The Extragalactic Infrared Background and its Cosmological Implications
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The Extragalactic Background at Ultraviolet, X-ray and Gamma Ray Energies

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Abstract. The extragalactic background at ultraviolet, X-ray and gamma ray energies is reviewed. Early work on the diffuse backgrounds in each of these bands was motivated, at least in part, by the idea that these fluxes were the result of processes which produced a truly diffuse flux with profound cosmological implications. As we will see, these processes were not observed. However, the study of this background has led to the discovery of unexpected processes at work in the Universe. Our current understanding of these backgrounds is presented.

1. Introduction

In the following I discuss the diffuse background in the ultraviolet, soft X-ray, X-ray and gamma ray bands for energies from 6 eV to 100 GeV. (Even higher energies are considered in another paper in this volume.) In this work I will make no attempt to provide a historical review since a full recounting of all the effort that has been expended on this topic would, by itself, overfill the Conference Proceedings. I will simply reference a few papers in each area which are particularly useful in providing our current understanding. This will, as a consequence, omit all detail of the huge experimental effort and the extremely clever observational and analytic techniques that were needed in order to obtain this information.

A fundamental problem in any attempt to identify a diffuse extragalactic background in these bands is that one needs a large field of view (with typically a low spatial resolution) to obtain sufficient flux for analysis. However, a small field of view (or some other method) is needed to identify point sources that may be contributing to the diffuse background, or, in fact, may be the entire source of what was thought to be a diffuse flux. Another complexity is that there are invariably other processes that contribute to the observed flux and greatly complicate the identification of an extragalactic background. These include various instrumental backgrounds and often include a background from Galactic emission which must be removed before an extragalactic background can be established.

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2. The Far Ultraviolet Background ($\sim$ 6 to 13 eV)

Early work in the study of this background was prompted, in part, by the possibility that this flux was produced by a "warm" (1 million K) intergalactic medium. Another intriguing possibility was that this flux was the product of an early phase in the Universe when galaxies were being formed. In some galaxy formation scenarios a burst of He II 304 Å radiation would be produced. This radiation would then be red-shifted into the Far UV and provide a diffuse background. Early observations provided support to these possibilities since they suggested that a diffuse Far UV flux was uniformly distributed over high Galactic latitudes.

A problem that beset all of this early work was that an evaluation of the contribution of stars was required since a substantial subset of stars were known to be UV emitters. The approach usually taken was to estimate the contribution of stars using estimates of their Far UV emission combined with (incomplete) stellar catalogues. This approach relied on the subtraction of a large and not well constrained stellar contribution from the not well determined observational flux which was of a similar magnitude. The resulting small difference was then identified as a diffuse background that was then attributed to some grand cosmological process.

The seminal paper establishing the true character of the diffuse Far UV background was provided by Paresce, McKee, & Bowyer (1980). These authors used data from a telescope flown on the Apollo-Soyuz orbital mission which carried out a photometric survey at 1400 Å in $\sim$ 300 separate view directions. This instrument had both a high sensitivity to diffuse flux and a sufficiently small field of view that stars could be identified and their emission removed from the data. The intensity of the diffuse flux obtained in these observations varied from 300 to 2000 photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{Å}^{-1}\,\mathrm{sr}^{-1}$. The flux showed a strong correlation with Galactic hydrogen column with a much weaker dependence on Galactic coordinates. This provided convincing evidence that the majority of the Far UV background originates in the Milky Way. Subsequent work established the components of this Galactic emission. A summary of the components of the Far UV diffuse background is provided in Table 1, taken from Bowyer (1991) with small modifications provided by J. M. Deharveng (1999). At this point there is no evidence for any diffuse extragalactic flux in the Far UV background, although it is possible that a very small part of the flux at high Galactic latitudes is extragalactic in origin.

3. The Soft X-ray Background ($\sim$ 1/4 keV)

Since its discovery in the late 1960s (Bowyer, Field, & Mack 1968), the origins of the 1/4 keV background has been a profound mystery. This initial work showed the flux was anti-correlated with Galactic hydrogen column. This demonstrated that most of the flux was connected with processes occurring in the Milky Way since an extragalactic flux at these energies would not be observable over much of the celestial sky because of absorption by the interstellar medium. However, the observed flux scaled as if a distant source was being absorbed by the interstellar medium. The absorption cross section was 1/3 of its true value. This was

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Table 1. The components of the Far UV diffuse background

Total Intensity	300–1500 photons cm^{-2} s^{-1}
Galactic components	
Scattering by dust	200–1500
HII two-photon emission	50
H_2 fluoresence	100 (in molecular clouds)
Components of the "uniform"	high-latitude background
Dust (?)	200
Summed from all galaxies	50
HII two-photon emission	50
Hot gas line emission	10
QSOs/AGNs	< 10
Intergalactic medium	< 10
Unexplained	none to < 200

a truly puzzling finding. These results were confirmed in exquisite detail in many subsequent studies. The correlation with interstellar medium cross section ultimately turned out to be misleading, but it was thirty years before a true understanding of the cause of this correlation was established.

The extensive observations of the 1/4 keV flux obtained with the ROSAT satellite (Snowden et al. 1997, and references therein) provided the data needed to solve this problem. Sidher et al. (1996) and Snowden et al. (1998) have used entirely different approaches in analyzing the ROSAT data, and both groups have reached essentially identical conclusions. It was found that the flux was produced by three separate components. The first is a local component (the so-called Local Bubble). This is shown schematically in Figure 1. A halo contribution and an extragalactic contribution are also needed. The summed effect of these components produce a result that mimics, purely by chance, a distant flux absorbed by the interstellar medium with an unnatural absorbing cross section. The results of Sidher et al. (1999) for the emission in the direction of the Galactic pole are shown in Figure 2.

The source of the flux in the Local Bubble is not well established. Most workers have concentrated on fitting this flux with emission from a hot (1 million K) plasma and emission from some sort of a boundary wall. These results all conflict in one way or another with some aspect of the observational data. An intriguing alternative, not yet fully developed theoretically or definitively tested, has been provided by Breitschwerdt & Schmutzler (1994). These authors show that the ionization state of the interstellar medium is strongly dependent upon the thermal history of the material, and that in extreme cases the thermal temperature of the electrons can be vastly different from the temperature derived from a low resolution photon spectrum. The halo flux may be the product of a 1 million K thermal plasma, or it may be produced by a plasma as described by Breitschwerdt & Schmutzler which has escaped into the halo. The extragalactic component of the flux shown in Figure 2 fits reasonably well with the higher energy X-ray flux.

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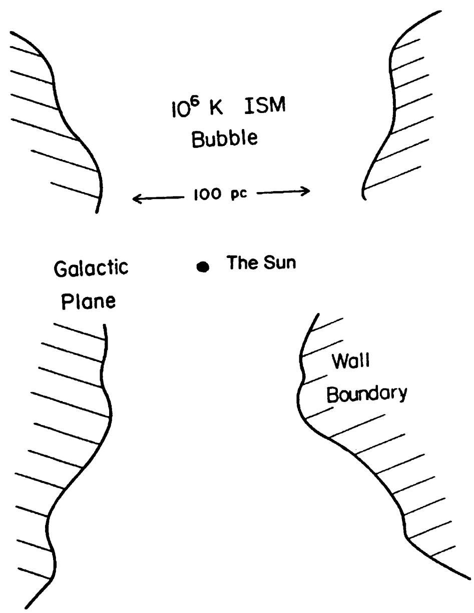

Figure 1. A depiction of the cross-section of the "Local Bubble" as seen perpendicular to the plane of the Galaxy. The North Galactic Pole is in the direction of the top of the figure.

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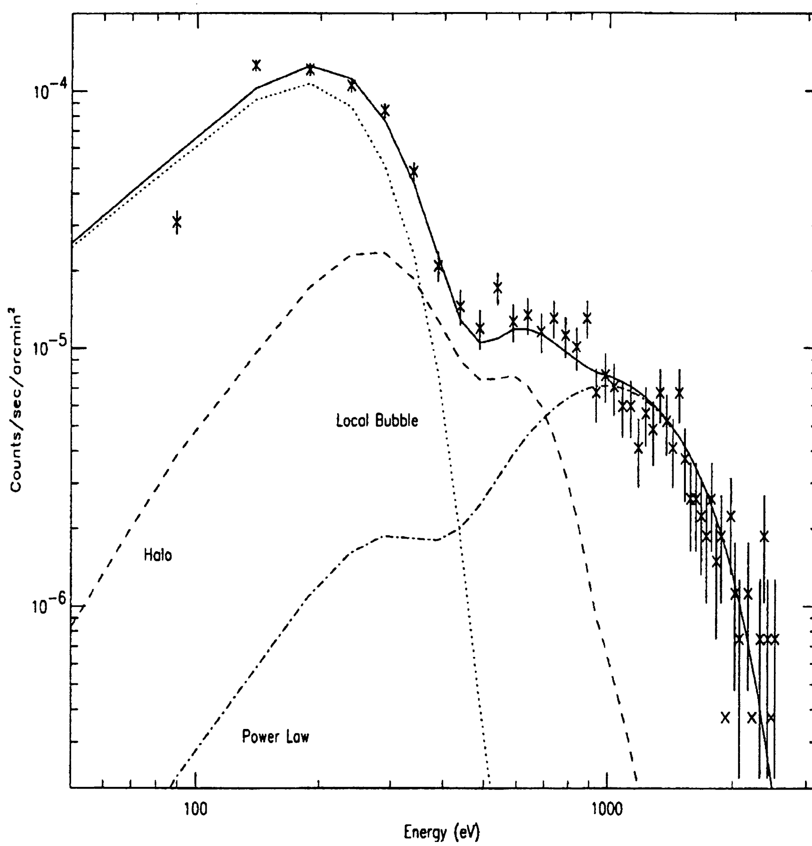

Figure 2. Components of the 1/4 keV flux in the direction of the North Galactic Pole. The data (small x's with error bars) are well fit by three components. The power law component is identified as an extragalactic flux; this fits the extragalactic background at higher energies.

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4. The X-ray Background (0.5 to 2 keV)

The most extensive data set now available, and the one which usually employed in current work, is the 1/2 to 2 keV ROSAT data from the direction of the North Galactic pole. The majority, but not all, of this flux has been shown to be the product of radiation from Active Galactic Nuclei (AGN), predominantly Seyfert galaxies. ROSAT observations of AGN at different red shifts have been used to evaluate the contribution of these sources to the total flux. The summed emission from these sources is less than the observed flux. The most common approach to obtain the total flux is to add density evolution and/or luminosity evolution to the AGN population thereby increasing the number of sources in the distant past which are contributing to the background. Miyaji, Hasinger, & Schmidt (2000) have analyzed these scenarios and have found that both of these models have difficulties. They derive several flavors of luminosity-dependent density evolution for AGN which produce the observed flux. These results, however, are dependent upon the cosmological models employed. This leads to the interesting possibility that these data can be used to discriminate among various cosmological models. A particular model of luminosity-dependent density evolution developed by Miyaji et al. produces 90% of the observed cosmic X-ray background intensity; the remaining 10% is produced by the known X-ray emission from clusters of galaxies. The results of Miyaji et al. are shown in Figure 3.

An alternative (or perhaps complementary) possibility is that entirely new sources are providing the extra flux required. Preliminary results from Chandra indicate the existence of X-ray emitting sources that are too faint to stand out in optical surveys. These objects are almost certainly X-ray luminous AGN. They outnumber optically selected AGN by a factor of seven. One-half of the sample have no optical signatures of activity and $\sim$ 40% show rather unusual optical spectra.

It seems reasonable to expect that the problem of the origin of the "diffuse" X-ray background will be solved in the near future. However, for the past ten years papers have appeared in the literature stating that the solution to this question had been achieved. We will have to await further developments to determine how this problem is ultimately solved.

5. The X-ray Background (3 to 50 keV)

An intriguing possibility that was explored with great interest well into the late 1970s was that this flux was produced by a high temperature intergalactic plasma. If present, this plasma would constitute the majority of the observable matter in the Universe. Major support for this hypothesis was that the X-ray background in this energy range was extremely well fit by free-free emission from an optically thin plasma at 40 keV. Subsequent work showed that the majority of this flux was due to the summed radiation from AGN. When the contributions of the flux produced by AGN were subtracted from the observed flux, the seductively appealing fit to a 40 keV plasma was destroyed, thus eliminating this intriguing hypothesis. Further work has shown that this background is a

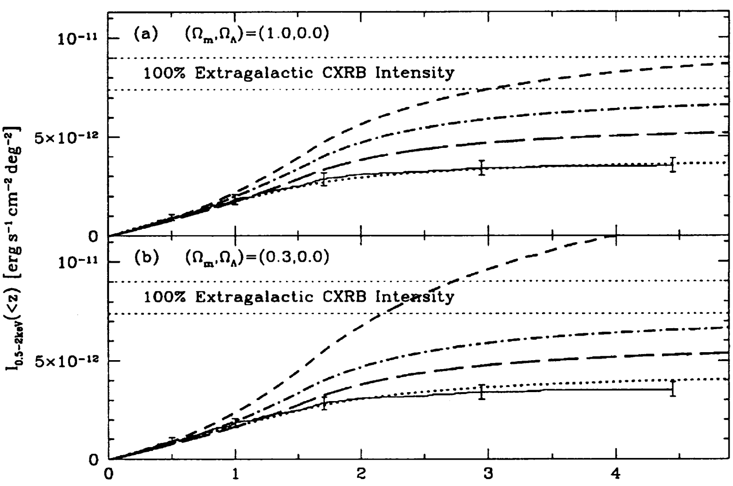

Figure 3. The cumulative extragalactic X-ray background produced by AGN as a function of red shift. Two cosmological models are shown. The upper panel shows a model with closure. The lower panel shows a cosmological model with omega $\sim 1/3$ of closure. The extragalactic background falls within the dotted lines near the top of each panel. The short dashed line shows pure density evolution; this overproduces the background in both cosmological models when the known contribution of galaxy cluster emission is added. The dotted line shows pure luminosity evolution. The two dot-dashed lines show particular models of luminosity-dependent density evolution.

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straightforward extension of the extragalactic background seen at 0.5 to 2 keV discussed above. The majority of this emission is produced by AGN.

6. The Diffuse Gamma-ray Background (50 keV to 100 GeV)

Early on, theorists postulated various types of fascinating production mechanisms that might be providing measurable flux in this band. These included such intriguing possibilities as annihilation of supersymmetric particles (>1 GeV), decay of 500–1000 GeV Higgs bosons (>1 GeV), and primordial black hole evaporation (the entire band). The detection of any of these processes would clearly be spectacular! Unfortunately, the predicted flux from each of these processes turned out to be far less than the flux ultimately observed, rendering these processes unobservable if they are, in fact, present.

Knowledge of the extragalactic gamma-ray background is extraordinarily difficult to obtain because of a variety of problems. The fact that gamma rays are produced by local cosmic rays interacting with the detector and spacecraft, and the fact that both our Galaxy and the upper atmosphere of the Earth are sources of gamma-ray emission make this problem especially difficult.

The removal of the Galactic component from the total flux is especially difficult since the Galaxy produces 90% of the photons observed in the gamma-ray sky. Work in the 1970s with SAS 2, but primarily COS-B, showed the Galactic emission at energies > 30 MeV was closely correlated with regions with high densities of hydrogen and CO. This result is consistent with the emission being produced by Galactic cosmic rays interacting with material in high-density Galactic clouds. Despite this early success, much remains unknown about the source of the Galactic flux even with the extensive data available from the Compton Observatory. For example, the origin of the 1 to 30 MeV Galactic flux is unknown. In any case, the identification and removal of the Galactic component even far from the plane of the Galaxy is challenging because of the comparatively low intensity of the extragalactic background.

Despite these difficulties, the extragalactic background is reasonably well characterized at this point. The extragalactic spectrum is shown in Figure 4 (from Watanabe et al. 2000). The flux from 50 keV to $\sim$ 0.5 MeV is well fit by an extrapolation of the lower energy X-ray results and is the product of AGN as is discussed above. The flux from 10 MeV to 100 GeV is well described as the summed effect of gamma ray emitting Blazars. Intriguingly, the source of the 0.5 MeV to 10 MeV flux is unknown. A candidate for this emission is the summed emission of Blazars that are not directly pointed at Earth, but are tilted slightly off axis with respect to our line of sight. This possibility appears plausible but is neither proven nor unproven at this point. Unfortunately, the premature termination of the Compton Observatory may well have eliminated the possibility of determining the true source of this radiation for the foreseeable future.

7. Conclusions

The measurement and study of the extragalactic background at ultraviolet, X-ray and gamma ray energies is intriguing in its own right. Early work in all

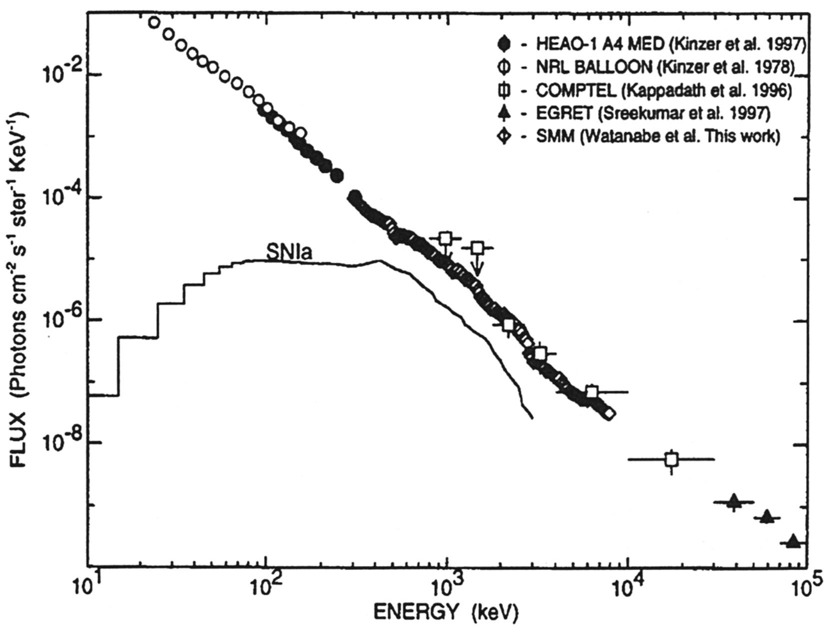

Figure 4. The extragalactic background from $\sim$ 2 keV to 100 GeV. The summed contributions from type Ia supernovae which produce emission in this range is shown as a solid line. This contribution is clearly masked by other processes producing flux in this range. The origin of the 0.5 MeV to 10 MeV flux is unknown.

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these bands had the added motivation of the possible detection of spectacular processes at work in the Universe. Amazing progress has been made in the characterization and understanding of the extragalactic flux in these bands over the last thirty years. The most spectacular processes proposed which would have produced a truly diffuse background were ultimately not detected. Nevertheless, the results that have been obtained have provided unique insights into processes occurring in the Universe.

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Discussion

Charles Ever: Your diagram of the Local Bubble makes it look like a Local Tube. Does the northern axis of this tube point toward the Lockman Hole? Is this also the direction of the bright region of the 1/4 keV ROSAT data?

Stuart Bowyer: Indeed, the "Local Bubble" is a local tube. More to the point, the term "Local Bubble" is an historical term and in its original concept it is clearly incorrect. The extent of the tube is uncertain but there is evidence that it extends well into the Galactic halo. This region, whatever one chooses to call it, is a region deficient in neutral material. The two most discussed possibilities as to the character of this material are that it is either a high temperature (1 million K) gas, or a plasma greatly out of thermal equilibrium a la Breitschwerdt & Schmutzler. In any case, the northern extension of this region is in the direction of the Lockman Hole and includes the brightest regions of the 1/4 keV ROSAT map.

Brian Boyle: Can you comment on the constraints provided by the lack of a correlation between the low energy X-ray background and AGNs as determined by Fabian and Barkas some ten years ago.

Bowyer: At the time of that study only the brightest AGNs had been identified. Subsequent work has shown that many (and perhaps most) galaxies exhibit Seyfert-like characteristics. I know of no recent correlation studies. However, the small fraction of the 1/4 keV flux that is extragalactic joins the low energy X-ray background reasonably well, and this in turn, fits the higher energy X-ray background. The majority of this flux is well established to be the product of AGNs as is discussed in my presentation.