ELLIPTICAL GALAXIES AND LARGE-SCALE VELOCITY FLOWS

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ABSTRACT. Motions of nearby elliptical galaxies reveal a large-scale velocity flow relative to cosmic rest towards the point l=307±10, b = 9±10. The data are fit best by a two-component flow model. The smaller component is due to Virgo, which induces a velocity at the Local Group of 250 km/s. The main flow is due to a more massive concentration located a distance of 4350±350 km/s towards l=307, b=9, which induces a local velocity here of 570±60 km/s. This larger component falls off away from the mass concentration roughly as r^{-1}. The Centaurus double cluster and its neighbors are in the direction of the mass concentration but are in the foreground and are falling into it. Galaxy counts, radial velocity surveys, and the motions of nearby spirals are consistent with the above model. The IRAS dipole results are less clear but may also be consistent. There is evidence that the distant mass concentration is non-spherical, with the Centaurus cloud a substantial sub-condensation in the foreground. The formal agreement of the large-scale flow with biased (b=2) cold dark matter is low, but the simple methods used so far to assess this are uncertain. The main weakness of the present data in comparing to theory is the fact that they do not penetrate far enough to show the velocity field on all sides of the mass concentration. Sphericity and total extent of the flow are therefore still unknown.

1. NATURE OF THE SURVEY

This talk summarizes the results of a large survey on the motions of nearby elliptical galaxies relative to the Hubble flow. The survey was undertaken by a group of seven astronomers including David Burstein, Roger Davies, Alan Dressler, Sandra Faber, Donald Lynden-Bell, Roberto Terlevich, and Gary Wegner. The target galaxy sample is in two parts: an intended magnitude-limited sample to B = 13.0 mag, which contains 270 galaxies and is 80% complete, plus a deeper, sample containing 120 galaxies in six calibrating clusters. We say "intended" for the magnitude-limited sample because of a recently discovered classification error in the ESO Catalog, which means that the magnitude limit in the south is not as deep as in the north. More is said on this point below.

For every galaxy, we have measured the nuclear velocity dispersion and determined the photometric profile using new aperture photometry or newly ho-

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mogenized photometry from the literature. We have defined a novel photometric diameter, D_n, as that diameter within which the fully corrected mean surface brightness is 20.75 B mag/arcsec. Empirically we find that this diameter, when correlated with nuclear σ, yields an improved distance indicator for elliptical galaxies with an error of ±21% (±0.45 mag). This is a factor of two better than the old $L - \sigma^4$ relation. Many galaxies are also members of groups, for which the distance error is reduced by $\sqrt{N}$.

All distances are expressed in km/s, which bypasses the need for a Hubble constant. However, there is an analogous scaling parameter that is adjusted so that, in the mean, our distances (in km/s) equal the observed radial velocities after correction for all modeled velocity flows. Model parameters describing the flow are derived using a maximum-likelihood method that corrects roughly for Malmquist bias in the estimated distances. This Malmquist correction is valid for a population of objects and/or clusters that is uniformly distributed in space.

2. MAJOR RESULTS

The conclusions of the study are described in a recent preprint (now in press) by Lynden-Bell *et al.* (1988). The principal result is apparent from a simple plot of the raw peculiar velocities relative to the microwave background frame (see Fig. 1a). Only the component due to the general Hubble expansion has been removed here. Qualitatively, this figure gives the impression of large peculiar motions. Quantitatively, the mean rms residual per point after allowance for measurement errors is 450 km/s. (A "point" in this case means either a single galaxy or a group barycenter, depending on the group assignments.) Figure 1a says that the Hubble flow in elliptical galaxies is far from quiet in the volume around us out to roughly 5000 km/s. Below, we shall see that this conclusion applies to spirals as well, but the volume that is well studied for spirals is considerably smaller.

Closer inspection of Fig. 1a reveals a coherent spatial pattern in the residuals. They are largest on the right-hand side of the figure, where they show a strong flow away from the location of the Local Group. Systematically over the whole figure there is a general left-to-right trend (recall that we detect only the radial component of the peculiar motion). After experimentation we have found that virtually all of the systematics can be accounted for using a simple two-component flow model. One component is a spherically symmetric Virgo inflow with a velocity at the radius of the Local Group of 250 km/s. The second is an analogous inflow toward a mass concentration located at a distance of 4350 ± 350 km/s towards l=307, b=9 (small cross in Fig. 1a) and having a flow velocity at the radius of the Local Group of 570 ± 60 km/s. The results of removing this model are shown in Fig. 1b. The impression of a systematic flow pattern has now disappeared. The rms residual in this figure is only 245 km/s.

The elliptical data thus suggest a second Virgo-like flow, but on a scale that is substantially more extended and more powerful than Virgo itself. Using the usual formula for a spherically symmetric mass perturbation ($G\Delta M/R = v\cdot\Delta v$), we can scale the excess mass involved in this flow to the excess mass in Virgo:

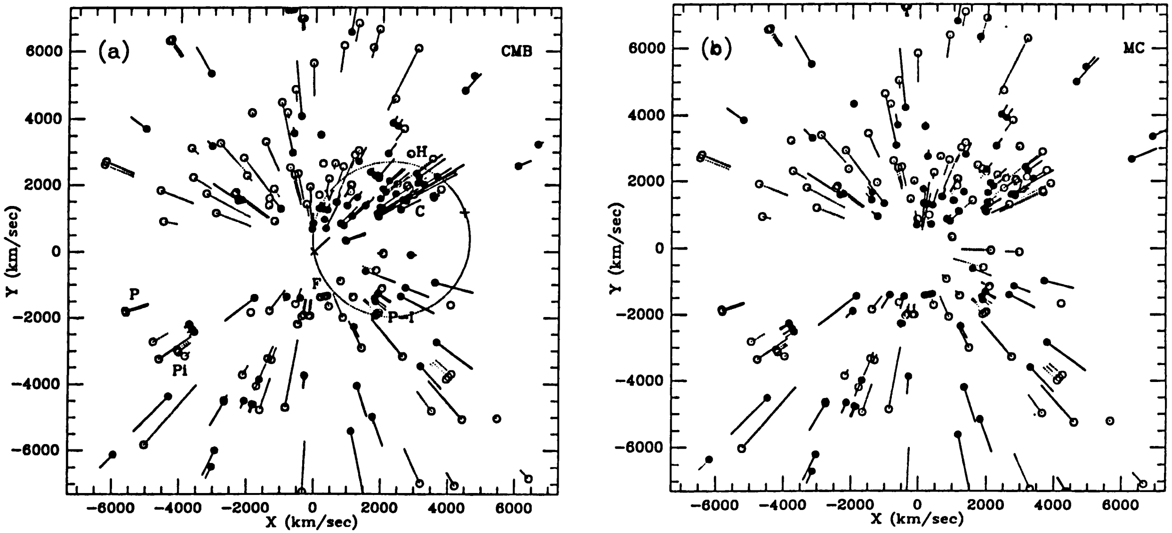

Figure 1. Peculiar radial velocity vectors of elliptical galaxies and galaxy groups within ±45° of the Supergalactic Plane. Each galaxy (or group) is placed at its estimated distance and a vector of length $v - R$ is drawn ending at v, the radial velocity in the microwave rest frame. Outward moving points are filled. (a) Raw peculiar velocities with respect to cosmic rest. Individual regions are labelled (P=Perseus, Pi=Pisces, F=Fornax, P-I=Pavo-Indus, C=Centaurus, H=Hydra, V=Virgo). The mass concentration in the two-component model is located roughly at the small cross to the right. The circle shows the region within which positive radial velocity residuals expected for a spherically symmetric flow. (b) Residuals after fitting to the two-component flow model described in the text.

$$\frac{\Delta M_{\rm MC}}{\Delta M_{\rm VIR}} = \left(\frac{v_{\rm MC}}{v_{\rm VIR}}\right) \cdot \left(\frac{R_{\rm MC}}{R_{\rm VIR}}\right) \cdot \left(\frac{\Delta v_{\rm MC}}{\Delta v_{\rm VIR}}\right)$$
$$= \left(\frac{4350}{1360}\right) \cdot \left(\frac{4350}{1360}\right) \cdot \left(\frac{570}{250}\right) = 23. \qquad (1)$$

The actual excess mass within the Local Group is 5×10^{16} h_{50}^{-1} $M_\odot$. From the cosmological overdensity formula $\Delta v = 1/3HR\Omega_0^{0.06}\Delta\rho/\rho$, one finds $\Delta M/M = 0.4$ for $\Omega_o = 1.0$ and $\Delta M/M = 1.0$ for $\Omega_0 = 0.2$. The best model uses a velocity that falls off from the mass concentration as $v \sim r^{-1}$, which corresponds to $\Delta\rho/\rho \sim r^{-2}$. However, the exact form of the fall-off is rather weakly constrained.

The direction 1=307, b=9 is only 13° away from the Centaurus double cluster of galaxies at 1=302, b=21. Together with Hydra at 1=270, b=26, Centaurus has been hypothesized (Tammann and Sandage 1985, Shaya 1984) as the culprit responsible for the extra motion of the Local Group over and above Virgo infall. The model we present here is similar – the Local Group receives a strong kick toward Centaurus from the mass over there – but the new data say that Centaurus itself and its neighbors are in the foregound and, like us, are being pulled by a bigger mass concentration that is farther away. The Centaurus double clusters are two of the fastest-moving objects in our sample, with velocities in excess of 1000 km/s. Hydra, in contrast, shows little motion, but, with an angular distance of 40° away on the sky, is predicted to move largely tangentially and have small radial velocity, as is observed.

So far, a spherically symmetric flow model adequately fits the data. This may be due to the fact that the sample does not penetrate through the mass concentration to the far side (see Fig. 1) and does not therefore place a strong constraint on the global geometry.

3. COMPARISON TO OTHER DATA

The new flow, if real, forces us to accept a different picture of the local topography of the universe. For several decades, astronomers have been used to thinking of Virgo as the center of the Local Supercluster. On the contrary, the new data say that both we and Virgo are comparative flotsam being pulled by a more massive and more distant mass concentration. Thanks to Alan Dressler, we now have a new name for this entity – the "Great Attractor."

There is considerable – and growing – independent evidence for the existence of the Great Attractor. Using optical galaxy catalogs, Ofer Lahav of the Institute of Astronomy in Cambridge has made a striking picture of the sky in that direction, which shows an impressive cloud of galaxies that covers nearly a steradian of sky (see Lynden-Bell *et al.* 1988). Lahav has helped us to count galaxies there and compare to Virgo with proper allowance for the difference in distances. Depending on the precise diameter limit used, the number of galaxies in the core of the Great Attractor exceeds that in the core of Virgo by a factor of between 15 and 30, roughly in the same proportion as the required ΔM's in equation (1). The core of the Great Attractor is comparable to typical Abell superclusters in dimension, although there is as yet no identified Abell-type cluster that marks the center.

Radial velocity surveys also show a significant excess of galaxies in the region. A recent survey by Da Costa *et al.* (1986) yields a strong peak at $v = 4500$ km/s with an rms width of 1000 km/s. There also seems to be subsidiary shoulder from 2000-3500 km/s of about half the height, associated with the foreground Centaurus concentration.

The most complete survey of the region is Alan Dressler's radial velocity survey now in progress, which targets 1400 galaxies over a steradian of sky centered on 1=320, b=8. The galaxies were selected in the same way as the Southern Redshift Survey by Davis, Huchra, da Costa, and collaborators, which means that the SRS can be used to predict the expected redshift distribution for a random sample. From the 900 galaxies measured so far, Dressler finds an overdensity of about a factor of three toward the Great Attractor between 3500 and 5500 km/s and a separate peak of similar height from 2000 to 3500 km/s. The more distant peak occupies a larger volume and contains roughly four times more galaxies. Dressler thus confirms a main concentration at the distance of the Great Attractor and a second foregound concentration associated with Centaurus. These inferred space distributions are preliminary since they are based on radial velocities in a region of space where radial velocities are believed to be strongly perturbed. However, they suggest that the region around the Great Attractor possesses a degree of substructure and may be significantly non-spherical. Note that the Centaurus grouping, with one-fourth the mass but roughly half the distance, exerts a gravitational pull on the Local Group that is comparable to the Great Attractor itself.

In earlier talks, the first author of this paper has stated – erroneously it now seems – that the Great Attractor is comprised largely of spirals with few early-type galaxies. This was surprising for such a high-density region, but the magnitude-limited sample showed a strong dearth of ellipticals there – at a distance where many ellipticals show up in other directions (mostly in the northern hemisphere, it turns out). Curiosity piqued, we have studied the ESO Catalog more closely and found that there is in fact a considerable *excess* of early-type galaxies toward the Great Attractor, but almost all of them are classified as S0 rather than E! Details will appear in a forthcoming paper on the sample selection (Faber *et al.* 1988), but it seems now that there is a systematic classification error in the ESO Catalog such that faint E's are miscast as S0's. The effective magnitude limit of our sample is thus considerably shallower in the south compared to the north. To see the full extent of the Great Attractor will require a deeper sample, for which the observations are now beginning.

Parenthetically, this sampling irregularity has no first-order impact on the computed flow velocities because the method for correcting Malmquist bias is valid regardless of sample bias or nonuniformities. To second order, however, there is an error due to the assumption of uniform space density in the method – an assumption that is clearly not valid in the direction of the Great Attractor. We have made a few numerical experiments as described in Lynden-Bell *et al.* (1988) to model the effect of variations in the space density along that line-of-sight. These tests suggest that only as much as 100 km/s of the 1000 km/s measured velocity of the Centaurus region could be due to residual Malmquist errors. The effect, though real, is not likely to be quantitatively important.

We have also begun to study flow motions deduced from other samples of galaxies. So far we have concentrated mainly on two samples of nearby spirals within 2500 km/s having Tully-Fisher distances (Aaronson *et al.* 1982 and de

Vaucouleurs and Peters 1985). The agreement with the Great Attractor flow model is good. Both samples give flow velocities of roughly 500 km/s towards 1=290, b=10, which is close to the model prediction. David Burstein (Burstein *et al.,* this volume) shows graphically the improvement in the Tully-Fisher relation that results when radial velocity distances of these galaxies are corrected for the two-component flow model.

Lilje, Yahil, and Jones (1986) have also reanalyzed the Aaronson *et al.* data allowing for a quadrupole term in the local Hubble expansion. Their results anticipate our own work to a great extent. Their quadrupole term has an axial ratio $h_\ell/h_s = 1.25$ and long axis toward 1=308, b=13. This quadrupole in the local spirals is the tidal distortion of the local Hubble flow induced by the Great Attractor. For a spherically symmetric flow, one can estimate the distance of the mass center expressed in km/s as $r_o = v_o(1+m)(h_\ell/h_\ell - h_s)$, where v_o is the flow velocity induced in the nearby region, m is the power-law index in $v \sim r^{-m}$, h_ℓ is the Hubble constant along the direction of maximum expansion, and h_s is the average along the two minimum directions. With $h_\ell/h_s \approx 1.25$, $m = 1$, and $v_o \approx 500$ km/s, one finds $r_o \approx 4000$ km/s, in good agreement with the elliptical value of 4350 km/s. The spiral value is less well determined, however, because the spirals are all fairly nearby, whereas the ellipticals extend virtually all the way to the Great Attractor and give greater geometrical leverage on its distance.

To elaborate slightly, the nearby spirals already tell us that a volume of space some 2500 km/s in radius is translating "sideways" toward the southern hemisphere with a velocity of roughly 500 km/s (LYJ said basically the same thing). A significant component of the Local Group's motion is due to this flow. The major new insight provided by the E's is the fact that the obvious candidate for producing this flow, Centaurus and its neighbors, is in fact in the foreground. This increases the distance of the main mass concentration and thus the scale of the phenomenon, which is a cosmologically important result. It is significant that Jeremy Mould at this conference also reports high velocities for the Centaurus spirals, which suggests that the ellipticals are not anomalous or otherwise in error.

It should be stressed that the bulk motion of the nearby spirals of 500 km/s is essentially equal to the rms mean velocity per point for the elliptical sample (450 km/s). One might have hypothesized that ellipticals (and elliptical groups) would move faster than spirals since they inhabit denser regions. This has not happened, however, because the main contributor to the velocities for both spirals and ellipticals is the Great Attractor flow, and this occurs on such a large scale that it affects ellipticals and spirals approximately equally.

The last major comparison is to the IRAS dipole. The raw IRAS counts give a dipole toward 1≈240, b≈40 (Meiksin and Davis 1986, Yahil *et al.* 1986), and the new direction based on radial velocities (Strauss and Davis, this volume) is similar: 1≈250, b≈50. Much has been made of the fact that the IRAS dipole agrees well in direction with the Local Group microwave motion of 614 km/s toward 1=270, b=28, whereas the Great Attractor is fairly far away at 1=307, b=9. The implication is that there must be something wrong with the Great Attractor: either it does not exist or it is in the wrong place.

This reasoning mixes apples and oranges, however. The IRAS dipole and the Local Group motion both show the net gravity vector *at the position of the Local Group.* This gravity vector contains a component due to the Great Attractor, but it also has other significant components due to Centaurus (see above), Virgo, and other nearby groups. It is a fact that the Great Attractor model (including Virgo) fits the Local Group motion rather badly, leaving a discrepancy of some 350 km/s. We conclude from this that there is a local gravity anomaly, but on what size scale is not yet clear. A major question to be asked of the IRAS – and also the optical – counts is where in space this local anomaly originates. It was encouraging to hear from Marc Davis at this conference that there is a strong acceleration towards the south side of the Supergalactic Plane in the IRAS galaxies. This z-vector is lacking in the two-component model (since both Virgo and the Great Attractor lie in the Supergalactic Plane) and by itself would explain a major fraction of the Local Group anomaly. The latest IRAS analysis also shows strong convergence in the magnitude of the gravity vector at a radius of 4500 km/s, the estimated distance to the Great Attractor. In short, we think that the IRAS results and our survey may be in reasonable agreement after all.

4. COSMOLOGICAL INTERPRETATION

Perhaps because we first announced our results in terms of a bulk motion of ellipticals in a volume out to 6000 km/s (Dressler *et al.* 1987), cosmological interpretation initially centered on the probability of finding bulk motions of spheres on such large scales. It has since become clear that this approach is too naive. For one thing, the effective size of the volume is smaller than the formal boundary owing to greater uncertainty for the most distant points (although the errors do not drop as rapidly as one might think because many of the most distant points are groups, for which the errors are reduced by $\sqrt{N}$). For another, the volume is populated inhomogeneously, cf. Fig. 1. There is an excess density of elliptical galaxies in the fastest moving region, potentially giving it too high weight.

It will probably be some time before the true cosmological significance of the motions is understood, as detailed simulations are required incorporating realistic density inhomogeneities, groupings of galaxies, and measurement errors. However, in an attempt to extract some rough information quickly, our group has used two very simple approaches (Lynden-Bell *et al.* 1988). In method one, we use the bulk motion method but pick a sub-volume containing only the highest velocities. This volume has a diameter of 4000 km/s and is located between us and the mass concentration. We assume the validity of the Great Attractor model and use a top-hat window for the shape of this volume. In method two, we assume a spherically symmetric flow about the Great Attractor and calculate the probability of finding the observed flow velocity and $\Delta M/M$ within the Local Group.

In both cases we compare to cold dark matter (CDM) and find that the flow is compatible with unbiased (b=1) CDM but not with biased (b=2) CDM. Although the probability of biased CDM is formally very low, the velocity discrepancy still boils down to just a factor of two. In our opinion, it is not yet clear that this discrepancy is fatal, as each of the above methods has obvious flaws: the velocities in method one may be in the non-linear regime, and the assumption of spherical symmetry in method two may be wrong.

In conclusion, we believe that the cosmological interpretation will be on safer ground when the galaxy distribution and velocity field all around the Great Attractor have been mapped and we can see for certain whether the flow occupies as large a volume as spherical symmetry would imply.

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