The Spectrum of Diffuse Cosmic Hard X-Rays Measured with HEAO–1

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ABSTRACT

The spectrum of the diffuse isotropic component of cosmic X-rays over the 13–180 keV range was determined by the UCSD/MIT Hard X-Ray and Gamma-Ray instrument (HEAO A4) on the High Energy Astronomical Observatory–1 (HEAO–1). The instrument consists of a complex of actively shielded and collimated scintillation counters, including the Low Energy Detector set from which the data reported here were obtained. These data join smoothly with the spectrum at lower energies reported by the GSFC HEAO A2 instrument and with that measured to 400 keV by the HEAO A4 Medium Energy Detectors. The HEAO data set also joins the recent results from COMPTEL on the Compton Gamma-Ray Observatory in the 1–10 MeV range, which failed to confirm the existence of an “MeV bump” in this range. Although the spectrum over the entire range 3 keV ≤ E ≤ 100 GeV can be fit by a simple empirical analytic expression, the origin is likely due to a number of distinct source components. The prevailing idea for the origin is that the hard X-ray spectrum is due to X-rays from various AGN components, particularly Seyfert galaxies extending to cosmological distances, and that the low energy gamma-rays may be due to emission from type 1a Supernovae, also integrated to cosmological distances. The higher energy gamma-ray spectrum defined by EGRET, also on the CGRO, may be due to unresolved gamma-ray emitting blazars. Models of production by these source components, extrapolated to the present epoch, must reproduce the observationally derived spectrum.

Subject headings: X-rays, gamma-rays, diffuse background
1. Introduction

The spectrum of the diffuse sky background of cosmic X- and gamma-rays has been a matter of considerable interest and some controversy since the discovery by rocket-borne X-ray counters (Giacconi 1962) and by a gamma-ray counter on the Ranger III lunar probe (Metzger et al. 1968). The known spectrum was extended beyond 100 MeV by an instrument on OSO-III (Kraushaar et al. 1972). Although there were many subsequent measurements by a variety of rocket, balloon and space-borne instruments during the 1960’s and early 1970’s (Horstman et al. 1975), the most definitive spectra below about 500 keV were obtained from the HEAO–1, launched in 1977 (Marshall et al. 1980; Kinzer et al. 1997).

At higher energies (i.e. > 800 keV) the spectrum has recently been clarified with data obtained from the Compton Gamma-Ray Observatory (CGRO). The COMPTEL instrument on the CGRO has failed to confirm the “MeV Bump” (Trombka et al. 1977) in the diffuse gamma-ray spectrum in the range 0.8 ≤ E ≤ 30 MeV (Kappadath et al. 1995, 1996), while the EGRET instrument (Kniffen et al 1996, Sreekumar et al. 1998) has generally confirmed the results presented earlier by Fichtel in the 100 MeV range by a spark chamber on the Small Astronomy Satellite–2 (SAS–2) (Fichtel et al. 1978), and has also extended the spectrum to about 100 GeV.

The near isotropy of the diffuse X-ray background and its large energy density point to an extragalactic and even cosmological origin. Early attempts to produce the spectrum above about 3 keV in terms of uniform emissions at truly cosmological distances seem to have been ruled out (Barcons, Fabian & Rees 1991); therefore discrete source populations which extends to high redshifts must be considered (Barber & Warwick 1994). Fabian and Barcons (1992) and Hasinger (1996) provide reviews of the observational and theoretical status of the subject as of these dates. The most recent concept, summarized by Zdziarski (1996) is that the background in the range of ∼3–300 keV is due to various AGN components, particularly Seyfert II’s, (Madau et al. 1994), and that the low energy gamma-ray background (∼ 300 keV < E < 10 MeV) is due to supernova 1a (The, Leising & Clayton 1993). The diffuse component at energies > 30 MeV measured by EGRET is attributed to unresolved blazars (Stecker & Salmon, 1996). The components in the range 0.4–10 keV, as determined with ASCA (Gendreau et al. 1995), may also be accounted for in terms of AGN’s; however, there exists an excess below 1 keV which, if not accounted for by effects in the local ISM, requires additional source components (Chen, Fabian & Gendreau 1997). The ROSAT deep X-ray survey in the Lockman hole has discovered enough sources to account for at least 70–80% of the diffuse flux in the 0.5–2 keV range (Hasinger 1998). Taking into account evolution, such as that which characterizes quasars, this source density
actually overproduces the X-ray background in this range (Hasinger, pvt comm).

This paper describes the final spectral results obtained by one of the UCSD/MIT Hard X-ray detectors on the HEAO–1 over the 13–180 keV range. This data is compared with related data on the diffuse component, and the total spectrum to 100 GeV is fit by a simple analytic function. Preliminary results of this work have been reported earlier (Rothschild et al. 1983; Gruber 1992).

2. Instrument and Operation

The UCSD/MIT Hard X-ray and Gamma-Ray Instrument launched on the HEAO–1 spacecraft has been described previously (Matteson 1978, Jung 1989, Kinzer et al. 1997). The instrument consists of an array of seven NaI/CsI “phoswich” detectors collimated with a thick CsI active anticoincidence shield. Three different detector configurations were optimized to cover different sub-ranges over the 13 keV – 10 MeV total range of the instrument. Relevant properties of the various detectors are indicated in Table 1. The data reported here were taken from one of the two lower energy detectors (LED’s) which operated over a nominal 13–180 keV energy range. The LED’s had a passive lead-tin-copper multiple-slat subcollimator within the circular active CsI aperture to give a 1.4° x 20° FWHM beam response.

The HEAO–1 was launched 1977 August 12 into a 22.7°, 400 km circular orbit. The spacecraft rotated about the Earth-Sun line with a nominal 33 minute period. The detector fields were centered perpendicular to this line, and thus scanned across the sky and the Earth below every rotation, and made a complete sky scan every 6 months. The mission produced usable data until 1979 January 13, and the spacecraft re-entered the atmosphere on 1979 March 5.

“Good” events, which met the criteria of no detectable energy losses in the CsI(Na) part of the phoswich and no anticoincidence shield event above \( \simeq 50 \) keV were coded in a 128 channel pulse height analyzer and transmitted in an event-by-event manner, with detector identifications, time tag, and dead time information. Auxiliary information on counting rates of the various functions, and housekeeping information were also transmitted. Commandable data modes allowed various diagnostics to be sent with each event.

Separating diffuse fluxes from various background effects requires a more sophisticated instrumental and data analysis approach than that for localized sources. A movable 20.0 cm dia. x 5.0 cm thick CsI (Na) blocking crystal was arranged to cover the various apertures so that intrinsic detector backgrounds could be separated from fluxes entering the apertures.
The blocking crystal or “shutter” could be operated in a “passive” or “active” mode by using or ignoring the telemetered anticoincidence information during data analysis. This allowed determination of second-order effects due to radiations from the blocking crystal. The analysis of the various background effects has been described in detail in the previous paper reporting on the results of the diffuse cosmic flux in the $\sim 80-400$ keV range (Kinzer et al. 1997) obtained with two of the Medium Energy Detectors.

3. Observations and Data Selection

One of the two Low Energy Detectors, LED #6 (Kinzer et al. 1997), was covered on 14 occasions by the blocking crystal for intervals of six to twelve hours each between 1978 November and 1979 January. Given losses from live time correction and incomplete data recovery, this resulted in 205 ks of observation with the aperture closed, therefore counting only the cosmic-ray induced internal background. The observing intervals were selected to avoid passage through the South Atlantic Anomaly (SAA) region of geomagnetically-trapped particles, which also induce sizeable internal background, most notably from the production of $^{128}$I, which decays with a 28 minute half life (Gruber, Jung & Matteson 1989; Briggs 1992). To further avoid this induced background component, observations were initiated at least three hours after the last of the daily sequence of passages through the SAA. This selection of orbits resulted, however, in a wide range of geomagnetic cutoffs, and therefore of fluxes due to cosmic rays and their atmospheric and spacecraft secondaries. Nevertheless, uniform sampling of the geomagnetic coordinate space $B$ (magnetic field) and $L$ (earth radii) (McIlwain, 1961) was assured by the large elapsed time, about 46 orbits. The closed aperture background was averaged over all zenith angles, since effects due to varying aspects of the internal background are expected to be very small.

Sky-looking data during this period totaling 224 ks was also selected for the same geomagnetic conditions ($B,L$) during the SAA-quiet part of the observing day. The average of the geomagnetic parameter $L$ agreed within 0.2 percent of that obtained during the orbits with aperture blocked. Data were obtained during scanning observations on a set of sky great circles whose center moved with the sun during this interval from 16h to 19h R.A. and with an average declination of -22 degrees. A small fraction of data containing catalogued sources (Levine et al. 1984) was excluded.
4. Control of Systematics

4.1. Variation of Detector Internal Background

While the counting rate from the diffuse background dominates the internal background at energies from threshold to $\sim$20 keV, the sky contribution to the total drops rapidly with energy to a few percent at 100 keV. Since the internal background varies with geomagnetic L to a power between 1 and 2 (Gruber 1974), the average of L to $<1\%$, as indicated above, implies an internal background mismatch between the open and blocked data sets of not more than 0.4%. The observed diffuse flux above 80 keV gives a count rate of about $6.7 \times 10^{-3}$ s$^{-1}$, about 1% of the average background level. The observed agreement of this diffuse flux with that from the Medium Energy Detectors at 80–100 keV (Kinzer et al. 1997), where the latter detectors have a signal about equal to the internal background, and which is therefore very reliable, shows that this limit of 0.4 percent is not too low at these higher energies. The flat spectrum of the internal background insures that background estimation errors will have a completely negligible effect at all lower energies, where the real strength of this measurement lies.

4.2. Variation of Detector Gain

The electron optics of the photomultiplier tube were insufficiently shielded from effects of the geomagnetic field, and therefore changed with orientation, resulting in gain variations as large as 20% peak-to-peak, with an RMS of the order of 5%. This gain variability was laboriously modeled in detail (Jung 1986) and corrected in the data so that the net instantaneous gain error was between one and 2% rms. The propagation of this error into the average spectrum over about 135 rotations of the spacecraft reduced the net effect by another order of magnitude, making it completely negligible.

4.3. Energy Calibration

Relative energy calibration was based on preflight measurements of the differential channel width for detector pulses. Absolute energy calibration, required by a sudden change post-launch and a slow drift thereafter, was monitored using two discrete features of the internal background. The primary calibrator was a K-capture line of $^{125}$I, which produces a gamma ray of 35 keV followed by a prompt decay, followed by K and L X-rays from the $^{125}$I daughter, for a total of 67 keV. Differential response of the NaI scintillator produced
Fig. 1.— The differential counting rates obtained by the Low Energy Detectors on the UCSD/MIT Hard X-ray and Gamma-Ray Instrument on the High Energy Astronomical Observatory–1. The difference between the rates with the detector blocked with an active shutter and unblocked when looking at the sky well above the horizon is due to the diffuse component at cosmic X-rays. The rates are averaged over similar ranges of B,L magnetic coordinates. The artifact at about 32 keV is due to an energy-loss anomaly in NaI near the K-edge. The diffuse flux is well above the detector background to at least 100 keV.

light equivalent to a single photon emitted at 62.7 keV, based on ground calibrations. Measurement of bright sources such as the Crab Nebula (Jung 1989) and Cyg X-1 (Nolan & Matteson 1982) using this gain calibration produced smooth spectra, but a variation of the formal gain value by only a few percent from this produced an artifact at 40 keV in each of these sources. Our secondary calibration line, a blend of Iodine and Tellurium K X-rays, was useful only as confirmation of the prime calibration, because of the unknown and possibly variable mix of the two species. The background spectrum in Figure 1 shows the features used to determine the energy calibration. The effective energy resolution in orbit was about 15 keV FWHM at 60 keV.
4.4. Emission from Blocking Crystal

The open minus blocked difference spectrum initially showed a strong deficit near 30 keV, the effective energy of the K X-ray blend from excited Iodine and Tellurium isotopes in the detector material. This deficit, and its identification as K X-rays, was traced to the blocking crystal, whose material also undergoes spallation by cosmic rays, followed in some cases by K-capture decay of the daughter, with a high-energy gamma that escapes the blocking crystal, and K radiation that produces a count in the detector. While this process is difficult to calculate, it was easier and more reliable to measure the effect in earth-looking data. We make the reasonable assumption that the earth’s secondary X-ray spectrum is featureless near 30 keV.

5. Results

The average counting rates of the selected Low Energy Detector (LED), after correction for gain variations, are shown in Figure 1 for both the blocked and unblocked data. The sky data taken when the beam was above the horizon, and the blocked data is averaged over all zenith angles. These rates correspond to an average L of 1.17 and an average B of 0.30. As indicated previously the diffuse sky component is dominant at the lower energies, and is a small fraction of the average background at above 100 keV. Except for small corrections, the difference of these two curves is the rate due to diffuse hard X-rays.

The resultant sky flux in units proportional to $\nu F_\nu$ is shown in Figure 2. The data here are corrected for the geometry factor, 3.0 cm$^2$-sr, and for the energy response matrix. The latter has been determined from a combination of direct pre-launch measurements, and Monte-Carlo calculations. At these low energies, photoelectron absorption in the thin NaI detector is the primary interaction, so a simple efficiency correction applies over most of the energy range. The sky flux is shown averaged over many PHA channels widths, comparable to the measured energy resolution of 15 keV at 59 keV. Selecting energy widths of approximately constant ratio helps to keep the statistical significance of the plotted channels comparable on a log-log plot.

Also shown in Figure 2 are the results obtained by a number of other experiments. The HEAO–A2 instrument (Marshall et al. 1980), which produced the most significant result on diffuse fluxes in the 3–45 keV range, overlaps and joins smoothly with the LED results. The LED data also join smoothly at the higher end to the data obtained from Medium Energy Detectors (MEDs) (Kinzer et al. 1997). Data obtained by a number of balloon and space experiments (Kinzer, Johnson & Kurfess 1978; Fukuda et al. 1975) are also
Fig. 2.— The corrected photon spectrum of the diffuse component measured with the HEAO–1 by several different detectors, compared with other data in this energy range, expressed as spectral intensity per logarithmic energy unit dI/d(log E). The HEAO A4 Low Energy Detectors join smoothly to other data at both higher and lower energies, and are in agreement with balloon data, for which that of Fukuda et al. (1975) has been chosen as representative. The fit is shown as a curved line. The data from HEAO-1 A2 were taken from High-Energy Detector no. 1 (E. Boldt, private communication). These A2 points may reflect minor artifacts of the spectral inversion.

shown for comparison. As discussed in Kinzer et al. (1997) it is significant that data in this range obtained with a number of different experimental techniques and in various radiation environments are in agreement within statistical and systematic uncertainties. We conclude the diffuse hard X-ray background is well determined in the range $3 < E < 500$ keV.

6. Total Diffuse Spectrum

With these and other recent results, it is now possible to define the spectrum over the entire observed energy range above 3 keV, and to generate an empirical analytic fit to this spectrum. Figure 3 shows selected data presented on an intensity scale, which is more useful for theoretical comparisons than the photon scale.
Fig. 3.— Selected recent results on the intensity spectrum of the diffuse cosmic component over the 3 keV to 100 GeV range. The results are fitted to simple empirical exponential and power-law functions. The reduced $\chi^2$ of the fit is about 1.3, over almost eight decades of photon energy. Various source classes and physical processes are postulated to dominate in different spectral ranges. Data below 500 keV were chosen and marked as in Figure 2. Comptel and Egret data are marked with filled and open squares, respectively.

The lower energy data ($< 500$ keV) is shown again, converted to intensities. The COMPTEL results in the $0.8 < E < 30$ MeV range, which fail to establish the “MeV bump” (Kappadath et al. 1996; Kinzer et al. 1997) are also shown. We do not plot the Apollo 15/16 results which overlap the HEAO and the COMPTEL work since uncertainty in the correction for induced background (Trombka et al. 1977) in detectors operating over the $0.5 < E < 10$ MeV range has almost certainly caused the artifact resulting in the “MeV bump”. We have also discarded other reported results from scintillators above 500 keV as unreliable. At higher energies, the earlier results obtained on SAS–2 are in substantial agreement with the more definitive results obtained over an extended energy range by EGRET on CGRO (Kniffen et al. 1996).

Since the various results in Figure 3 obtained with many instruments and techniques over eight decades in energy appear to join smoothly, it is possible to empirically fit
an analytic function to the data from the full energy range. Such a function had been
developed previously by Gruber (1962), based on the data as it was available at the time.

The present data and selected earlier data, all shown in Figure 3, have been empirically
fit to a combination of exponential and power law functions, operating over different energy
ranges. Criteria are that the functions join smoothly in first and second order at the break
point, and that \( \chi^2 \) be minimized. Such a function is:

\[
\begin{align*}
3–60 \text{ keV:} & \quad 7.877 E^{-0.29} e^{-E/41.13} \text{ keV/keV-cm}^2\text{-sec-sr} \\
> 60 \text{ keV:} & \quad 0.0259 (E/60)^{-5.5} \\
& \quad + 0.504 (E/60)^{-1.58} \text{ keV/keV-cm}^2\text{-sec-sr} \\
& \quad + 0.0288 (E/60)^{-1.05} \text{ keV/keV-cm}^2\text{-sec-sr}
\end{align*}
\]

Overall, the reduced \( \chi^2 \) is about 1.3, which may be regarded as an excellent fit,
considering the data used for the fitting was obtained from five different instruments. The
function is shown as a solid line in Figures 2 and 3.

The function below 60 keV is that introduced by Boldt (1987, 1988, 1989, 1992) as an
excellent fit to the HEAO-1 A2 data, but has slightly different values for the normalization
and e-folding energy, reflecting, of course, the fit to a different and larger data set consisting
of the A4 LED data from HEAO-1 and HEAO-1 A2 data from the High-Energy Detector
no. 1 (E. Boldt, private communication), which was independent of the set analyzed by
Marshall et al. (1980). This lower-energy fit with the present best-fit values was first
reported by Gruber (1992). Boldt (1988) and Holt (1992) have both emphasized that the
two spectral parameters, index and e-fold energy, of this function are particularly revealing
for characterizing the residual CXB spectra obtained when subtracting various foreground
components.

Above 60 keV selected data sets included the HEAO A4 (LED and MED), balloon,
COMPTEL and EGRET data. The fit required the sum of three power laws, the flattest
of which largely characterizes the EGRET observations (it ignores a likely “ripple” at
70 MeV), and the next steeper, with index 1.58, may be said to represent the spectrum
between 70 keV and an MeV. The steepest component, with index 5.5, is almost certainly
only a numerical necessity for matching to the lower-energy spectrum and its derivative,
and represents nothing physical.

The three main functional components may possibly be identified with separate
physical components. If the flat EGRET component continues unbroken to much lower
energies, and the rollover at tens of keV is an actual cutoff for the lower energy component,
then the index 1.58 power law characterizes a separate component dominant at hundreds of keV.

Given the lower-energy spectral form, the maximum in $\nu F_\nu$ (see Figure 2) of 42.6 kev(sec cm$^2$ sr)$^{-1}$ occurs at 29.3 keV, very close to the values of 41.3 kev(sec cm$^2$ sr)$^{-1}$ and 28.4 keV, respectively, for A2 data alone (E. Boldt, private communication), indicating that the results from the HEAO-1 experiments are robust, both with respect to normalization and spectral shape.

7. Discussion

The final analysis of the HEAO A4 Low Energy Detectors presented here, and that of the Medium Energy Detectors presently earlier (Kinzer et al. 1997) have provided a completely consistent set of measurements of the diffuse component of cosmic X-ray over the range $13 < E < 400$ keV. These data join smoothly to other recent data obtained at higher energies by the COMPTEL (Kappadath et al. 1996) and EGRET (Sreekumar et al. 1998) instruments on the Compton Gamma Ray Observatory. ASCA and ROSAT (Chen, Fabian & Gendreau 1997) have presented new results in the 0.1–7 keV band. These data, and those of the HEAO A4, agree well with those previously presented in the 3–45 keV range from the HEAO A2 instrument (Marshall et al. 1980). Only in the range $\sim 300 < E < \sim 1$ MeV is a set of new or confirming data missing; the earlier Apollo 15/16 data in this range now being suspect. To obtain an accurate, definitive spectrum in this range will require a new instrumental concept, since instruments designed for this range, such as OSSE on CGRO (Kurfess 1996) and the spectrometer SPI to be launched on INTEGRAL (Mandrou et al. 1997) have relatively narrow apertures and high background, more optimized for discrete source studies.

The excellent (reduced $\chi^2 = 1.3$) of a simple exponential at lower energies and three summed power law functions above 60 keV to our selected set of data over the entire 3 keV to 100 GeV range can only be described as remarkable. This is particularly so, considering that different discrete source classes producing X- and gamma-rays by different mechanisms are certainly operating in the different energy ranges. It seems at present that a truly cosmological origin for the “diffuse” cosmic component is unlikely in any energy range, and that the integrated effects of various evolving classes of discrete sources are sufficient to explain the phenomenon. Small discontinuities and inflections expected in the combined spectra due to various physical processes predicted by The et al. (1993) have not been observed with high resolution instruments (Barthelmy et al. 1996). The data presented here is of low resolution ($\Delta E/E \geq 0.1$), or is averaged over wide bands ($\Delta E/E \geq 0.2$),
precluding searches for narrow band discontinuities or inflection phenomena.

Even so, it requires a rather unique combination of power law quasar X-ray spectra and absorbed Seyfert II’s to produce the very smooth exponential in the 3–60 keV range. Such a class has been postulated by Madau et al. (1994), Comastri et al. (1995) and Zdziarski (1996). Studying a large red-shifted class of absorbed Seyferts II’s to determine the distributions of low-and high-energy cutoffs is crucial to resolving this problem. A similar problem exists for the integrated effect of Supernova Ia’s to cosmological distances to explain the diffuse spectrum in the MeV range (The et al. 1993). Here effects due to line emission are expected to produce discontinuities; as indicated above such effects have been searched for and not found. However, the recent discovery of a class of “MeV blazars”, with emission concentrated near 1 MeV (Collmar, private communication 1998) may provide an alternative to the supernova component.

To make further progress on understanding the diffuse component of cosmic X- and gamma-rays therefore requires advances on two observational fronts. First, high sensitivity, high resolution class studies of postulated source components are needed to determine the luminosity function of the various spectral types. Second, high resolution, low background instruments specifically designed to measure the diffuse cosmic flux are required for precise determination of spectral features, particularly in the range about 10 keV to 1 MeV, where the various postulated components join, and where phenomena due to discrete lines may be operative.

8. Acknowledgements

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### TABLE 1
Detector Properties

<table>
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<tr>
<th>Detector</th>
<th>Number</th>
<th>Energy (nominal)</th>
<th>Area (ea)</th>
<th>FOV (FWHM)</th>
<th>Geometry cm²-ster</th>
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<td>150–10000</td>
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<td>30</td>
<td>100</td>
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