THE COSMIC X-RAY BACKGROUND

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ABSTRACT. As the sky in the microwave band is dominated by a cosmic background, so too is the X-ray sky. In this presentation the observational situation regarding the extragalactic X-ray background is reviewed, emphasizing data obtained from HEAO-1 and the Einstein Observatory (HEAO-2). Spectral characteristics and spatial variations are described and discussed within the context of what is currently known about individual extragalactic sources. It is concluded that the bulk of the cosmic X-ray background is yet to be understood. Possibilities range from genuinely diffuse emission to an "as yet" unknown large population of unresolved discrete sources. The role of cosmological effects is examined and could be important.

Most of our current knowledge about the cosmic X-ray background and the sources contributing to it comes from observations carried out with instruments aboard the HEAO (High Energy Astronomy Observatories) of NASA's program in space astrophysics. With mechanically collimated detectors HEAO-1 provided an all-sky survey (i.e., coverage corresponding to 41 x 10^3 deg^2) over a broad band of photon energies ranging from 0.1 keV to over an MeV. Two of the HEAO-1 experiments were developed especially for the measurement of sky background. The HEAO-1 A2 experiment, a collaboration between Goddard Space Flight Center and Penn State University, was based on multi-celled gas proportional counters with various fields of view ranging from 4.5 deg^2 to 18 deg^2; these detectors were extremely low noise devices that allowed for an absolute measurement of sky surface brightness for energies up to about 60 keV. The HEAO-1 A4 experiment, a collaboration between the University of California at San Diego and M.I.T., employed solid scintillation counters to detect harder X-rays collimated with fields of view corresponding to 34 deg^2 and 200 deg^2. These experiments established the broadband spectrum (Marshall et al. 1980; Rothschild et al. 1983) and large-scale spatial structure (low-level anisotropy) of the cosmic X-ray background (Boldt 1981; Shafer 1983). The HEAO-1 all-sky survey detected about 300 bright X-ray sources via the A2 experiment and about 70 hard X-ray sources (mostly galactic) via the A4 experiment.

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Appropriately classified HEAO-1 objects have been used for estimating the present-epoch luminosity function for extragalactic sources (Piccinotti et al. 1982).

The HEAO-2 Einstein Observatory, a consortium led by SAO, was based on a grazing incidence telescope for soft X-rays, mainly below about 3 keV in energy. Having arc-second resolution it could be used for detecting relatively faint sources with sufficient precision to obtain optical identifications. The high sensitivity surveys (HSS) covered 1.4 deg^2, yielding 19 sources down to the level 2.6 x 10^{-14} ergs $cm^{-2}s^{-1}$ (1-3 keV); see Giacconi et al. (1979) and Griffiths et al. (1983). The medium sensitivity surveys (MSS) are still being investigated (Gioia, this symposium), but a subset of 112 sources corresponding to 89 deg^2 coverage has already been completely identified (Gioia et al. 1984). Based on data from the imaging proportional counter in the focal plane of the Einstein Observatory telescope, sky surface brightness could be estimated with arc-minute resolution, yielding upper limits on small scale fluctuations of the background (Hamilton and Helfand 1986).

The cosmic X-ray background spectrum measured with HEAO-1 over the band 3-100 keV may be characterized by an optically thin isothermal model with kT = 40 keV (Marshall et al. 1980; Rothschild et al. 1983; Gruber 1984). This energy spectrum may be well approximated by an expression of the following form (Boldt and Leiter 1984):

$$dI/dE = A\ (E/3\ \mathrm{keV})^{-\alpha}\ \exp(-E/B) \qquad (1)$$

where E is photon energy (in keV), A = 5.6 keV/(keV cm^2 s sr), B = kT = 40 keV and α = 0.29. Although data from the HEAO-2 Einstein Observatory are for soft X-rays (mostly below about 3 keV) HEAO-1 results on the extragalactic background are clearly uncontaminated by galactic effects only for energies greater than about 3 keV. Hence, comparisons between HEAO-1 and HEAO-2 results are most reliably made in a relatively small band of spectral overlap at $E \sim 3$ keV. Using X-ray data on extragalactic objects obtained with HEAO-1 and HEAO-2, in association with optical data, Schmidt and Green (1986) have estimated the contribution of discrete sources to the cosmic X-ray background, albeit in the HEAO-2 band (< 3 keV). Extrapolating their estimate to an evaluation at E = 3 keV, the composite contribution of all galaxies (including AGN and quasars) and clusters of galaxies amounts to 40%-55% of the extragalactic background. With HEAO-2 HSS sources having power-law spectra characterized by $\alpha \geq 0.7$ at 3 keV (see Setti, this symposium, for a review), the faintest sources resolved with the Einstein Observatory would account for $\leq$ (21±9)% of the background at that energy. Furthermore, the observed energy spectrum of the extragalactic background is much flatter than that of known sources (Boldt 1981; DeZotti et al. 1982); at $\sim$ 3 keV the effective power-law index is only 0.4 (Marshall et al. 1980).

Subtracting the estimated spectral contribution of discrete sources to the cosmic X-ray background (normalized to 40% at 3 keV) yields a residual spectrum (Leiter and Boldt 1982) that is well fitted by an analytical expression of the form given by equation (1), under

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the constraints:

$$0.2 > \alpha \geq 0 \qquad (2)$$

$$30 \text{ keV} > B \geq 23 \text{ keV}. \qquad (3)$$

Assuming that this residual background arises from optically thin thermal bremsstrahlung, the constraint provided by (2) implies that $kT > 200$ keV for the radiating plasma (Boldt and Leiter 1984). For an isothermal plasma at a redshift (z) to produce this residual background, the constraint provided by (3) then requires that $z > (kT/B)-1 = 6$ (i.e., well beyond any known quasar). Alternatively, Guilbert and Fabian (1986) have considered a hot IGM (intergalactic medium) that is heated to $kT > 200$ keV at $z > 3$ and then adiabatically cooled (for $z < 3$) to $kT = 14(1+z)^2$ keV due to the expansion of the universe. This hot IGM model provides a remarkably good broadband spectral fit to the residual cosmic X-ray background but requires that the baryonic mass involved be greater than 20% of the closure value. Since such a hot IGM would induce a spectral distortion of the 2.7 K blackbody background amounting to an effective temperature variation as much as 0.1 K, Danese (personal communication) has suggested that current microwave spectral measurements are already getting close enough to the precision needed for providing a meaningful diagnostic of the model.

Severe integral constraints on the possible discrete source contribution to the residual background (unresolved with the HEAO-2 Einstein Observatory) have been obtained by evaluating upper limits to the corresponding apparent surface brightness fluctuations observed on the scale of arc-minute pixels. In this way Hamilton and Helfand (1986) conclude that the number of point sources needed would have to exceed 5×10^3 degree^{-2}, much larger than the estimated total number of quasars (Schmidt and Green 1986). Extrapolating the known background spectrum (at > 3 keV) into the 1-3 keV band appropriate for HEAO-2 makes it possible for us to use this lower limit on the number of sources to estimate an upper limit on their average X-ray intensity, viz:

$$\langle S \rangle \leq 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ (1-3 keV)}. \qquad (4)$$

This upper limit on the average intensity is only about 4% of the threshold sensitivity used for the HEAO-2 HSS of faint point sources.

Based on the spectral constraints for the residual background provided by equations (1-3) we can approximate the spectrum characteristic of those discrete sources that would be needed, viz (the appropriately redshifted spectrum viewed by us):

$$dS/dE \sim \exp[-E/(23 \text{ keV})]. \qquad (5)$$

Normalizing to the narrow band limit given by equation (4), we integrate this spectrum to obtain an upper limit on the average value for the apparent X-ray luminosity of such sources. Assuming a Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ the corresponding luminosity upper

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limit becomes:

$$\langle L \rangle \quad < \quad 10^{45.2} \text{ ergs s}^{-1} \qquad \text{for} \quad z \leq 4 \tag{6}$$

$$\langle L \rangle \quad < \quad 10^{44.5} \text{ ergs s}^{-1} \qquad \text{for} \quad z \leq 2 \tag{7}$$

A clue as to the possible nature of such sources is obtained by noting that these luminosities are comparable to the bolometric luminosity of a typical Seyfert galaxy; the median mass value of the central compact object inferred for such galaxies is about 10^8 $M_\odot$ (Wandel and Mushotzky 1986). Hence, if the sources of the residual background are early precursor AGN powered by accretion (Leiter and Boldt 1982) then the mass build-up in a Hubble time could well be comparable to that of the central object characteristic of present-epoch Seyfert galaxies. For such a situation these compact precursor Seyfert galaxies would initially have to be of relatively small mass, radiating at the Eddington luminosity limit or close to it. If the luminosity of an accretion powered AGN starts out at the Eddington limit and remains constant (i.e., constant accretion rate) then the central mass would increase about a hundred-fold after a Hubble time (Boldt and Leiter 1986) and the source would now be radiating at ∿ 1% of the Eddington limit, as observed for Seyfert galaxies (Wandel and Mushotzky 1986). While these compact precursor AGN are still young and close to being Eddington limited, non-thermal electron emission mechanisms are suppressed (Cavaliere and Morrison 1980) and a significant electron-positron "pair photosphere" would be produced, thereby maintaining $kT < mc^2$ (Rees 1984) for the thermal source and yielding a comptonized thermal spectrum of the flattened form required for the residual X-ray background. Even though these relatively low luminosity precursor AGN are numerous (compared with quasars) they might not be easy to find in usual optical surveys (Boldt and Leiter 1984).

If the residual X-ray background is found to be genuinely diffuse and a hot IGM origin becomes untenable, then we may have to consider a non-standard cosmology. For example, Segal (1987) has suggested that the residual background could be a cosmological X-ray albedo associated with discrete source radiation which has undergone multiple traversals of the universe.

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DISCUSSION

ULMER: When creating the residual cosmic X-ray background by subtracting the spectra of Seyfert galaxies did you worry about K corrections or spectral evolution?

BOLDT: In the spectral band of interest (3-100 keV) we assume pure power-law spectra for Seyfert galaxies, consistent with HEAO-1 observations. After subtracting the expected contribution of such unresolved foreground sources we conclude that the dominant sources of the residual background have a substantially different spectrum (i.e., an exponential form, implying severe spectral evolution).

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