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COMMENTARY ON: ZEL'DOVICH YA. B., 1970, A&A, 5, 84

The conjecture of the cosmic web

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The well-known term "Zel'dovich approximation" was coined after Zel'dovich published his paper, and it is widely used in modern cosmological literature. He introduced a novel approach to the problem of structure in the universe. It is based on the Lagrangian version of the first-order perturbation theory of gravitational instability in the expanding universe. In 1969, when the paper was submitted, gravitational instability was considered one of the most promising models explaining the structure in the universe. However, its simplest mathematical formulation was based on the hydrodynamic equations that are next to impossible to analyze in the nonlinear regime for realistically posed initial conditions e.g., a realization of a random Gaussian field. The standard approach of the time was either to rely on particularly simple models, notably spherically symmetric and uniform ellipsoidal collapse, or to employ the Eulerian linear theory that was understood by that time. After 40 years of studies, we can state with confidence that neither approach could provide the slightest hint of the richness of the large-scale structures that can form via gravitational instability from Gaussian fields.

Zel'dovich was one of the main experts in gas dynamics; therefore, it was commonplace for him to use the Lagrangian description that is the most natural method when pressure is negligible. Deriving the equation of motion of particles to the linear order of accuracy is straightforward:

$$\boldsymbol{r} = a(t)\boldsymbol{q} + b(t)\boldsymbol{p}(\boldsymbol{q}). \quad (1)$$

Here, $\boldsymbol{r}$ and $\boldsymbol{q}$ are the Eulerian and Lagrangian coordinates of a particle, $a(t)$ is the scale factor describing the uniform cosmological expansion, $b(t) = a(t)D(t)$, where $D(t)$ is the function describing the linear growth of density fluctuations $\delta\rho/\bar{\rho} \propto D(t)$. The vector field $\boldsymbol{p}(\boldsymbol{q})$ is determined by the initial density fluctuations.

He did not stop there; instead, he applied Eq. (1) well into the nonlinear stage when orbit crossing occurred and, as he correctly thought, shocks must be formed. Filaments and pancakes do not emerge until the nonlinear stage (Aragón-Calvo et al. 2007)! In 1969, the idea of the universe dominated by collisionless dark matter had not yet been fully recognized, so Zel'dovich assumed that all mass was baryonic, therefore collisional. It was obvious for him that the motion of the fluid elements that collide with the shocks formed earlier cannot be described by his formula, but he believed that it is still applicable to other particles. Formally, the Zel'dovich approximation is accurate only to the first order; however, numerically it is significantly more accurate than the first-order Eulerian perturbation theory, and it is often described as a 1.5-order perturbation theory. More importantly, its extrapolation to the nonlinear stage does not produce nonphysical results such as negative density. A comprehensive discussion of the reasons it is so good cannot be done in a short commentary (see e.g. Shandarin & Zel'dovich 1989; Yoshisato et al. 2006, "Why is the Zel'dovich Approximation So Accurate?"). In short, studies of its accuracy have shown that it works better if the initial power spectrum of density fluctuations has a negative effective slope on the scale of nonlinearity. This is exactly the case in the ΛCDM cosmological model.

The synergy of the Lagrangian perturbation theory with its extrapolation to the beginning of the nonlinear regime is crucial for understanding and appreciating the Zeldovich approximation. Although the figures in his paper can be interpreted as correctly illustrating the formation of the three-stream flow region in collisionless medium, he treated them as a purely formal technical aid in 1969. However, as soon as the idea of the massive neutrino-dominated universe received experimental support (although erroneously) in the early 1980s, he realized that the formation of the regions bounded by the caustics resembling saucers did not tell the whole story. The deep physical and mathematical intuition of Zel'dovich urged him to initiate a deeper mathematical examination of the consequences of a seemingly simple Eq. (1). Zel'dovich attracted the attention of a great mathematician, Arnold, to this problem. The collaboration with Arnold resulted in the analysis of all generic singularities in 2D and an explanation for filaments was offered (Arnold et al. 1982). In addition, they promised to extend the analysis to 3D in the second part of the paper but it has not been written, although the full list of the normal forms has been found in 3D (Arnold 1982). Later, Vladimir Arnold (2004) pointed out that some mathematical ideas of Zel'dovich "anticipated subsequent mathematical investigations, sometimes by tens of years".

No matter how elementary the initial formulation of the Zel'dovich approximation may look at the present time, his ideas apparently did not seem trivial at all forty years ago. The vision that Zel'dovich laid out in this work was at least 10 or even 20 years ahead of its time. Initially very few cosmologists embraced the model: according to NASA ADS the first decade brought less than 30 references to the paper, about a half of which were either self-references or from his close collaborators. However, the number of references to the paper reached almost 500 in the last decade of the 20th century, and its annual rate has remained approximately steady since.

This recognition has apparently come from a new, younger generation of cosmologists. The majority of Zel'dovich's contemporaries seemed to strongly believe that the gravitational collapse must be close to spherical and that no structure can exist on scales greater than the correlation scale of galaxies i.e. several megaparsec. Unfortunately, the first cosmological N-body simulations in 1970s gave the impression that this was the case. In addition, full recognition of the reality of highly anisotropic superclusters of galaxies also had not happened until the second half of the 1980s despite strong support of the idea by some prominent astronomers including Oort (1983), who also argued that the superclusters are related to Zel'dovich's pancakes.

The first unambiguous recognition of the Zel'dovich approximation followed the realization of its practical use as a tool for generating the initial conditions in cosmological N-body simulations. The technique had already been used by Doroshkevich et al. as early as 1973. The other cosmologists started using it about ten years later. At present the majority, if not all, N-body codes that are used for cosmological simulations utilize the Zel'dovich approximation or, better to say, its linear ingredient.

Following the ideas of the classical hierarchical clustering scenario, some cosmologists have argued that the structure formation in the cold dark matter models including ΛCDM went through the sequence of halo mergers without significant coherence on scales of several tens of megaparsec. However, starting from the second half of 1980s the innate concepts of the Zel'dovich approximation, such as anisotropic collapse, tidal fields, and deformation tensor, have been steadily proliferating into papers on structure formation. Finally, it was realized that, in fact, large-scale structure in the cold dark matter models form an interconnected cosmic web of filaments and sheets, in agreement with the Zel'dovich insight (e.g. Bond et al. 1996).

Zeldovich was always looking for the observational consequences of his theories. It was necessary to find the physical mechanisms making filaments and pancakes long-lived, hence observable. Already in the last part of this paper, he mentioned the cooling of the gas compressed by shock waves arising from the intersecting trajectories of gas particles. He discussed this subject with one of us. As a result, the paper "Formation of Clusters of Galaxies; Protocluster Fragmentation and Intergalactic Gas Heating" was written (Sunyaev & Zel'dovich 1972). In this paper the properties of the shock formed by the gas entering the future cluster of galaxies was discussed; however, the same consideration was applicable to any of the shocks formed due to formation of the large scale structure of the Universe including filaments, peripheral regions in the clusters, and even superclusters of galaxies. At that time, we were discussing among ourselves the possibility of cosmic ray acceleration by these shocks in analogue with the shocks in supernovae. The main difficulty for us was how to convincingly explain the generation of the magnetic field in the shocked and preshocked gas. Finally we decided to postpone this part of the paper, and we never returned to it again. Today the shocks connected with large-scale structure and acceleration of cosmic rays by them are widely discussed as one of the principal sources of extragalactic cosmic rays including that of ultrahigh energies (see e.g. Miniati et al. 2001).

Zeldovich was explaining his solution to scientists who worked with available observational data on the large-scale distribution of galaxies. In particular, Zeldovich regularly visited the observatory near Tartu University in Estonia and often invited Jaan Einasto and Enn Saar to Moscow. This collaboration was very successful and led to the appearance of the well-known paper "Giant voids in the universe" (Zel'dovich et al. 1982), among several others.

Finally, the publication story may be of historical interest as well. At the end of the 1960s, it took several months for scientists in the USSR to obtain a permit to send an article to a foreign journal. An article that had passed an expert commission at the Institute had to be turned over to GLAVLIT (a special agency responsible for ensuring that no state secrets and no suspicious information got into the open press) and then sit and wait for permission for the article to be sent abroad. It was next to impossible to publish an article in a journal like ApJ. The security staff responsible for mailing articles abroad was aware that publishing in such journals requires payment in hard currency, and just did not let these envelopes go through. In 1969 during the IAU symposium N 36 in Lunteren, the Netherlands, Stuart Pottash, who at that time was one of the editors of A&A, invited one of us (RS) to publish in A&A. Sometime later, Stuart sent official letters to Zel'dovich and RS with an offer to send him articles that he was ready to publish for free, if the referee reports were satisfactory. Initially, Zel'dovich planned to publish his paper only in Astrophysics, Journal of Armenian astronomers (Zel'dovich 1970a), but then submitted another version to A&A. This paper was the first Zel'dovich ever submitted to A&A.

It is worth noting that the paper is written in the very characteristic Zel'dovich style that is especially conspicuous in the papers written solely by himself, i.e. very understandable without redundancy or repeating commonplaces, so it could be demanding for some readers. The Zel'dovich approximation is now a standard part of the most modern medium- and high-level textbooks on cosmology and is often used without reference to the original publication (see e.g. Springel et al. 2005), indicating one of the highest forms of recognition in science.

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