxies than you get by adding up all the local ones and evolving them (Bernstein et al. 2002; Minowa et al. 2005; Wright et al. 2001). Well, all right. Many of us expect an initial burst of population III star formation to have started off reionization (Santos et al. 2002). Their UV light will be optical or NIR now, and indeed some near infrared observers have reported spectral signatures of that redshifted first light when they looked between obvious galaxies with the Spitzer Space Telescope (Kashlinsky et al. 2005) and the Japanese InfraRed Telescope in space (Matsumoto et al. 2005).

And this brings us right into the heart of the third problem. Visibility of 1−3 TeV photons from blazars at z = 0.186 and 0.165 (Aharonian et al. 2006) sets an upper limit to the optical-IR photon density they could have encountered en route. That limit is no larger than the sum of known galaxies, leaving no energy-space for light left from population III. Madau (2006) points out that there are ways of getting around either the IR detections or the TeV limits, but concludes that the discrepancy will surely spark further work on "the crucial early stages of the galaxy formation process". This probably counts as cosmological as well as astrophysical significance.

9. Farther infrared

The flux bands for 10 μm to 1 mm are, once you get outside the Solar system and Milky Way filled almost entirely by reradiated light from dusty star formation (Lagache et al. 2005). Some of the star formation is nearby, but the rates rise back to z=2−3 at least. The fraction of the flux that has been resolved ranges downward from 80% at 15 μm to 5−10% at 0.5−1.2 mm. The main problem is not sensitivity but source confusion, suggesting yet another opportunity for the rediscovery of P(D) (Scheuer 1957, but observers of the X-ray and other backgrounds have reinvented it several times). Some of the sources are X-ray bright, indicating the presence of accreting central black holes, but Lagache et al. concude that, even in these cases, nearly all the FIR, submm, and millimeter emission comes from dusty star formation. The photons are too soft to pose a threat to anything likely to be passing through them.

The topics of redshift evolution of star formation rate and the kinds of galaxies in which it occurs at various times are obviously of enormous importance and would fill a comparable-length paper if addressed properly. A couple of concepts that have become prominent in recent years are those of the 'last gasp' (the Universe really is running out of gas to form more stars) and 'downsizing' (the dominant hosts of star formation are smaller and fainter than they used to be; and you find, at every redshift, the oldest stars are in the biggest galaxies). In addition, it is worth noting that there are a number of indicators of star formation rates other than reprocessed far infrared. These include blue and UV light directly from young, massive stars, Hα from gas they have ionized (or Lyα at sufficiently large redshift), and supernovae, X-ray sources, and synchrotron radio emission from the deaths of massive stars. When all of stellar evolution, including

Table 1. Summary of other backgrounds: non-photon.

Entity	Predicted	Discovered	Produced by	Source sum or diffuse	Significance
Cosmic Rays	——	1900–1935	SNe, remnants	sum	astrophysical
UHECRs	——	1962 Linsley	AGN, particle decays, annihilation	sum diffuse	astrophysical cosmological/ dark matter
Magnetic fields					
Galactic	1943 Alfven	1949–51	‘bottom up’: pulsars, stars, SNe, AGNs	sum	astrophysical
Intergalactic	1958 Hoyle	(unconfirmed)	‘top down’: early Universe	diffuse	cosmological /baryogenesis(?)
Gravitational radiation					
nHz-kHz	1916 Einstein to 1941 Landau and Lifshitz	1974 Taylor and Hulse: indirect (driver for LIGO etc.)	NS/BH formation and binaries, SMBH formation and mergers	sum sum	astrophysical /GR tests astrophysical /GR tests
Mpc scale	1970s Grischuk, Starobinsky, et al.	(Planck mission 2011?)	inflation (or other very early Universe)	diffuse	cosmological /inflation epoch and energy
Neutrinos					
UHE	1970 Zatsepin, Berezinsky, others	(driver for IceCube etc.)	co-produced with cosmic rays, result of GZK UHECR destruction, other	sum diffuse	astrophysical/high energy physics beyond the standard model
MeV	Sun: 1939 Bethe to Bahcall, 1963	1972 Davis	nuclear reactions in stars	sum	astrophysical/weak interaction physics
	supernovae: 1959 Pontecorvo	1987 IMB, Kamiokande, Baksan, Mt. Blanc	plasma processes; URCA etc.in core collapse SNe	sum	astrophysical/weak interaction physics
1.9 K	1960–65, Peres, Zeldovich	——	inflation, other Planck-scale processes	diffuse	cosmological/before standard hot big bang

formation processes and the clearance of gas and dust from around the products, has been understood, all will, one hopes, give the same answers. This hasn’t happened yet, but progress is being made (Dopita et al. 2005). The far infrared background is apparently of purely astrophysical importance.

10. 21 cm and other radio

The 21 cm (1421 MHz) line in emission or absorption is a signature of neutral hydrogen gas out of thermal equilibrium with photons coming from the same region of space (van de Hulst 1945). Its relevance here as a sort of cosmic background comes from the facts that (a) known physical

Table 2. Summary of other backgrounds: photon.

Entity	Predicted	Discovered	Produced by	Source sum or diffuse	Significance
Gamma Rays					
TeV/PeV	1960s: Hayakawa, Ginzburg, Syrovatskii	1990s: Whipple Observatory	X-ray binaries, AGN, SNRs, pulsars, pp reactions	sum	astrophysical/limits on UV, optical, NIR backgrounds
	1990s	?	DM particle decays, other non-standard interactions	diffuse	cosmological/DM etc
50−100 MeV	1960s	1962 Kraushaar and Clark	AGN	sum	astrophysical/some limits of cosmological importance
MeV	1960s	1962 Arnold	AGN	sum	astrophysical
X-rays	——	1962 Giacconi	hot IGM	diffuse	cosmological/baryon density ruled out by COBE
			AGN	sum	astrophysical
UV (ionising radiation)	1967 Weymann	1965 Gunn-Peterson (indirect)	hot IGM	diffuse	cosmological/baryon density ruled out by COBE
		1980s proximity effect (indirect)	AGN	sum	astrophysical
	1964−67 Zeldovich, Partridge and Peebles, others	Reionization: WMAP 2003-06, (indirect)	population III stars: other ‘first lights‘	sum	astrophysical and cosmological for structure formation
	1980s Sciama	——	decay of 28 eV neutrinos	diffuse	cosmological; ruled out by Shuttle UV observations.
Optical/NIR	1826 Olbers	1990+ HST, IRTS, SST (direct)	galaxies, redshifted first lights	sum	astrophysical/ galaxy evolution
Far IR	1968 Low and Tucker	1996 Puget . et al.	dusty star foramtion, some obscured AGNs	sum	astrophysical/history of star formation
Radio					
21 cm	1944 van de Hulst	1951 Purcell, Ewen	neutral hydrogen in many contexts, including early Universe	sum diffuse	astrophysical, cosmological/ earliest probe of structure formation.
continuum	——	1932 Jansky	synchrotron and other processes in galaxies, AGN,	sum	astrophysical
	——		Possible intergalactic synchrotron.	diffuse	astrophysical/particles cosmological/ magnetic field

processes can keep it slightly out of thermal equilibrium during the beginnings of structure formation and (b) unlike Lyα it has a transition probability small enough that emission from times before reionization can reach us. The 1421 MHz photons are the only ones that can make that claim (Furlanetto 2006; Carilli 2006). The disadvantages are, first that the disequilibrium is small, and the signals therefore very weak, and second, that 21(1+z) cm is 3.26 m (92 MHz) at $z \sim 15$, implying the need for very large collecting areas operating in an unquiet band. Several incipient and planned arrays, including LOFAR and SKA may, however, be able to see 21 cm from before the epoch of reionization in either emission or absorption, coming from the very first, pre pre galactic structures.

Radio astronomy, like X-ray astronomy, began life with one source (the Galactic centre rather than the Sun) and a background (Jansky 1935; Reber 1940). Then there was a war (World War II). And then there was "a frank discussion of topics of mutual interest" between, among others, the steady state cosmologists and the counters of radio sources, which the counters intially took to be active 'radio stars' in our Galaxy. Records of discussions from the period sound also a bit like WWII, perhaps because the major protagonists were native speakers of British English and of German. In any case when even the shouting was over, it became clear (Ryle 1968), (a) that most of the radio sources were extragalactic, (b) sources were much commoner in the past than at z=0, and (c) that more than half of the total flux had already been resolved into sources in the early 1960s. You will be pleased to hear that, when venturing into radio astronomy, you encounter at least two more units, the Jansky = 10^{-26} W/(m^2-Hz), and brightness temperature, measured in K.

Galactic emission has both sources (stars of many flavours, supernova remnants, HII regions, and all) with both thermal and non-thermal spectra and a diffuse continuum from interstellar cosmic ray electrons spiraling in the Galactic magnetic field. After you remove the Galactic components, the cosmic brightness temperature between 17 and 178 MHz is 2.8 K (Ryle 1968). This is close enough to the CMB temperature that the radio astronomers could have created a good deal of confusion with it, but did not. Another interesting sidelight is that this absolute value (e.g. Henry 1991) is still anchored to measurements made by Bridle (1967).

Ought there to be also truly diffuse intergalactic synchrotron? Well, perhaps, though we have no current evidence for either of the required ingredients. It is left as an exercise for the reader to calculate what the volume emissivity could be. You may assume a magnetic field of, at most a few nG and a relativistic electron energy density of at most 10^{-3} of that inside the Milky Way, where, in turn, the electron energy density is about 1% of the 1 eV/cm^3 belonging to the protons. And as you set out on the calculation, we leave you with a parting thought from Scheuer (1966, lecture in radio astronomy at Caltech): "Allen's *Astrophysical Quantities* contains the only formula for synchrotron radiation that is wrong under all circumstances." We hope this no longer applies to the fourth edition.

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