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Astrophysical Russian Dolls

Abraham Loeb and Nia Imara

“As it unfolded, the structure of the story began to remind me of one of these Russian dolls that contains innumerable ever-smaller dolls within.”

Carlos Ruiz Zafón, “The Shadow of the Wind” (2001)

Russian dolls display a miniature doll embedded in the belly of an identical version of itself, which lies in turn within an even larger doll replica and so on. *Does the Universe exhibit Russian dolls?* The immediate example which comes to mind is that electrons move around nuclei within atoms that lie inside planets which orbit around stars, as those stars circle around the center of the Milky Way galaxy. Each of the “dolls” in this classic example attracts the attention of a separate community of scientists which often ignores the other “dolls” despite their similarities. Aside from the aesthetic pleasure of recognizing scaled versions of similar systems, drawing analogies between them may unravel a fundamental truth that unifies their governing principles. The art of identifying common themes on different scales resembles the search for the common DNA characteristics of relatives from the same family.

Are there other examples of astrophysical Russian dolls, and what could we learn from their similarities? Below we list a few such examples.

- **Disks within disks.** Our Milky Way Galaxy consists of a disk of stars and gas, circling at a characteristic speed of 235 kilometers per second around a common center. At the Galactic Center lies a $4 \times 10^6 M_{\odot}$ black hole around which swirls a circumnuclear disk of stars and gas. Throughout the Galactic disk, newly forming stars, which are embedded in the molecular clouds circling the Galactic center, are also encircled by disks. The gas and dust in such protoplanetary disks eventually clump into planets, as was the case in our own Solar System five billion years ago. But this may not be the final “doll” in this system of astrophysical disks. State-of-the-art simulations suggest that planets, in the early stages of their evolution, are surrounded by a miniature disk of gas (see the smallest doll in Figure 1). Future advancements in technology might enable us to detect the presence of such disks around nascent planets.

Asteroid formation in a disk around a planet and planet formation in a disk around a star may have fundamental similarities to molecular cloud formation in the Galactic disk and star formation around the central black hole. By recognizing generic dynamical processes in one of these systems, one could make new predictions for the properties of the others.

Of course, in drawing such analogies one should keep in mind the important differences between galactic and protoplanetary disks, including the different temperature scale, magnetic field strength, turbulence, and ionization state of the gas.

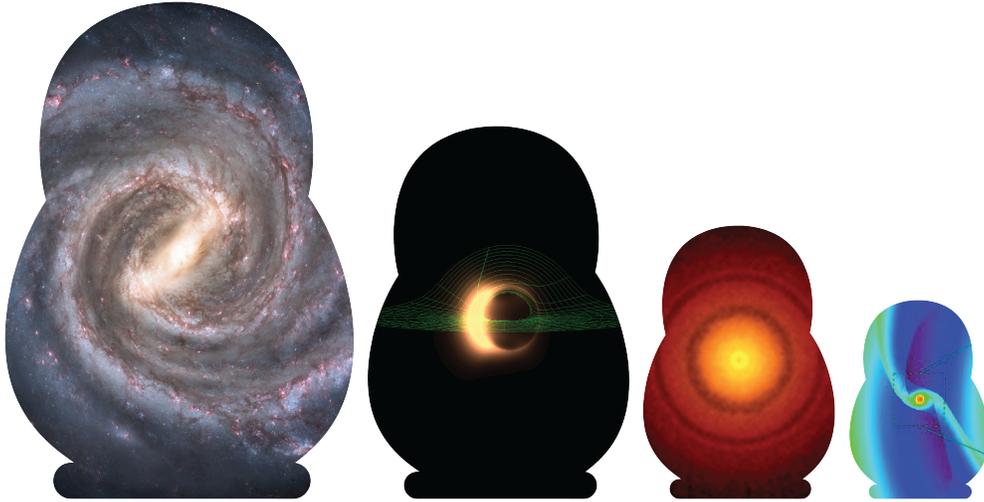


Fig. 1.— Astrophysical Russian dolls—disks. Credits for dolls, largest to smallest: Artist’s impression of a spiral galaxy (NASA). Simulation of Sgr A* and its disk (A.E. Broderick & A. Loeb). Observation of protoplanetary disk (S. Andrews/B. Saxton/ALMA). Simulation of a disk around a planet (James Stone and collaborators, Princeton.)

- **Filaments within filaments.** Under the action of its own gravity, each overdense region in the Universe tends to collapse first along its short axis - creating a sheet, then along its medium axis - creating a filament, and finally along its long axis - creating a compact object like a galaxy or a group of galaxies. As a result, the diffuse intergalactic medium (IGM) is organized into sheets and filaments, constituting a “cosmic web” (see Figure 2) that serves as a skeleton for the large scale structures in the Universe. Inside galaxies, which are located at the nodes of intersecting intergalactic filaments, the interstellar medium (ISM) repeats this pattern. Within the Milky Way disk, for example, blast waves set off by supernovae may be responsible for the network of sheets and filaments characterizing the morphology of the interstellar atomic gas, as revealed by recent high-resolution observations. Colliding flows of neutral atomic gas or other types of instabilities trigger the formation of molecular clouds, the dark, frigid structures inside of which stars form. In recent years, infrared observations by the *Herschel Space Telescope* have revealed that molecular clouds are threaded by complex webs of parsecs-long, skinny, dense filamentary structures. Once the mass per unit length of a filament exceeds a critical value, it may become gravitationally unstable and fragment into pre-stellar cores. Observations and simulations of interstellar filaments indicate that embedded cores grow by accreting gas channeled along these filaments. Similarly, cosmological simulations suggest that cold streams of gas flowing along IGM filaments supply galaxies with the bulk of the fuel required for star formation. Scaled threadlike versions of similar substructure may exist in this system of filamentary Russian dolls. Possible evidence for so-called “fibers” have been observed in Galactic molecular clouds and in ISM simulations. The leading interpretation

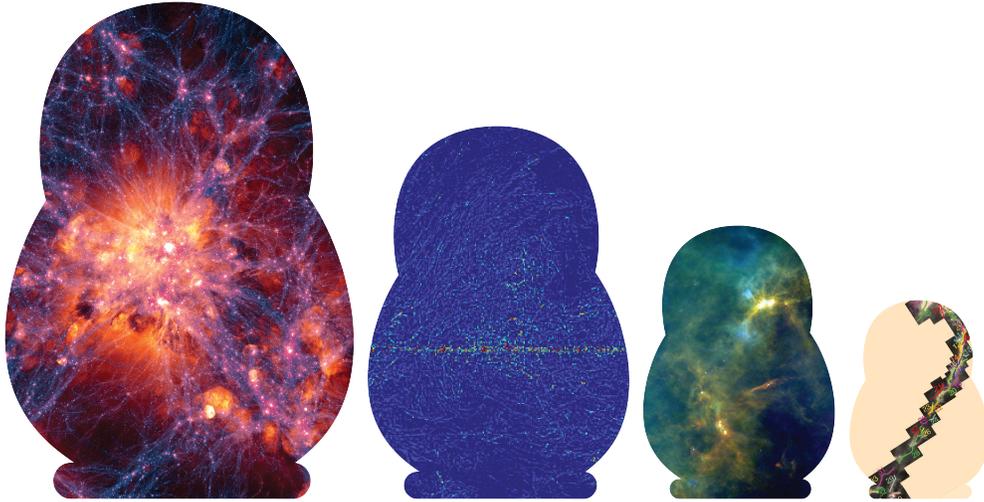


Fig. 2.— Astrophysical Russian dolls—filaments. Credits for dolls, largest to smallest: Simulation of intergalactic filaments (Lars Hernquist and collaborators, Harvard). Observation of Galactic neutral atomic hydrogen (P. M. W. Kalberla et al.). Observation of filaments in a molecular clouds (ESA/Herschel/PACS/SPIRE/V. Roccatagliata, U. München). Observation of fibers within a filament (A. Hacar et al.).

is that large scale filaments in the ISM are not simple cylindrical structures but, rather, are composed of intricate bundles of fibers which, if they are gravitationally unstable, ultimately fragment into cores.

Despite the similarities in appearance, the formation mechanisms of intergalactic and interstellar filaments may be quite different. The consensus view of cosmologists is that the IGM filaments grew out of gravitational instability, whereas filaments inside molecular clouds may arise from magneto-hydrodynamic turbulent compression of interstellar gas. However, some fine structure of the IGM filaments may be induced by outflows from galaxies which shape the gas around them similarly to the way stellar feedback and turbulence shape the small-scale structure in the ISM.

- **Clusters within clusters.** Galaxies tend to cluster. And each spiral galaxy includes a gravitationally bound disk of gas, containing molecular clouds that are frequently clustered in giant molecular associations, which are possibly held together by the mutual gravitational attraction. While the smallest molecular clouds in our Galaxy may be confined by the pressure of the ambient interstellar medium, it is widely accepted that the most massive, *giant* molecular clouds are held together by gravity. Nested hierarchically within molecular clouds are dense cores of gas, the very densest of which go on to form clusters of stars.

Thus, the long range, scale free, force of gravity manifests itself in similar ways over a wide range of clustering scales.

The pursuit of scientific knowledge is rooted not only in human curiosity and the desire to understand the natural world, but also in our innate need to enjoy and seek the beauty associated with the patterns and symmetries of nature. Forging connections across disciplinary borders enhances our perception of beauty, while simultaneously leading to a more comprehensive understanding of the Universe. The reinforcement acts also in reverse—as our understanding of the Universe improves, so is our sense of its beauty.

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