Peculiar motions of galaxies as a test for cosmological models

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Abstract

During the last 15 years of cosmology considerable efforts have been made to measure and interpret the peculiar motions of galaxies, i.e. the actual deviations from the pure Hubble flow one would expect in a homogeneous and isotropic Universe. In this contribution I briefly summarize the theoretical framework of the gravitational instability picture, which links the observed peculiar motions of galaxies to the density perturbations. I discuss the distance estimators used to observe the peculiar motions of the ≈ 3000 galaxies contained in the Mark III catalogue. These data allow one to derive the density field of the universe at redshifts less than 8000 km/s by means of the POTENT algorithm. The comparison of this reconstructed field with the one derived from redshift surveys constrains the value of the density parameter of the universe Ω_0 to be $0.3 \leq \Omega_0 \leq 1$. Finally, I present the EFAR project, aiming at measuring the peculiar motions of galaxies in two distant superclusters at redshifts $8000 \leq cz \leq 15000$ km/s.

1 Introduction

Following the "Cosmological Principle" introduced by Einstein, the standard framework of modern cosmology assumes that on large enough scales the Universe is homogeneous and isotropic. Under this assumption one derives the Friedman-Robertson-Walker metric (see Weinberg 1972) for the line element:

$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right], \tag{1}$$

where k is the curvature constant. The scale factor $a(t)$ follows the dynamical equations derived from General Relativity and the ideal fluid approximation. Its temporal evolution depends on the actual density of the Universe. One defines the present day Hubble constant as $H_0 = \dot{a}(t_0)/a(t_0)$, where t_0 is the present time (or age of the universe, see below), the critical density $\rho_{crit} = \frac{3H_0^2}{8\pi G}$, and the cosmological density parameter $\Omega_0 = \frac{\rho_0}{\rho_{crit}}$. Then one finds that $\Omega_0 < 1$ produces an open universe ($k < 0$), $\Omega_0 > 1$ a closed universe ($k > 0$) and $\Omega_0 = 1$ a (spatially) flat ($k = 0$) one. If the cosmological constant Λ is introduced, then the flat case is obtained if $\Omega_0 + \Omega_\Lambda = 1$, where $\Omega_\Lambda = \frac{\Lambda}{3H_0^2}$. If $\Omega_0 = 1$ and $\Lambda = 0$ the age of the Universe is $t_0 = \frac{2}{3}H_0^{-1}$. Finally, one defines the acceleration parameter $q_0 = -\frac{\ddot{a}a}{\dot{a}^2}$. For the present state of the measurements of the cosmological parameters H_0, Ω_0, Λ and q_0 please refer to Hähnelt and Bender in the present volume. In the following, the uncertainty on the value of H_0 will be parametrized as $H_0 = 100h$ km/s/Mpc, with $0.5 < h < 1$.

Luminosity distances of galaxies are linked to their redshift z through the formula (valid for $\Lambda = 0$):

$$d_L(z) = \frac{cz}{H_0}\left[\frac{1+z+(1+2q_0z)^{1/2}}{1+q_0z+(1+2q_0z)^{1/2}}\right], \tag{2}$$

which, for small z, gives the well known Hubble law:

$$d_L \approx cz/H_0. \tag{3}$$

Therefore in a homogeneous and isotropic Universe galaxies are expected to have radial recessional velocities proportional to their distance.

The homogeneity and isotropy of the Universe at the redshift of decoupling is indeed testified by the extreme smoothness of the Cosmic Microwave Background radiation. Only recently the COBE satellite has been able to measure the temperature fluctuations of the CMB and finds them to be $\Delta T/T \approx 10^{-5}$ (Bennett et al. 1994).

At nearby distances, however, the situation is much different. Redshift surveys have nowadays mapped the three-dimensional distribution of galaxies out to $cz \approx 15000$ km/s. As the first "slice of the Universe" showed (de Lapparent et al. 1986), the galaxy distribution is far from uniform, with galaxies aligned along sheet-like structures which delimit ubiquitous giant voids like that in Boötes. One can quantify the departures of the galaxy distribution from homogeneity in terms of the two-point correlation function $\xi(r)$. If n is the mean number density of galaxies, then the mean number of galaxies in a spherical shell of thickness dr and at distance r from a given galaxy is:

$$N(r) = 4\pi r^2 n[1+\xi(r)]dr. \tag{4}$$

One finds $\xi(r) = \left(\frac{r}{5.4h^{-1}}\right)^{-1.8}$ (Davis and Peebles 1983).

If the distribution of galaxies is not homogeneous, one has to expect the galaxy velocities not to follow exactly the Hubble expansion law of Eq. 3. In fact, this was somehow already known in the seventies with the discovery of the dipole anisotropy of the CMB. When interpreted as a Doppler effect due to the motion of the earth relative to the frame of the last scattering surface, the dipole anisotropy implies that the Local Group must be moving with respect to the CMB with a velocity of 627 ± 22 km/s towards $l = 276 \pm 3^0$, $b = +30 \pm 3^0$ (galactic coordinates, Yahil et al. 1977).

In the following Sections I will briefly review the theoretical relations linking the density perturbations to the peculiar velocity fields (Sect. 2), the measurements of the peculiar velocity field of nearby galaxies ($cz < 8000$ km/s, Sect. 3) and their theoretical interpretations and implications (Sect. 4). For a comprehensive and up to date description of the subject one should refer to Deckel (1994) and Strauss and Willick (1995). Sect. 5 describes the EFAR project, aiming at measuring the peculiar motions in two superclusters, at distances $8000 < cz < 15000$ km/s. Conclusions are drawn in Sect. 6.

2 Peculiar motions: the gravitational instability picture

The current understanding of the inhomogeneities of the distribution of galaxies and of their motions in the Universe explains them as the result of the gravitational growth and evolution of the small density fluctuations present at the beginning and seen in the CMB by COBE (see Sect. 1). Once these primordial fluctuations are specified, their time evolution can be followed using fluid equations. Let $\overline{\rho}(t)$ be the mean density at time t.

Then one can write the density at the position $\vec{r}$ and the time t as $\rho(\vec{r},t) = \overline{\rho}(t)(1+\delta(\vec{r},t))$ and the velocity field as $\vec{w}(\vec{r},t) = H(t)\vec{r} + \vec{v}(\vec{r},t)$. In the linear regime ($\delta << 1$), the continuity equation, the Euler equation and the Poisson equation for the peculiar density contrast δ and for the peculiar density field will read:

$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla \cdot \vec{v} = 0, \tag{5}$$

$$\frac{\partial \vec{v}}{\partial t} + \frac{\dot{a}}{a}\vec{v} + \frac{1}{a}\nabla\Phi = 0, \tag{6}$$

$$\nabla^2\Phi = 4\pi G\overline{\rho}\delta. \tag{7}$$

Taking the time derivative of Eq. (5) and substituting into the divergence of Eq. 6, one gets with the help of Eq. 7:

$$\frac{\partial^2 \delta}{\partial t^2} + \frac{2\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G\overline{\rho}\delta. \tag{8}$$

The solution of Eq. 8 can be written as $\delta = A(\vec{x})D_1(t) + B(\vec{x})D_2(t)$, where $\vec{x} = \vec{r}/a$ and D_1 and D_2 are growing and decaying modes, respectively. In the case of a flat universe ($a \propto t^{2/3}$) one finds $\delta = A(\vec{x})t^{2/3} + B(\vec{x})t^{-1}$. In general the growing mode is:

$$D_1(t) = \frac{\dot{a}}{a}\int_0^a \dot{a}^{-3}da. \tag{9}$$

At late enough times, the growing mode will dominate and the peculiar velocity field will be:

$$\nabla \cdot \vec{v} = -a\delta\frac{\dot{D}_1}{D_1} = -aH_0 f\delta, \tag{10}$$

where (Lahav et al. 1991):

$$f(\Omega_0, \Lambda) = \frac{d\log D_1}{d\log a} \approx \Omega_0^{0.6} + \frac{\Omega_\Lambda}{70}(1 + \frac{1}{2}\Omega_0). \tag{11}$$

Once the similarity of Eq. 10 to the electrostatics equation is recognized, it is easy to find:

$$\vec{v}(\vec{r}) = \frac{H_0 f}{4\pi}\int d^3\vec{r'}\frac{\delta(\vec{r'})(\vec{r'} - \vec{r})}{\mid \vec{r'} - \vec{r}\mid^3} \tag{12}$$

Eq. 12 shows that a comparison between the measured peculiar velocities and the ones predicted by the actual distribution of mass of the universe would constrain the value of Ω_0. In fact, one is not able to measure δ, but only the density distribution δ_g of galaxies. This uncertainty can be parametrized by the *bias parameter* b, so that $\delta_g = b\delta$. Only f/b can therefore be derived from Eq. 12.

When $\delta \approx 1$ the linear approximation is not valid anymore. At this point the temporal evolution of δ and $\vec{v}$ must be followed with the aid of N-body simulations. These assume a given density of the Universe, with or without Λ, a given type of Dark Matter (Cold, Hot, Cold plus Hot), a power spectrum for the initial fluctuations. An algorithm for the identification of galaxies must be specified, for example the linear biasing model quoted above. Finally, the evolved models of the universe can be compared with the observations. For a more detailed discussion of the related problems and conclusions please refer to Jing in the present volume.

3 Peculiar motions: observations

Radial peculiar velocities v_r of galaxies can be measured once an additional estimation of the distance D of the objects has been obtained in addition to their redshift cz. Then one has:

$$v_r = cz - H_0 D. \tag{13}$$

During the last 15 years mainly two methods have been developed and used to estimate distances of galaxies. Distances to spiral galaxies have been determined using the Tully-Fisher relation; distances to ellipticals using the $D_n - \sigma$ relation. The Tully-Fisher relation (Tully and Fisher 1977) links the maximum rotational velocity V_{max} of a spiral galaxy to its absolute magnitude M: $M = a \log V_{max} + b$. It is therefore possible to compute the distance of a spiral by measuring its apparent magnitude. The velocity V_{max} can be obtained from optically derived rotation curves (Courteau 1992) or, more commonly, from the width ΔV_{20} of 21 cm integrated line profiles, easily obtained with single-dish radiotelescopes (Aaronson et al 1986). If i is the inclination of the galaxy to the line of sight as measured from the axial ratio, then $V_{max} \sin i$ and ΔV_{20} are well correlated. This follows from the fact that spiral galaxies have flat rotation curves (van Albada et al. 1985). Magnitudes M are measured in the optical (typically the B band) or in the infrared to take advantage of the diminished importance of absorption corrections. The slope a of the relation depends on the used band and on the details of how M and V_{max} are defined, ranging from 5 to 10. The scatter of the relation gives the precision for the distance to a single object of typically 15% .

The $D_n - \sigma$ relation (Dressler et al. 1987) links the central stellar velocity dispersion σ of elliptical galaxies to the aperture of diameter D_n which encloses a fixed average surface brightness in a given band. One derives $\log D_n = a \log \sigma + b$, where $a \approx 1.2$. Again, from the comparison with the apparent value of D_n one can derive the distance of the galaxy. The quantity σ can be measured from the width of the absorption lines (typically Mg_2 and Fe around $\lambda = 5150$ Å) present in the optical spectra of ellipticals. The diameter D_n can be derived from aperture photometry data or, in the last years, CCD photometry, typically in the B, V or R band. The scatter in the $D_n - \sigma$ relation gives a precision of $\approx 23\%$ in the derived distance of the single objects. Somewhat better precision ($\approx 18\%$) is achieved, if the Fundamental Plane (FP) equation is used. This relates the half-luminosity radius R_e to $< SB_e >$, the average surface brightness inside R_e, and σ: $\log R_e = 1.35 \log \sigma + 0.35 < SB_e >$ (Faber et al. 1987). The FP equation implies the $D_n - \sigma$ relation because the luminosity profile of elliptical galaxies follows the $R^{1/4}$ law (de Vaucouleurs 1948), so that one finds $\log(D_n/R_e) \approx -2 < SB_e >$.

Nowadays distances and peculiar velocities for more than 3000 galaxies have been measured, $\approx 80\%$ of which are spirals where the Tully-Fisher relation has been used (Aaronson et al. 1986, Mathewson et al. 1992a, b). Most of the distances for ellipticals come from the work of the 7 Samurai (Lynden-Bell et al. 1988) with the discovery of the Great Attractor (see Sect. 4). All of the available data have been now homogenized, corrected for systematics and bias effects in the *Mark III Catalogue of Galaxy Peculiar Velocities* (Willick et al. 1995). The radial velocity field as determined in this catalogue is shown in Figure 3, from Strauss and Willick (1995).

To conclude, one should mention at least three of some recently proposed and promising distance indicators. The surface brightness fluctuation method (Tonry and Schneider 1988) uses the fact that the intensity collected in a single CCD pixel comes from a finite number of stars of a galaxy and is therefore subject to Poisson fluctuations. These decrease with the distance of the galaxy, because a larger number of stars will be present in a pixel. The method gives distances with a precision of 5% . The fitting of the planetary

Figure 1: The Mark III peculiar velocities of all galaxies within 22.5^0 of the Supergalactic plane. The points are drawn at the measured distance of the galaxies, while the lines are drawn to their redshifts, in the CBM rest frame. Positive peculiar velocities are shown as filled points and solid lines, negative ones as opened points and dashed lines. Points representing groups of more than three galaxies are drawn somewhat larger (from Strauss and Willick 1995).

nebula luminosity function (Jacoby et al. 1989) yields the distance of a galaxy with similar accuracy (for details see Mendez in this volume). Finally, Lauer and Postman (1994) used the $L_m - \alpha$ distance indicator for the brightest cluster galaxies (BCG) to measure the distances of 119 Abell clusters with a precision of 18% . Here the luminosity inside a radius of 10 kpc of BCG appears to be correlated with the slope of the luminosity profile $\alpha = d\log L/d\log r$.

4 Peculiar motions: analysis

As explained in Sect. 10, Eqs. 10 and 12 link the velocity field of Fig. 3 to the density field δ at distances < 8000 km/s from us. Two algorithms have been developed to exploit this link.

The first approach, the POTENT technique (Bertschinger and Deckel 1989), uses the fact that Eq. 10 implies $\nabla \times \vec{v} = 0$. As a consequence, $\vec{v} = -\nabla\Phi$, and the scalar potential Φ can be obtained by integration of the measured radial component of the velocity field $v_r(r,\theta,\phi)$:

$$\Phi(\vec{r}) = \int_0^r v_r(r',\theta,\phi)dr'. \qquad (14)$$

The application of Eq. 10 (or of a non-linear generalization of this equation, see Nusser et al. 1991) to the so reconstructed velocity field yields δ. A crucial part of POTENT involves the smoothing of the available data points, noisy and sparsely sampled, to obtain a continuous velocity field. The resulting density field is shown in the left panel of Figure 4 from Strauss and Willick (1995).

Figure 2: Left: the POTENT density field in the supergalactic plane from the MarkIII peculiar velocity data. Right: the density field implied by the IRAS galaxies. The local group is at the center of each panel. A smoothing of 1200 km/s has been applied and the axes are labeled in 1000 km/s (from Strauss and Willick 1995).

The second approach starts from the galaxy density field as estimated from redshift surveys, for example those of IRAS selected galaxies (Rowan-Robinson et al. 1990, Fisher et al. 1995). Under the assumption that galaxies trace the mass of the Universe (see Sect. 2), one can first solve Eq. 12 using redshifts as an estimate of distances. The derived velocity field $\vec{v}$ can be used to derive an improved estimate of distances from Eq. 13 and a new density field. The procedure is iterated until convergence is achieved. The resulting δ is shown in the right panel of Fig. 4.

Both panels of Fig. 4 show the same features. At $(x, y) \approx (-4.5, -0.5)$ one recognizes the strong overdensity region of the Great Attractor. At $(-2, 5)$ there is the A1367-Coma supercluster, separated from the Pisces-Perseus supercluster (at $(5, 0)$) by the void at $\approx (3, 3)$. South of the Great Attractor one sees the Sculptor Void ($\approx (-3, -4)$). A detailed comparison of the two fields (see Deckel 1994) shows that they are compatible within the measurement errors and at this smoothing length. More significant differences appear at smaller smoothing lengths, where the POTENT assumption of a curl-free velocity field may break down.

As described in Sect. 2, these tests, together with the analogous comparisons between the measured velocity fields and the one derived from Eq. 10 yield a range of possible values for the quantity $f(\Omega)/b$. Strauss and Willick (1995) discuss the different determinations given in the literature and conclude that $0.45 < f(\Omega)/b < 1.11$. For the small values of the biasing parameter nowadays popular ($1 < b < 1.5$) one derives that $0.3 < \Omega < 2.3$. The comparison of the (COBE normalized) power spectrum predicted by cosmological models such as CDM with the data derived from the galaxy correlation function tends to prefer the low end of this range (see Jing in this volume).

5 The Efar project

Presently, peculiar velocity surveys extend out to 8000 km/s (see Fig. 3). Lauer and Postman (1994)'s controversial result (a bulk flow motion of $\approx$ 700 km/s of the 119 Abell

Figure 3: The distribution of the EFAR clusters in galactic coordinates.

Clusters at distances less than 15000 km/s) is based on the use of a particular class of objects, the Brightest Cluster Galaxies (see Sect. 3). A confirmation of this result with a larger sample of more "normal" galaxies is crucial, because it would exclude all available cosmological models of the structure of the Universe (see Sect. 2).

Goal of the EFAR Project (Wegner et al. 1995a) is to establish the peculiar motions of elliptical galaxies and clusters in two superclusters at distances between 8000 and 15000 km/s, using the Fundamental Plane distance estimator (see Sect. 3). We selected 82 elliptical-reach clusters in the Hercules-Corona Borealis and Pisces-Cetus Superclusters and a list of 742 candidate ellipticals (9-10 galaxies per cluster) was obtained. Such a number of objects is needed to reduce the typical distance measurement error per object ($\approx$ 2000 km/s at 12000 km/s) to $\approx$ 700 km/s per cluster. In this way a bulk flow of 500 km/s (similar to the one produced by the Great Attractor in the Local Supercluster, see Sect. 3) in the two superclusters can be detected at a 3σ level. Figure 5 shows the distribution of the clusters in galactic coordinates. The superclusters lie in the two galactic hemispheres, so that possible systematic effects due to the galactic absorption can be checked. 30 of the 119 BGC of the Lauer and Postman sample are part of the EFAR list, so that an independent distance estimate will be available. In addition, Giovannelli, Haynes and collaborators are measuring distances to spiral galaxies in the Pisces-Cetus supercluster using the Tully-Fisher relation. This will allow a further check on the derived peculiar velocity field.

Photoelectric photometry in the B and the R band has been obtained for almost a half of the sample (Colless et al. 1993). The reduction of the CCD photometry (in the R band) has now been completed (Saglia et al. 1995a). The photometric parameters are derived using a bulge plus disk decomposition technique which takes into account seeing effects (Saglia et al. 1993) and allows to identify objects with disks (Saglia et al. 1995b). The spectroscopic data (Wegner et al. 1995b) have been analyzed to measure the redshift, the central velocity dispersion and the Mg_2 line strengths. The complete data set is under study to derive peculiar velocities. The analysis incorporates selection effects and Malquist bias corrections (Bertschinger et al. 1995).

6 Conclusions

In a Universe where the initial (small) perturbations to the uniform density have grown gravitationally to form the large-scale structure we see today as clusters of galaxies, superclusters and voids, one expects the velocities of galaxies to deviate from the smooth Hubble flow. These peculiar velocities can be measured with the aid of distance estimators and have been mapped out to distances of 8000 km/s from us. The study of these cosmic velocity fields is an important tool to test the predictions of cosmological models of the Universe. It allows one to derive the (nearby) peculiar density field, which can be compared to the one of galaxies, as determined from redshift surveys. Under reasonable assumptions for the value of the biasing parameter, the data constrain the density parameter Ω to be larger than 0.3. The EFAR project, which is supported by SFB 375, will extend the measured galaxy velocity field out to distances of 15000 km/s in two superclusters.

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