A discrepancy observed in the dipole anisotropy in the radio sky at 1.4 GHz and that in the CMBR – A threat to the cosmological principle?

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Abstract. According to the cosmological principle, the sky brightness at any frequency should appear uniform in all directions to an observer considered to be fixed in the co-moving coordinate system of the expanding universe. However a peculiar motion of the observer introduces a dipole anisotropy in the observed sky brightness, which should be independent of the observing frequency. We have examined the angular distribution in the radio-sky brightness, i.e., an integrated emission from discrete sources per unit solid angle, from the NVSS sample containing 1.8 million discrete radio sources at 1.4 GHz. Our results give a dipole anisotropy which is in the same direction as that of the CMBR from the COBE or WMAP, but the magnitude we find is about 4 times larger at a statistically significant (about 3σ) level. A genuine difference between the two dipoles cannot arise from the observer’s motion alone, and it would imply intrinsically anisotropic universe, with anisotropy changing with the epoch. This would violate the cosmological principle where isotropy of the universe is assumed for all epochs, and on which the whole modern cosmology is based upon.

1. Introduction
An observed dipole anisotropy in the Cosmic Microwave Background Radiation (CMBR), when attributed to the peculiar motion of the solar system through the universe, yields a velocity of 369 km/s in the direction $l = 264^\circ, b = 48^\circ$ [1,2]. A study had found a similar anisotropy in the number counts of radio sources [3]. Here we examine the presence of such an anisotropy in the sky brightness due to radio galaxies. This will provide a confirmation on the interpretation of CMBR dipole anisotropy being due to solar motion. Also CMBR provides information about the isotropy of the universe for redshift $z \sim 700$, but the radio source population refers to a much later epoch $z \sim 1$. Thus it also provides an independent check on the cosmological principle where isotropy of the universe is assumed for all epochs.

2. The source catalogue
We have used the NVSS catalogue (NRAO VLA Sky Survey [4]) for our investigations. This survey covers whole sky north of declination $-40^\circ$, a total of 82% of the celestial sphere, at 1.4 GHz. There are about 1.8 million sources in the catalogue with a flux-density limit $S > 3$ mJy. The catalog is available in a compact form, giving for each source right ascension (RA),
Table 1. The observed dipole asymmetry in sky brightness and the construed solar velocity

| S (mJy) | N   | ΔF/F (10^{-2}) | RA (°) | Dec (°) | υ (10^3 km/s) |
|---------|-----|---------------|--------|---------|---------------|
| 1000 > S ≥ 100 | 39625 | 1.6 ± 0.4 | 154 ± 17 | −08 ± 18 | 1.7 ± 0.6 |
| 1000 > S ≥ 50  | 90360 | 1.7 ± 0.4 | 163 ± 12 | −11 ± 11 | 1.8 ± 0.5 |
| 1000 > S ≥ 30  | 153759 | 1.7 ± 0.3 | 159 ± 11 | −07 ± 10 | 1.8 ± 0.5 |
| 1000 > S ≥ 20  | 228128 | 1.5 ± 0.2 | 158 ± 10 | −06 ± 9  | 1.7 ± 0.4 |
| 1000 > S ≥ 15  | 296811 | 1.5 ± 0.2 | 157 ± 9  | −03 ± 8  | 1.6 ± 0.4 |
| 100 > S ≥ 50   | 50735 | 1.7 ± 0.2 | 194 ± 16 | −19 ± 17 | 1.8 ± 0.6 |
| 100 > S ≥ 30   | 114134 | 1.4 ± 0.2 | 169 ± 12 | −05 ± 11 | 1.5 ± 0.4 |
| 100 > S ≥ 20   | 188503 | 1.2 ± 0.2 | 165 ± 11 | −02 ± 10 | 1.3 ± 0.4 |
| 100 > S ≥ 15   | 257186 | 1.2 ± 0.1 | 162 ± 10 | +06 ± 10 | 1.3 ± 0.3 |

declination (Dec) and flux density (S) at 1.4 GHz in a tabular form, and is downloadable by anonymous FTP from ftp://ftp.aoc.nrao.edu/pub/software/aips/TEXT/STARS.

3. Effects of aberration and Doppler boosting

An observer moving with a velocity υ, will find sources in the forward direction brighter by a factor δ^{1+α}, due to Doppler boosting [5], where δ = 1 + (υ/c) cos θ is the Doppler factor, c is the velocity of light and α (≈ 0.8) is the spectral index defined by S ∝ ν^{−α}. Here we have used the non-relativistic formula for the Doppler factor as CMBR observations indicate that υ ≪ c. Further, the increased flux density due to Doppler boosting in the forward direction will cause a telescope of a given sensitivity limit to detect comparatively a larger number of sources. With the integral source counts of extragalactic radio source population following a power law N(> S) ∝ S^{−x} (x ≈ 1), the observed number of sources in any given flux-density range will therefore change [5] by a factor ∝ δ^{x(1+α)}.

Also due to the aberration of light, the apparent position of a source at angle θ will be shifted in the forward direction by an angle (υ/c) sin θ, as a result there will be a higher number density per steradian in the forward direction as compared to that in the backward direction. This excess [5] in number density ∝ δ^{2}. Thus as a combined effect of Doppler boosting and the aberration, the observed sky brightness (an integrated emission from discrete sources per unit solid angle) will vary as ∝ δ^{2+x(1+α)} which (for υ ≪ c) can be written as 1 + D cos θ, a dipole anisotropy over the sky [5,6] with amplitude D = [2 + x(1 + α)](υ/c).

Let ri be the position vector (of unit magnitude) of i\textsuperscript{th} source of observed flux density Si in the sky. Then for a uniform angular distribution of the sky brightness, ∑Si ri = 0. However because of the observer’s peculiar motion in an otherwise isotropic universe, the vectorial sum ∑Si ri will yield a net vector in the direction of motion, thereby fixing the direction of the dipole. If θ is the polar angle of the i\textsuperscript{th} source with respect to the dipole direction, then the magnitude of the vectorial sum can be written as ∆F = ∑Si cos θi. Writing F = ∑Si |cos θi| and converting the summation into an integration over the sphere, we get for the dipole magnitude,

\[
\frac{\Delta F}{F} = k \int_0^\pi (1 + D \cos \theta) \cos \theta \sin \theta d\theta = \frac{2kD}{3} = \frac{2k}{3} [2 + x(1 + \alpha)] \frac{\upsilon}{c}.
\]

The formula is equally valid for samples with finite upper and lower flux-density limits. Here k is a constant of the order of unity (k = 1 for a sky fully covered by the sample) and as such may need to be determined numerically for individual cases when there are finite gaps in the sky coverage.
Table 2. The velocity vector from the number counts

| S (mJy) | N | D (10^{-2}) | RA (°) | Dec (°) | v (10^3 km/s) |
|--------|---|-------------|-------|--------|-------------|
| ≥ 50   | 091597 | 2.1 ± 0.5 | 171 ± 13 | −18 ± 14 | 1.7 ± 0.4 |
| ≥ 40   | 115837 | 1.8 ± 0.4 | 158 ± 12 | −19 ± 12 | 1.4 ± 0.4 |
| ≥ 35   | 132930 | 1.9 ± 0.4 | 157 ± 11 | −12 ± 11 | 1.5 ± 0.3 |
| ≥ 30   | 154996 | 2.0 ± 0.4 | 156 ± 11 | −02 ± 10 | 1.6 ± 0.3 |
| ≥ 25   | 185474 | 1.8 ± 0.4 | 158 ± 11 | −02 ± 10 | 1.4 ± 0.3 |
| ≥ 20   | 229365 | 1.8 ± 0.3 | 153 ± 10 | +02 ± 10 | 1.4 ± 0.3 |
| ≥ 15   | 298048 | 1.6 ± 0.3 | 149 ± 09 | +15 ± 09 | 1.3 ± 0.2 |

As the NVSS catalogue has a gap of sources for Dec < −40°, in that case our assumption of ∑S_i r_i = 0 for a stationary observer does not hold good. However if we drop all sources with Dec > 40° as well, then with equal and opposite gaps on opposite sides ∑S_i r_i = 0 is valid for a stationary observer. Further we also excluded all sources from our sample which lie in the galactic plane (|b| < 10°) as the excess of galactic sources towards the galactic centre is likely to contaminate the determination of velocity. Of course exclusion of such strips, which affect the forward and backward measurements identically, to a first order do not have systematic effects on the results [5]. Using Monte–Carlo simulations we estimated k ∼ 1.1 (Eq. (1)), for the effect of the gaps in our samples.

4. Results and discussion

Our results are presented in Table 1, which is almost self-explanatory. As a relatively small number of strong sources at high flux-density levels could introduce large statistical fluctuations in the sky brightness, we have restricted our sample to below 1000 mJy level. At the lower end we have restricted it to 15 mJy levels as the completeness of the sample at weaker flux-density levels could be doubtful [3]. The estimation of errors for ∆F/F are described in Ref. [7].

From Table 1 the direction the velocity vector (with our best estimate RA = 157° ± 9°, Dec= −03° ± 8° or in galactic co-ordinates l = 248° ± 12°, b = 44° ± 8°) is quite in agreement with those determined from the CMBR (RA= 168°, Dec= −7° or l = 264°, b = 48° with errors less than a degree) [1, 2]. However the estimates of the magnitude of the velocity vector (1600 ± 400 km/s) appear much higher than the CMBR value (369 ± 1 km/s) by a factor ∼ 4 at a statistically significant (∼ 3σ) level.

A previous attempt [3] had used the number counts of radio galaxies to find peculiar velocity which seemed consistent with that from the CMBR observations, but from the sky brightness anisotropy we got the velocity ∼ 4 times the CMBR value. To ascertain that the difference somehow is not between the dipoles arising from the sky brightness and the number counts, we have determined the velocity from the number counts as well, using a technique [6] slightly different from that of Ref. [3]. First the direction of the dipole was determined from Σr_i, the three vector components (x, y, z) obtained essentially the same as the three l = 1 spherical harmonic coefficients giving the dipole [3]. Then the dipole magnitude was calculated from the fractional difference ∆N/N = ∑|cos θ_i|/Σ|cos θ_i| = (2k/3)[2 + x(1 + a)](v/c) = 2kD/3, similar to that for ∆F/F in the case of sky brightness. The results are summarized in Table 2. Comparing with Table 1 we notice that the observed anisotropies in both the sky brightness and the number counts yield similar velocities with magnitudes ∼ 4 times the CMBR value in both cases.

To conclusively eliminate the possibility of some local clustering on our results, we determined
the velocity components for three different polar angles for the last flux-density bin (> 15 mJy) which had the largest number of sources in Table.2. Starting from the dipole direction we first divided the sky into six equal-area zones. Then computing fractional difference in source counts between symmetrically placed pairs of sky zones, we determined the peculiar velocity components for three different polar angles. Fig. 1 shows a plot of the three components, which seem to fit very well with the expected \( \cos \theta \) variation of the 1300 km/s speed for that bin. Also plotted is the projection of the CMBR value (369 km/s) for a comparison. A local clustering in certain regions of the sky could not have influenced the three velocity components by the same factor and this indeed is a clinching evidence that some local clustering is not the cause of the inferred high velocity values.

Our unexpected results have recently been verified by two independent groups [8,9]. Assuming that the CMBR dipole estimates do not suffer from any residual errors during subtraction of galactic and other contributions, one cannot escape the conclusion that there is a genuine discrepancy in the two dipoles and that the reference frame defined by the radio source population at \( z \sim 1 \) does not coincide with that defined by the CMBR originating at \( z \sim 700 \). The implication are therefore serious as any differential perturbations to the Hubble flow on the scale of radio galaxies vis-à-vis that of CMBR would be truly on a universal scale. A differential anisotropy between two frames would imply anisotropic universe where anisotropy itself is changing with epoch. This would violate the cosmological principle where the isotropy of the universe is assumed for all epochs, and on which the whole modern cosmology rests upon.

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