Predictive modelling of galactic star and planet formation

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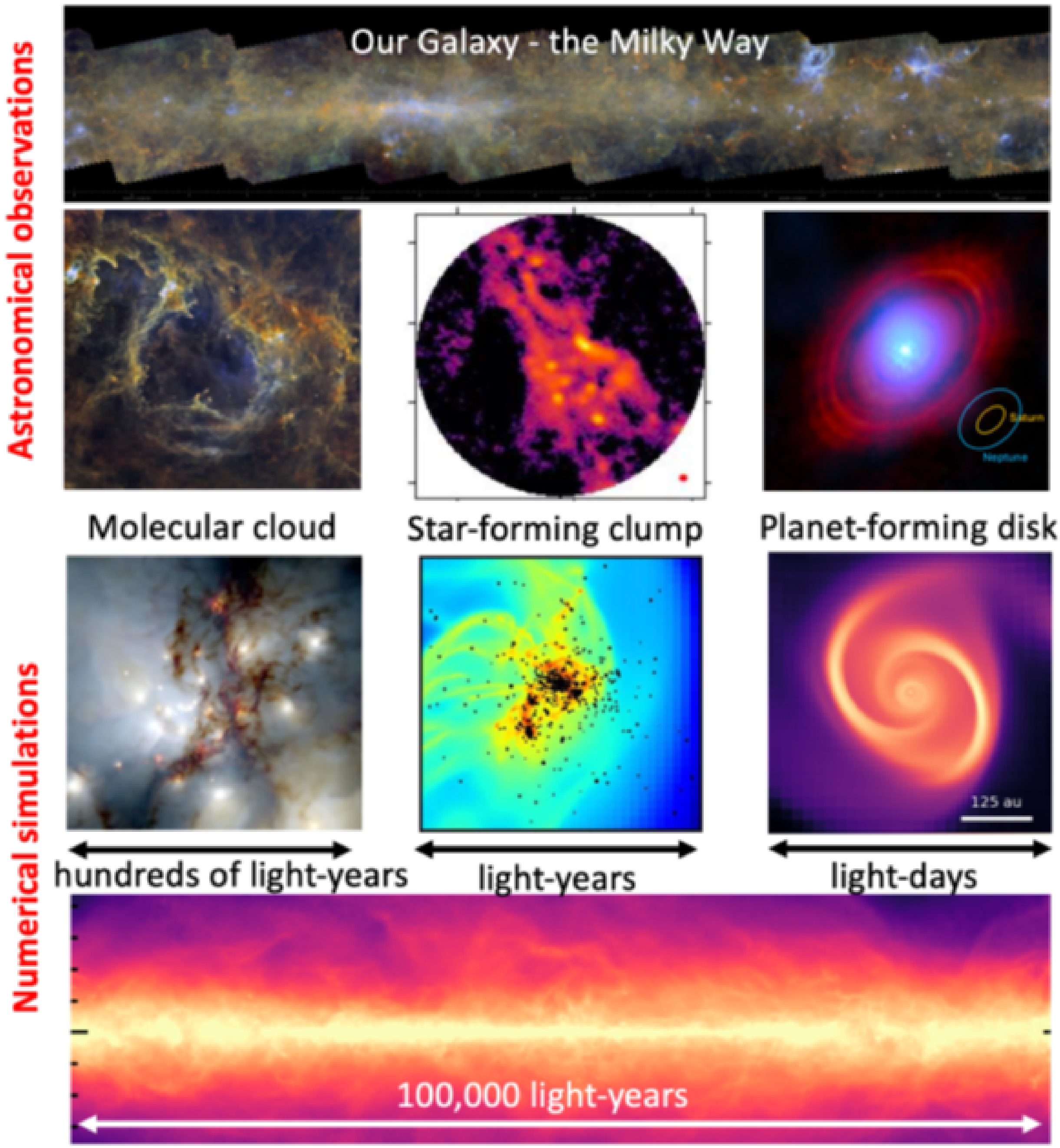

Figure 1 - The figure illustrates the diversity and multi-scale nature of the structures in the Galaxy. The first two lines are real astronomical images, which go from the galactic disk itself and down to the planet-forming disks. The last two lines are generated from numerical simulations and aim to understand and interpret the observations. [adapted from Facchini et al. 2025, Göller et al. 2025, Hennebelle et al. 2022, Lebreuilly et al. 2024, Molinari et al. 2016, 2025, Reissl et al. 2016]

This article details advancements in our understanding of star and planet formation within galaxies, emphasising the transition from steady-state models to recognising the dynamic nature of the interstellar medium (ISM) in these processes

Modern astronomy has revealed that the Universe began in an extraordinarily simple state – almost perfectly uniform, with only minute fluctuations in density. Today, more than 13 billion years after the Big Bang, the cosmos is richly structured on every scale, from vast galaxy clusters down to stars, planets, and even complex organic molecules. In this cosmic hierarchy, galaxies – along with the stars and planets they contain – serve as fundamental building blocks. Understanding their origins and the physical processes that drive their evolution is one of the most significant challenges in contemporary astrophysics.

We are currently witnessing a paradigm shift in our understanding of galactic and stellar evolution. Earlier models typically assumed that galaxies like the Milky Way and their internal structures exist in a quasi-steady state, evolving slowly over long timescales.

However, it is now clear that the interstellar medium (ISM) – and the formation of stars and planets within it – is governed by highly dynamic, non-equilibrium processes. These span vast ranges of space, time, and energy, and are regulated by complex networks of feedback loops. To build a comprehensive model of the Galaxy, we must view it as a single, interconnected ecosystem (as illustrated by Figure 1) – an inherently nonlinear, far-from- equilibrium system that demands a statistical treatment, an extensive inventory of galactic environments, and an understanding of how these environments vary across scales.

From galaxies to solar systems: A multi-scale, multi-physics challenge

It is well established that galaxies host a continuous, complex cycle of matter and energy. At the heart of this cycle is the ISM – a turbulent, multi-phase medium whose flow patterns govern the rate and location of star and planet formation. Stars emerge in regions of the ISM that collapse under their own gravity, increasing in density by over 25 orders of magnitude and heating up by factors of millions. This process culminates in the ignition of nuclear fusion, marking the birth of a star.

Star formation is regulated by the intricate interplay between gravitational collapse and opposing forces such as supersonic turbulence, magnetic fields, radiation pressure, and thermal gas pressure. The gas's thermodynamic evolution – shaped by the balance of heating and cooling processes – depends critically on chemical composition and the interaction between dust, gas, and the ambient radiation field.

Moreover, star formation does not occur in isolation. It is influenced by large-scale galactic dynamics, including spiral density waves and interactions with satellite galaxies. Feedback from newly formed stars – via radiation, stellar winds, and supernovae – plays a crucial role in shaping the ISM's thermal and chemical state, thereby affecting future generations of star formation. This ongoing cycle also produces and redistributes heavy elements, which are essential for forming planets and complex molecules. Without this recycling of matter, the chemical diversity we observe on Earth and throughout the cosmos would not exist.

The need for multi-wavelength, multi-scale observations

Direct observations of the ISM remain a cornerstone of astrophysical research. These require cutting-edge facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) – currently the world's most advanced radio interferometer – and space-based observatories like the James Webb Space Telescope, which can observe wavelengths inaccessible from the ground. Crucially, it is the combination of observations across multiple wavelengths, resolutions, and physical scales that provides the comprehensive diagnostics needed to unravel the physical and chemical conditions across different galactic environments. This is illustrated in the first two rows of Figure 1, which highlight several key structures: the galactic disk midplane (top row), spanning several hundred thousand light-years; molecular clouds, measuring hundreds of light-years; star-forming clumps, a few light-years across; and finally, planet-forming disks, only a few light-days in size.

The role of high-performance numerical modelling

To fully capture the complexity of the Galaxy and interpret the complex, highly degenerated astronomical observations – from large-scale galactic dynamics down to circumstellar and protoplanetary disks – state-of-the-art numerical simulations are indispensable. Thanks to advances in high-performance computing, simulations can now incorporate a wide range of relevant physics, including gravity, turbulence, radiative transfer, magnetic fields, and chemical evolution.

One of the key challenges lies in bridging the enormous range of spatial scales – from hundreds of light-years down to fractions of an astronomical unit. This demands adaptive zoom-in techniques. Typically, a simulation begins with a large-scale model of an entire galaxy or star-forming region, computed at a resolution that balances physical accuracy with computational feasibility. Within these simulations, high-density regions – where star formation is likely to occur – can be identified and then re-simulated with much finer resolution. This local refinement drastically increases the number of computational elements in targeted regions, allowing for a detailed exploration of star and planet formation while maintaining the broader galactic context (see the last two rows of Figure 1).

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