Bulk Motions in Large-Scale Void Models

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Abstract. To explain the puzzling situation in the observed bulk flows on scales $\sim 150 h^{-1} \text{Mpc}$ ($H_0 = 100 h^{-1} \text{km sec}^{-1} \text{Mpc}^{-1}$), we consider the observational behavior of spherically symmetric inhomogeneous cosmological models, which consist of inner and outer homogeneous regions connected by a shell or an intermediate self-similar region. It is assumed that the present matter density parameter in the inner region is smaller than that in the outer region, and the present Hubble parameter in the inner region is larger than that in the outer region. Then galaxies in the inner void-like region can be seen to have a bulk motion relative to matter in the outer region, when we observe them at a point O deviated from the center C of the inner region. Their velocity $v_p$ in the CD direction is equal to the difference of two Hubble parameters multiplied by the distance between C and O. It is found also that the velocity $v_d$ corresponding to CMB dipole anisotropy observed at O is by a factor $\approx 10$ small compared with $v_p$. This behavior of $v_d$ and $v_p$ is consistent with the observed cosmic flow of cluster galaxies, when the radius of the inner region and the distance CD are about $200 h^{-1} \text{Mpc}$ and $40 h^{-1} \text{Mpc}$, respectively, and when the gaps of density and Hubble parameters are $\approx 0.5$ and $18\%$, respectively. Moreover, the $[m, z]$ relation in these models is discussed in connection with SNIa data.

1. Introduction

The dipole moment in the cosmic background radiation (CMB) is thought to come mainly from the Doppler shift due to the motion of the Local Group (LG), relative to the cosmic homogeneous expansion. As the main gravitational source which brings the velocity vector of LG, the existence of the Great Attractor (GA) was found by Lynden-Bell et al. (1988) and Dressler et al. (1987). It has the position at the redshift of $4300 \text{km sec}^{-1}$. On the other hand, the motion of LG relative to the inertial frame consisting of many clusters on larger-scales was studied observationally by several groups: A bulk flow of $\sim 700 \text{km sec}^{-1}$ was found by Lauer and Postman (1994, 1995) and Colless (1995) as the motion of the Abell cluster inertial frame relative to LG in the region with redshift $< 15000 \text{km sec}^{-1}$, but in the other approach the different result was derived by Giovannelli et al. (1998), Dale et al. (1999) and Riess et al. (1997) in the regions with similar redshifts. Lauer and Postman’s work is based on the assumption that the brightest cluster galaxies as standard candles and the Hoessel relation can
be used, but at present these assumptions have been regarded as questionable or unreliable.

Independently of these works, the motion of cluster frames relative to CMB was measured by Husdon et al. (1999) and Willick (1999) due to the global Hubble formula using the Tully-Fisher distances of clusters and their redshifts with respect to CMB, and the flow velocity vector was derived in the region with about $150h^{-1}$ Mpc ($H_0 = 100h^{-1}$ km sec$^{-1}$ Mpc$^{-1}$). The remarkable and puzzling properties of these flows are that the flow velocity reaches a large value $\sim 700$ km/sec on a large scale, while the dipole velocity (not due to GA) corresponding to the CMB dipole anisotropy seems to be much small, compared with the above flow velocity.

In the present note we first consider inhomogeneous models on sub-horizon scale, corresponding to matter flows on scales $\sim 150h^{-1}$ Mpc. They are assumed to be spherically symmetric inhomogeneous models which consist of inner and outer homogeneous regions connected by a shell being a singular layer, and the behavior of large-scale motions caused in the inner region is considered. Next we consider light rays which are emitted at the last scattering surface and reach an observer situated at a point O (in the inner region) deviated from the center C, and the CMB dipole anisotropy for the observer is shown. On the basis of these results we show the consistency with various observations of cosmic flows. Moreover the $[m, z]$ relation is discussed in connection with SNIa data, and finally concluding remarks are presented.

2. Cosmological models and the bulk motions

In previous papers (Tomita 1995, 1996) we treated spherically symmetric inhomogeneous models which consist of inner and outer homogeneous regions connected with an intermediate self-similar region and have the boundary on a super-horizon scale. Here we consider a similar spherically symmetric inhomogeneous model which consists of inner and outer homogeneous regions, but is connected by a shell being a singular layer on a sub-horizon scale $\sim 150h^{-1}$ Mpc. This shell may be associated with large-scale structures or excess powers observed by Broadhurst et al.(1990), Landy et al.(1996), and Einasto et al.(1997). The physical state in each region is specified by the Hubble constant density and the density parameter. It is assumed that the present Hubble parameter in the inner region ($H_0^{\text{in}}$) is larger than that in the outer region ($H_0^{\text{out}}$), and the present inner density parameter ($\Omega_0^{\text{in}}$) is smaller than the present outer density parameter ($\Omega_0^{\text{out}}$). The evolution of physical states in each region and the boundary has been studied in the form of void models (e.g., Sakai et al. 1993).

The average motion of CMB is comoving with matter in the outer region, while it is not comoving with matter in the inner region or matter in the inner region moves relative to CMB, because their Hubble constants are different. The bulk motion appears as the result of this relative motion to CMB. The relative velocity ($\Delta v$) is $(H_0^{\text{in}} - H_0^{\text{out}})r$ in the radial direction, where $r$ is the radial distance from the center C to an arbitrary point (a cluster’s position) in the inner region. When an observer O sees this velocity vector $\Delta v$, it can be divided into two parts: the component in the observer’s line of sight ($\Delta v_{ls}$) and the
bulk-velocity component in the direction of $C \rightarrow O$ ($v_p$). The latter component $v_p$ is constant, irrespective of the cluster’s position. In the case when the present radius of the boundary and the observers’s position are $\sim 200h^{-1}$ and $40h^{-1}$ Mpc, respectively, we have $v_p \sim 700$ km sec$^{-1}$.

3. Dipole anisotropy and the consistency with various observations of cosmic flows

If the observer were in the center C, he never sees any CMB anisotropy, as long as the two regions are homogeneous. For the non-central observer O we have nonzero dipole anisotropy $D$ which is derived by calculating curved paths from the last scattering surface to O and the directional variation of the temperature $T_r$. The velocity $v_d$ corresponding to $D$ is defined by $v_d \equiv c[(3/4\pi)^{1/2}D]$ and derived. As the result it was found that $v_d$ is small compared with $v_p$, if O is near to C. In our above example, $r(OC)/r(\text{boundary}) \sim 1/5$, we obtain $v_d \sim 0.1v_p$.

As described in §2, the bulk velocities at arbitrary two points are equal and so their difference is zero. Accordingly the relative velocity of the Local Group (LG) to the frame of clusters ($v_{LG}$) is only the peculiar velocity ($v_{GA}$) caused by the small-scale nonspherical gravitational field of the Great Attracter. The above result gives the dipole velocity of LG, $v_d(LG) = v_{GA} + v_d$, so that $v_{GA}$ and $v_d(LG)$ are comparable and the difference is $v_d (\sim 0.1v_p)$. This situation in the present models is consistent with the observations (Giovanelli et al. (1998), Dale et al. (1999) and Riess et al. (1997)) for relative velocities of LG to the cluster frame, and the observations (Husdon et al. (1999) and Willick (1999)) for the bulk flows of clusters, since the observed values of $v_{LG}$, $v_d(LG)$ and $v_p$ are 565 km sec$^{-1}$, 627 km sec$^{-1}$ and $\sim 700$ km sec$^{-1}$, respectively, in the similar directions. The observed difference of first two velocities is about $0.1 \times v_p$.

The detail derivation of the contents in §2 and §3 is shown in Tomita (1999a).

4. $[m, z]$ relation and SNIa data

Here the behavior of distances in the present models is studied. First we treat the distances from a virtual observer who is in the center C of the inner void-like region in models with a single shell, and derive the [$m$ - redshift $z$] relation. This relation is compared with the counterpart in the homogeneous models. Then the relation in the present models is found to deviate from that in the homogeneous models with $\Lambda = 0$ at the stage of $z < 1.5$. It is partially similar to that in the nonzero-$\Lambda$ homogeneous models, but the remarkable difference appears at the high-redshift stage $z > 1.0$. Moreover, we consider a realistic observer who is in the position O deviated from the center, and calculate the distances from him. The distances depend on the direction of incident light and the area angular diameter distance is different from the linear angular diameter distances. It is shown as the result that the $[m, z]$ relation is anisotropic, but the relation averaged with respect to the angle is very near to the relation by the virtual observer. When we compare these theoretical relations with SNIa data (Riess et al.(1998), Garnavich et al.(1998), and Schmidt et al.(1998)), we
can determine which of the present models and nonzero-Λ homogeneous models are better, and the fittest model parameters. At present, however, there are few data at $z \sim 1.0$, so that the model selection may not be performed. The detail description of the content in this section is given in Tomita (1999b).

5. Concluding remarks

The density perturbations in the inner region and their influence of on CMB anisotropy are another important factor to the selection of model parameters, which should be studied next.

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