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COLD FLOWS AND LARGE SCALE TIDES

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ABSTRACT. We propose a different view of the dilemma concerning the coldness of the local cosmic flow and its repercussions for the global Universe. We stress the fact that our cosmic neighbourhood embodies a region of rather particular circumstances, whose dynamics and kinematics are substantially influenced by its location in between the Great Attractor region and the Pisces-Perseus chain. On the basis of constrained simulations of our cosmic neighbourhood we indicate through the cosmic Mach number that we live in an extraordinarily cold niche of the Universe.

1 Cosmic Chills and Universal Truths

Early assessment of the small-scale random motions of galaxies, estimated on the basis of pairwise velocity dispersions, revealed that locally the Universe is rather cold. While we participate in a bulk flow of approximately 600km/s, the random velocities with respect to the mean flow are estimated to be in the range of a mere $200--300$km/s (see e.g. Suto, Cen & Ostriker 1992) This low value of the velocity dispersion in combination with the pronounced structure displayed by the distribution of galaxies was in fact a strong argument for either a low Ω-Universe the or for the latter being a biased tracer of the underlying matter distribution. The assumption of bias, in particular in the form of the oversimplifying linear bias factor b, would then imply the matter distribution not to have evolved as far as suggested by the pronounced nature of the galaxy distribution, and hence would be in agreement with the low value of the "thermal" motions in the local Universe.

An interesting elaboration on the assessment of the implications of the coldness of the local velocity flow for the properties of the global Universe, in particular for the value of the cosmological density parameter Ω, was suggested by Ostriker & Suzo (1990). They pointed out that a comparison between the properties of the small-scale "dispersion" velocities, $\sigma(\mathbf{v})$, and the large-scale bulk motions, $|\mathbf{v}|_{bulk}$, would not only provide valuable information on the relative amount of large-scale and small-scale power in the spectrum of density- and velocity fluctuations, but that to do this on the basis of their ratio, the "cosmic Mach number" $\mathcal{M}$,

$$\mathcal{M} \equiv \frac{|\mathbf{v}|_{bulk}}{\sigma(\mathbf{v})}\,. \tag{1}$$

has the additional advantage of providing this information in a way that is independent of both the – not yet definitively settled – amplitude normalization of the power spectrum as well as of a possible – linear, scale-indepent – bias between galaxies and matter. The only intrinsic assumption is that the velocities of galaxies do form an unbiased tracer of the underlying velocity field. One of the most striking conclusions reached on the basis of extensive tests of the discriminatory virtues of the Mach number was that the velocity field in our local Universe appeared to exclude the viability of the standard CDM model (Ostriker & Suzo 1990).

2 Local versus Global

In an attempt to interpret the significance of the coldness of the local cosmic flow, we postulate an alternative view. Rather than interpreting the coldness of the flow as a property of the global Universe, we hold the view that it is our rather uncommon cosmic location that lies at the basis of the issue and that we should be careful in drawing conclusions con-

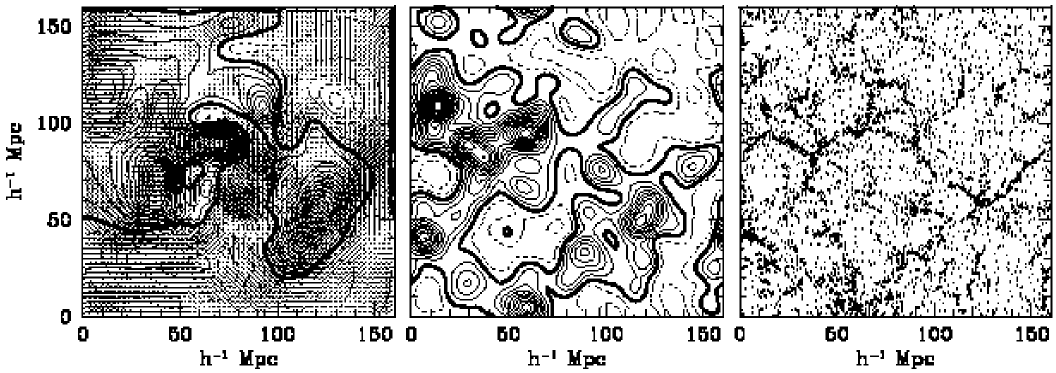

Figure 1.
Left: The density distribution in a constrained reconstruction of our Local Universe. Based on the Mark III catalogue peculiar motions, smoothed on a Gaussian scale of $R_f = 5h^{-1}$Mpc, the Wiener filter reconstruction yields the density field in the top left frame, represented by a density contour plot in the central $x - y$ plane. The solid contours correspond to $\delta > 0.0$, the dashed ones to low-density regions with $\delta < 0.0$. The indicated density levels range between -0.6 and 1.3, with the linear increment between contour levels amounting to $\Delta\delta = 0.1$. The heavy solid line is the $\delta = 0.0$ contour. We, the Local Group, are at the centre of the box, clearly recognizable are the mass concentrations around the Perseus-Pisces complex (lower lefthand side) and the Great Attractor region (upper righthand corner). Superimposed on the Wiener filtered density field contours are the bars representing the compressional component of the tidal shear within the $x - y$ plane (see van de Weygaert & Hoffman 1998). Notice the strength of the tidal field in the underdense region near our own cosmic location. Centre: the constrained linear density field realization after including a constrained contribution of small-scale waves according to the standard CDM scenario, Gaussian smoothed on a scale of $R_f = 5h^{-1}$Mpc. The density contours are characterized in the same way as the ones in the top frame, with the linear increment of the contour levels amounting to $\Delta\delta = 0.2$, ranging in value from $\delta = -1.6$ to $\delta = 3.0$. Right: outcome of the nonlinear evolution of the constrained realization of our local Universe, as evolved by means of an N-body simulation.

cerning the global value of cosmic parameters as well as of the validity of structure formation scenarios.

Figure 1a contains a reconstruction of the linear density field (Gaussian scale $R_f = 5h^{-1}$ Mpc) in our local Universe, in a slice approximately coinciding with the Supergalactic Plane, based on the set of measured peculiar velocities of galaxies in the Mark III catalogue (Willick et al. 1997). The Local Group is located at the center of the box. On the upper lefthand side we can discern a huge positive density complex, the Great Attractor region, while on the other side, lower righthand corner, we observe the presence of another massive density enhancement, corresponding to the Perseus-Pisces supercluster region. Moreover, in perpendicular directions we have vast regions of lower than average density. Hence, seemingly we find ourselves located right near the centre of a configuration strongly reminiscent of a canonical quadrupolar mass distribution. The direct dynamical implication of this is that we are located near the saddle point of a strong field of tidal shear. In fact, when turning to Figure 1b we see the compressional component of the tidal field corresponding to the density distribution in the local Universe (Van de Weygaert & Hoffman 1998), superposed on the isodensity contours in the same slice. The tidal field, illustrated by bars whose size and direction are proportional to the strength of the compression along the indicated direction is, evidently, very strong within the realm of the two huge matter concentrations where the density reaches high values. In addition, however, we also

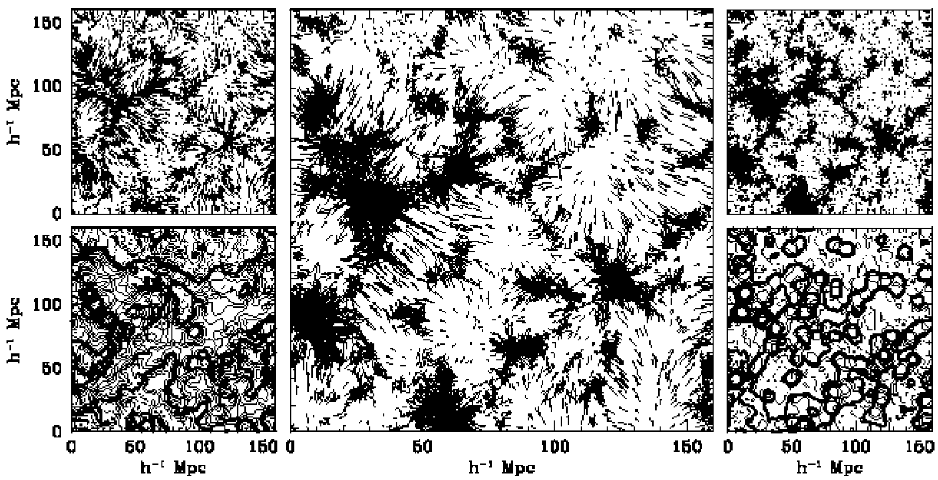

Figure 2.
Notice 90° change in figure orientation. The velocity field structure in our local Universe. Central frame: full velocity field at particle locations, represented by velocity vectors of velocity components in central $x - y$ plane. Left frames contain the bulk velocity component of the velocity field at the particle locations, with the top frame displaying the vector representation, and the bottom frame the contour plot of the amplitude of the bulk velocity in the central $x - y$ plane. The righthand frames display the same for the small-scale velocity 'dispersion' component. The bulk velocity is defined as the velocity after filtering out the contributions on scales smaller than $5h^{-1}$Mpc, while the velocity dispersion is the remaining small-scale residual velocity.

see that the tidal shear is indeed very strong at our own location, precisely due to the fact that we are hanging in between the Great Attractor and the Perseus-Pisces chain. In fact, through the anisotropic nature of the induced tidal forces we can recognize a situation that was for instance already recognized within the context of the Cosmic Web picture (see Bond, Kofman & Pogosyan 1997, also see van de Weygaert & Bertschinger, 1996, fig. 4), the collapse and formation of filamentary and tenuous wall-like features in regions bordered by massive matter clumps like clusters of galaxies. This appears to be the generic outcome of the evolutionary path of regions of moderately low overdensities immersed in an external tidal field whose strength is of the same order of magnitude as the selfgravity of the region. In such situations we may expect the contraction itself to be accelerated with respect to the situation of the same initial region having been spatially isolated. In fact, the shearing nature of the forces will accelerate the contraction along the shortest axis of the region that will experience an accelerated contraction, while the longest axis will experience a slow down of its contraction rate. This in turn will very likely imply a slower mixing, "thermal" settling and virialization of the matter involved in the contraction process.

It is the preceding sketch of events that prompts us to expect our local corner of the Universe, because of its special location in between the Great Attractor and the Perseus-Pisces complex, to have a substantially lower velocity dispersion than we may expect to encounter in an average patch of our Universe.

3 Wiener filtering the Mark III Local Cosmos

In an attempt to address the implications of the coldness of the local cosmic flow, we investigated the dynamical and kinematical evolution of cosmic regions resembling as closely as possible our own local Universe.

First issue in this approach is to set a cosmic environment resembling our local Universe. This is achieved by invoking relevant observationally determined properties of the local cosmos. As we are specifically interested in dynamical issues, we base ourselves on a local cosmic primordial linear density field that represents an optimally significant reconstruction of the prevailing matter distribution in the early Universe. We achieve this by applying a Wiener filter algorithm to the sample of measured peculiar velocities of galaxies in the Mark III catalogue (Willick et al. 1997, and Zaroubi et al. 1995 for technical aspects). Such a reconstruction restricts itself to regions that arguably are still within the linear regime, and whose statistical properties are still Gaussian. We discard further observational constraints on the small-scale clumpiness and motions in the local Universe. Instead, we generate and superpose several realizations of small-scale density and velocity fluctuations according to a specific power spectrum of fluctuations, global cosmological background specified by H_0 and Ω_0, and with the small-scale noise being appropriately modulated by the large-scale Wiener filter reconstructed density field. To this end we invoke the technique of constrained random fields (see Hoffman & Ribak 1991, van de Weygaert & Bertschinger 1996), with the Wiener filtered field playing the role of "mean field".

4 Small-scale evolution of the Local Cosmos

Having generated a full realization of a patch of the Universe resembling the primordial density field in our local cosmic neighbourhood, we trace its development by means of an P^3M N-body simulation. The outcome of our simulations is reduced and analyzed with the help of a 'dynamical fields' code. The resulting distribution of the particles in a central slice through the simulations box is shown in the central frame of Figure 2. Clearly recognizable are massive concentrations of matter at the locations where in the real Universe we observe the presence of the Great Attractor region (slightly "north" of the "west" direction) and the Perseus-Pisces region (slightly "south" of the "east"). Interesting is to see how vast and extended these regions in fact are, certainly not to be identified with well-defined singular objects. The corresponding velocity field in the same region of the simulations is displayed by means of a decomposition in the large-scale bulk flow $\mathbf{v}_{bulk}$, top-hat filtered in a sphere of radius $R_{TH} = 5h^{-1}$Mpc, and the small-scale velocity "dispersion" $\mathbf{v}_\sigma$ (for technical details see Van de Weygaert & Hoffman 1998). The top-lefthand frame and the top-righthand frame contain contour plots of the amplitude of these velocity field components, while the lower lefthand and lower righthand frame show the corresponding vectorial representation of the velocities at the locations of the particles. In particular the bulk flow field provides a beautiful impression of the displacement of matter towards the emergence of large-scale features like filaments and voids. Most interesting though is that also the small-scale dispersion field appears to bear the marks of underlying large-scale features: not only do we see large "thermal" velocities at the sites of cluster concentratios, but we can also recognize sizeable small-scale velocities near the locations of filaments (see Van de Weygaert & Hoffman 1998).

When we compare the contour plots of the bulk motion and the dispersion velocities, we can already discern the fact that while we (i.e. the centre of the simulation box) are still embedded in a region of high bulk flow, evidently incited by the GA and the PP region, we also find ourselves in a region of exceptional low velocity dispersion. Evidently a nice reflection of the observed "coldness" of the local cosmos. We should not fail to notice that apparently these small-scale repercussions are the natural outcome of the dynamical evolution of a region possessing the large-scale features ($R > 5h^{-1}$Mpc) of the local universe.

Secondly, an inspection of the contour map of the spatial comsic Mach number distribution illuminates the significance of the "coldness" of the local cosmic flow. A comparison with the density map in Figure 1 reveals the interesting aspect of a large coherent band of high Mach number values running from the lower lefthand side to the upper righthand side of the simulation box, avoid-

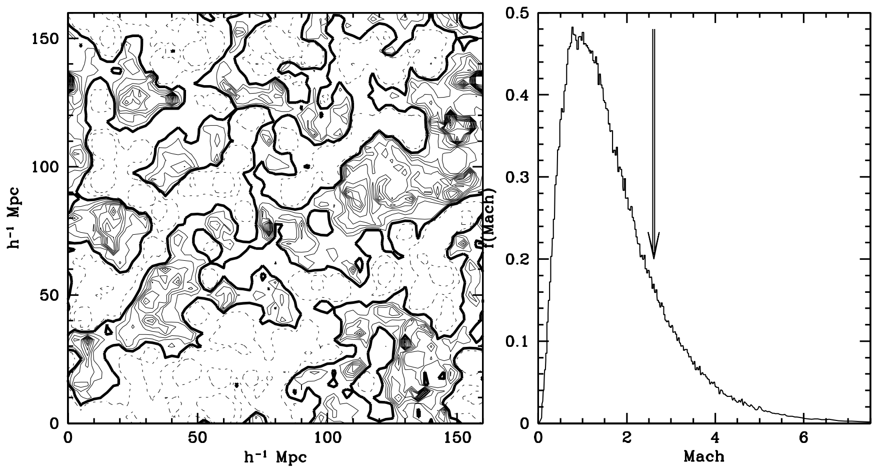

Figure 3.
Contour plot of the Mach number distribution in the central $x - y$ slice, together with the probability distribution function of the Mach number (bottom frame). The arrow indicates the location of the value of the Mach number at our cosmic location (centre of box), equal to $M = 2.61$ for the presented Local Universe simulated realization.

ing both the Great Attractor region and the Pisces-Perseus region, situated approximately in between those two complexes, almost along the bisecting plane that they define (see van de Weygaert & Hoffman 1998). Superposed on this large-scale pattern are a plethora of small-scale features. For our purpose the most significant of these is the fact that we appear to be right near a towering peak of the Mach number distribution. In fact, for this N-body realization of our Universe we find at the location of the Local Group a bulk velocity of 695.5km/s, a velocity dispersion of 266.5km/s and a Mach number of 2.61, corresponding to a percentile level of 82.1%. That point is stressed further by invoking the statistical distribution function of the Mach number in Figure 3b. Clearly we find ourselves somewhere in the tail of the distribution, potentially rendering it possible that we do live in a high-density Universe even though locally it's chilly ... Although the exact numbers differs for various realizations, and for instance the spatial patterns in the Mach number distribution amy display different features (narrower band, no conspicuous peak), the Mach number consistently assumes a value in the range above the 80% percentile value.

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