THE 2–10 KeV X-RAY BACKGROUND DIPOLE AND ITS COSMOLOGICAL IMPLICATIONS

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ABSTRACT

The hard X-ray (>2 keV) emission of the local and distant universe as observed with the HEAO 1 A-2 experiment is reconsidered in the context of large-scale cosmic structure. Using all-sky X-ray samples of active galactic nuclei (AGNs) and galaxy clusters, we remove the dominant local X-ray flux from within a redshift of ~0.02. We evaluate the dipolar and higher order harmonic structure in four X-ray colors. The estimated dipole anisotropy of the unresolved flux appears to be consistent with a combination of the Compton-Getting effect due to the Local Group motion (dipole amplitude Δ = 0.0042) and remaining large-scale structure (0.0023 < Δ < 0.0085), in good agreement with the expectations of cold dark matter models. The observed anisotropy does, however, also suggest a non-negligible Galactic contribution that is more complex than current, simple models of >2 keV Galactic X-ray emission. Comparison of the soft and hard color maps with a harmonic analysis of the 1.5 keV ROSAT all-sky data qualitatively suggests that at least a third of the faint, unresolved ~18° scale structure in the HEAO 1 A-2 data may be Galactic in origin. However, the effect on measured flux dipoles is small (~3%). We derive an expression for dipole anisotropy and acceleration and demonstrate how the dipole anisotropy of the distant X-ray frame can constrain the amplitude of bulk motions of the universe. From observed bulk motions over a local scale of ~50 h⁻¹ Mpc radius volume, we determine 0.14 < Ω₀^h_b/λ(0) < 0.59, where Ω₀ is the universal density parameter and b(0) is the present-epoch bias parameter, defined as the ratio of fluctuations in the X-ray source density and the mass density.

Subject headings: cosmology: observations — large-scale structure of universe — X-rays: general

1. INTRODUCTION

Establishing all the sources of the extragalactic flux dominating the X-ray sky remains a fundamental challenge. In the soft X-ray band (0.5–2 keV), some 70%–80% of the observed flux can be accounted for by extrapolation of those objects resolved in deep fields (Hasinger et al. 1998). Such objects are QSOs, active galactic nuclei (AGNs), and possibly narrow emission line galaxies. In the hard X-ray band (≥2 keV), however, the situation is less clear. Deep surveys with ASCA, reaching 1 × 10⁻¹³ ergs s⁻¹ cm⁻² in the 2–10 keV band, now account for ~30% of the X-ray background (XRB; Cagnoni, Della Ceca, & Maccacaro 1998; Ueda et al. 1999). Although recent results with Chandra (e.g., Mushotzky et al. 2000) have now pushed this to ~75%. In addition, the spectral form of the still unresolved flux does not fit with the spectra of any single class of known objects, although more detailed models have had some success (Leiter & Boldt 1992; Comastri et al. 1995; Madau, Ghisellini, & Fabian 1994). The investigation of X-ray emission associated with the local universe has produced more tangible results. The autocorrelation function (Jahoda 1993) of the unresolved X-ray flux and its cross-correlation with other extragalactic catalogs (Jahoda et al. 1991, 1992; Lahav et al. 1993; Miyaji et al. 1994; Barcons et al. 1995; Refregier, Helfand, & McMahon 1997; Almaini et al. 1997) provides useful information on the volume emissivity of that fraction of X-ray emission correlated with galaxies.

For such studies, the HEAO 1 A-2 all-sky survey continues to be the best hard-band all-sky data available. The integrated flux in this survey originates from z = 0 to a redshift of z ~ 4, and might therefore be considered the most complete survey of baryonic matter currently available at any wavelength. Less than 2% of the total extragalactic flux comes from sources identified in existing all-sky catalogs (Piccinotti et al. 1982; Grossan 1992). Since the majority of the observed flux comes from high z, we expect it to be highly isotropic, at least to O(10⁻³), with possible deviations caused by anisotropies in the population of nearby but unresolved sources. Indeed, the extragalactic hard X-ray emission associated with foreground sources within z ~ 0.02 is highly anisotropic, indicative of the pronounced structure in the mass distribution traced by present-epoch AGNs. For example, the dipole-to-monopole...
ratio observed in this population (Miyaji & Boldt 1990; Miyaji et al. 1991, 1994) is very large, $\sim 0.5$, while the monopole contribution to the total extragalactic emission is $\sim 1\%$. The observed AGN dipole has also been demonstrated in these studies to be compatible with the direction and magnitude of the local group velocity. This is a crucial observational “calibration,” which supports the idea that AGN X-ray sources do in fact trace the underlying gravitational mass distribution responsible for peculiar motion.

Lahav, Piran, & Tseytlin (1997, hereafter LPT97) have evaluated the expected large-scale angular fluctuations in the XRB for a range of power spectra of mass fluctuations (e.g., cold dark matter [CDM] models) and X-ray evolution scenarios. In a follow-up paper, and companion to this present work (Treyer et al. 1998), we have investigated these large-scale ($10^3$–$10^4$) fluctuations. Using the HEAO 1 A-2 data, the power spectrum of mass fluctuations can be probed on scales of $\sim 600 h^{-1}$ Mpc (where $h$ is the present-epoch Hubble constant in units of $100$ km s$^{-1}$ Mpc$^{-1}$). These data can also be used to constrain the fractal correlation dimension ($D_2$) of structure on this scale (Peebles 1993; Wu, Lahav, & Rees 1999) and hence test the homogeneity of the universe and the validity of the cosmological principle. A value of $D_2 = 3$ to a precision of $10^{-4}$ is observed, strongly supporting homogeneity on large ($\sim 600 h^{-1}$ Mpc) scales.

Work has also been done (Shafer 1983; Boldt 1987; Jahoda et al. 1992; Jahoda 1993) to determine the extragalactic X-ray flux dipole from the HEAO data. The motivation for this is the determination of the expected Compton-Getting (CG) dipole due to our motion with respect to the distant X-ray frame, which is expected to agree with the direction and velocity inferred from the CMB dipole (Lineweaver et al. 1996). The amplitude of such a dipole constrains the distance of the frame that can be considered to be at rest with respect to the CMB.

However, as demonstrated in LPT97, for a typical observer in (for example) a CDM universe, the amplitude of the expected CG dipole and that due to emission correlated with large-scale structure (LSS) are comparable. This coupling of the two dipole terms makes it difficult to use the XRB dipole to confirm the CG motion. Other investigations (Plionis & Georgantopoulos 1999) of the XRB dipole using the soft, 1.5 keV ROSAT all-sky survey data seem to provide some confirmation of this prediction. However, as we demonstrate below, data in this softer band are strongly contaminated by Galactic emission compared to the hard, $>2$ keV HEAO data.

In this present work we reconsider the HEAO 1 A-2 data and examine the X-ray background dipole together with higher order structures using the relative importance of the CG effect, LSS, Galactic emission, and the relationship of dipolar structure to bulk motions. In §2 we describe the HEAO 1 A-2 all-sky data, and discuss a newly discovered small instrumental effect and a prescription for its removal. In §3 we describe and apply spherical harmonic analysis to the large angular scale structures in the data and investigate the effects of removing known sources. In §4 we present angular power spectra. In §5 we measure the flux dipole of the unresolved XRB and assess its significance through simple simulations. In §6 we derive the full cosmological expression for dipole anisotropy and its relationship to peculiar velocity. In §7 we discuss observations of local bulk motions and apply these results to our X-ray dipole estimates to obtain constraints on bias parameters. In §8 we summarize our results and present conclusions.

## 2. THE HEAO 1 A-2 DATA

We have taken the present data from the on-line archives at the High-Energy Astrophysics Science Archive Research Center (HEASARC) at the NASA/Goddard Space Flight Center. In its raw state, the data used here consist of the “small field of view” (SFOV) surface brightness in counts s$^{-1}$ per beam, stored in $0.25 \times 0.5$ (a total of $720 \times 720$) pixels in a rectangular projection in ecliptic coordinates. The intrinsic resolution size of independent data points is, however, $1.5 \times 3^\circ$. In addition, for the purposes of estimating the instrumental background, we have utilized the equivalent “large field of view” (LFOV) data, which, although stored in similar format ($720 \times 720$ pixels), has an intrinsic resolution of $3^\circ \times 3^\circ$. The all-sky survey is available in four overlapping energy bands or colors: soft, hard, total, and R15. Allen, Jahoda, & Whitlock (1994) presents effective area curves (detection efficiency as a function of energy) for these bands. The “soft” color consists primarily of photons detected in the first layer of the argon- and xenon-filled detectors and with pulse height less than 6 keV; the “hard” color consists of second-layer photons and large pulse heights from the first layer, and has very little response below 6 keV, while the soft color has very little response above 8 keV. The R15 color was, throughout the mission, the unweighted sum of X-rays detected in the first and second layers of the High-Energy Detector (HED) 3, and the second layer of the Medium-Energy Detector. The weights that define these colors are chosen so that a source characterized by a photon index of $-1.7$ that produces 1 R15 count s$^{-1}$ per beam will also produce 1 total (or 1 soft, or 1 hard) count s$^{-1}$ per beam. The R15 band is the most stable color over the period of observations; the total band has the highest signal-to-noise ratio. The four bands have effective areas peaking at 3, 7, 6, and 10 keV for soft, hard, total, and R15, respectively. All data were taken from the 6 month observation period beginning day 322 of 1977. To convert the raw surface brightness data into standard units, we use a conversion factor of $2.2 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$ (5.4 deg$^{-2}$)$^{-1}$ counts$^{-1}$ s$^{-1}$. The beam area (4.5 deg$^2$) reflects the intrinsic $1.5 \times 3^\circ$ resolution of the SFOV.

In Figure 1, the raw HEAO 1 A-2 data is presented in a Hammer-Aitoff Galactic projection. The data consist of one complete scan of the sky using the total band (Allen et al. 1994).

The darkest pixels are associated with individual bright sources and diffuse Galactic emission. Only $\sim 100$ of the brightest sources at high Galactic latitudes can be identified (Piccioni et al. 1982 identifies 17 galactic and 68 extragalactic sources). In all the following discussion we restrict ourselves to $|b| > 20^\circ$, where complete catalogs are available.

The data are first corrected for the locally estimated instrumental background. This is achieved by using both the LFOV and SFOV data to solve the following two equations at each pixel for $I_{\text{background}}$: $I_{\text{background}} = I_{\text{LFOV}} + I_{\text{sky}}$ and $I_{\text{LFOV}} = I_{\text{background}} + 2.26I_{\text{sky}}$, where the factor of 2.26 is

1. Available at: ftp://legacy.gsfc.nasa.gov/heaol/a2/maps/heasarc_med.html.
2. Allen (1994) also available at: http://heasarc.gsfc.nasa.gov/docs/journal/heaol-a2_5.html.
the ratio of area solid-angle products for the LFOV and SFOV. To reduce noise in the background estimate, we then correct the data by subtracting the mean background estimated in strips of constant ecliptic longitude. Prior to the background calculation, we remove sources and mask Galactic regions, as described below.

In the course of examining the data, we observed a systematic change in the measured flux as a function of observation date. Since the data were taken in great circles through the ecliptic pole, data separated by 180° in ecliptic longitude correspond to approximately the same epoch of observation. Taking the mean flux at fixed longitude of the source removed/masked data (see below), wrapped by 180°, we discovered a clear linear trend in the observed counts. In Figure 2 we plot the observed effect in the total-band data. The least-squares linear models for all four $HEAO$ colors are shown in Figure 3. The slopes of the trends (in units of counts s$^{-1}$, versus longitudinal pixel index) are $-0.000716$, $-0.000194$, $-0.000357$, and $-0.000265$ for the soft, hard, total, and R15 colors, respectively, with maximum and minimum at longitudinal pixel indices 69 and 429, respectively.

The time-dependent term therefore ranges from 0 to 7% of the mean intensity for the soft band, and less for the other colors. In all subsequent analysis, the $HEAO$ data have been corrected by subtracting the least-squares trend. The resulting change in all quantities discussed is small and always less than 10%.

To improve computational efficiency, in all the following analysis we have rebinned the data (following background, total, and R15 colors, respectively, with maximum and minimum at longitudinal pixel indices 69 and 429, respectively.

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systematics correction, and source removal as described below) into $3^\circ \times 6^\circ$ pixels in ecliptic coordinates (smaller resolution pixels are more strongly correlated due to the instrument beam).

3. LARGE-SCALE STRUCTURES IN THE HEAO DATA

Unlike many all-sky catalogs (e.g., IRAS, optical surveys, etc.), the ability to unambiguously separate foreground (Galactic/local emission) from background (extragalactic) information is limited in the HEAO X-ray data. The total number of resolved foreground and background sources is small ($\sim 100$), and a detailed model of possible large-scale Galactic emission is difficult to determine. The Galactic 2–60 keV emission model of Iwan et al. (1982) predicts that some 2% of the observed emission at the Galactic poles in the A2 band is of Galactic origin. The largest contribution at latitudes $b \geq 20^\circ$ is 5%. (The Iwan model predicts Galactic contributions of up to 10% at low latitudes, although there is certainly another, more centrally concentrated component as well; Worrall et al. 1982; Warwick 1998; Valinia & Marshall 1998). More recently, studies in the soft bands (<0.75 keV) by ROSAT (Snowden et al. 1997) indicate that at these lower energies the picture is more complicated, with structure at all scales. Whether this soft emission distribution is a good indicator of the much harder >2 keV emission is unclear; the Galactic contribution in this soft band is almost certainly larger than that above 2 keV, and is potentially more variable as well. In this present work we attempt to at least qualitatively evaluate the likely foreground versus background contributions to further constrain our estimates of the extragalactic flux anisotropy. In order to evaluate the structure in the map of Figure 1, we use spherical harmonic analysis to filter the high (noisy) frequencies from the map and to reconstruct the flux variations (e.g., Scharf et al. 1992). Briefly, the map is expanded into the orthonormal set of spherical harmonics $Y_{lm}(\theta, \phi)$ by determining the harmonic coefficients as a sum over the flux cells:

$$a_{lm} = \sum_I I_I \Delta \omega_I Y_{lm}(\hat{\omega}_I),$$

where $I_I$ is the mean surface brightness in a cell, and $\Delta \omega_I$ is the cell area in direction $\hat{\omega}_I$. The surface brightness at any point can then be reconstructed using only lower order harmonics, where the resolution is determined by the highest harmonic and scales as $\sim \pi/l_{\max}$. In our definitions below, the monopole $M_X$ is defined as $4\pi I$; thus, $a_{00} \equiv (4\pi)^{1/2} I = M_X/(4\pi)^{1/2}$.

3.1. Higher Order Anisotropies

In Figure 4, a harmonic reconstruction of the raw (total-band) HEAO data are shown to a resolution of $\sim 18^\circ$ ($l_{\max} = 10$). The data are clearly dominated by emission associated with the Galaxy (either resolved or unresolved sources). As a first step toward removing this foreground, we construct a “mask” using the list of resolved and identified Galactic X-ray sources (Piccinotti et al. 1982) and a $|b| < 22^\circ$ Galactic plane mask. Regions of sizes varying from $\sim 8^\circ$ diameter to $12^\circ$ diameter are excised around resolved sources; larger regions are removed around the Large and Small Magellanic Clouds (LMC, SMC). A total of $\sim 38\%$ of the sky area is removed by this mask. The results are dramatic; in Figure 5 the harmonic reconstruction (to $l_{\max} = 10$) of the data is shown in all four bands, with the above Galactic masking applied. Those regions excised have been filled with the new mean flux as a first-order correction (see discussion of dipole estimation below). As described in §2, the counts per second in each color are weighted to be equivalent for emission with a photon index of $-1.7$. The observed differences in the structure between (for example) the soft and hard bands can then be directly interpreted as spatial differences in the mean spectral index of X-ray emission (modulo variations in the signal-to-noise ratio).

![Figure 4](image-url)
Two strong flux enhancements are apparent. The uppermost (at $b \geq 80^\circ$ and spanning the northern Galactic cap) we associate with the Virgo and Coma Clusters. The lower peak (at $l \sim 315^\circ$ and $b \sim 30^\circ$) is close to the Centaurus/Great Attractor region (e.g., Scharf et al. 1992; Webster, Lahav, & Fisher 1998). However, we note that it is also closer to the Galactic plane and may not be free of Galactic contamination.

Next, we make use of the Pincinotti (1982) catalog of extragalactic sources (supplemented with the clusters of Edge et al. 1990 with $z < 0.003$) and excise these regions (in $\sim 8^\circ$ diameter cuts) in addition to the above Galactic masking. This results in a data set with all sources removed down to a flux limit of $3 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$ (cf. Treyer et al. 1998). The median redshift of sources in the extragalactic Pincinotti sample is known to be $z \sim 0.02$. In a further effort to remove all significant X-ray sources from within the local volume, we have made use of the HEAO A-1 catalog of source detections (R. Remillard 1994, private communication). Using these data, we have removed all sources to a slightly lower flux limit of $2 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$ (2–10 keV). We determine this flux limit value from both our chosen limiting count rate in the A-1 catalog (0.006 counts s$^{-1}$) and by normalizing with respect to the extrapolated Pincinotti log N–log S. This yields a final monopole value corresponding to $M_X \approx 6.2 \times 10^{42}$ ergs s$^{-1}$ Mpc$^{-2}$. The final unmasked sky area is 48%; in Figure 6 the corresponding harmonic reconstructions (to $l_{\text{max}} = 10$) are shown.

From the X-ray luminosity functions of Grossan (1992) and Boyle et al. (1998), we estimate that the mean luminosity of the local X-ray source population is $L_\times \sim 5 \times 10^{32}$ ergs s$^{-1}$, assuming a lower luminosity cutoff of $10^{42}$ ergs s$^{-1}$ and a present-day Hubble constant $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$. Since the luminosity function is dominated by faint objects and the low-luminosity cutoff is somewhat arbitrary, $L_\times$ is likely to be a lower limit. Removing sources brighter than $2 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$ corresponds to removing all sources brighter than $L_{\text{min}}^\times$ out to $z \sim 0.015$, and all sources brighter than $10 \times L_{\text{min}}^\times$ out to $z \sim 0.05$. Therefore, most X-ray sources with $z > 0.015$ are still unresolved and contribute to the measured dipole (see below).

The contour levels in Figure 6 are approximately a factor of ~3 more exaggerated relative to the mean than in Figure 5. Unlike the extragalactic sky dominated by resolved sources, significant differences in structure are now seen between the soft and hard colors. Notably, in the soft band two strong patches are seen at ($\sim 10^\circ$, $\sim -28^\circ$) and ($\sim 80^\circ$, $\sim -40^\circ$), and a significant structure is seen at $l \approx 180^\circ$, extending over $15^\circ \leq b \leq 80^\circ$. In the hard band, the most significant features are seen at ($\sim 200^\circ$, $\sim -40^\circ$) and ($\sim 280^\circ$, $\sim 60^\circ$). Possible identifications with known structures are given in the caption to Figure 6.

In Figure 7 we plot the harmonic reconstructions of “noise” skies for both the Galactic and full extragalactic mask cases in Figures 5 and 6, to provide a qualitative guide to the significance of features. From these figures we can assess the signal-to-noise ratio of structures seen in Figures 5 and 6 (total band). The most significant individual features are typically a factor of 2–3 higher in counts per second when compared to the equivalent peaks in the pure noise levels. It is apparent that there are at least two likely real, positive features in Figure 5, and possibly four in Figure 6.

In an attempt to assess the likely amplitude and morphology of Galactic contamination in the HEAO 1 A-2 data, we have analyzed the all-sky X-ray data from the ROSAT All-Sky Survey (RASS) using the maps of Snowden et al. (1997, 1995). In Figure 8 we present a harmonic reconstruction of the 1.5 keV RASS data, subject to the same Galactic and extragalactic source mask as the HEAO 1 A-2
data shown in Figure 6. The RASS data were used in a 480 × 240 pixel Hammer-Aitoff Galactic projection, as available from the on-line archives; no further processing was made, other than filling empty pixels with the mean flux after applying the HEAO 1 A-2 Galactic and extragalactic source masks. As discussed in Snowden et al. (1995), the 1.5 keV band data span the energy range ~0.7–2 keV, with essentially no counts above 2 keV. The HEAO 1 A-2 hard band is therefore the only color with no response in this energy range. The response in the other bands is also modest at 2 keV; the effective area is down from its maximum by factors of ~3, 10, and 10 for the soft, total, and R15 colors, respectively. The three most prominent features in the RASS reconstruction are coincident with the features identified in Snowden et al. (1995) as the northern spur/loop 1 (l ~ 20°, b ~ 40°), and the northern and southern parts of a Galactic bulge emission (l ~ 340°, b ~ 30°; l ~ 0°, b ~ –30°).

The location of the two bulge structures is particularly worrying for our interpretation of the structures in Figure 6. In particular, the southern structure seen most strongly in the soft band at l ~ 10°, b ~ –30° is not present in the hard-band data and might indeed be correlated with the RASS southern bulge feature. Snowden et al. (1997) have further investigated the RASS maps and propose that a soft Galactic bulge component is well modeled by a cylindrical volume (with exponential density falloff away from the Galactic plane) of ~10−6.6 K gas. As discussed above, this does not preclude Galactic bulge emission above 2 keV, but for a thermal spectrum, very little emission would be expected. The southern HEAO “bulge” feature appears to fall into this category. The southern HEAO “bulge” feature is more likely to have an extragalactic origin. Therefore, we conservatively estimate that at least one out of three of the dominant faint (soft), unresolved structures in the HEAO 1 A-2 data may be Galactic in origin. This is consistent with the detailed investigation of the RASS 1.5 keV dipole made by Plionis & Georgantopoulos (1999), who estimated that 20%–30% of the total background is Galactic in origin in that data.

Without much more rigorous cross-comparison, any correlations of the RASS with HEAO 1 A-2 should be made with caution, since the intrinsic spatial resolution of the RASS (~2°) is significantly different from that of the HEAO 1 A-2. In § 5, we investigate the effect on the flux dipole of Galactic emission as described by the Iwan et al. (1982) model, as well as the effect of removing the putative “southern bulge” feature.

4. ANGULAR POWER SPECTRA

In an associated paper (Treyer et al. 1998), we have investigated the angular fluctuations of the XRB in the context of models of large-scale structure (as formulated by LPT97).

Following the formalism used in those papers, the total predicted angular power (taken as an ensemble average) is a combination of a large-scale structure component (signal) and a component due to the discreteness of sources (shot noise):

\[
\langle |a^n_m|^2 \rangle_{\text{model}} = \langle |a^n_m|^2 \rangle_{\text{LSS}} + \langle |a^n_m|^2 \rangle_{\text{sn}}. \tag{2}
\]

This is then convolved with the foreground mask to produce the observed angular power spectrum,

\[
\langle |c^n_m|^2 \rangle = \sum_{l'm'} |W_{lm'}^{ll'}|^2 \langle |a^n_{m'}|^2 \rangle. \tag{3}
\]

Finally, we normalize over the monopole, and for total
signal use the notation

\[ C_l = \left( \frac{\langle |e_l^2|^2 \rangle_{\text{LSS}} + \langle |e_l^2|^2 \rangle_{\text{sn}}}{\langle |a_{00}|^2 \rangle_{1/2}} \right)^{1/2} \]  \hspace{1cm} (4)

(see §3).

Figure 9 plots the normalized angular power spectra (i.e., relative to the monopole; Treyer et al. 1998, eq. [14]) of the HEAO data for the complete extragalactic plus Galactic mask in all four colors. The expected CG effect (see § 5) has also been subtracted from the data. (Note that in Treyer et al. 1998, fewer sources were removed, corresponding to a slightly higher flux limit of \(3 \times 10^{-11}\) ergs s\(^{-1}\) cm\(^{-2}\) [2\text{–}10\ keV]).) The total-band spectra used in Treyer et al. (1998) are consistent with those shown here, despite some differences in data processing and source removal. The solid curve in Figure 9 shows the predicted total-band angular spectra for a low-density CDM model with pure X-ray source density evolution and constant, linear biasing (see § 6 and Treyer et al. 1998), and including the predicted noise due to unresolved sources (LPT97).

It is reassuring that the four spectra are in generally close agreement (despite different noise characteristics). We do, however, note that in Figure 9, the soft-band spectra (possibly subject to the most Galactic contamination) shows a strongly discrepant quadrupole \((l = 4)\) term.

In Figure 10 we also plot the mean spectra obtained from “noise” simulations. As described in § 5, these consist of sky fluxes randomly drawn from the real data and masked as per the real data. The complete sky mask is applied both to the data from which fluxes are drawn and to the simulations. The noise estimated from simulations is in agreement with the analytic estimate given in LPT97 and Treyer et al. (1998).

It is apparent that the harmonic shot-noise level varies between the HEAO colors. As expected, the total band has...
the lowest noise level, followed by the R15 band, with the
highest noise in the soft and hard bands, at very similar
levels. Comparing these spectra with those in Figure 9, we
can see that by \( l \sim 5 \) in the real data, we are approaching
the shot-noise level, and by \( l \sim 10 \) we have practically
reached the shot-noise level.

5. THE OBSERVED FLUX DIPOLE

The dipole flux anisotropy is described by the harmonic
coefficients \( a_{lm} \), and can also be written or derived as a
simple vector \( D_X \),

\[
D_X = \sum_i I_i \Delta \omega_i \hat{r}_i
\]  

(5)

We can, of course, parameterize this differently. For example, the CG effect due to our motion with respect to a
radiation field (cf. CMB dipole, etc.) is a purely dipolar
effect of the form \( I' = I(1 + \Delta \cos \theta) \), where \( I \) is surface
brightness, and \( \theta \) is measured from the direction of motion,
in which case |\( D_X | / M_X = \Delta / 3 \) (note that \( M_X = 4\pi I \)). The
factor \( \Delta \) for the 2–10 keV X-ray band CG effect is

\[
\Delta = \frac{3v}{c} \left( 1 + \frac{v^2}{c^2} \right)
\]  

(6)

Fig. 8.—Harmonic reconstruction to \( l_{\text{max}} = 10 \) of the RASS 1.5 keV data. The complete HEAO 1 A-2 mask (Galactic and extragalactic sources removed)
has been applied to the data. Horizontal dotted lines at \( b = \pm 20^\circ \) delimit the Galactic plane mask. Contours are spaced at \( \sim 1.7\% \) of the monopole;
uppermost contour is at \( \sim 17\% \) of the monopole.

Fig. 9.—Normalized spherical harmonic power spectrum of the HEAO 1 XRB, plotted to \( l = 20 \) for soft (dotted line), hard (short-dashed line), total
(long-dashed line), and R15 (dot-dashed line) colors. The Galactic and extragalactic mask has been applied, corresponding to source removal to a flux
limit of \( 2 \times 10^{-11} \) erg s \(^{-1}\) cm \(^{-2}\) (2–10 keV). The solid line shows a
fiducial "best-fit" model for the total band, as described in Treyer et al. (1998); low density CDM \( P(k) \) with pure X-ray source density evolution
and constant biasing \([b_X(0) = 1]\), including the expected noise (see also § 6).

Fig. 10.—Mean angular power spectrum over 10 realizations for each
HEAO color, plotted for "noise" skies. Error bars correspond to the 1 \( \sigma \) scatter expected between individual realizations.
where the energy spectral index is $\alpha = 0.4$ (Boldt 1987). Assuming the solar velocity with respect to the CMB (Lineweaver et al. 1996), we determine $\Delta = 4.2 \times 10^{-3}$ for the X-ray CG effect. Here we choose to present the dipole amplitude as $\Delta$, using the above conversion from $D_\Delta$.

If an all-sky, foreground-removed, X-ray surface brightness map existed, the flux dipole could be immediately obtained as a vector sum over the flux cells. However, as demonstrated above, removing the foreground involves removing information about the background as well. The first-order correction to the removal (masking) of regions when the harmonic decomposition is performed is to fill those regions uniformly with the mean density/flux of the unmasked regions. This will not, however, remove cross-talk between the true (full-sky, orthonormal) harmonic coefficients (including the dipole; e.g., Scharf et al. 1992). One solution is to attempt to reconstruct the full-sky harmonics by inversion of the coefficient matrix, suitably controlled by (for example) a Wiener filter (e.g., Lahav et al. 1994). While this is a very powerful method, it does require a model of the expected harmonic power and a full knowledge of the noise matrix. In addition, such reconstruction is severely limited by the amount of masking (for a realistic harmonic spectrum of large-scale structure); in the case of the HEAO data, this is large: if all resolved Galactic and extragalactic sources and the Galactic plane are masked, $\sim 52\%$ of the sky is removed.

In the present work we use two different methods of dipole estimation. First, we perform the vector sum over all flux cells, with a first-order correction of filling masked cells with the mean flux over the unmasked regions (the spherical harmonic approach, hereafter method 1). Second, we perform a least-squares fit of a $\cos \theta$ dependence dipole to the data and determine the best-fit $(l, b)$ and $\Delta$ (hereafter method 2). This latter method does not make use of the masked region, and does not suffer from cross-talk, but it does assume the specific form of the dipole anisotropy, and (unrealistically) that the residuals are negligible. In the following discussion we apply it only to the total-band data, since these data have the best signal-to-noise ratio, and we evaluate both methods using Monte Carlo simulations below.

The results of the various dipole estimations for the HEAO data are presented in Tables 1 and 2 for methods 1 and 2, respectively.

As a comparison with previous works on the dipole moment of X-ray AGN (Miyaji & Boldt 1990; Miyaji, Jahoda, & Boldt 1991; Miyaji 1994), we subtract the total-band, source-removed extragalactic dipole (Table 1, row 7) from the full extragalactic total-band dipole (Table 1, row 3). The resulting vector (which is equivalent to the dipole vector of the removed extragalactic sources) has $\Delta \approx 8.2 \times 10^{-3}$ and points at $(316^\circ, 53^\circ)$. Miyaji (1994) found that the flux dipole of resolved AGN (which has different shot noise) in the HEAO 1 survey to $z \leq 0.015$ has a direction $(293^\circ, 33^\circ) \pm 20^\circ$, consistent with this difference vector. In their analysis of the RASS 1.5 keV XRB dipole, Plionis & Georgantopoulos (1999) determine a best dipole direction of $(288^\circ, 25^\circ)$ and amplitude $\Delta = 0.051$ (converting their $D_\Delta/M_\chi$). While the direction is in general agreement with our results, their amplitude is more than a factor of $\sim 10$ higher compared to our results in Tables 1 and 2. This discrepancy is likely due to the increased difficulty of diffuse foreground removal in the soft ROSAT band (<2 keV) and an increased soft-band contribution from galaxy clusters and groups. Indeed, Plionis & Georgantopoulos (1999) estimate that Virgo contributes as much as 20% to the RASS dipole amplitude.

As a demonstration of the effect of applying a correction assuming the Iwan et al. (1982) Galactic emission model, the third block of Table 1 presents the results of removing a Iwan Galactic emission model (normalized to 3% of the

| Table 1 |
|---|

| Spherical Harmonic (Method 1) Dipole Measurements of HEAO 1 A-2 Data |
|---|

| HEAO Band | Amplitude ($\Delta$) | Direction* |
|---|---|---|
| Galactic mask | | |
| Soft | 0.0132 | 325 | 51 |
| Hard | 0.0084 | 355 | 45 |
| Total | 0.0114 | 327 | 51 |
| R15 | 0.0111 | 324 | 53 |
| Complete mask | | |
| Soft | 0.0036 | 343 | 35 |
| Hard | 0.0060 | 29 | 2 |
| Total | 0.0036 | 345 | 43 |
| R15 | 0.0030 | 346 | 48 |
| Complete mask, 3% Iwan model removed | | |
| Soft | 0.0033 | 336 | 40 |
| Hard | 0.0032 | 32 | 2 |
| Total | 0.0034 | 338 | 47 |
| R15 | 0.0029 | 337 | 54 |
| Complete mask, CG effect removed | | |
| Soft | 0.0030 | 3 | 3 |
| Hard | 0.0048 | 41 | 27 |
| Total | 0.0027 | 8 | 5 |
| R15 | 0.0022 | 15 | 0 |
| Complete mask, CG effect and 3% Iwan removed | | |
| Soft | 0.0025 | 1 | 4 |
| Hard | 0.0045 | 18 | 44 |
| Total | 0.0023 | 6 | 6 |
| R15 | 0.0017 | 15 | 1 |

* Directions in Galactic coordinates.

As a demonstration of the effect of applying a correction assuming the Iwan et al. (1982) Galactic emission model, the third block of Table 1 presents the results of removing a Iwan Galactic emission model (normalized to 3% of the

| Table 2 |
|---|

| Least-Squares Fit (Method 2) Dipole Amplitudes of Total-Band HEAO Data |
|---|

| Data Set | Amplitude ($\Delta$) | Direction |
|---|---|---|
| Galactic mask | 0.0225 ± 0.0005 | 335 ± 24 | 46 ± 12 |
| Complete mask | 0.0095 ± 0.0005 | 344 ± 24 | 35 ± 12 |
| Complete mask, 3% Iwan model removed | 0.0090 ± 0.0005 | 327 ± 24 | 25 ± 12 |
| Iwan model removed | 0.0085 ± 0.0005 | 353 ± 24 | 1 ± 12 |
| Complete mask, CG effect removed and 3% Iwan removed | 0.0065 ± 0.0005 | 342 ± 24 | 7 ± 12 |

Note.—Errors correspond to finite search grid scales.
monopole) from the distant flux data set. The effect is relatively modest and systematically decreases the dipole amplitude, $\Delta$, and moves the observed dipole direction away from the Galactic center. We also assess the effect of removing the expected CG effect from the data (Table 1, block 4). The dipole is significantly altered; $\Delta$ drops by 15%–20%, and the direction changes by as much as $\sim 50^\circ$, toward the Galactic center. Combined with a 3% Iwan et al. correction (Table 1, block 5), $\Delta$ is further reduced. We also measure the variation in $\Delta$ and direction; see Fig. 13) as a function of increasing Galactic correction (Fig. 11), for cases with and without removal of the expected CG effect (lower and upper curves, respectively). In the case in which the CG effect is removed (after the Galactic correction), the amplitude of the Galactic normalization is the most pronounced, reducing $\Delta$ by a factor of 4 between a 1% and 13% correction.

In Table 2 the equivalent results from the method 2 dipole measurements (using the total band) are presented. While the directions agree fairly well with those of the method 1 dipole estimates, the amplitudes appear to be systematically larger by factors of $\sim 2.5$–3 (see below).

Finally, we test the effect of removing a $30^\circ \times 30^\circ$ patch of sky around the putative “southern Galactic bulge” region, centered on $l = 0^\circ$, $b = -25^\circ$. As above, this region is filled with the mean flux. The effect on both method 1 and 2 dipole estimates is small, reducing $\Delta$ by 3%–5% and altering the direction by $\delta \theta \sim 10^\circ$.

In order to test the significance of the dipole measurements and the ability of the two methods to recover a genuine dipole signal, we use simple Monte Carlo simulations. Taking the fluxes of a data set with the Galactic and extragalactic mask applied, we resample the flux distribution and construct a random sky map (equivalent to assuming no correlation between flux cells) that is subject to the same sky incompleteness (in this case the complete mask). The results of harmonic analyses on the simulations over all bands and to $l = 20$ have been shown in Figure 10. Here we concentrate on the dipolar measurements.

The mean dipole amplitudes over 10 realizations are shown in Table 3. It is clear that the “noise sky” dipoles are significantly smaller than the dipoles seen in the real data, indicating the presence of genuine correlated structure. The

### Table 3

| Simulation                        | Dipole Measure | Mean Amplitude$^a$ (\(\Delta\)) | Mean Separation from (265, 48') (deg) |
|----------------------------------|----------------|----------------------------------|--------------------------------------|
| Complete mask, randomized fluxes | Method 1       | 0.00135 ± 0.00031                | ...                                  |
|                                  | Method 2       | 0.0022 ± 0.0014                  | ...                                  |
| +4.2 \times 10^{-3} CG effect    | Method 1       | 0.0024 ± 0.0007                  | 31 ± 20                              |
|                                  | Method 2       | 0.0043 ± 0.0015                  | 25 ± 15                              |

* Amplitudes are taken as the mean over 10 realizations; errors correspond to 1 $\sigma$ standard deviations.
bottom two rows of Table 3 show the result of adding a realistic CG effect to the simulated data. It is encouraging that the estimated amplitudes are close to the input value ($\Delta = 4.2 \times 10^{-3}$), and the dipole directions are in general agreement, but we note that the two methods appear to differ in a systematic way, with the method 1 estimate being consistently smaller by a factor of 1.5–1.8. This is not unexpected. As discussed in Treyer et al. (1998) and Scharf et al. (1992) and references therein, an incomplete sky creates cross-talk between the harmonic coefficients. In the case of the mask used here, the net result is to systematically lower the observed amplitude of the method 1 dipole. The method 2 dipole estimate does not suffer from such an effect, although it is a less general estimate of dipole anisotropy.

The difference seen in the simulations accounts for at least 50% of the method 1/2 discrepancy seen in the HEAO 1 A-2 data. More detailed simulations would be needed including realistic fluctuations instead of pure noise) to determine the precise difference expected. A full treatment of the significance of the observed dipole is beyond the scope of the present work.

However, on the basis of the simulations (Table 3) and the results of Tables 1 and 2, we estimate that our observed dipoles are significant at greater than a $\sim 2–3 \sigma$ level, and have a typical direction error of $\sim 30^\circ$.

6. THE FLUX DIPOLE AND BULK MOTIONS

The X-ray flux dipole observed at frequency $v_0$ is defined as

$$D_X = \sum_i f_i v_0 \hat{r}_i ,$$

where the sum is over all directions in the sky, and $f_i v_0$ is the integrated X-ray flux in the direction $\hat{r}_i$.

Following the formalism given in LPT97 and assuming linear, epoch-dependent biasing, $b_X(z)$, such that fluctuations in X-ray sources and mass are related by $\delta_X(r_v) = b_X \delta(r_v)$, then

$$D_X = \int \phi(L_v, z) \frac{L_v(1 + z)}{4 \pi L_v^2} \left[1 + b_X(z) \delta(r_v, \hat{r}) \right] \hat{r} dV_c dL_v ,$$

where $\phi$ is the radial probability of a source with luminosity $L_v$ at redshift $z$ and $\delta$ is the mass density contrast.

If the number density of the X-ray sources evolves as $(1 + z)^q$, their luminosity as $(1 + z)^r$, and $L_v \propto v^{-z}$, then we can define $q = d + e - \alpha + 1$, and the X-ray volume emissivity as

$$\rho_X(z) = \int L_v \phi(L_v, z)(1 + z) dL_v = \rho_X(0)(1 + z)^q .$$

The dipole can then be written in the form of a “dipolar Olbers integral”:

$$D_X = \frac{1}{4\pi} \int \rho_X(z) b_X(z) \delta(r_v, \hat{r}) \hat{r} dV_c .$$

Recall that in an Einstein–de Sitter universe ($\Omega_0 = 1$), $dV_c = r^2 \hat{r} dr d\omega$, and $r_v = 2r_H[1 - (1 + z)^{-1/2}]$, where $r_H = c/H_0$ is the Hubble radius.

Since we do not have a model for $\delta(r)$ in our neighborhood, we can only make statistical predictions using a model for the power spectrum, $P(k)$ (LPT97; Treyer et al. 1998). Of course, what we observe is a single realization, and this one realization may not be well represented by the rms value. The rms dipole ($l = 1$) can be expressed as (see eq. [7] in Treyer et al. 1998)

$$\langle |a_{1m}|^2 \rangle_{LS} = \frac{[r_H \rho_X(0)]^2}{(2\pi)^3} \int k^2 P(k) \Psi_1(k)^2 dk ,$$

where the window function $\Psi_1$ contains the various model parameters,

$$\Psi_1(k) = \int_{z_{min}}^{z_{max}} \sigma_8 b_X(z)(1 + z)^{q-9/2} j_1(kr) W_{cut}(z)dz ,$$

and the function $W_{cut}(z)$ accounts for the removal of sources brighter than a given flux cutoff, $S_{cut}$. Here $\sigma_8$ is the usual rms mass fluctuation in an $8h^{-1}$ Mpc radius sphere. As in Figure 8, we use a fiducial model assuming low-density CDM, pure density evolution with $q = 4.6$ and $z_{max} = 1.3$ (based on Hasinger 1998), and constant biasing.

Figure 12 shows the growth of the rms flux dipole as a function of the outer radius cutoff, $z_{max}$ for our fiducial cosmological model, and three scenarios for $W_{cut}(z)$. The figure shows, first, that a flux cutoff of $2 \times 10^{-11}$ ergs $s^{-1}$ cm$^{-2}$, as used in the present data analysis, is very similar to removing all sources within $z < 0.01–0.15$; and secondly, that the rms dipole converges very rapidly, so that most of it originates from $z < 0.05–0.1$. Consequently, there is very little signal due to structure lying farther out, and in the presence of noise we will have effectively no information from $z > 0.1$, at least in the rms sense. Since the growth of the dipole depends on the power spectrum, $P(k)$, in models with more large-scale power, the convergence with $z$ will be slower. Note that this convergence is not due to an “Olbers’ effect.” The total intensity $I$ of the XRB keeps increasing to much higher redshift than do the fluctuations: $I \propto \int_{z_{min}}^{z_{max}} (1 + z)^{q-9/2} dz$, while $\Psi_1(k) \propto \int_{z_{min}}^{z_{max}} (1 + z)^{q-9/2} j_1(kr) dz$ (to first approximation). Unlike the monopole, the high-redshift fluctuations (dipole and higher harmonics) are effectively washed out by angular averaging over the sky (governed by the Bessel function dependency).

Therefore, we can only use the XRB flux dipole to constrain large-scale structures out to 150–300 $h^{-1}$ Mpc. Coupled with our estimate that the bright sources we remove are distributed to a distance of $\sim 60 h^{-1}$ Mpc, we should be able to compare our XRB dipole measurement with direct measurements of bulk flows over a similar volume.

In linear perturbation theory, the peculiar motion at any point in space is directly proportional to the gravitational acceleration; we can therefore write (assuming all motion was zero a Hubble time ago; Peebles 1980)

$$v \approx \frac{3}{2} \Omega_0^{-0.4} \rho H_0^{-1} ,$$

where $\Omega_0$ is the density parameter. The gravitational acceleration $g$ in Newtonian gravity is

$$g = G\rho(0) \int \frac{\delta(r)}{r^2} \hat{r} dV ,$$

where $\rho(0)$ is the present-epoch mean mass density. We note that this expression only holds in on small scales, by choosing locally Minkowski coordinates (Peebles 1993, p. 268). We can therefore approximate equation (10) above for the
The well-known direct linear-theory relationship between the peculiar velocity and the absolute flux dipole is therefore (from eqs. [13], [14], and [15])

\[ v = \frac{\Omega_{b_0}^{0.6}}{b_x(0)} D_x \]  

(cf. Boldt 1987; Lynden-Bell, Lahav, & Burstein 1989; Miyaji 1994). To express the linear velocity in terms of the LSS and CG dipole anisotropies.

We again note that the CG effect produces a dipole pattern on the sky of the form (see eq. [6])

\[ \frac{\Delta I}{I} = (3 + \alpha) \frac{V_{\text{obs}}}{c} \cos \theta . \]  

Consequently, the observed dipole will always be a coupling of the LSS and CG dipole anisotropies.

Therefore, at low redshift the flux of a source follows an inverse-square law, and if light traces mass in a spatially invariant and linear way, then any anisotropies seen in the X-ray data reflect the local gravitational acceleration (assuming linear theory).

We express the linear velocity in terms of the peculiar velocity and the absolute flux dipole is there-

\[ H \approx \frac{0.6}{\Omega_{b_0}^{0.6}} \frac{b_x(0)}{D_x} \]  

hence we arrive at

\[ |v| = 2.2 \times 10^5 \Delta \frac{\Omega_{b_0}^{0.6}}{b_x(0)} \text{ km s}^{-1} . \]  

7. COMPARISON WITH OBSERVED BULK MOTIONS

As discussed above, we estimate that the bright sources we remove from the HEAO data are distributed to a distance of \( \sim 60 \text{ h}^{-1} \text{ Mpc} \); we can therefore compare our XRB dipole measurement with direct measurements of bulk flows over this scale.

Several studies provide generally consistent estimates of the bulk flow of a \( \sim 50 \text{ h}^{-1} \text{ Mpc} \) radius sphere; \( 305 - 370 \) (\( \pm 110 \)) km s\(^{-1}\) (MII catalog; POTENT; Dekel et al. 1999), \( \sim 300 \text{ km s}^{-1} \) (SFI data; Dale et al. 1999; Giovanelli et al. 1997), and \( \sim 250 \text{ km s}^{-1} \) (SN Ia data; Riess, Press, & Kirshner 1995). The directions of these flows are summarized in Figure 13. Using a crude mean of these numbers, we estimate \( v_{60} \sim 300 \pm 100 \) km s\(^{-1}\). The range of dipoles measured in the total band (after removal of the dominant X-ray sources from within \( \sim 60 \text{ h}^{-1} \text{ Mpc} \)) is 0.0023 \( \leq \Delta \leq 0.0095 \) (depending on the measurement method used and corrections for the Galaxy and CG effect). This anisotropy is at most 2 times larger than the expected X-ray CG dipole. Applying equation (19), the dipole measurements imply that \( 1/7.1 \leq \Omega_{b_0}^{0.6}/b_x(0) \leq 1/1.7 \). The favored method 2 dipole amplitude given in the last row of Table 2 is \( \Delta = 0.0065 \), which yields \( \Omega_{b_0}^{0.6}/b_x(0) = 1/4.8 \).

The quantity \( \Omega_{b_0}^{0.6}/b_x(0) \) has also been estimated from studies of the X-ray--selected AGN dipole under certain assumptions about local dynamics. Generally, \( \Omega_{b_0}^{0.6}/b_x(0) \) ranges from 1/3.5, if all the local gravitational acceleration is assumed to arise from the volume with \( R \leq 45 \text{ h}^{-1} \text{ Mpc} \), to 1/7 if only half the acceleration arises from within this.
volume (Miyaji 1994). Using the new IRAS Point Source Catalog Redshift (PSCz) survey, Schmoldt et al. (1999) predict that some 65% of the Local Group acceleration is generated within 40 \( h^{-1} \) Mpc, and that convergence is not reached until \( \sim 140 \) \( h^{-1} \) Mpc. Therefore, \( \Omega_0^{b.0}/b_x(0) \) is almost certainly larger than 1/3.5 using this method. These results are in good agreement with our above constraints from bulk flows and the HEAO dipole. The observed HEAO dipole therefore appears to be quite compatible with current measurements of the bulk flow of the local \( \sim 60 \) \( h^{-1} \) Mpc volume. The dominant population of X-ray emitters (AGNs) in the 2–10 keV band is then highly biased with respect to other tracers, e.g., optical or IRAS galaxies. Over larger scales (\( \sim 100–150 \) \( h^{-1} \) Mpc), there is less agreement on the reality of bulk-flow measurements. For example, the work of Lauer & Postman (1994) has suggested, with much controversy, that the Local Group has a motion relative to the \( z < 0.05 \) Abell cluster frame of \( 561 \pm 284 \) km s\(^{-1}\) in a direction \( l = 220^\circ, b = -28^\circ(\pm 27^\circ) \). Assuming a dynamical origin of the observed CMB dipole, this implies that the Abell cluster frame (to \( z = 0.05 \)) is itself moving in bulk with respect to the CMB frame with velocity of \( 689 \pm 178 \) km s\(^{-1}\) toward \( l = 343^\circ, b = 52^\circ(\pm 23^\circ) \). If correct, this could imply that \( \sim 50\% \) of the Local Group motion is due to matter on scales greater than \( 100 \) \( h^{-1} \) Mpc. This specific result has been strongly refuted by several other works (e.g., Riess et al. 1995; Giovanelli et al. 1997; Hudson et al. 1999; Muller et al. 1998; Dale et al. 1999). More recently, however, independent observational evidence for bulk motion over these scales has emerged, in the range of \( \sim 600–700 \) km s\(^{-1}\) (e.g., Hudson et al. 1999; Willick 1998). All such studies, however, obtain directions for these motions greater than \( 60^\circ \) away from the Lauer & Postman result, and are themselves highly fraught with potential systematic effects.

In criticism of these results, it can be noted that there is an inconsistency between (for example) the Lauer & Postman measurement and the results of gravity dipole estimation using galaxy catalogs. For example, the results of Strauss et al. (1992) using the 1.2 Jy IRAS redshift survey found an extraordinary convergence of the \emph{direction} of the inferred gravity dipole out to \( \sim 20,000 \) km s\(^{-1}\). This convergent dipole direction is only some \( 20^\circ \) from the CMB dipole direction. (There are good arguments why the velocity dipole of the Local Group is not necessarily converged until \( z \sim 1 \) [Peacock 1992], but that does not preclude a genuine convergence in a smaller volume.) Recently, the IRAS PSCz survey has largely confirmed these observations (Schmoldt et al. 1999).

Scaling our above estimates for the HEAO XRB dipole anisotropy, we predict that if all X-ray sources within \( \sim 100–150 \) \( h^{-1} \) Mpc were removed, then \( 700 \) km s\(^{-1}\) bulk flow would correspond to \( 0.0054 \leq \Delta \leq 0.0225 \) [assuming the measured range of allowed \( \Omega_0^{b.0}/b_x(0) \)]. This would be approximately 1.5–5.0 times larger than the expected X-ray CG dipole amplitude.

The directions of both the bulk flow estimated from other works and our present dipole measurements are, however, scattered over a large area of the sky. Figure 13 summarizes most of these directions. As mentioned above, the Lauer & Postman (1994) flow direction is \( \sim 60^\circ \) from all others; the Hudson et al. (1999) result is also significantly farther from the solar CMB velocity direction. Interestingly, the \emph{HEAO} 1 A-2 measurements appear to be somewhat intermediate to the Lauer & Postman result, and the majority of the other, more local volume estimates (SFI, MIII, PSCz). However, recalling that we estimate an XRB dipole direction error of at least \( \sim 30^\circ \) for either method, then the \emph{HEAO} dipole directions are not inconsistent with (for example) the SFI and MIII flows.

8. SUMMARY AND CONCLUSIONS

The \emph{HEAO} 1 A-2 X-ray data offer the best all-sky survey of baryonic matter to \( z \sim 4 \) currently available. Although low-level anisotropies in the X-ray sky background arise largely from Galactic contributions, relatively crude foreground removal clearly demonstrates the presence of extragalactic emission associated with well-known large-scale structure (Virgo, Coma, Centaurus/Great Attractor, etc.) in the local universe.

Qualitative comparison of the RASS 1.5 keV data with the four \emph{HEAO} 1 A-2 bands used here suggests that at least one-third of the faint, unresolved \emph{HEAO} 1 A-2 structure may be Galactic in origin, and possibly associated with the Galactic Bulge.

The local extragalactic hard X-ray emission is dominated by AGNs and galaxy clusters. If we remove the flux associated with these sources to a flux limit of \( 2 \times 10^{-11} \) ergs s\(^{-1}\) cm\(^{-2}\) (2–10 keV), which removes all sources more luminous than \( 5.2 \times 10^{42} \) ergs s\(^{-1}\) (2–10 keV) out to \( z \sim 0.015 \), we measure a dipole anisotropy of \( \Delta = 0.0023–0.0095 \) (depending on the method used and the details of the data processing). This range of anisotropy is consistent with our expectations (LPT97) of comparable amplitude CG and LSS dipoles. It is significantly smaller than that measured in the RASS 1.5 keV all-sky data by Plionis & Georgantopoulos (1999). However, we have argued that the hard (>2 keV) band XRB suffers less from Galactic contamination, and we have shown how removal of the foreground of bright sources reduces the dipole amplitude and shot noise (see also Treyer et al. 1998).

We have derived the fully cosmological expressions for X-ray dipole anisotropy. Unlike the often-used Euclidean case, the relationship of the local acceleration to the dipole anisotropy is no longer straightforward. However, in the case of the current \emph{HEAO} data set, we show that for a reasonable choice of the cosmology and matter density fluctuation power spectrum, most of the dipole anisotropy arises from \( z \lesssim 0.1 \), and the low-redshift linear-theory approximation can be used.

Using current estimates of the bulk flow of the local 60 \( h^{-1} \) Mpc radius volume and our XRB dipole measurements, we find that \( 1/7.1 \leq \Omega_0^{b.0}/b_x(0) \leq 1/1.7 \). With our preferred dipole anisotropy measurement, then \( \Omega_0^{b.0}/b_x(0) = 1/4.8 \). This implies that the population of X-ray sources is highly biased with respect to optical- or infrared-selected objects. Studies of the dipole anisotropy of the local AGN distribution (Miyaji 1994) and other analyses of the \emph{HEAO} data (Boughn, Crittenden, & Turok 1998, assuming epoch-independent biasing) also yield high values. Interestingly, our previous analysis of the angular power spectrum of the \emph{HEAO} data set (Treyer et al. 1998), which included terms as high as \( l = 20 \), yielded a present-epoch biasing factor of \( b_q(0) \sim 1–2 \). The model fit to this data was, however, not particularly good, and the lower order harmonics (\( l = 1–3 \)) are better fitted with a higher \( b_q(0) \). If \( \Omega_0 = 0.3 \), then the values of \( b_q(0) \) estimated from the \emph{HEAO} dipole/bulk flows fall into this lower range;
however, our formalism is all based on an $\Omega = 1$, Einstein-de Sitter cosmology. We also note that in all conventional models, the bulk flow amplitude of a sphere with radius $R$ drops with $R$ [specifically, if $P(k) \propto k^\alpha$, then $V_{\text{bulk}} \propto R^{-(\alpha+1)/2}$]. Therefore, if we overestimate the volume within which we remove X-ray emission, but continue to apply the observed bulk-flow amplitudes for a larger sphere, we will then underestimat $\Omega^{1/6}/b_2(0)$ from equation (15).

If ~700 km s $^{-1}$ bulk flows over 100–150 h $^{-1}$ Mpc radius volumes did exist, as suggested by some studies (e.g., Lauer & Postman 1994; Willick 1998; Hudson et al. 1999), then we predict that an XRB dipole anisotropy of 0.054 $\leq \Delta \leq 0.0225$ would be seen after removing source emission within this volume.

It is worth noting that we should not discount further complications, such as a spatially varying local X-ray emissivity to mass biasing. Indeed, in their study of the X-ray properties of the Great Attractor region and the Shapley supercluster, Raychaudhury et al. (1991) found that for these similarly massive regions the number counts of X-ray luminous clusters is quite different (Shapley having the most). This is suggestive of a spatial variation in cluster formation and brings into doubt the naive linear biasing scheme.

To fully exploit this, or future, hard X-ray all-sky data for cosmological or dipole studies, a better knowledge of the foreground contamination is essential. In particular, a significantly more detailed model of the Galactic (and local, e.g., LMC and SMC) emission is needed. Probably the best way to achieve this will be through the use of softer band data (to provide spatial parameters), combined with point-by-point spectroscopic information, which will allow extrapolation to the harder, less contaminated X-ray bands. A spectroscopy-capable all-sky imaging survey, such as that discussed by Jahoda (1998), would be well suited to this (see also discussion in Treyer et al. 1998).

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