The ROSAT X-ray background dipole

M. Plionis and I. Georgantopoulos
National Observatory of Athens, I. Mεταξα & B. Παντου, Λοφος Κούφου, Παλαιά Πεντέλη, 15236, Athens, Greece

Accepted 1999 January 18. Received 1998 December 30; in original form 1998 March 19

ABSTRACT
We estimate the dipole of the diffuse 1.5-keV X-ray background from the ROSAT all-sky survey map of Snowden et al. We first subtract the diffuse Galactic emission by fitting an exponential scaleheight, finite-radius, disc model to the data. We further exclude regions of low galactic latitudes, of local X-ray emission (e.g. the North Polar Spur) and model them using two different methods. We find that the ROSAT X-ray background dipole points towards \((l, b) \approx (288^\circ, 25^\circ) \pm 19^\circ\) in consistency with the cosmic microwave background (within \(\sim 30^\circ\)); its direction is also in good agreement with the HEAO-1 X-ray dipole at harder energies. The normalized amplitude of the ROSAT XRB dipole is \(\sim 1.7\) per cent. Subtracting from the ROSAT map the expected X-ray background dipole resulting from the reflex motion of the observer with respect to the cosmic rest frame (Compton–Getting effect) we find the large-scale dipole of the X-ray emitting extragalactic sources having an amplitude \(D_{\text{LSS}} \sim 0.9D_{\text{XRB}}\), in general agreement with the predictions of Lahav et al. We finally estimate that the Virgo cluster is responsible for \(\sim 20\) per cent of the total measured XRB dipole amplitude.

Key words: cosmic microwave background – cosmology: observations – large-scale structure of Universe – X-rays: general.

1 INTRODUCTION
According to the paradigm that the X-ray background (XRB) originates mainly from sources at redshifts \(1 < z < 3\) (e.g. Shanks et al. 1991), it should provide a means of measuring the well-established solar motion with respect to the cosmic rest-frame, defined by the cosmic microwave background (CMB), towards \(l = 264^\circ, b = 48^\circ\) (cf. Lineweaver et al. 1996). An imprint of this reflex motion should be a dipole pointing towards the direction of the CMB dipole (Compton–Getting effect). The available all-sky X-ray maps (HEAO-1 and ROSAT) are composed by X-ray counts not only originating from such distant sources but also from local extragalactic objects (\(z < 0.1\)). These gravitating extragalactic objects, which cause our peculiar motion with respect to the cosmic rest frame, emit X-rays and therefore their dipole should also point towards the CMB dipole. This has been demonstrated for the case of active galactic nuclei (AGNs: Miyaji & Boldt 1990) and of X-ray clusters (Lahav et al. 1989; Plionis & Kolokotronis 1998). Therefore, the dipole pattern of the XRB results from at least two effects: (a) the motion of the observer with respect to the XRB which in the context of the cosmic-ray background was discussed first by Compton & Getting (1935) and (b) the X-ray emission of extragalactic objects the gravitational field of which causes the observers motion with respect to the cosmic rest frame. The relative contribution of these effects have been analytically estimated by Lahav, Piran & Treyer (1997) and were found to be of the same order of magnitude.

The dipole anisotropy of the XRB has been measured in hard X-rays (2–10 keV) using UHURU (Protheroe, Wolfendale & Wdowczyk 1980) and HEAO-1 data (Shafer & Fabian 1983; Jahoda 1993). The resulting dipole was found to point towards the general direction of the CMB dipole but with a large uncertainty: the 90 per cent confidence levels quoted by Shafer & Fabian (1983) cover 12 per cent of the whole sky. The use of the ROSAT all-sky survey can extend these studies to soft energies with higher sensitivity and angular resolution. Kneissl et al. (1997) presented a cross-correlation of the COBE DMR and the ROSAT all-sky survey maps. However, their attempt to measure the extragalactic dipole was hampered by the contamination of the Galactic emission which is appreciable, especially at low Galactic latitudes, even in the hard ROSAT band. They concluded that proper modelling of the Galactic contribution is necessary in order to obtain a measurement of the dipole. In this paper, we attempt to model the diffuse Galactic component using a simple disc model. After subtracting our Galaxy model, we estimate the cosmological X-ray dipole using the ROSAT all-sky survey hard maps (1.5 keV) of Snowden et al. (1995).

2 THE ROSAT ALL-SKY SURVEY DATA
We use the ROSAT all-sky survey maps at a mean energy of 1.5 keV (PSPC PI channels 91–201). These maps are now publicly released and are described in detail in Snowden et al. (1995). The maps cover \(~98\) per cent of the sky with a resolution of 2 degrees. Point sources

© 1999 RAS
detected in the all-sky survey are included in the maps. The particle background, scattered solar X-ray background and other noncosmic background contamination components have been removed (see Snowden et al. 1994, 1995).

The X-ray emission in the 1.5-keV band is mainly extragalactic: Hasinger et al. (1998) have resolved about 70 per cent of the background at these energies into discrete extragalactic sources. However, there is some contamination, owing to the poor energy resolution of the ROSAT PSPC, from a Galactic component. This is well-fitted with a Raymond–Smith spectrum, having a temperature of $\sim 0.17$ keV, and may be associated with the Galactic halo (see Wang & McCray 1993; Gendreau et al. 1995; Hasinger 1996; Pietz et al. 1998). We note that at higher energies (3–60 keV) there is evidence for a even harder Galactic component with a bremsstrahlung spectrum of 9 keV (Iwan et al. 1982); however, this is expected to contribute less than one per cent in the ROSAT 1.5-keV band. Moreover, the 1.5-keV maps of Snowden et al. (1995) show some extended features superimposed on the extragalactic and the diffuse hard Galactic component (see Snowden et al. 1995) mainly originating from nearby supernova remnants (eg the North Polar Spur, the Cygnus superbubble). All the above local features must be subtracted before deriving the extragalactic X-ray dipole.

### 2.1 Modelling the Galactic emission

The derivation of a detailed Galactic emission model requires observations in many wavebands and is outside the scope of this paper; detailed modelling of the Galactic halo is discussed in Iwan et al. (1982), Nousek et al. (1982) and Pietz et al. (1998). Here instead, we attempt to make a rough model of the Galactic contamination in our energy band. We model the diffuse Galactic components with a finite radius disc with an exponential scaleheight, (e.g. Iwan et al. 1982) which provides a good description of the Galactic component at both soft (0.75 keV) and hard energies (2–60 keV). This is given by:

$$C(l, b) = C_b \left[ 1 + \frac{E_h}{\sin |b|} \left( 1 - e^{-f(l,R_d)\tan|b|/h} \right) \right],$$

where $f(l,R_d) = \cos l + \sqrt{R_d^2 - \sin^2 l}$, with $C$ the total X-ray intensity, $C_b$ the average extragalactic component, in units of $10^{-6}$ count s$^{-1}$ arcmin$^{-2}$, $E$ the fraction of the total X-ray emission which is due to the Galaxy, $h$ and $R_d$ the disc scaleheight and disc radius, respectively both in units of 10 kpc (the galactocentric distance of the Sun). We exclude from the fit the regions of the most apparent extended emission features: the bulge and the North Polar Spur (i.e. $-40^\circ < b < 75^\circ$ and $300^\circ < l < 30^\circ$, e.g. Snowden et al. 1995) as well as the Galactic plane strip (with $|b| < 20^\circ$ or $30^\circ$). Although it is unknown whether there is some small residual bulge emission outside the above excised region, our rough model should provide a good first-order approximation to the Galactic halo emission. Furthermore, applying a homogeneous mean count we mask the most apparent 'local' extragalactic features; a 4° radius region around the Virgo cluster ($l, b \approx 287^\circ, 75^\circ$) and a 10° radius region around the Magellanic clouds ($l, b \approx 278^\circ, -32^\circ$).

In the minimization procedure we weight each pixel by $1/\sigma$, where $\sigma = (\sigma_I^2 + \sigma_P^2)^{1/2}$, with $\sigma_I$ the variance of the X-ray ROSAT - counts as a result of the intrinsic extragalactic fluctuations and $\sigma_P^2$ the variance owing to Poisson count statistics. We estimate $\sigma_I$ excluding from the map the North Polar Spur and the $|b| \leq 45^\circ$ regions and find $\sigma_I \approx 0.27$. Starting from different initial guesses of the input parameters the minimization procedure does not reach a unique minimum, although the reduced $\chi^2$ is around one and the output model parameters are closely clustered. This suggests the existence of a broad and shallow minimum. We therefore run 1000 $\chi^2$ minimizations starting from a broad range of initial values. These values are centred on those that Iwan et al. (1982) find for the Galactic component using HEAO-1 data, i.e., $\langle h \rangle \approx 7$ kpc, $\langle R_d \rangle \approx 28$ kpc and $\langle E \rangle \approx 10$ per cent; while the input extragalactic contribution is centred on $\langle C_b \rangle \approx 120$, the value obtained from the ROSAT XRB spectral fits in this band (e.g. Georgantopoulos et al. 1996). The results cluster around some preferred values as can be seen in Fig. 1, in which we show as hatched histograms the distribution of the input parameters and as thick lines the best-fitting output parameter distribution. The most probable values of the fitted parameters as well as their standard deviation over the 1000 minimizations are presented in Table 1. For $|b| > 20^\circ$ we have typically that $\chi^2 \approx 33600$ for 30064 degrees of freedom and hence this model cannot be rejected. The Galaxy contributes a significant fraction (50–30 per cent) of the average total ROSAT 1.5 keV X-ray emission. As discussed earlier this Galactic component could arise as contamination from lower energies (e.g. from the 0.17 keV Raymond–Smith Galactic component) resulting from the coarse energy resolution of the ROSAT PSPC. Although this percentage is rather high it is not inconsistent with XRB spectral fits in deep ROSAT and ASCA pointings: the excellent spectral resolution ASCA

![Figure 1. Distribution of the finite Galaxy disc model parameters. Continuous lines represent the output parameter distribution while the hatched histograms the corresponding input ones, used to start the $\chi^2$ minimization procedure.](https://academic.oup.com/mnras/article-abstract/306/1/112/1033202/fig1)
3.1 Dipole-fitting procedure

The multipole components of the ROSAT X-ray intensity are calculated by summing moments. The dipole moment is estimated by weighing the unit directional vector pointing to each 40 arcmin$^2$ ROSAT cell with the X-ray intensity $C_i$ of that cell. We normalize the dipole by the monopole term (the mean X-ray intensity over the sky):

$$\mathcal{D} = \frac{|\mathbf{D}|}{M} = \frac{\sum C_i \hat{r}_i}{\sum C_i}. \quad (2)$$

We attempt to estimate the cosmological XRB dipole by applying the above procedure to the ROSAT counts after subtracting our best Galaxy model (Table 1) and the regions of Galactic and ‘local’ extragalactic X-ray emission. To this end we mask: (a) The Galactic plane, (b) the area dominated by the Galactic bulge and the North Polar Spur (see definitions in Section 2.1) and (c) a region of 10$^°$ radius around the Large Magellanic Clouds (we have verified that small variations in the limits of all the above regions do not change appreciably our results).

We use two methods to model these regions: the first consists in substituting the observed intensity with the mean value estimated at high galactic latitudes (homogeneous filling procedure) and the second based on a spherical harmonic extrapolation procedure (cf. Yahil, Walker & Rowan-Robinson 1986). Since the latter is slightly more involved we briefly review the method which is based on expanding the sky surface density field $\sigma(\theta, \varphi)$ in real spherical harmonics:

$$\sigma(\theta, \varphi) = \sum_{l,m} a_l^m Y_l^m(\theta, \varphi), \quad (3)$$

where the factor 3 enters for consistency with the definition of equation (2). The observed $\Sigma(\theta, \varphi)$ and intrinsic surface density field $\sigma(\theta, \varphi)$ are related according to: $\Sigma(\theta, \varphi) = M(\theta, \varphi) \sigma(\theta, \varphi)$, where the mask $M(\theta, \varphi)$ takes values of 1 or 0 depending on whether the $(\theta, \varphi)$ direction points in an observed or excluded part of the sky, respectively. Since we are interested in recovering the dipole ($l = 1$) components of $\sigma(\theta, \varphi)$, the correction terms should at least involve the quadrupole ($l = 2$) components. Expanding $\Sigma(\theta, \varphi)$ up to the quadrupole order and allowing for the orthogonality relation of the Legendre polynomials, we can express the observed coefficients $A_l^m$, in terms of the intrinsic ones, $a_l^m$, forming a 9 x 9 matrix, the inversion of which then gives $a_l^m$. A more accurate procedure would entail an expansion to higher order $l$ (cf. Lahav et al. 1994) but to recover a smooth underlying dipole structure (in which higher order $l$ terms are negligible) we have verified, using mock samples, that the above procedure recovers extremely accurately the direction and amplitude of the true underlying dipole.

3.2 Dipole Results

In Table 2 we present our main results for different treatment of the data. It is evident that when using the raw ROSAT data, the dipole points roughly towards the Galactic Centre (in agreement with Kneissl et al. 1997). However, when we exclude both the Galaxy and the North Polar Spur, the measured dipole is in much better directional agreement with the CMB dipole. For the homogeneous filling method we find $\theta_{\mathrm{dip}} < 20^°$ excluding the Galactic plane below $|b| = 20^°$ or $|b| = 30^°$. For the spherical harmonic method the misalignment angle is larger, $\theta_{\mathrm{dip}} > 35^°$. The Virgo cluster, being quite near and very bright in X-rays, could contribute significantly to the measured dipole. Excluding an area of 4° radius around the Virgo cluster ($l, b = 287°, 75°$), which is very apparent in the X-ray map, we find that it is responsible for $\approx 20$ per cent of the total dipole, while the dipole misalignment angle with the CMB increases by $\approx 15°$.

However, it should be expected that many Galactic sources, probably dominating the higher ROSAT counts, are still present in the data and could affect the behaviour of the extragalactic XRB dipole. We therefore present in Fig. 2 the misalignment angle between the ROSAT and CMB dipoles as well as the normalized dipole amplitude, $\mathcal{D}$, as a function of the ROSAT upper count limit ($C_{\mathrm{up}}$). The errorbars have been estimated by using the different Galactic model parameters resulting from the $\chi^2$ fits of Section 2.1 and presented in Fig. 1. We do find that our main results are very robust in such variations of the Galactic model. The two methods, used to mask the excluded regions, give consistent dipole results for $C_{\mathrm{up}} \leq 140$ (which cover $\approx 97$ per cent of the unmasked sky). For this limit the ROSAT –CMB dipole misalignment angle is $\approx 26°$ and $33°$ for the homogeneous filling and spherical harmonics methods respectively. It is evident that the ROSAT –CMB dipole misalignment angle increases substantially when we include the...
The 

parameters within their range of validity. Using 6000 dipole Monte Carlo simulation approach in which we vary all the model parameters.

Table 2. The ROSAT dipole results for |b| > $b_{lim}$.

<table>
<thead>
<tr>
<th>mask model</th>
<th>$b_{lim}$</th>
<th>$l^*$</th>
<th>$b^*$</th>
<th>$\delta\theta_{CMB}$</th>
<th>$\delta\theta_{CMBl}$</th>
<th>$D$</th>
<th>sky masked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw counts</td>
<td>Homogeneous</td>
<td>20</td>
<td>342.7</td>
<td>20.4</td>
<td>67.6</td>
<td>59.5</td>
<td>0.050</td>
</tr>
<tr>
<td>Galaxy, North Polar Spur</td>
<td>Spherical Harmonic</td>
<td>20</td>
<td>343.0</td>
<td>11.0</td>
<td>74.5</td>
<td>63.8</td>
<td>0.092</td>
</tr>
<tr>
<td>&amp; Magellanic Clouds excluded</td>
<td>Homogeneous</td>
<td>20</td>
<td>208.3</td>
<td>29.1</td>
<td>21.2</td>
<td>3</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>Spherical Harmonic</td>
<td>20</td>
<td>318.3</td>
<td>20.1</td>
<td>51.1</td>
<td>38.5</td>
<td>0.037</td>
</tr>
<tr>
<td></td>
<td>Homogeneous</td>
<td>30</td>
<td>290.9</td>
<td>41.6</td>
<td>19.8</td>
<td>16.1</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Spherical Harmonic</td>
<td>30</td>
<td>313.5</td>
<td>14.9</td>
<td>51.7</td>
<td>36.7</td>
<td>0.049</td>
</tr>
</tbody>
</table>

few higher intensity cells, before however the Virgo cluster (which enters at $C_{up} \simeq 200$ counts) starts reducing again the misalignment angle, as can be clearly seen in Fig. 2. The interpretation that the high-intensity ($C \simeq 140$) cells are associated with Galactic sources is supported by the fact that when we include these few cells the resulting dipole direction moves towards the Galactic Centre. We therefore consider as our best estimate of the XRB dipole its value at $C_{up} \simeq 140$, for which both methods used to model the masked areas agree and the XRB-CMB dipole misalignment angle is minimum.

To take into account all possible sources of uncertainty, we use a Monte Carlo simulation approach in which we vary all the model parameters within their range of validity. Using 6000 dipole realizations to take into account (a) the uncertainties of the Galactic model subtracted from the raw counts, (b) the different methods used to mask the excluded sky regions (c) the different galactic latitude limits and (d) variations of the excision radii around the bulge and the North Polar Spur we conclude that the XRB ROSAT dipole has:

$$D_{XRB} \approx 0.017 \pm 0.008 \ (l, b) \approx (286^\circ, 22^\circ) \pm 19^\circ,$$

which deviates from the CMB dipole directions in the heliocentric and Local Group frames by $\delta \theta_{CMB} \sim 30^\circ$ and $\delta \theta_{CMBl} \sim 10^\circ$, respectively. It is interesting that the ROSAT dipole is nearer to the Local Group frame CMB dipole direction. Our results are consistent with the HEAO-1 (2–10 keV) dipole (Shafer & Fabian 1983) which points in a similar direction ($282^\circ$, $30^\circ$), albeit with a larger uncertainty, but has a lower amplitude: $D_{HEAO-1} \sim 0.005$.

3.3 Interpretation

The motion of the Sun with respect to an isotropic radiation background produces a dipole in the radiation intensity according to:

$$\delta C \left/ \langle C \rangle \right. = (3 + \alpha)V_\odot \cos \theta/c,$$

where $\alpha$ is the spectral index of the radiation ($C \propto \nu^{-\alpha}$). For the 1.5-keV ROSAT band we have $\alpha \sim 0.4$ (Gendreau et al. 1995). If the ROSAT dipole was totally a result of the motion of the Sun with respect to the XRB (Compton–Getting effect) then we would obtain a solar velocity with respect to the XRB of $V_\odot = 1300 \pm 600$ km s$^{-1}$, which should be compared with $V_\odot = 369$ km s$^{-1}$ with respect to the CMB (Lineweaver et al. 1996).

We therefore verify that the observed XRB ROSAT dipole cannot be only due to the Compton-Getting effect but it is significantly contaminated by the dipole produced by X-ray emitting sources that trace the large-scale structure. We estimate the large-scale dipole component of the XRB by subtracting from the ROSAT map the expected Compton–Getting dipole and we obtain a dipole with $D_{LS} \approx 0.9D_{XRB}$ pointing towards $(l, b) \sim (284^\circ, 18^\circ)$. This is in general agreement with Lahav et al. (1997) who found that the two effects, contributing to the XRB dipole, are of the same order of magnitude.

4 CONCLUSIONS

We have estimated the dipole of the diffuse 1.5-keV X-ray background using the ROSAT all-sky survey maps of Snowden et al. (1995). We have first subtracted from the ROSAT counts the diffuse Galactic emission (the halo and bulge components) as well as local extended features such as the North Polar Spur. The Galactic halo model used is that of a finite radius disc model with an exponential
scaleheight (e.g. Iwan et al. 1982). The mean Galactic X-ray component is \(\sim 20 - 30\) per cent of the background and the scale-height and radius are \(\sim 16 \pm 5\) and \(27 \pm 5\) kpc respectively. We model the excluded regions by either homogeneously ‘painting’ these regions with the mean X-ray count (derived after subtracting the Galaxy) or using a spherical harmonic expansion of the X-ray surface intensity field.

We estimate that the ROSAT XRB dipole is pointing towards \((l,b) = (286\degree, 22\degree) \pm 19\), within \(\sim 30\degree\) of the CMB direction and having a normalized amplitude of \(\sim 1.7\) per cent. The dipole direction is in agreement with previous estimates in hard X-rays (Shafer & Fabian 1982) but the positional errors have now been improved. We also find that the two effects expected to contribute to the XRB, i.e., the Compton–Getting effect and the anisotropy owing to X-ray sources tracing the large-scale structure, are of the same order of magnitude, in general agreement with the predictions of Lahav et al. (1997). However, the latter dominates having \(D_{\text{LSS}} \sim 0.9D_{\text{XRB}}\). Finally, we estimate that the nearest cluster, Virgo, contributes \(\sim 20\) per cent to the total measured XRB dipole.

ACKNOWLEDGMENT

We thank the referee, Dr Marie Treyer, for her helpful comments and suggestions.

REFERENCES


This paper has been typeset from a TEX/LATEX file prepared by the author.