A large disparity in cosmic reference frames determined from the sky distributions of radio sources and the microwave background radiation

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The angular distribution of the Cosmic Microwave Background Radiation (CMBR) in sky shows a dipole asymmetry, ascribed to the observer’s motion (peculiar velocity of the solar system!), relative to the local comoving coordinates. The peculiar velocity thus determined turns out to be 370 km s$^{-1}$ in the direction RA= 168°, Dec= −7°. On the other hand, a dipole asymmetry in the sky distribution of radio sources in the NRAO VLA Sky Survey (NVSS) catalogue, comprising 1.8 million sources, yielded a value for the observer’s velocity to be $\sim 4$ times larger than the CMBR value, though the direction turned out to be in agreement with that of the CMBR dipole. This large difference in observer’s speeds with respect to the reference frames of NVSS radio sources and of CMBR, confirmed since by many independent groups, is rather disconcerting as the observer’s motion with respect to local comoving coordinates should be independent of the technique used to determine it. A genuine difference in relative speeds of two cosmic reference frames could jeopardize the Cosmological Principle, thence it is crucial to confirm such discrepancies using independent samples of radio sources. We here investigate the dipole in the sky distribution of radio sources in the recent TIFR GMRT Sky Survey - First Alternative Data Release (TGSS-ADR1) dataset, comprising 0.62 million sources, to determine observer’s motion. We find a significant disparity in observer’s speeds relative to all three reference frames, determined from the radio source datasets and the CMBR.

I. INTRODUCTION

Due to the assumed isotropy of the Universe – à la Cosmological Principle – an observer stationary with respect to the comoving coordinates of the cosmic fluid, should find the number counts of distant radio sources as well as the sky brightness therefrom (i.e., an integrated emission from discrete sources per unit solid angle), to be uniform over the sky. However, an observer moving with a velocity $v$ relative to the cosmic fluid will find, as a combined effect of the aberration and Doppler boosting, the number counts and the sky brightness to vary as $\propto \delta^{2+\alpha(1+\alpha)}$, where $\delta = (1 + \alpha(v/c)\cos \theta$ for a non-relativistic case) is the Doppler factor, $c$ is the velocity of light, $\alpha \approx 0.8$ is the spectral index, defined by $S \propto \nu^{-\alpha}$, and $x$ is the index of the integral source counts of extragalactic radio source population, which follows a power law $N(\geq S) \propto S^{-x}$ ($x \sim 1$). The angular variation of the number counts as well as of the sky brightness can be expressed as $1 + D \cos \theta$, implying a dipole anisotropy over the sky with amplitude $D = [2 + x(1 + \alpha)](v/c)$, by observing such angular variation over sky for a sufficiently large dataset of distant radio sources, one can compute the dipole $D$ and thereby velocity $v$ of the observer with respect to the comoving coordinates.

Let $\hat{r}_i$ be the angular position of $i^{th}$ source of observed flux-density $S_i$ with respect to the stationary observer, who should find $\Delta F = \Sigma S_i \hat{r}_i = 0$. However, for a moving observer, due to the dipole anisotropy over the sky, $\Delta F$ would yield a finite value. Writing $F = \Sigma S_i |\hat{r}_i|$, a summation over the whole sky determines magnitude of the dipole in the sky brightness as $\frac{\Delta F}{F} = \frac{2k_1D}{3} = \frac{2k_1}{3}[2 + x(1 + \alpha)]\frac{v}{c}$.

Here $k_1$ is a constant, of the order of unity ($k_1 = 1$ for a sky uniformly covered by the sample), and as such would need to be determined numerically for individual samples where there might be finite gaps in the sky coverage.

A study of the angular variation in the temperature distribution of the CMBR has given quite accurate measurements of a dipole anisotropy, supposedly arising from the observer’s motion (peculiar velocity of the solar system), to be 370 km s$^{-1}$ in the direction $l = 264^\circ$, $b = 48^\circ$ or equivalently, RA= 168°, Dec= −7°. Some earlier attempts to determine the dipole from the observed angular asymmetry in the sky distribution of distant radio sources claimed the radio source dipole to match the CMBR dipole within statistical uncertainties. However, Singal, from a study of the anisotropy in the number counts as well as sky brightness from discrete radio sources in the NVSS catalogue, covering whole sky north of declination $-40^\circ$ and containing $\sim 1.8$ million sources with a flux-density limit $S > 3$ mJy at 1.4 GHz, found for the solar peculiar motion a rather large value, $\sim 1600 \pm 400$ km s$^{-1}$, $\sim 4$ times the CMBR value at a statistically significant ($\sim 3\sigma$) level. At the same time, the direction of the velocity vector, though, was surprisingly found to be in agreement with the CMBR value.

These unexpected findings of the NVSS dipole being many times larger than the CMBR dipole, have since been confirmed in a number of publications. Such a difference between two dipoles would imply a relative motion between two cosmic reference frames which will be against the Cosmological Principle on which the whole
TABLE I. The dipole and velocity vector from the sky brightness for the TGSS-ADR1 dataset

| Flux-density Range (mJy) | $N$ | $\mathcal{D}$ ($10^{-2}$) | RA ($^\circ$) | Dec ($^\circ$) | $v$ ($10^3$ km s$^{-1}$) |
|-------------------------|-----|---------------------------|--------------|--------------|-------------------|
| $5000 > S \geq 250$     | 098205 | 5.8 ± 0.7             | 174 ± 11    | −08 ± 10     | 4.6 ± 0.5         |
| $5000 > S \geq 200$     | 122549 | 5.6 ± 0.6             | 174 ± 11    | −06 ± 10     | 4.4 ± 0.5         |
| $5000 > S \geq 150$     | 160133 | 5.4 ± 0.6             | 173 ± 10    | −06 ± 09     | 4.3 ± 0.5         |
| $5000 > S \geq 100$     | 226242 | 5.2 ± 0.5             | 172 ± 10    | −05 ± 09     | 4.1 ± 0.4         |

TABLE II. The dipole and velocity vector for TGSS-ADR1 dataset with $S_{\text{GB}} > 10^5$ (mJy)

| Flux-density Range (mJy) | $N$ | $\mathcal{D}$ ($10^{-2}$) | RA ($^\circ$) | Dec ($^\circ$) | $v$ ($10^3$ km s$^{-1}$) |
|-------------------------|-----|---------------------------|--------------|--------------|-------------------|
| $5000 > S \geq 250$     | 082336 | 6.1 ± 0.7             | 170 ± 12    | −12 ± 11     | 4.8 ± 0.6         |
| $5000 > S \geq 200$     | 102700 | 5.8 ± 0.7             | 169 ± 12    | −10 ± 11     | 4.6 ± 0.5         |
| $5000 > S \geq 150$     | 134106 | 5.6 ± 0.6             | 167 ± 11    | −10 ± 10     | 4.4 ± 0.5         |
| $5000 > S \geq 100$     | 189416 | 5.3 ± 0.6             | 167 ± 11    | −10 ± 10     | 4.2 ± 0.5         |

modern cosmology is based upon. Therefore it is imperative that an investigation of the radio source dipole be made employing some independent radio source samples. A recent estimate from the TGSS-ADR1 data [16], has yielded an even larger amplitude for the radio dipole [16], which is all the more disconcerting. Here we investigate this radio dipole in further details, by choosing different flux-density levels, to examine the self-consistency of the dipole in the TGSS-ADR1 data and relate the results to those from NVSS catalogue by using the spectral index information between the two datasets [17, 18].

II. TGSS-ADR1 DATASET

TIFR GMRT Sky Survey (TGSS) is a 150 MHz, continuum survey, carried out between 2010 and 2012 using the Giant Metrewave Radio Telescope (GMRT) [19], and the raw data are available at the GMRT archive. A First Alternative Data Release of the TGSS (TGSS-ADR1) [10], that includes direction-dependent calibration and imaging, is available online in the public domain. The TGSS-ADR1 data release [10] covers whole sky north of declination $−53^\circ$, a total of 3.6$\pi$ sr, amounting to 90% of the celestial sphere, with an rms noise below 5 mJy/beam and an approximate resolution of 25$''$ × 25$''$. Using a detection limit of 7-sigma, the TGSS-ADR1 catalogue comprises 0.62 Million radio sources with an accuracy of about 2$''$ or better in RA and Dec. The survey is essentially complete above 100 mJy at 150 MHz [16, 17].

As the TGSS-ADR1 catalogue [10] has a gap of sources for Dec $< −53^\circ$, in that case our assumption of $\Sigma S_i \hat{f}_i = 0$ for a stationary observer does not hold good. However if we drop all sources with Dec $> 53^\circ$ as well, then with equal and opposite gaps on two opposite sides, $\Sigma S_i \hat{f}_i = 0$ is valid for a stationary observer [8]. Exclusion of such sky-strips, which affect the forward and backward measurements identically, to a first order do not have systematic effects on the results [1]. We also exclude all sources from our sample which lie in the galactic plane (|$b|$ < $10^\circ$); the excess of galactic sources towards the galactic center is likely to contaminate the determination of the radio source dipole. To ascertain effects of some systematics like local clustering (mainly the Virgo super-cluster), we also examined any alterations in our results by restricting our dataset to regions outside the super-galactic plane by rejecting sources with low super-galactic latitude (|$B|$ < $10^\circ$).

III. RESULTS AND DISCUSSION

A. Sky brightness

Results for the dipole, determined from the anisotropy in sky brightness for the TGSS-ADR1 dataset, for sources in various flux-density ranges, are presented in Table I. Here $N$ is the total number of sources in the corresponding flux-density range, $\mathcal{D}$ is the strength of the estimated dipole whose computed direction in sky is given by RA and Dec, and $v$ is the magnitude of the inferred velocity of the observer (solar system!) with respect to the reference frame of radio sources in that flux-density range. The direction of motion, of course, is given by RA and Dec of the dipole. 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 here to below 5,000 mJy level. At the other end we chose 100 mJy as the lowest limit since
the TGSS-ADR1 catalogue is essentially complete only above that flux-density level $10^2$. The errors in the dipole direction and magnitude are computed following the procedure in ref. [3].

From Table I, our estimate of the direction of the velocity vector (RA $= 173^{\circ} \pm 10^{\circ}$, Dec $= -96^{\circ} \pm 09^{\circ}$), is quite in agreement with those determined from the CMBR (RA $= 168^{\circ}$, Dec $= -7^{\circ}$, with errors less than a degree) [7]. However the strength of the dipole ($D \simeq 5.4 \times 10^{-2}$) appears a factor of $\sim 1.4$ smaller than an earlier estimate ($7 \times 10^{-2}$) [13], though our inferred velocity ($v \simeq 4.3 \pm 0.5 \times 10^5$ km s$^{-1}$), is still an order of magnitude (a factor of $\sim 10$) higher than the CMBR value ($v = 370$ km s$^{-1}$), at a statistically significant ($\sim 8\sigma$) level. Also when compared with the dipole determined from the sky brightness in the NVSS dataset [3], the TGSS-ADR1 dipole ($\simeq 5.4 \times 10^{-2}$) is a factor of $\sim 2.5$ stronger than the NVSS dipole ($\simeq 2.2 \times 10^{-2}$).

To rule out the possibility that the excessive dipole strength in Table I might be the result of some local clustering (e.g., the Virgo super-cluster), we determined the dipole from the sky brightness from radio sources outside the super-galactic plane by dropping sources with low super-galactic latitude, $|sgb| < 10^{\circ}$. We see that the computed dipole (Table II) is still an order of magnitude larger than the CMBR dipole, but lies in the same direction, and that this anomalous result is not due to a local clustering.

### B. Number counts

We have determined the dipole and the solar peculiar velocity from the number counts as well. First the direction of the dipole was determined from $\Sigma r_1$. With $\theta_i$ as the polar angle of the $i^{th}$ source with respect to the dipole direction, the dipole magnitude was then calculated from the fractional difference

$$\Delta \mathcal{N} / \mathcal{N} = \frac{\Sigma \cos \theta_i}{\Sigma |\cos \theta_i|} = \frac{2k_1}{3} \left[ 2 + x(1 + \alpha) \right] \frac{v}{c} = \frac{2k_1 D}{3},$$

similar to that for $\Delta \mathcal{F} / \mathcal{F}$ (Eq. (11)) in the case of sky brightness. Since, unlike in the case of sky brightness, a small number of bright sources do not adversely affect the number counts, in the latter case we have relaxed the upper limit of 5000 mJy on the flux density. The number count results are summarized in Table III. Comparing with Table I we notice that the directions of the observed dipoles determined both from the sky brightness as well as from the number counts, are consistent with that of the CMBR, though the number counts yield a magnitude of the dipole (and the thereby inferred Solar peculiar velocity) to be somewhat smaller than that from the radio source sky brightness, but still an order of magnitude larger than the CMBR value. It should be noted that while in number counts, the weaker sources, because of their much larger numbers ($x S^{-x}$), dominate the dipole determination, in the case of sky brightness, the contribution of each source being proportional to its flux density, the dipole determination depends equally on the stronger sources, $S^{-x} \times S \sim 1$ (for $x \sim 1$).

If we now compare the dipole determined from number counts for the TGSS-ADR1 dataset with that determined from the NVSS dataset [3, 11–12], we find that the directions of the dipole from both these datasets match well with the CMBR measurements, implying that the cause of the dipoles is common and a peculiar motion of the solar system seems to be the only reasonable interpretation for that. However, such a statistically significant disparity in their magnitudes, with the TGSS-ADR1 dipole being an order of magnitude (a factor of $\sim 10$) larger than the CMBR dipole, while the NVSS dipole being $\sim 4$ times larger than the CMBR dipole, is rather disconcerting.

### C. Radio survey dipoles with respect to the CMBR dipole direction

The fact that the directions of the dipole from the radio source data and the CMBR measurements are matching well, suggests that the direction of the CMBR dipole, known with high accuracy, could be taken to be the direction for the radio source dipoles too. However, we need to first explicitly examine for both TGSS-ADR1 and NVSS datasets if there exist indeed dipoles in the radio source sky distribution with respect to the CMBR dipole direction. For this we compute the dipole strength and the inferred velocity for both radio source datasets, but now with respect to the CMBR dipole direction, viz. RA $= 168^{\circ}$, Dec $= -7^{\circ}$. For this we employ an alternate procedure which is more transparent, simpler in nature and more easily visualized.

Using the great circle at $90^{\circ}$ from the CMBR dipole direction, we divide the sky into two equal hemispheres, $\Sigma_1$ and $\Sigma_2$, with $\Sigma_1$ containing the CMBR dipole, and $\Sigma_2$ containing the direction opposite to the CMBR dipole. Then if there is indeed a motion of the observer along the CMBR dipole direction, due to a combined effect of the aberration and Doppler boosting, the number counts will have a dipole anisotropy, $1 + D \cos \theta$, over the sky with amplitude $D = |2 + x(1 + \alpha)(v/c)|$, $\theta$ being the angle measured from the CMBR dipole direction. Then $N_1$, the number of sources in the hemisphere $\Sigma_1$, should be larger than $N_2$, the number of

| $S$ (mJy) | $N$ | $\mathcal{D}$ (10$^{-2}$) | RA ($^\circ$) | Dec ($^\circ$) | $v$ ($10^3$ km s$^{-1}$) |
|---------|-----|-----------------|----------|----------|-----------------|
| $\geq 250$ | 099736 | 4.8 $\pm$ 0.5 | 168 $\pm$ 10 | $-08 \pm 09$ | 3.8 $\pm$ 0.4 |
| $\geq 200$ | 124080 | 4.4 $\pm$ 0.4 | 166 $\pm$ 10 | $-03 \pm 09$ | 3.5 $\pm$ 0.3 |
| $\geq 150$ | 161664 | 4.2 $\pm$ 0.4 | 164 $\pm$ 09 | $-01 \pm 08$ | 3.3 $\pm$ 0.3 |
| $\geq 100$ | 227773 | 3.9 $\pm$ 0.3 | 162 $\pm$ 09 | $+03 \pm 08$ | 3.0 $\pm$ 0.3 |
TABLE IV. The dipole magnitude and speed estimates for the TGSS-ADR1 and NVSS samples with respect to the CMBR dipole direction

| Sample   | $\nu$ (MHz) | $S$ (mJy) | $N$ | $\sigma_N$ | $N_1$ | $N_2$ | $\delta N$ | $D$ | $v$ (10^5 km s^{-1}) |
|----------|-------------|-----------|-----|------------|-------|-------|-------------|-----|---------------------|
| TGSS     | 150 > 250   | 99736     | 316 | 51254      | 48482 | 2772 | 4.8 ± 0.6    | 3.8 ± 0.4 |
| TGSS     | 150 > 200   | 124080    | 352 | 63648      | 60432 | 3216 | 4.5 ± 0.5    | 3.6 ± 0.4 |
| TGSS     | 150 > 150   | 161664    | 402 | 82852      | 78812 | 4040 | 4.3 ± 0.4    | 3.4 ± 0.3 |
| TGSS     | 150 > 100   | 227773    | 477 | 116532     | 111241| 5291 | 4.0 ± 0.4    | 3.2 ± 0.3 |
| NVSS     | 1400 > 50   | 91652     | 303 | 46372      | 45280 | 1092 | 2.1 ± 0.6    | 1.6 ± 0.5 |
| NVSS     | 1400 > 40   | 115905    | 340 | 58547      | 57358 | 1189 | 1.8 ± 0.5    | 1.4 ± 0.4 |
| NVSS     | 1400 > 30   | 155110    | 394 | 78434      | 76676 | 1758 | 2.0 ± 0.4    | 1.6 ± 0.3 |
| NVSS     | 1400 > 20   | 229551    | 479 | 115932     | 113619| 2313 | 1.8 ± 0.4    | 1.4 ± 0.3 |

sources in the hemisphere $\Sigma_2$. If $N_0$ were the number density per unit solid angle for the isotropic distribution, then $N_1 = 2\pi N_0 [1 + D_\Sigma \int_0^{\pi/2} \cos \theta \sin \theta \, d\theta]$ and $N_2 = 2\pi N_0 [1 + D_\Sigma \int_0^{\pi/2} \cos \theta \sin \theta \, d\theta]$, and the fractional excess in number of sources in $\Sigma_1$ as compared to that in $\Sigma_2$, will be:

$$\frac{\delta N}{N} = \frac{N_1 - N_2}{N_1 + N_2} = \frac{k_2 D}{2} = k \left[ 1 + \frac{x(1 + \alpha)}{2} \right] \frac{v}{c},$$

Here $k_2$ is a constant, of the order of unity ($k_2 = 1$ for a sky uniformly covered by the sample), and as such would need to be determined numerically for individual samples where there might be finite gaps in the sky coverage. From a large number ($\sim 100$) computer simulations we find that due to the gaps in the sky coverage for our both dataset, $k_2 \sim 1.15$. Our results are presented in Table IV, which is almost self-explanatory. The velocity vector was estimated for samples containing all sources with flux-density levels $> S$, starting from $S = 250$ mJy and going down to $S = 100$ mJy levels. Of course the accuracy in our estimate improves as we go to lower flux-density limits since the number of sources increases as $N(> S) \propto S^{-x}$ (for $x \sim 1$).

This method is less prone to statistical errors in the radio source data. For one thing, the errors in the CMBR dipole direction themselves are negligible, secondly errors in the sky positions of individual sources do not affect the count of total numbers in each hemisphere. Only a very small number of sources in the two small strips of widths $\sim 2$ arcsec (which is the typical error in source positions in the TGSS-ADR1 catalogue) on either side of the great circle at the boundary between the two hemispheres could add to the error in dipole magnitude. However the solid angle covered by this strip of width $\sim 2 \times 2/2 \times 10^5 = 2 \times 10^{-5}$ radian is $\sim 2\pi \times 2 \times 10^{-5}$ sr or $10^{-5}$ fraction of the sky, which for the $N$ values in Table IV contains only one or two sources, with negligible contribution to $\delta N$ (or even to $\sigma_N$) at any flux-density level.

Our estimate of the magnitude of the velocity vector ($v \sim 3500 \pm 300$ km s$^{-1}$) from Table IV appear order of magnitude higher than the CMBR value $(370 \text{ km s}^{-1})$. The quoted errors for $v$ in Table IV are from the expected uncertainty $\sigma_N(= \sqrt{N})$ in $\delta N(= N_1 - N_2)$, the uncertainty here being that of a binomial distribution, similar to that of the random-walk problem (see, e.g. [21]).

For a comparison, we also employed the same technique to estimate the magnitude of the velocity vector from the NVSS data, with respect to the CMBR dipole direction. From the spectral index data of common sources in the TGSS-ADR1 and NVSS catalogues [12, 17, 18], it has been pointed out that the number counts in the two datasets could be compared above the flux-density limits of 100 mJy and 20 mJy respectively, using a relation $S_{\text{NVSS}} = 0.2 S_{\text{TGSS}}$, and that the two catalogues are essentially complete above these respective flux-density limits. The results for NVSS dataset are also summarized in Table IV, where $v$ turns out to be $\sim 1500 \pm 300$ km s$^{-1}$. In Table IV, the four rows of TGSS-ADR1 dataset at various flux-density levels could be compared to the corresponding four rows of the NVSS dataset. We notice that while the total number $N$ of sources at each flux-density level do match reasonably well, the difference $\delta N$ between two hemispheres in respective flux-density bins, and the thereby derived magnitudes of dipole $D$ and velocity $v$, differ as much as by a factor of $\sim 2.5$. Of course all estimates of dipole $D$ and velocity $v$ in either dataset are way above the values expected from the CMBR.

Here we have explored the radio source dipole by studying any excess of radio source density with respect to the CMBR direction, the latter itself incidentally did not use any information from the radio survey datasets. Moreover, as we move to lower flux-density levels, $\delta N$ seems to steadily increase, specifically, in none of the flux-density bin, for either dataset, we find $N_2$ to be larger than $N_1$. Now if an excess in the sources due to some local clustering in certain regions of the sky were indeed instrumental for the radio source dipole, only in a very
contrived situation would one expect to get $N_1 > N_2$ at all flux-density levels and that too for both radio catalogues. The evidence seems irrefutable that the velocity estimated from the distant radio source distribution in sky is indeed much larger than that inferred from the CMBR sky distribution. Such a statistically significant difference in the estimates of the magnitude of the velocity vector is puzzling and one cannot escape the conclusion that there is a genuine disparity in the three reference frames defined by the radio source populations selected at different frequencies and the CMBR.

From the clustering properties of radio sources in the TGSS-ADR1 angular spectrum on large angular scales, corresponding to multipoles $2 \leq l \leq 30$, the amplitude of the TGSS-ADR1 angular power spectrum is found to be significantly larger than that of the NVSS, and from that questions have been raised [21] that some unknown systematic errors may be present in the TGSS dataset. At the same time, while the amplitude of the dipole ($l = 1$) too is significantly larger than that of the NVSS, the self-consistency of the TGSS-ADR1 dipole in different flux-density bins and the fact that the direction of the dipole coincides with that of the CMBR dipole, indicates that the TGSS dataset may not be affected to such a great extent by systematics.

Now, unless one wants to disregard dipoles, derived for both radio source datasets (NVSS and TGSS-ADR1), altogether, it may not be premature to say that at this stage one is left with only two main alternatives. One of them is to say that there may be something amiss in the interpretation of an observed dipole as reflecting observer’s motion (peculiar velocity of the Solar system!) and that the strength of the dipole may not be representing an observer’s relative speed. In this line of thinking, one will then have to explain the existence of a common direction of all three dipoles and that what is so peculiar about this direction and whether it represents some sort of an “axis” of the universe. The other alternative would be to still follow the conventional wisdom that these dipoles are arising as a result of observer’s motion and that the three dipole magnitudes differing by as much as an order of magnitude, indicates that there may be a large relative motion of the three cosmic reference frames. Either alternative does not fit with the Cosmological Principle, which is the starting point for the standard modern cosmology. Perhaps it points out the need for a fresh look at the role of the Cosmological Principle in the cosmological models.

IV. CONCLUSIONS

From the dipole anisotropy computed for the TGSS-ADR1 dataset, it was found that the dipole strength and the inferred peculiar motion of the Solar system is an order of magnitude larger than that observed for the CMBR dipole. The TGSS-ADR1 dipole is also larger than the NVSS dipole by a factor of $\sim 2.5$. But the direction of the dipole in all three cases turns out to be the same within errors. An obvious inference is that the reference frames determined from the CMBR, NVSS 1400 MHz dataset of radio sources and the TGSS-ADR1 150 MHz dataset of radio sources, somehow do not coincide with each other, which raises uncomfortable questions about the Cosmological Principle, the basis of the modern cosmology.

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