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Astrophysical Russian dolls

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Scientists are comfortable in their own communities but other groups working on similar phenomena at different length scales could provide unexpected insights. Collaborations are more likely to uncover common underlying principles.

Russian dolls feature 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 that 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 centre 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 fundamental truths 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 provide a few such examples.

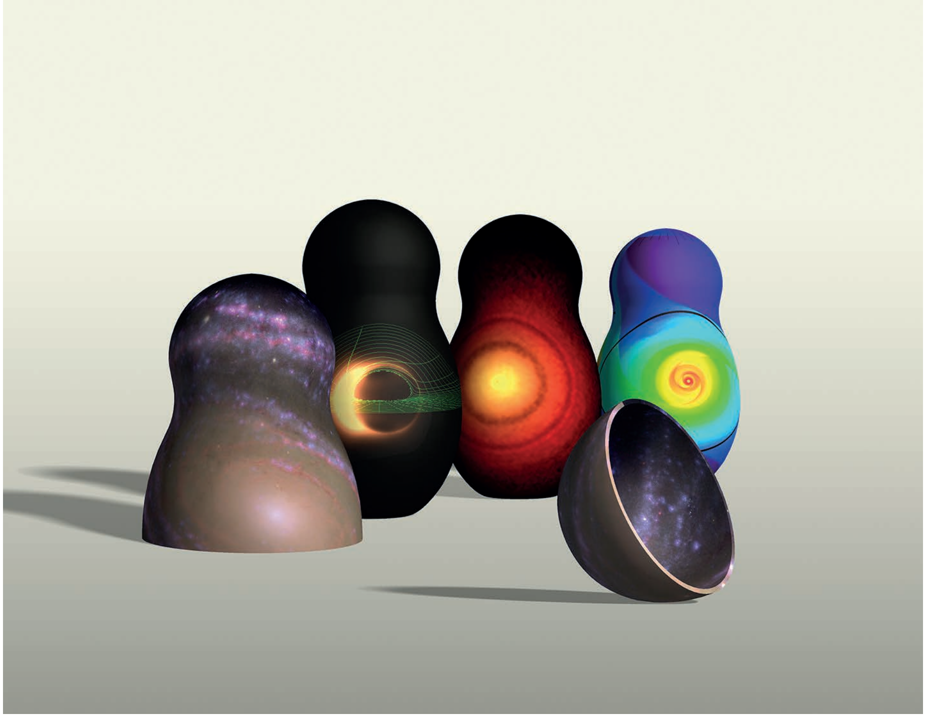

Figure 1 | Disks as astrophysical Russian dolls. The physics of a disk-like spiral galaxy may have similarities with the physics of protoplanetary disks. Unless separate groups of scientists collaborate, they might as well live on disconnected surfaces, as represented by the nested dolls. From largest to smallest: observation of a spiral galaxy (Messier 81, image credit: NASA/JPL-Caltech/ESA/Harvard-Smithsonian CfA); a simulation of Sgr A* and its disk (reproduced from ref. [5], Scientific American, a division of Nature America); observation of a protoplanetary disk[6] (image credit: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)); a simulation of a disk around a planet (reproduced from ref. [1], IOP).

Disks within disks

Our Milky Way galaxy consists of a disk of stars and gas, circling at a characteristic speed of 235 kilometres per second around a common centre. At the Galactic Centre lies a black hole, with a mass of four million Suns, 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 Centre, 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 smallest doll in this system of astrophysical disks. State-of-the-art simulations[1] suggest that planets, in the early stages of their evolution, are surrounded by a miniature disk of gas (see the smallest doll in Fig. 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, we could make novel predictions for the properties of the others.

Of course, in drawing such analogies we 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.

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[2], constituting a 'cosmic web' (Fig. 2) that serves as a skeleton for the large-scale structures in the Universe.


ILLUSTRIS COLLABORATION

Figure 2 | The cosmic web. A large-scale simulation of galaxy formation by the Illustris Project shows filaments around a massive cluster[2]. Filaments stretch between galaxies and clusters of galaxies, but are also present in molecular clouds within the interstellar medium.

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[3]. 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 channelled 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 such 'fibres' have been observed in Galactic molecular clouds and in ISM simulations[4]. The leading interpretation is that large-scale filaments in the ISM are not simple cylindrical structures but, rather, are composed of intricate bundles of fibres 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 magnetohydrodynamic turbulent compression of interstellar gas. However, some fine structure of the IGM filaments may be induced by outflows from galaxies that shape the gas around them similar 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 also acts in reverse — as our understanding of the Universe improves, so does our sense of its beauty.

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