Searching for a Cosmological Preferred Direction with 147 Rotationally Supported Galaxies

Yong Zhou1,2, Zhi-Chao Zhao1,2, and Zhe Chang1,2
1 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
2 School of Physics Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Received 2017 July 1; revised 2017 August 20; accepted 2017 August 28; published 2017 September 25

Abstract

It is well known that the Milgrom’s modified Newtonian dynamics (MOND) explains well the mass discrepancy problem in galaxy rotation curves. The MOND predicts a universal acceleration scale below which the Newtonian dynamics is still invalid. We get the universal acceleration scale of 1.02 × 10^{−10} ms^{−2} by using the Spitzer Photometry and Accurate Rotation Curves (SPARC) data set. Milgrom suggested that the acceleration scale may be a fingerprint of cosmology on local dynamics and related to the Hubble constant g_{1} \sim cH_{0}. In this paper, we use the hemisphere comparison method with the SPARC data set to investigate possible spatial anisotropy on the acceleration scale. It is found that the hemisphere of the maximum acceleration scale is in the direction (l, b) = (175.5^{±6.5}, −6.5^{±6.5}) with g_{1,max} = 1.10 \times 10^{−10} m s^{−2}, while the hemisphere of the minimum acceleration scale is in the opposite direction (l, b) = (355.5^{±6.5}, 6.5^{±6.5}) with g_{1,min} = 0.76 \times 10^{−10} m s^{−2}. The level of anisotropy reaches up to 0.37 ± 0.04. Robust tests show that such an anisotropy cannot be reproduced by a statistically isotropic data set. We also show that the spatial anisotropy on the acceleration scale is less correlated with the non-uniform distribution of the SPARC data points in the sky. In addition, we confirm that the anisotropy of the acceleration scale does not depend significantly on other physical parameters of the SPARC galaxies. It is interesting to note that the maximum anisotropy direction found in this paper is close with other cosmological preferred directions, particularly the direction of the “Australia dipole” for the fine structure constant.

key words: galaxies: fundamental parameters – galaxies: kinematics and dynamics – large-scale structure of universe

1. Introduction

The cosmological principle states that the universe is homogeneous and isotropic on large scales (Weinberg 2008). However, this principle seems to be faced with great challenges (Perivolaropoulos 2008, 2011). On large scales, the cosmological anisotropy has been tested by astronomical observations many times. For example, by investigating the peculiar velocities of the clusters of galaxies, physicists found that there exists a large-scale bulk flow (Kashlinskty et al. 2009, 2010; Watkins et al. 2009; Feldman et al. 2010). This bulk flow points toward the direction (l, b) = (282° ± 11°, 6° ± 6°). In this direction, the peculiar velocity reaches up to 400 km s^{−1} on scales of 100 h^{−1} Mpc, which is much larger than the value 110 km s^{−1} constrained by WMAP5 (Dunkley et al. 2009).

By analyzing the quasar absorption spectra, physicists found the variation of the fine structure constant \alpha = e^{2}/c\hbar could be well represented by an angular dipole that points to the direction (l, b) = (330° ± 15°, −13° ± 10°) with significance at the 4.2\sigma confidence level (Webb et al. 2011; King et al. 2012). In addition, the analysis of Union2 SN Ia data hints that the universe also has a privileged direction pointing to (l, b) = (309°^{+29°}_{−30°}, 18°^{+18°}_{−19°}). In this direction, the universe expansion has a maximum acceleration (Antoniou & Perivolaropoulos 2010; Cai & Tuo 2012). Furthermore, the anisotropy of cosmic microwave background (CMB) from the Planck satellite has been confirmed with significance at the 3\sigma confidence level (Ade et al. 2014). And the low multipoles in the CMB angular power spectrum approximately point to a common direction (Tegmark et al. 2003; Bielewicz et al. 2004; Land & Magueijo 2005; Mariano & Perivolaropoulos 2013; Chang et al. 2015). All of these facts indicate that there may exist a privileged direction in our universe.

Recently, McGaugh et al. (2016) employed the new extended Spitzer Photometry and Accurate Rotation Curves (SPARC) data set to investigate the radial acceleration relation in rotationally supported galaxies. They analyzed 2693 points in 147 galaxies and found a fitting function with a unique parameter. This function shows a tight correlation between the centripetal acceleration traced by rotation curves and the baryonic (gravitational) acceleration predicted by the observed distribution of baryons. The correlation can hardly be explained by the dark matter hypothesis, but it can be predicted by the MOND theory (McGaugh 2008; Milgrom & Sanders 2008; Milgrom 2016), and the unique parameter corresponds to the universal acceleration scale in the MOND.

The acceleration scale is a vitally important quantity in the MOND, below which the Newtonian dynamics is still invalid. Usually, the MOND predicts a universal acceleration scale for all galaxies (Milgrom 1983a, 1983b, 2002, 2008, 2014). However, in practice, physicists take the acceleration scale as a free parameter to fit the galaxy rotation curve, and they found that different galaxies may somehow deduce a different acceleration scale (Begeman et al. 1991; Bottema et al. 2002; Swaters et al. 2010; Gentile et al. 2011; Chang et al. 2013a). It is this fact that inspires us to investigate the possibility of spatial anisotropy on the acceleration scale. In addition, the acceleration scale is independent from other physical parameters, so that the spatial anisotropy on the acceleration scale is probably related to the cosmological preferred direction. In fact, Milgrom (1998) has suggested that cosmology is not simply an
application of a relativistic version of MOND but a unit within it. The acceleration scale may be a fingerprint of cosmology on local dynamics and related to the Hubble constant as \( g_\ast \sim cH_0 \).

In this paper, we make use of the hemisphere comparison method (Schwarz & Weinhorst 2007) with the SPARC data set to investigate the spatial anisotropy on the acceleration scale. The anisotropy level is described by the normalized difference of the acceleration scale on two opposite hemispheres. The best-fitting value of the acceleration scale on each hemisphere is obtained by using the orthogonal-distance-regression algorithm (Boggs et al. 1987; Boggs & Rogers 1990) of McGaugh’s function (McGaugh et al. 2016). Then, we would find the maximum anisotropy level and the corresponding direction from all selected directions. In order to check the validity of the maximum anisotropy level, we rebuild the SPARC data set by a statistically isotropic data set, and we examine whether the maximum anisotropy level from the SPARC data set could be reproduced by this isotropic data set. We also check the correlation between the spatial anisotropy on the acceleration scale and the non-uniform distribution of the SPARC data points in the sky. In addition, we confirm that the anisotropy of the acceleration scale does not depend significantly on other physical parameters of the SPARC galaxies.

The rest of this paper is organized as follows. In Section 2, we present a brief introduction to the SPARC data set and the radial acceleration relation. In Section 3, we use the hemisphere comparison method to search for the maximum anisotropy level and corresponding direction from the SPARC data set. Then, we compare such an anisotropy level with that from the statistically isotropic data set, the non-uniform distribution of the SPARC data points in the sky, and other physical parameters. Finally, conclusions and discussions are given in Section 4.

2. The SPARC Data Set and the Radial Acceleration Relation

The SPARC data set is a sample of 175 disk galaxies with new surface photometry at 3.6 \( \mu \)m and high-quality rotation curves from previous HI/H\( \alpha \) studies (Lelli et al. 2016). All of these galaxies are rotationally supported galaxies. The SPARC spans a broad range of morphologies, luminosities, sizes, and surface brightnesses. This is a good platform for investigating the radial acceleration relation. The SPARC data set could be available on this website.\(^3\)

For seeking the radial acceleration relation, a few modest quality criteria have been implemented to exclude some unreliable data. This operation finally leaves a sample of 2693 data points in 147 galaxies. More details could be found in McGaugh et al. (2016). Using these data, McGaugh et al. obtain a fitting function that describes well the observations. The fitting process employs an orthogonal-distance-regression algorithm that considers errors on both variables. The fitting function is of the form

\[ g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-f g_{\text{bar}}/g_{\ast}}}, \]

where \( g_{\text{obs}} \) is the observed centripetal acceleration traced by rotation curves and \( g_{\text{bar}} \) is the baryonic (gravitational) acceleration predicted by the distribution of baryonic mass. There is a unique fitting parameter, which corresponds to the acceleration scale \( g_\ast \). They found \( g_\ast = [1.20 \pm 0.02 \text{ (random)}] \pm 0.24 \text{ (systematic)} \times 10^{-10} \text{ m s}^{-2} \). The original 2693 data points and the fitting curve are plotted in Figure 1.

The fitting function (1) has two limiting cases. In the Newton limit \( g_{\text{bar}} \gg g_\ast \), the function (1) becomes \( g_{\text{obs}} \approx g_{\text{bar}} \) and the Newtonian dynamics is restored. In the deep-MOND limit \( g_{\text{bar}} \ll g_\ast \), the function (1) becomes \( g_{\text{obs}} \approx \sqrt{g_{\text{bar}} g_\ast} \), where the mass discrepancy appears. This is consistent with the MOND theory (Milgrom 1983a, 2016).

The radial acceleration relation between the centripetal acceleration and the baryonic acceleration is tight for all 2693 data points in 147 galaxies. From Figure 1, one can see clearly that a large majority of the data points are close to the fitting curve. However, for individual galaxies, the data points could have some deviation from the fitting curve. It implies that there may be other acceleration scales corresponding to these galaxies. Furthermore, the spatial distribution of the acceleration scale may reflect the cosmological anisotropy.

We use the same orthogonal-distance-regression algorithm (Boggs et al. 1987; Boggs & Rogers 1990) in the fitting process and define the chi-square as

\[ \chi^2 = \sum_{i=1}^{n} \left[ \frac{g_{\text{obs}}(g_{\text{bar},i} + \delta_i, g_\ast) - g_{\text{obs},i}}{\sigma_{\text{obs},i}} \right]^2 + \frac{\delta_i^2}{\sigma_{\text{bar},i}^2}, \]

where the subscript \( i \) represents the \( i \)th data, and \( n = 2693 \) is the total number of data points. \( \sigma_{\text{bar}} \) and \( \sigma_{\text{obs}} \) are the uncertainty of \( g_{\text{bar}} \) and \( g_{\text{obs}} \), respectively. \( \delta_i \) is an auxiliary parameter for determining the weighted orthogonal (shortest) distance for the \( i \)th data point from the curve \( g_{\text{obs}}(g_{\text{bar}, g_\ast}) \). The expression for the curve is the same as the right-hand side of the function (1), i.e.,

\[ g_{\text{obs}}(g_{\text{bar}}, g_\ast) = \frac{g_{\text{bar}}}{1 - e^{-f g_{\text{bar}}/g_\ast}}, \]

where \( g_{\text{th}} \) represents the theoretical centripetal acceleration. Then, the chi-square is the sum of the squares of the weighted orthogonal distances from the curve \( g_{\text{obs}}(g_{\text{bar}, g_\ast}) \) to the \( n \) data points. Finally, we minimize the chi-square to find the best-fitting value of \( g_\ast \).

Before searching for the maximum anisotropy direction from the SPARC data set, we repeat the fitting process with the chi-square (2) for all 2693 data points in 147 galaxies. The best-fitting value of the acceleration scale is \( g_\ast = (1.02 \pm 0.02) \times 10^{-10} \text{ m s}^{-2} \). Here, we have not accounted for the systematic uncertainty. This fitting curve is also plotted as the red dotted line in Figure 1. It is worth noting that McGaugh et al. (2016) use the same orthogonal-distance-regression algorithm but take the logarithmic distance of the first term in the chi-square (2); thus, they got a value of small difference for the best-fitting parameter. Although there is a small difference in the chi-square, it did not greatly impact the hemisphere comparison result. What we are concerned with here is the normalized difference of the acceleration scale between two opposite hemispheres. Further study shows that both chi-squares could deduce the same maximum anisotropy direction. Therefore, we always use the chi-square (2) to fit McGaugh’s function (1).

\(^3\) http://astroweb.cwru.edu/SPARC/
3. Maximum Anisotropy Direction of the SPARC Data Set

The hemisphere comparison method has been widely adopted in searching for the cosmological anisotropy (Antoniou & Perivolaropoulos 2010; Cai & Tuo 2012). We also employ this method in the present study. One reason we chose this method is that it optimizes the statistics because there is a large number of data points in each hemisphere. The SPARC data set does not include the galactic coordinate for each galaxy. We complement the galactic coordinate for each galaxy from previous work (de Blok et al. 1996; Begum & Chengalur 2005) and by using the NED database. Together with the radial accelerations and its uncertainties from the SPARC data set, the data are completed now for our study.

The hemisphere comparison method mainly consists of the following steps.

1. Generate an arbitrary direction with a unit vector \( \hat{n} = (b) \cos(l) \hat{i} + \cos(b) \sin(l) \hat{j} + \sin(b) \hat{k} \) in the sky, where \( l \) and \( b \) are longitude and latitude, respectively, in the galactic coordinate system.

2. According to the sign of the inner product \( \cos \theta_i = \hat{n} \cdot \hat{p}_i \), where \( \hat{p}_i = \cos(b_i) \cos(l_i) \hat{i} + \cos(b_i) \sin(l_i) \hat{j} + \sin(b_i) \hat{k} \) is the unit vector pointing to the \( i \)th galaxy, split the data set into two subsets. Thus, the hemisphere aligned with the direction of the unit vector \( \hat{n} \) (defined as “up”) corresponds to one subset, while the opposite hemisphere (defined as “down”) corresponds to another subset.

3. Find the best-fitting value of the acceleration scale \( g_t \) on each hemisphere. Define the anisotropy level by the normalized difference

\[
D_{g_t}(l, b) = \frac{\Delta g_t}{g_t} = 2 \frac{g_{t,u} - g_{t,d}}{g_{t,u} + g_{t,d}},
\]

where \( g_{t,u} \) and \( g_{t,d} \) are the best-fitting values of the acceleration scale \( g_t \) in the “up” and “down” hemispheres, respectively.

4. Repeat steps 1–3 for a sufficient quantity of directions, and select the maximum value of \( |D_{g_t}| \), as well as its corresponding direction \((l, b)\).

In the step 3, the best-fitting value of the acceleration scale on each hemisphere is also obtained by the orthogonal-distance-regression algorithm. In order to find the reliable maximum anisotropy level, the number of directions in our setting must be large enough. Here, we divide the whole sky into \( 1^\circ \times 1^\circ \) grids, and we choose the center of each grid as the direction of hemisphere. The total number of directions is 64,800. Searching for all of these directions, we find that the hemisphere of the maximum acceleration scale is toward the direction \((l, b) = (175^\circ.5, -6^\circ.5)\) with \( g_t,_{\text{max}} = (1.10 \pm 0.02) \times 10^{-10} \text{ m s}^{-2} \). While the hemisphere of the minimum acceleration scale is in the opposite direction \((l, b) = (355^\circ.5, 6^\circ.5)\) with \( g_t,_{\text{min}} = (0.76 \pm 0.02) \times 10^{-10} \text{ m s}^{-2} \). The error in the acceleration scale is a 1\( \sigma \) value derived from the fitting process. The result is plotted in Figure 2. Based on the definition of anisotropy level in Equation (4), we get the maximum anisotropy level, \( D_{g_t,_{\text{max}}} = 0.37 \). And the 1\( \sigma \) error for the maximum anisotropy level is propagated from the uncertainties of acceleration scale,

\[
\sigma_{D_{g_t}} = 4 \sqrt{\frac{g_{t,u,}^2 + \sigma_{g_{t,u}}^2 + g_{t,d,}^2 + \sigma_{g_{t,d}}^2}{(g_{t,u} + g_{t,d})^2}}, \quad (5)
\]

where the \( \sigma_{g_t} \) is the 1\( \sigma \) value for the hemisphere acceleration scale. Thus, the maximum anisotropy level is \( D_{g_t,_{\text{max}}} = 0.37 \pm 0.04 \).

To find the confidence angular region of the maximum anisotropy direction, we pick the direction that corresponds to an anisotropy level within 2\( \sigma \) from the maximum anisotropy one. Here, we assume that the distribution of anisotropy level is Gaussian, and we choose 2\( \sigma \) instead of 1\( \sigma \) (there is only two directions located in the 1\( \sigma \) region). The final maximum anisotropy direction (with a 2\( \sigma \) random error) is

\[
(l, b) = (175^\circ.5^+6^\circ.5^-10^\circ.0, -6^\circ.5^+9^\circ.0^-3^\circ.3), \quad (6)
\]

or equivalently, the minimum anisotropy direction is its opposite direction

\[
(l, b) = (355^\circ.5^-6^\circ.5^+6^\circ.5^+3^\circ.3^-10^\circ.0). \quad (7)
\]

These results are plotted in Figure 3. Except for the maximum anisotropy direction, we find that there is another direction \((l, b) = (114^\circ.5^-3^\circ.3^+6^\circ.0^-10^\circ.0, 2^\circ.5^-3^\circ.3^+1^\circ.3)\) (1\( \sigma \)); in this direction, the
anisotropy level is up to \( D_{\text{g}, \text{sub}} = 0.34 \pm 0.05 \). At all of the other directions, the anisotropy level is less than 0.3.

As a robust check, we examine whether the maximum anisotropy level is consistent with the statistical isotropy. We rebuild the SPARC data set with a statistically isotropic data set. The baryonic acceleration \( g_{\text{bar}} \) and its uncertainty \( \sigma_{\text{bar}} \) remain unchanged. The centripetal acceleration \( g_{\text{obs}} \) has been replaced by a random number that has a Gaussian distribution with a central value determined by the theoretical centripetal acceleration \( g_{\text{th}} \) in Equation (3); here, \( g_{\text{th}} = 1.02 \times 10^{-10} \text{ m s}^{-2} \) is the universal acceleration scale, and the standard deviation is the same as the uncertainty \( \sigma_{\text{obs}} \) of the centripetal acceleration \( g_{\text{obs}} \). For generality, we repeat the hemisphere comparison method for this statistical isotropic data set 100 times. Because the centripetal acceleration is made up of random values, the result of hemisphere comparison is different each time. The result is plotted in Figure 4. Even though the distribution of the anisotropy level seems to have some structures, the maximum anisotropy level for each time is around \( D_{\text{g}, \text{max}} = 0.05 \pm 0.02 \). The upper limit of the maximum anisotropy level is \( D_{\text{g}, \text{max}} = 0.10 \pm 0.03 \), which is fainter than that from the SPARC data set. This means that the maximum anisotropy level from the original SPARC data set could not be reproduced by such a statistically isotropic data set.

Another issue worth discussing is whether the maximum anisotropy level from the SPARC data set comes from the non-uniform distribution of the data points in the sky. In the study of the anisotropy on supernova, it was pointed out that the anisotropy could be originated from the non-uniform distribution of the data points (Beltran Jimenez et al. 2015; Chang & Lin 2015; Lin et al. 2016). Here, we perform a similar investigation for the SPARC data set. In order to trace the correlation between the anisotropy level on the acceleration scale and the distribution of the data points, we repeat the hemisphere comparison method again, but here we calculate the number difference of the SPARC data points in two opposite hemispheres. The direction we choose here is same as that in Figure 3. For a given direction \((l, b)\), we define the number difference as

\[
D_N(l, b) = \frac{\Delta N}{N} = \frac{N_u - N_d}{N_u + N_d},
\]

where \( N_u \) and \( N_d \) are the numbers of the SPARC data points in the “up” and “down” hemispheres, respectively. The distribution of \( D_N(l, b) \) is shown in Figure 5. As can be seen clearly, the most clustered direction is toward \((l, b) = (149^\circ.1, 29^\circ.4)\), while the most sparse direction is its opposite direction \((l, b) = (329^\circ.1, -29^\circ.4)\). In the most clustered direction, the “up” hemisphere has 2452 data points, while the “down” hemisphere has only 241 data points. The corresponding maximum number difference is \( D_N, \text{max} = 1.64 \). In the direction of the maximum anisotropy level on the acceleration scale, we find the number of data points in the “up” and “down” hemispheres are 2173 and 520, respectively. The corresponding number difference is \( D_N = 1.23 \). Comparing the direction of the maximum anisotropy level with that of the maximum number difference, we find a large angular separation \( \Delta \theta \approx 44^\circ \) between these two directions. In addition, the distributions of \( D_N \) in Figure 3 and \( D_N \) in Figure 5 have large differences in the overall outline. This implies that the spatial anisotropy on the acceleration scale has little correlation with the non-uniform distribution of the SPARC data points in the sky. To further confirm the independence of the anisotropic acceleration scale with other physical parameters of the SPARC galaxies, we also perform the hemisphere comparison for these parameters. These parameters include the Hubble Type (T; a large sample has been investigated by Javanmardi & Kroupa 2017), Distance (D), Inclination (Inc), Total Luminosity (\( L_{[3.6]} \)), Effective Radius (Reff), Effective Surface Brightness (SBeff), Disk Scale Length (Rdisk), Disk Central Surface Brightness (SBdisk), Total HI mass (MHI), HI radius at 1 \( M_\odot \text{ pc}^{-2} \) (RHI), and Asymptotically Flat Rotation Velocity (Vflat), which have been listed on this website. In each hemisphere, we take the average value of these parameters to calculate the anisotropy level. By comparing the distribution of the anisotropy level between these physical parameters and the acceleration scale, we find that none of these parameters has the same distribution with the acceleration scale. This implies that the anisotropy of the acceleration scale is possibly independent of other physical parameters. Instead, we suggest that the spatial anisotropy on the acceleration scale may be related with the cosmological preferred direction.

\[\text{http://astroweb.cwru.edu/SPARC/SPARC_Lelli2016c.mrt}\]
which corresponds to the direction \(\theta = \pm \theta_0\) to the direction \(\theta = \pm \theta_0\). The maximum anisotropy level is around statistically isotropic data set in 100 simulations. The maximum anisotropy level is \(D_{\theta,\text{max}} = 0.37 \pm 0.04\), which corresponds to the direction \((l, b) = (175^\circ 5^\prime 3^\prime, -6^\circ 5^\prime 3^\prime)\) \((2\sigma)\). The submaximum anisotropy level is \(D_{\theta,\text{sub}} = 0.34 \pm 0.05\), which corresponds to the direction \((l, b) = (114^\circ 2^\prime 5^\prime, 2^\circ 5^\prime 1^\prime)\) \((1\sigma)\). Except for these two directions, anisotropy level of the whole sky is less than 0.3.

\[D_{\theta,\text{max}} = 0.37 \pm 0.04, \quad D_{\theta,\text{sub}} = 0.34 \pm 0.05\]

![Figure 3](image3.png)

**Figure 3.** Pseudo-color map of the anisotropy level \(D_{\theta}\) derived from the hemisphere comparison method. The maximum anisotropy level is \(D_{\theta,\text{max}} = 0.37 \pm 0.04\), which corresponds to the direction \((l, b) = (175^\circ 5^\prime 3^\prime, -6^\circ 5^\prime 3^\prime)\) \((2\sigma)\). The submaximum anisotropy level is \(D_{\theta,\text{sub}} = 0.34 \pm 0.05\), which corresponds to the direction \((l, b) = (114^\circ 2^\prime 5^\prime, 2^\circ 5^\prime 1^\prime)\) \((1\sigma)\). Except for these two directions, anisotropy level of the whole sky is less than 0.3.

\[D_{\theta,\text{max}} = 0.37 \pm 0.04, \quad D_{\theta,\text{sub}} = 0.34 \pm 0.05\]

![Figure 4](image4.png)

**Figure 4.** Histogram of the maximum anisotropy level \(i.e., D_{\theta,\text{max}}\) from the statistically isotropic data set in 100 simulations. The maximum anisotropy level is around \(D_{\theta,\text{max}} = 0.37 \pm 0.04\), and the upper limit is \(D_{\theta,\text{max}} = 0.10 \pm 0.03\).

\[D_{\theta,\text{max}} = 0.37 \pm 0.04, \quad D_{\theta,\text{sub}} = 0.34 \pm 0.05\]

### 4. Conclusions and Discussions

In this paper, we employed the hemisphere comparison method with the SPARC data set to search for the maximum anisotropy direction of the acceleration scale in the MOND, which is probably related to the cosmological preferred direction. The anisotropy level is derived by the normalized difference of the acceleration scale on two opposite hemispheres. Repeating for 64,800 directions that are on the center of each grid, we found that the maximum anisotropy level is \(D_{\theta,\text{max}} = 0.37 \pm 0.04\), which corresponds to the direction \((l, b) = (175^\circ 5^\prime 3^\prime, -6^\circ 5^\prime 3^\prime)\) \((2\sigma)\). We also found that the submaximum anisotropy level is \(D_{\theta,\text{sub}} = 0.34 \pm 0.05\), which corresponds to the direction \((l, b) = (114^\circ 2^\prime 5^\prime, 2^\circ 5^\prime 1^\prime)\) \((1\sigma)\). At all other directions, the anisotropy level is not significant and is less than 0.3. We then rebuilt the SPARC data set with a statistically isotropic data set and found that the maximum anisotropy level from the SPARC data set could not be reproduced by such an isotropic data set. We also pointed out that there is little correlation between the spatial anisotropy on the acceleration scale and the non-uniform distribution of the SPARC data points in the sky. Finally, we further confirmed that the anisotropy of the acceleration scale is possibly independent of other physical parameters of the SPARC galaxies and may be related to the cosmological preferred direction.

As discussed in Section 1, the cosmological preferred directions have been reported by a series of independent astronomical observations. These directions are all located in an angular region less than a quarter of the North Galactic Hemisphere. In this paper, we found a possible preferred direction from the SPARC data set. This direction is close to the above angular region. In particular, we found that the preferred direction is close to the direction of the dipole model that describes the variation of the fine structure constant, and these two directions only have an angular separation of \(\Delta \theta \approx 32^\circ\). The consistency of these directions may suggest that our universe is indeed anisotropic, and it could be caused by an underlying physical effect, such as the spacetime anisotropy (Campanelli et al. 2006, 2007; Chang et al. 2012, 2013b, 2014a, 2014b; Li et al. 2015).

If the cosmological preferred direction is confirmed, the standard ΛCDM model should be modified. However, inevitably, the research on the cosmological preferred direction still has a large number of uncertainties. This research is in the same situation. The possible uncertainty partly comes from the original data. As we presented in Section 2, the baryonic acceleration is predicted by the distribution of baryonic mass, while the baryonic mass is converted by the near-infrared luminosity. For different galaxies, their mass-to-light ratio also could be different. In McGaugh et al. (2016), a uniform mass-to-light ratio was adopted for all galaxies. They emphasized that it could only have a slight impact on the fitting result for all data points, but it may impact the result of the hemisphere comparison method. The maximum anisotropy level may increase or reduce. Another possible uncertainty comes from the deficiency of the galaxy, and most data points cluster in the
same direction. For the future research on the anisotropy with the galaxy rotation curves, the data set needs to be extended and better cover the sky uniformly. By that time, the maximum anisotropy direction could be more convincing.

We are grateful to Dr. Hai-Nan Lin for useful discussions. We appreciate Dr. Federico Lelli for his help in cross checking our program. We are also thankful for the open access of the SPARC data set. This work is supported by the National Natural Science Fund of China under grant Nos. 11375203, 11675182, and 11690022.

ORCID iDs

Yong Zhou https://orcid.org/0000-0002-3901-0228

References

Ade, P. A. R., Aghanim, N., Armitage-Caplan, C., et al. 2014, A&A, 571, A23
Antoniou, I., & Perivolaropoulos, L. 2010, JCAP, 1012, 012
Begeman, K. G., Broeils, A. H., & Sanders, R. H. 1991, MNRAS, 249, 523
Begum, A., & Chengalur, J. N. 2005, A&A, 424, 509
Beltran Jimenez, J., Salzano, V., & Lazkoz, R. 2015, PhL, B741, 168
Bielewicz, P., Gorski, K. M., & Banday, A. J. 2004, MNRAS, 355, 1283
Boggs, P. T., Byrd, R. H., & Schnabel, R. B. 1987, SIAM Journal on Scientific and Statistical Computing, 8, 1052
Boggs, P. T., & Rogers, J. E. 1990, Contemporary Mathematics, 112, 183
Bottema, R., Pestana, J. L. G., Rothberg, B., & Sanders, R. H. 2002, A&A, 393, 453
Cai, R.-G., & Tu, Z.-L. 2012, JCAP, 1202, 004
Campanelli, L., Cea, P., & Tedesco, L. 2006, PhRvL, 97, 131302 [Erratum: PhRvL, 97, 209903 (2006)]
Campanelli, L., Cea, P., & Tedesco, L. 2007, PhRvD, 76, 063007
Chang, Z., Li, M.-H., Li, X., Lin, H.-N., & Wang, S. 2013a, EPJC, 73, 2447
Chang, Z., Li, M.-H., & Wang, S. 2013b, PhL, B723, 257
Chang, Z., Li, X., Lin, H.-N., & Wang, S. 2014a, EPJC, 74, 2821

Figure 5. Pseudo-color map of the number difference of the SPARC data points between two opposite hemispheres. The most clustered direction (pentagram) is toward \((l, b) = (149.1°, 29.4°)\), while the most sparse direction is in its opposite direction \((l, b) = (329.1°, -29.4°)\).

Chang, Z., Li, X., Lin, H.-N., & Wang, S. 2014b, MPLA, 29, 1450067
Chang, Z., Li, X., & Wang, S. 2015, ChPhC, C39, 055101
Chang, Z., & Lin, H.-N. 2015, MNRAS, 446, 2952
Chang, Z., Wang, S., & Li, X. 2012, EPJC, 72, 1838
de Blok, W. J. G., McGaugh, S. S., & van der Hulst, J. M. 1996, MNRAS, 283, 18
Dunkley, J., Komatsu, E., Nolta, M. R., et al. 2009, ApJS, 180, 306
Feldman, H. A., Watkins, R., & Hudson, M. J. 2010, MNRAS, 407, 2328
Gentile, G., Famaey, B., & de Blok, W. J. G. 2011, A&A, 527, A76
Javanmardi, B., & Kroupa, P. 2017, A&A, 597, A120
Kashlinsky, A., Atrio-Barandela, F., Ebeling, H., Edge, A., & Kocevski, D. 2010, ApJL, 712, L81
Kashlinsky, A., Atrio-Barandela, F., Kocevski, D., & Ebeling, H. 2009, ApJL, 686, L49
Kong, J. A., Webb, J. K., Murphy, M. T., et al. 2012, MNRAS, 422, 3370
Land, K., & Magueijo, J. 2005, PhRvL, 95, 071301
Lelli, F., McGaugh, S. S., & Schombert, J. M. 2016, AJ, 152, 157
Li, X., Lin, H.-N., Wang, S., & Chang, Z. 2015, EPJC, 75, 181
Lin, H.-N., Li, X., & Chang, Z. 2016, MNRAS, 460, 617
Mariano, A., & Perivolaropoulos, L. 2013, PhRvD, 87, 043511
McGaugh, S. 2008, ApJ, 683, 137
McGaugh, S., Lelli, F., & Schombert, J. 2016, PhRvL, 117, 201101
Milgrom, M. 1983a, ApJ, 270, 365
Milgrom, M. 1983b, ApJ, 270, 371
Milgrom, M. 1998, arXiv:astro-ph/9810302
Milgrom, M. 2002, NewAR, 46, 741
Milgrom, M. 2008, arXiv:0801.3133
Milgrom, M. 2014, MNRAS, 437, 2531
Milgrom, M. 2016, arXiv:1609.06642
Milgrom, M., & Sanders, R. H. 2008, ApJ, 678, 131
Perivolaropoulos, L. 2008, arXiv:0811.4684
Perivolaropoulos, L. 2011, JCos, 15, 6054
Schwarz, D. J., & Weinhorst, B. 2007, A&A, 474, 717
Swaters, R. A., Sanders, R. H., & McGaugh, S. S. 2010, ApJ, 718, 380
Tegmark, M., de Oliveira-Costa, A., & Hamilton, A. 2003, PhRvD, 68, 123523
Watkins, R., Feldman, H. A., & Hudson, M. J. 2009, MNRAS, 392, 743
Webb, J. K., King, J. A., Murphy, M. T., et al. 2011, PhRvL, 107, 191101
Weinberg, S. 2008, Cosmology (New York: Oxford Univ. Press)