THE ASTROPHYSICAL JOURNAL, 353: L3–L6, 1990 April 10

THE X-RAY FLUX DIPOLE OF ACTIVE GALACTIC NUCLEI AND THE PECULIAR MOTION OF THE LOCAL GROUP

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Received 1989 December 4; accepted 1990 January 19

ABSTRACT

An X-ray flux-limited sample of 30 AGNs detected with the *HEAO 1* A-2 experiment, which is complete for $|b| > 20°$, is used as a tracer of the total gravitational mass distribution in the nearby universe. The dipole moment of the flux saturates at about $z = 0.017$ and gives the direction $(l, b) = (313°, 38°)$ with an error circle of about 30° in radius. This direction is 39° away from the direction of the Local Group's motion with respect to the microwave background radiation. The amplitude of the dipole is about 50% of the corresponding monopole. Applying our data to linear perturbation theory, we get a value of $b\Omega_0^{-0.6}$ close to previous results using optical galaxies and somewhat greater than values obtained from *IRAS* galaxies. This suggests that the X-ray emission from AGNs traces the underlying mass distribution at least as strongly as optical and IR emission from galaxies.

Subject headings: cosmology — galaxies: nuclei — X-rays: sources

I. INTRODUCTION

The anisotropy of the microwave background radiation (MBR) and the solar motion relative to the Local Group of galaxies (LG) implies that the LG has a peculiar velocity of 600 km s^{-1} toward $(l, b) = (268°, 27°)$ (Lahav, Rowan-Robinson, and Lynden-Bell 1988, hereafter LRL, and references therein). Since both gravitational force and flux of radiation vary as the inverse square of the distance, the sky surface brightness of electromagnetic radiation should be a measure of the gravity field at the LG. According to linear perturbation theory (Peebles 1980), the peculiar motion of the LG is in the same direction as the gravitational acceleration arising from the distribution of mass outside of the LG. Attempts to trace this mass distribution responsible for the gravitational acceleration associated with the peculiar velocity of the LG have been made using *IRAS* galaxies (Yahil, Walker, and Rowan-Robinson 1986, hereafter YWR; Meiksin and Davis 1986; LRL; Rowan-Robinson 1989), optical galaxies (Lahav 1987; LRL; Lynden-Bell, Lahav, and Burstein 1989), and X-ray clusters (Lahav *et al.* 1989). Except for X-ray clusters, these dipole moments of fluxes give reasonable alignments with the direction of the LG motion relative to MBR.

In this study, we have used X-ray emission from resolved AGNs as a tracer and investigated the dipole moment of their flux distribution on the sky. The *HEAO 1* A-2 experiment provided a complete sky survey in the band 2–10 keV; extragalactic point sources above a certain flux limit in this survey listed by Piccinotti *et al.* (1982) are almost fully identified for those far from the Galactic plane ($|b| > 20°$). Because the sample is unbiased and complete, only objects from this catalog are used. There are some distinct advantages and interesting aspects of this sample for studying the underlying mass distribution. First, X-radiation is not heavily obscured by the Milky Way; unlike radiation in optical wavelengths, one can therefore avoid the problem of corrections for its extinction. Second, in the 2–10 keV band, AGNs show a quite homogeneous property of having a power-law spectrum with a universal spectral index (e.g., Mushotzky 1982). This means that one can avoid the bias caused by objects which exhibit a variety of spectral behavior. This is particularly important for a small sample where extreme peculiarities in a few objects could seriously bias the result. The third point is that with objects that are totally identified with redshift values, one can explore the dipole behavior in redshift space. The only known extragalactic objects for which X-radiation represents an appreciable portion of the bolometric luminosity are AGNs and clusters of galaxies. Since the local number density of AGNs is much greater than that of clusters, we start with the working hypothesis that AGNs are the most suitable X-ray tracers of the underlying mass distribution in the nearby universe responsible for the peculiar motion of the LG. Since the X-ray luminosity of an AGN measures the central black hole mass (Padovani and Rafanelli 1988; Wandel and Mushotzky 1986), we are in effect testing the notion that such compact objects could be strongly indicative of the total mass density field arising from stars, gaseous components, dark matter, and all other constituents.

The nature of the sample taken from the catalog of Piccinotti *et al.* is explained in § II. The dipole analysis of X-ray fluxes with an emphasis on the alignment with the LG direction is given in § III along with a possible correction for the uncatalogued part of the sky ($|b| < 20°$). In § IV, our results are discussed and compared with other studies.

II. THE SAMPLE

We use sources marked as class 1 (Seyfert 1), class 2 (Seyfert 2 and other active galaxies), and class 3 (BL Lac objects) in column (6) of Table 1 (hereafter the catalog) in Piccinotti *et al.* Among sources marked as class 2, the starburst galaxy M82 (H0952+699) is excluded because of the difference in the nature of the galactic activity. We also exclude the few sources with redshift larger than 0.1. Some objects which were left unidentified in the catalog are now identified with their redshift values. These are H0111−149 (Mrk 1152; $z = 0.0536$) (redshift from Palumbo, Tanzella-Nitti, and Vettolani 1983), H0235−52 (ESO 198−G24; $z = 0.045$) (redshift: Ward *et al.* 1987), H1829−591 (IRAS 18325−5926; $z = 0.02$)

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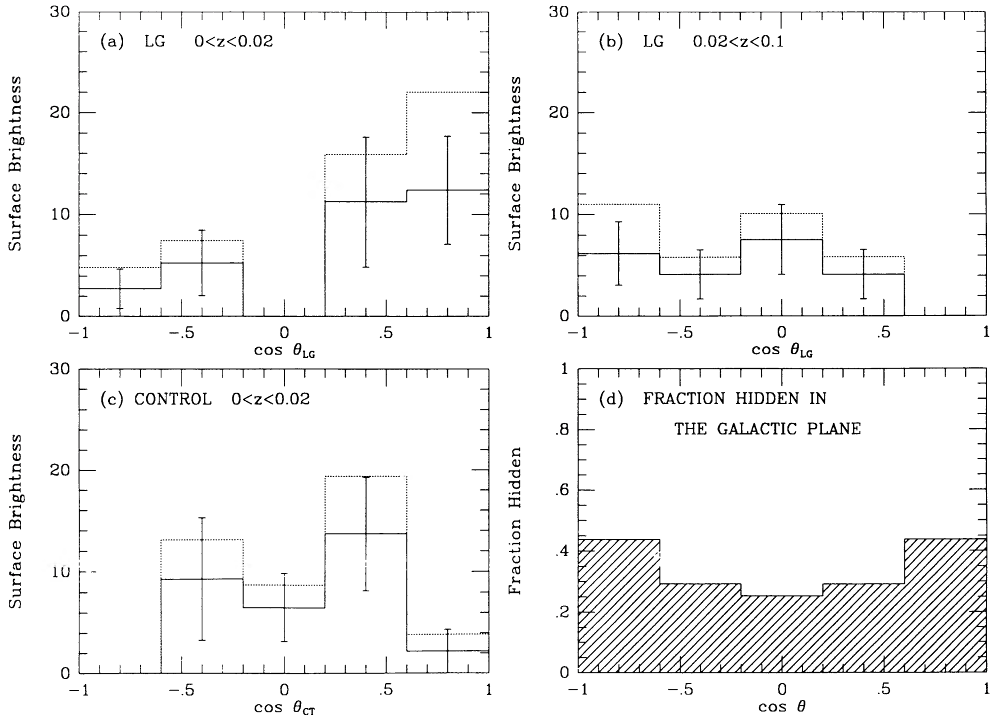

FIG. 1.—Distribution of X-ray surface brightness vs. cosine of the angle from the axis is shown in (*a*)–(*c*). Each bin has the same solid angle in this representation. The unit of surface brightness is 10^{-11} ergs cm^{-2} s^{-1} sr^{-1}. The dotted lines show corrected surface brightness for the effect of hidden part in $|b| < 20°$. The fraction hidden for each bin is shown in (*d*). Error bars show statistical sampling errors.

(identification: Ward *et al.* 1988; redshift: de Grijp *et al.* 1985), and H1846−786 (1M1849−781; $z = 0.074$) (redshift: Remillard *et al.* 1986) (identification from Shafer 1983 if not noted).

The catalog is complete and unbiased for $|b| > 20°$ with a flux limit of 1.25 *R*15 counts s^{-1} (first scan) corresponding to 2.7×10^{-11} ergs cm^{-2} s^{-1} for a typical AGN power-law spectrum. Although sources within a circle around the Large Magellanic Cloud (LMC) of 6° in radius are excluded in the catalog, the effect is ignored in our analysis since its solid angle is only 0.3% of the whole sky. The completeness of the catalog is discussed by Piccinotti *et al.*

First-scan AGN fluxes listed by Piccinotti *et al.* given in *R*15 counts s^{-1} are converted to cgs units using the conversion factor (col. [9] of the catalog). For the four newly identified objects, we use 2.175 (10^{-11} ergs cm^{-2} s$^{-1}/R_{15}$ counts s^{-1}) assuming a 0.65 energy index power law.

Comprehensive *IRAS* and optical studies of galaxies show that the associated dipole moment comes mainly from redshifts corresponding to $v < 4000$ km s^{-1} ($z < 0.013$) (LRL; Lynden-Bell, Lahav, and Burstein 1989). In this connection, we note that 12 of 30 AGNs in our sample are in this relatively nearby region of particular interest whereas only three of the 53 clusters considered by Lahav *et al.* (1989) have small enough redshifts to qualify.

III. THE DIPOLE ANALYSIS

To examine the AGN X-ray flux distribution with respect to the LG velocity, the whole sky is divided into five annular bands about this reference direction. Each band corresponds to one-fifth of the solid angle of the whole sky, i.e., $4\pi/5$ sr. This partition is equivalent to an equal division in the cosine of the angle from the axis. We also divided the whole sample into two redshift bins, each containing the same number of objects. This division is made at $z = 0.02$. Figures 1*a* and 1*b* show accumulated fluxes in these bins. Because the catalog gives only sources for $|b| > 20°$, some fraction in each band of the sky is uncataloged, and one may expect to have hidden sources. The accumulated fluxes expected if the hidden part of the sky were exposed are shown in these figures as dotted lines; this is obtained by assuming that, for each band, the hidden part has the same mean surface brightness as the observed part. The hidden fraction of the sky in each annular division is shown in Figure 1*d*. Only statistical sampling errors are considered for error bars. Another direction is considered for comparison as a control (the CONTROL direction). To minimize the possible bias due to the Galactic plane, the CONTROL direction is taken such that it is the mirror reflection of the LG velocity with respect to the Galactic plane: i.e., $(l, b) = (268°, -27°)$. Only the redshift bin of $z \leq 0.02$ is shown for the CONTROL direction in Figure 1*c*. Because of the symmetric property of the hidden part, Figure 1*d* can be used for both the LG and the CONTROL directions. Figure 1 shows that there is an appreciable dipole anisotropy associated with the LG velocity for $z \leq 0.02$. Comparable dipole moments are not apparent for the sample associated with $z > 0.02$ or the CONTROL direction.

Further exploration in redshift space is made by constructing source by source dipole growth curves in the direction of the LG velocity and other directions (Figs. 2*a*–2*c*). Two directions orthogonal to the LG velocity are taken such that they are also mutually orthogonal and have the same Galactic latitude. The directions thus constructed are $(l, b) = (22°, 39°)$ (marked X) and $(l, b) = (154°, 39°)$ (marked Y). The growth curve of the dipole moment along a given axis is given by

$$D(\leq z) = \frac{1}{4\pi} \sum_{\leq z} F_i \eta_i \cos\theta_i \,, \tag{1}$$

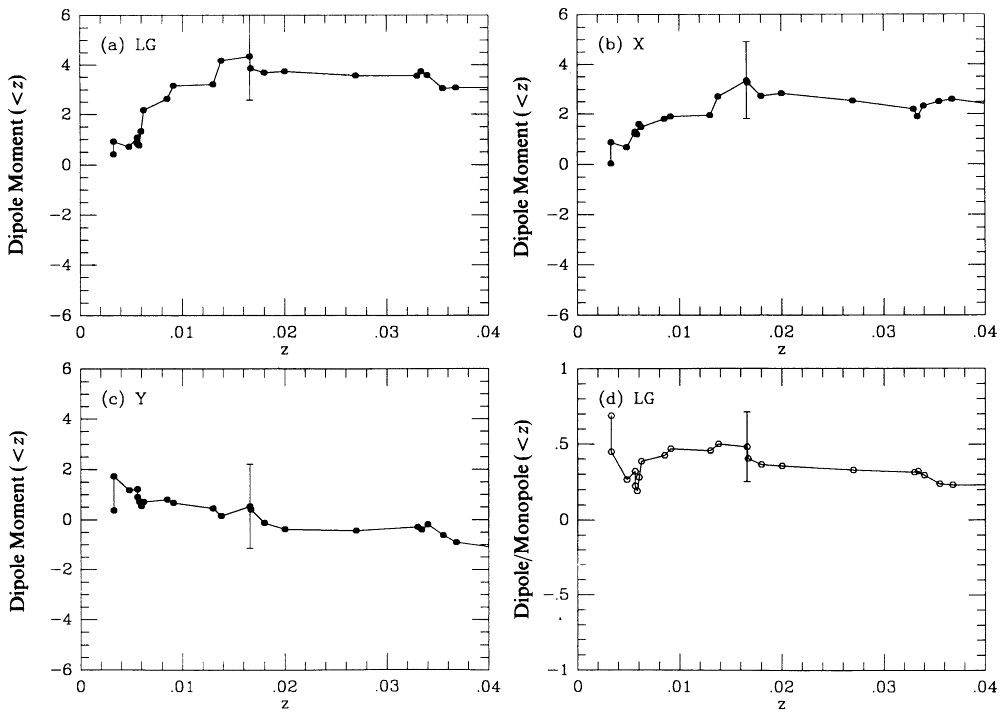

FIG. 2.—Dipole growth curves (eq. [1]) for the components in three orthogonal directions are shown in (*a*)–(*c*). Fig. 2*d* shows growth curve of the ratio of dipole/monopole (eq. [2]) for LG direction. Error bars show statistical sampling errors.

where F_i is the observed flux in the unit of 10^{-11} ergs cm^{-2} s^{-1}, θ_i is the angle from the axis, and η_i is the correction factor discussed below. The sum is over all those AGNs having redshifts no larger than z. Figure 2*d* also shows the growth of the ratio of dipole to monopole:

$$D/M(\leq z) = \left(\sum_{\leq z} F_i \eta_i \cos \theta_i\right) \Big/ \left(\sum_{\leq z} F_i \eta_i\right) . \qquad (2)$$

A correction for the hidden part of the survey is made in a similar way to the one used in Figure 1. We take $1/\eta_i$ = (the fraction of the ring θ_i from the axis for which $|b| > 20°$) assuming that, for a ring at a given θ_i and redshift, the hidden part has the same surface brightness as the exposed part. Because of the symmetric property of the hidden part, this correction does not change the shape of the growth curve significantly. This correction, however, changes the vertical scale of the growth curves. In any event, if the sources trace the global mass distribution, this may be a better correction than assuming that the hidden part has the same surface brightness as the all sky average.

Figure 2*a* shows that the dipole moment along the LG velocity rises steeply up to about $z = 0.017$ and then saturates. Figure 2*d* shows that, at the peak, the dipole moment is about 50% of the monopole of the objects up to this point. This dipole is composed of the 14 closest AGNs in the sample. By a Monte Carlo simulation, the probability of a random sky distribution of 14 sources with observed fluxes to make a dipole-to-monopole ratio of more than 50% along a given axis is found to be about 0.2%. There are no significant dipole components in the Y and the CONTROL directions. Some dipole component is seen in the X direction. The resultant direction of the dipole component up to $z = 0.02$ obtained from the direct vector sum of the fluxes, without any corrections, is $(l, b) = (313°, 38°)$. Two effects are considered for the estimation of the error, a statistical sampling error and an error associated with random orientations of flux vectors. The former is related to statistical variations in the number of objects. The sum of the flux vectors projected onto the plane perpendicular to the resultant direction is zero by construction; this direction is subject to the second error corresponding to the random walk dispersion obtained from the vectors randomly oriented on this plane. This estimation gives a combined error circle of about 30° in radius. We get a comparable direction from the vector addition of the LG, X, and Y dipole components for $z = 0.02$ in Figures 2*a*–2*c*. This dipole direction deviates from the LG velocity by 39°. The probability of a random vector lying within 39° of a given direction is about 10%; this indicates a reasonable alignment of the X-ray dipole with the LG velocity. We note that nonlinear effects, as inferred from *N*-body simulations (Villumsen and Davis 1986), would cause a typical misalignment between a presently observed acceleration and the associated peculiar velocity of about 25°. However, this much misalignment may be an overestimate for the local universe of particular interest here (Lahav, Kaiser, and Hoffman 1990).

IV. DIPOLE ANISOTROPY AND THE LOCAL GROUP MOTION

According to the linear perturbation theory (Peebles 1980), the peculiar motion of the LG is expressed by

$$\boldsymbol{v} = \tfrac{2}{3}\Omega_0{}^{-0.4}\boldsymbol{g}/H_0 , \qquad (3)$$

where Ω_0 and H_0 are the density parameter and the Hubble constant at the present epoch. The peculiar gravitational acceleration of the LG is expressed by

$$\boldsymbol{g} = G \int \rho(\boldsymbol{r})\boldsymbol{r}/r^3 \, d^3\boldsymbol{r} . \qquad (4)$$

To apply our data to these formulae, we use the simple shell model following LRL. We express the density distribution as

$$\rho(\boldsymbol{r}) = \rho_0 + \delta\rho(r) \cos \theta + (\text{higher moment terms}) , \quad (5)$$

where ρ_0 is the mean density of the local universe, $\delta\rho$ is the dipole amplitude, and θ is the angle from the dipole axis of mass distribution. We assume that ρ_0 is constant, $\delta\rho(r) = \delta\rho$ (constant) for $r \leq R_0$, and $\delta\rho(r) = 0$ for $r > R_0$. Expressing the volume emissivity of the tracer in the same way as equation (5) and denoting it by a subscript t, we can define the bias parameter b as

$$b = (\delta\rho_t/\rho_{0t})/(\delta\rho/\rho_0) \quad (6)$$

following Lahav *et al.* (1989). Since $\rho_0 = \Omega_0 \rho_c$, where $\rho_c \equiv 3H_0^2/8\pi G$ is the critical density to close the universe, equation (4) becomes

$$|\boldsymbol{g}| = \frac{4\pi G \Omega_0 \rho_c}{3b} R_0 \left(\frac{\delta\rho_t}{\rho_{0t}}\right) . \quad (7)$$

Because

$$\sum_{\leq z} F_i \eta_i \cos \theta_i \sim \int_{\leq R} \frac{\delta\rho_t}{4\pi r^2} \cos^2 \theta \, d^3r = \frac{1}{3} \delta\rho_t R$$

$$\sum_{\leq z} F_i \eta_i \sim \int_{\leq R} \frac{\rho_{0t}}{4\pi r^2} d^3r = \rho_{0t} R , \quad (8)$$

where the sum is over the objects with redshift less than z ($\leq z_0 = R_0 H_0/c$), we get the observed ratio of the dipole to the monopole as

$$\frac{D}{M}(\leq z) = \frac{1}{3}\frac{\delta\rho_t}{\rho_{0t}} , \quad (z \leq z_0) . \quad (9)$$

From equations (4), (7), (9), and the definition of ρ_c, we get

$$\frac{|\boldsymbol{v}|}{c} = \frac{\Omega_0^{0.6} z_0}{b} \times \frac{D}{M}(\leq z_0) , \quad (10)$$

where c is the speed of light. Note that the Hubble constant does not appear in this relation.

Figure 2*a* shows that the dipole saturates at about $z = 0.017$ to a plateau beyond that point, justifying the approximation used in the above treatment. Figure 2*d* shows that $D/M(\leq 0.017) \approx 50\%$. Taking $D/M(\leq z_0) = 0.5 \pm 0.2$, $z_0 = 0.017$, and $|v| = 600$ km s^{-1}, we get, from equation (10), $b\Omega_0^{-0.6} = 2.5$–6. The values we get are closer to the values using the optical sample ($b\Omega_0^{-0.6} = 2$–2.5; Lynden-Bell, Lahav, and Burstein 1989) than the ones using the *IRAS* sample ($b\Omega_0^{-0.6} \approx 1.1$; YWR; LRL; Rowan-Robinson 1989). These differences probably reflect the variation in how these tracers depend on the real mass distribution. The *IRAS* sample consists mainly of spiral galaxies, while the optical sample consists of both elliptical galaxies and spiral galaxies. The abundance of elliptical galaxies in clusters may cause the higher density contrast in the optical sample (i.e., the larger value of b for the optical sample compared with that of the *IRAS* sample). Since Seyfert galaxies (i.e., most of our X-ray sample) are associated with spiral galaxies, one might expect our sample to yield a b value closer to the *IRAS* one. If most of the Seyfert activities are triggered by interactions between galaxies, then our result could be an indication of an enhancement of the contrast in the AGN distribution compared with normal spiral galaxies that arises from this effect.

There is a possibility that the region of the sky responsible for our dipole causes only a part of the peculiar acceleration at the LG. In fact, most of the so-called great attractor (GA) region (i.e., that which has been proposed as the cause of coherent deviations from the Hubble flow observed in the nearby universe) is not in our sample. Jahoda and Mushotzky (1989) have found a 4% excess in X-ray surface brightness in a 40° diameter region of the GA (centered at $l = 310°$, $b = 10°$) compared with the equal patch of sky in the opposite direction. To obtain an upper limit on the local gravitational acceleration arising from this X-radiating GA region, we take that the average X-ray volume emissivity of the nearby universe is greater than that inferred from the local luminosity function for X-ray–bright AGNs (Piccinotti *et al.* 1982). By further assuming that the bias parameter (b) for the GA–associated X-ray surface brightness enhancement is the same as that for our AGN X-ray dipole, we find that this upper limit to its gravitational effect is approximately equal in magnitude to that associated with the AGN X-ray dipole discussed here. The possible significant contribution of such GA–associated X-ray–bright regions at low Galactic latitudes would cause still a higher estimation of $b\Omega_0^{-0.6}$ than that obtained from the present analysis of the X-ray sky foreground at higher latitudes.

We would like to thank Ofer Lahav for stimulating discussions and his encouragement for our work.

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