PERSPECTIVES TO SIMULATE GALAXY DYNAMICS

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Abstract. The current practices of modeling the dynamics of galaxies can be projected for the next decade. The exponential growth of computer capabilities has reached a threshold where the particle representation is a superior way to capture subtleties of galactic dynamics than Boltzmann's perfect phase-space fluid representation. The up-to-now often neglected departures of strict symmetries and time invariance of the actual Milky-Way, and the impact on dynamics of stellar physics will need to be modeled in more detail in order to match the observational data and extract more information of it . This will be possible with the coming generation of computers which will allow to represent each individual star of a galaxy. Modeling the interstellar medium will remain a difficult problem for more time though.

1 Introduction

The continuous advances in observational techniques require sometimes to set back and re-examine whether current theoretical methods and assumptions need to be readjusted. The joined exponential growths of the amount of observational data and of the computer capabilities mean that some threshold may be reached beyond which radical changes must be made: this is a typical sign of a scientific "revolution", although this word sounds exaggerated when applied to a specialized field like Galactic astronomy. Indeed, the real major revolution impacting all the society comes from the continuous advances over 60 years of the technologies associated with semi-conductor electronics.

The question we want to address here is whether Galactic astronomy is close to such a threshold. The answer is clearly yes for the period 2010-2020 as argued below.

2 Moore's law

The growth of computing power is a historically unprecedented technological jump, where we have seen about a 30 times performance growth every 10 years over 60 years for electronic components based on semi-conductors. This is commonly called the Moore law, after Gordon E. Moore pointed out (1965) that the transistor density in integrated circuits doubled every year. This growth leads to technological and economical pressure on other technologies like data storage which are incited to follow a similar exponential growth. Almost all the sectors of the society are progressively transformed, including sciences. Most of the progress achieved for example in medicine, or astronomy, follows actually for a substantial part from this technological revolution, which allows pervasive computing.

The other essential aspect of Moore's law is economic. The growth of performance occurs not only in an absolute way, but also on the proportionate decrease of cost for a given performance. This means that a given computational capability is accessible to a larger and larger proportion of laboratories, scientists and people. The performance of the present top super-computers will become easy to afford for average scientists after about 5 to 15 years, and for the general public after 20 to 30 years. For example, a present-day laptop computer is comparable in power to a top high-performance computer of the 80's.

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3   Purpose of computer simulations

For sciences dealing with complex problems, like biology, earth-sciences, or astronomy, high performance computing plays the role that mathematics has fulfilled over the last centuries for physics: to provide tools for modeling the studied objects in a controlled and abstracted way. Physics could profit more of the tools of mathematics than other fields because the studied systems are selected to be as simple as possible. In complex fields the simplest systems are already too complicated to be handled by a pen and paper approach. In astronomy, already an isolated star or an isolated galaxy as a whole are too complicated to be described without computers. This is the reason why the understanding of these objects really progressed since the availability of computers.

Modeling with mathematics or computers is invaluable to reduce the apparent complexity of the studied problems to a level which can be grasped with our finite brains. Indeed, understanding a process is reaching a level of mental representation sufficiently intuitive for not requiring any calculation. As an example, practitioners of galaxy simulations can eventually figure out the outcome of particular initial conditions before performing the computation, like "seeing" in advance how the collision of two galaxies will proceed.

Thus computational science plays an increasingly important role in sciences, complementing traditional mathematics with new tools with no earlier counterpart. Once a complex process is understood, i.e., represented in a way manageable by a human brain, it is possible to think about it, and either find applications for applied sciences, or how to progress along the quest of knowledge in fundamental sciences. In astronomy, typically a better understanding allows to steer observations or instrument development in a more efficient, intelligent way than practicing blind search.

4   Change of paradigm

For a long time the best representation of a collisionless stellar system was thought to be Boltzmann's equation without collision term,

$$\partial_t f + \vec{v} \cdot \partial_{\vec{x}} f - \partial_{\vec{x}} \Phi \cdot \partial_{\vec{v}} f = 0, \tag{4.1}$$

where $f(\vec{x}, \vec{v}, t)$ represents the phase space mass density, and $\Phi(\vec{x}, t) = -G \int d^3 x' \rho(\vec{x}', t) / |\vec{x} - \vec{x}'|$ is the gravitational potential generated by the spatial density distribution $\rho(\vec{x}, t) = \int d^3 v f(\vec{x}, \vec{v}, t)$. This continuous representation of, in reality, a granular mass distribution was made on the model of gas or plasma kinetic where the number of particles is typically of the order of 10^{26}, suggesting to take the limit of an infinite number of particles and to represent the flow of particles as a smooth differentiable flow in phase-space. Note that in gas kinetic the molecule collisions, even if rare, are the essential ingredient making the path of molecules chaotic, rapidly unpredictable, and leading to a smooth f. In stellar dynamics, without collisions the star trajectories may preserve correlations and memory of the past that should lead, a priori, to irregular, non-differentiable f. This point, how and why f should be differentiable, is an open question in stellar and galactic dynamics. A smoothing mechanism is required. A possible candidate is Miller's (1966) exponential N-body system instability, but this remains to be better documented.

In a galaxy made of N stars, N is however never very large as for molecules in a gas container. If we adopt $N = 10^{11}$ and want to discretize phase space in a number of bins, we can have at most N populated bins, that is, at most $N^{1/6} \approx 68$ divisions per phase space coordinate, which is not a very smooth representation of the, in principle, differentiable function f. Actually, with 1 cell per particle the representation is like a sum of delta functions, far from representing a differentiable function; using, say, 100 particles per cell to smooth fluctuations brings down the number of divisions per phase space coordinate to 32: the averaged function is smoother but the bin resolution is then lower.

So the collisionless Boltzmann equation when applied to galaxies has conceptual difficulties to match well the intended systems. In contrast, the N-body model is a much more faithful representation of an ensemble of stars in mutual gravitational interaction. The problem in the past was that the description of the N-body evolution was leading to a unaccessible amount of computations. Contrary to gas kinetics, classical thermodynamics is not applicable to stellar systems since gravitation is a long ranged force, making gravitational systems non-extensive. Extensivity is an essential assumption with usual statistical mechanics. As a result, astronomers have been forced to use numerical simulations to describe self-gravitating systems, which they did as soon as computers became available.

There are several observational constraints which also demand to abandon the idea that a differentiable f is a good way to represent the distribution of stars:

1. The local stellar kinematics obtained from from Hipparcos and other sources (e.g. Dehnen 1998) shows that the velocity distribution of local stars is non-smooth, made of clumps in phase-space. Here we obtain an observational local evidence that f is not well represented by a differentiable function resembling a Maxwellian distribution.

2. Infrared view of the spiral stellar content (e.g. Seigar & James 1998) shows that spiral arms are strong non-linear density perturbations, so that self-gravity is locally not negligible in stellar arms. This raises doubt that axisymmetric static Milky-Way models where spirals are at most weak perturbations in a smooth potential assumptions for describing the stellar motions inside the Milky-Way.

3. Milky-Way CO surveys, such as the one of Dame et al. (2001), show that cold gas distribution is very clumpy and irregular, unlike what would be expected using classical gas dynamics of non-self-gravitating gases. The clumpiness of molecular clouds actually shows the evidence that the gas distribution at least is highly time-dependent at small scale, introducing a "noise" in the global potential. Again molecular clouds are at least partly self-gravitating over a range of scales, which raises doubt about a straight use of thermodynamics in such systems.

4. The stellar halos of the Milky-Way and nearby galaxies has been progressively mapped in sufficient detail (e.g. Ibata et al. 2005) to show a highly intricate structure made of stellar streams and dissolving dwarf galaxies contradicting the classical representation of these halos as virialized, steady structures. If we include in the stellar halo the galaxies orbiting the Milky-Way and also perturbing it, we obtain again another source of time-dependence.

Otherwise there are theoretical evidences that typical galactic potentials must be time-dependent:

1. Sellwood & Sparke (1988) showed first that barred galaxies are surrounded by spiral arms that rotate at one or several pattern speeds, but slower than the bar one. This breaks the time invariance that can be kept in barred galaxies when describing the galaxy in the bar rotating frame of reference. There is no way to avoid therefore time-dependence in barred galaxies with surrounding spiral arms.

2. Fux (1997,1999) could match several of the inner Milky-Way characteristics and fine details in the stellar and gas distribution by running N-body simulations and finding the best location of the Sun in the disk and at a given time in the run. Each of the best fits found is only valid over a very short time, of order of a few 10^6 yr, which means that the model is highly time-dependent with respect to the level of detail of the Milky-Way that we can use for constraining models. It means that if we would observe the Milly Way a few 10^6 yr earlier or later, we would observe substantial differences, especially in the gas distribution.

All these works point to the need to consider the Milky-Way as a time-dependent and non-axisymmetric system. Only self-consistent N-body models can achieve the detail level required by future observational data.

5   Future simulations

Moore's law has brought us today to reach the level where $N \sim 10^{10} - 10^{11}$ particles can be followed in a super-computer. This has been achieved recently in cosmological simulations (Teyssier et al. 2009; Boylan-Kolchin et al. 2009), because cosmological simulations require less integration time steps than typical galaxy simulations. However with the growth of computer power it is clear that the threshold of representing every star, or every star more massive than the Sun, in a Milky-Way type galaxy model is within reach, less than 10 years. The sensible problem of softening then almost disappears. Only in this way can phase space correlations such as streams be studied and compared with observations. At this level star formation and evolution can be followed too, first in simplified ways. Energy and momentum transfer between stars and the interstellar gas is an important aspect of the global dynamics, but also it will be important to follow the stellar mass loss from AGB stars that over several Gyr must have also a dynamical effect on the global galactic structure.

The effects of the environment such as accretion will be more and more taken into account in galaxy models, because from the cosmological context the environment appears as having played an especially important factor in the past, but will continue to impact the evolution of the Milky-Way for the next billions years. For example our version of the Milky-Way/Andromeda merging, is forecast for taking place during the next $\sim 3 - 8$ Gyr. A snapshot of a movie of the whole sky appearance made for educational purpose is shown in Fig. 1.
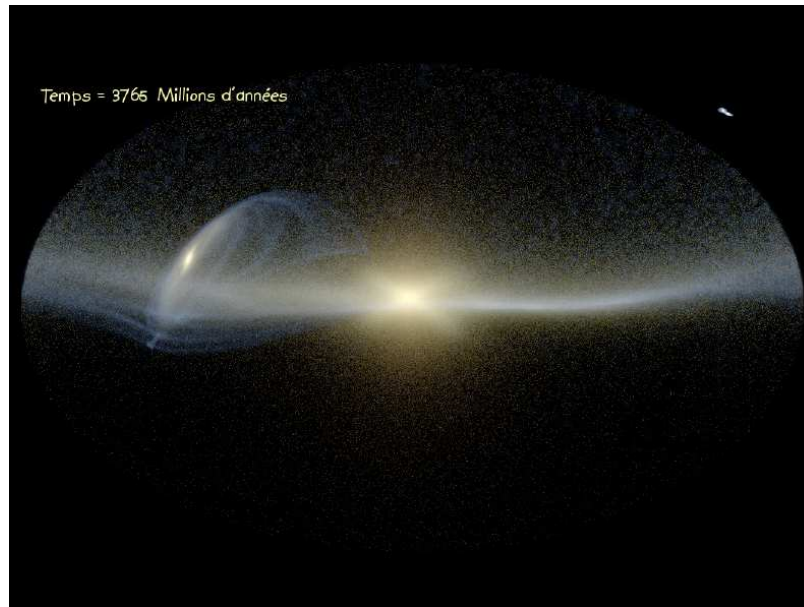
Fig. 1. The whole sky 3765 Myr from now as viewed from the Sun in a $30 \cdot 10^6$ particle simulation of the Milky-Way/Andromeda merging (Revaz & Pfenniger 2010). A drastic change of the Milky-Way appearance will occur illustrating how time-dependence then will still be a relevant property of the Milky-Way.

Interstellar gas dynamics will stay a very hard physical and computational problem though, due to the high dynamical and time ranges taking place in the interstellar medium. Springel (2009) using computational geometry methods (Voronoi cell spatial decomposition and finite volume scheme preserving flow invariants) has showed how to solve several pending problems in traditional Eulerian and Lagrangian hydrodynamical simulations. His scheme seems promising and removes in an elegant way shortcomings of both the Eulerian and Lagrangian approaches, at the expense of a larger software complexity.

In addition, the physics of the interstellar medium, and in particular of dust grains, is crucial for representing correctly cooling, chemistry and radiation transfer in the Galaxy. Presently the main barrier is more understanding the basic physics at play rather than modeling it on the computer. This is certainly an aspect that will need much more time than global dynamics for being mastered.

6   Conclusion

At the level of precision reached by present and future instruments, disk galaxies must be seen as time-dependent structures with multiple patterns rotating at different speeds. Modeling the optical part of the Milky-Way with N-body models containing as much particles as stars is feasible during the next decade. However gas and dust modeling will remain a difficult, not to underestimate problem for a longer time.

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