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Report on the PhD thesis manuscript of Ivana Ebrova

I have read the thesis document of Ivana Ebrova with great pleasure, since it is a very elaborate work on a fascinating topic: the formation of shells in galaxies due to minor mergers. Ivana Ebrova has studied in great detail the dynamic of the systems, and shown through numerical simulations that it is possible to use shells to derive information on the dark matter potential around elliptical galaxies, up to 100kpc in radius. She goes beyond the previous models of shells to derive more detailed predictions of their line-of-sight velocity structures, and predicts a quadruple split of the velocity profile for travelling shells, while two only were predicted in the approximation of stationary shells. This is a first step towards a more realistic prediction, and this opens a path for an application to real systems.

In her introduction, Ivana Ebrova has made a very detailed and up to date review of the nature of shells, and all the work done since decades on these systems. It is very interesting to see how astronomers have approached the problem, according to the performance of their instruments, and also their dynamical knowledge. Although shells were already seen in the Arp Atlas of Peculiar Galaxies, the topic has emerged with the work of Malin & Carter in 1983, and their particular clever unsharp masking techniques, to emphasize high spatial frequency features. Nowadays, with the sharp HST images, and the sophisticated numerical data processing, a lot of progress has been made to determine the frequency of shells (10% of elliptical, more in isolated sample, and less in clusters), the number of shells, their color (which varied with time, since large uncertainties were hindering early work), presence of dust, atomic and molecular gas, correlation with starburst (or post-starburst), with kinematically decoupled cores (confirming the merger scenario for the origin of shells), radio activity, etc..

On the modeling side, there were a large activity in the 1980s, since already shells carried the hope of probing the radial distribution of matter in elliptical galaxies. But disappointment was then brought by the realization that dynamical friction could blur the picture. Indeed, shells are thought to be formed when a small satellite is progressively stripped of its stars by tidal interaction, in the potential of a big elliptical in which is is falling. The satellite stars then move in nearly radial orbits, and phase-wrap in shells, as density waves peaking in density at apocenters. The remnant of the satellite experiments dynamical friction and is slowed down, and progressively the stripped stars will form shells in the inner parts of the elliptical potential, with less total energy. The radial distribution of stars then reflect the history of the stripping and slowing down of the satellite, but not the elliptical potential. A decade ago, the topic was revived by the consideration of the velocity profile at the tangent point of a shell. If the spatial region is small enough, it is possible to ignore dynamical friction, and just probe the gradient of the potential at the location of the shell. A simple approximation of zero velocity at the shell radius, leads to the prediction of a velocity profile split in two components.

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In a second large chapter, Ivana Ebrova has made more detailed calculations of shell formation in a spherical potential, and shows that if the velocity of the shell is considered, then stars moving out and moving in at a given point have not the same radial velocity in absolute value, and therefore the velocity profile along the line-of-sight is split in a quadruple instead of a double component. Of course, if the measurement is made close to the shell tangent, the amplitude of the splitting is relatively small, of the order of 40km/s, but this should be feasible with high resolution and sensitive observations, may be in the future. The analytical calculations are pushed quite far, to study all possible approximations, and the dependency of the results on the chosen parameters. Higher order approximations are pursued when possible. A good and thorough discussion is made of the validity of all approximations. Test-particule simulations are carried out and compared to the analytical work. It would have been nice to carry some simulations in non-radial orbits, which is not possible to do analytically, but is certainly closer to what is happening in nature. The gradient of the potential at the location of the shell can be retrieved, in the approximation that the observed velocities are the projection of radial velocities. Ivana Ebrova makes the mock observation of the model, and shows that indeed it is possible to retrieve correctly the potential introduced in the model, in the case of quadruple splitting, but not in the case of the double split of Merrifield and Kuijken (1998). However, it there exists tangential velocity (due to a non-radial merger), than the LOS velocity is a combination of tangential and radial components, and this needs to be taken into account, to estimate the potential gradient. This should be computed in a future study.

In a third part, Ivana Ebrova studies the dynamical friction in mergers of galaxies that will provide stellar shells. For that test-particule simulations are used, since a completely self-consistent simulation would be too expensive in CPU. More exactly, the Multiple Three-Body Algorithm (MTBA) is used, ignoring the self-gravity of the response of the primary particles, but trying to include the sum of the effects of each particle individually. With MTBA, a large enough number of particules (100 000) has been computed. These test-particule simulations were compared to a true N-body simulation performed with GADGET-2 by Bartoskova et al (2011). The number of particles and also the value of the time-step were varied, such as to reach convergence in the decay curve, and the time-scale of merging through dynamical friction.

Not only the dynamical friction is difficult to estimate, but also the tidal disruption of the satellite, which requires a large number of particles, and a high spatial resolution, especially for large values of mass-ratio between the primary and secondary galaxies. To deal with these complex matters, Ivana Ebrova has implemented an analytical approach, computing the tidal radius at each time-step. Particules that are considered unbound to the satellite can then freely start their independent radial oscillations in the potential of the primary galaxy. Another refinement is to consider for the spherical primary, two components, the luminous stellar one, and the dark matter halo, the differences being the radial scales and the velocity dispersions. Several test-particule simulations have been run, and one is compared to a full N-body simulation. Although the shells are not found at the same places, and the morphology of the shells are different, there is a rough correspondence between the two simulations.

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Finally, in the summary, Ivana Ebrova draws the main conclusions of her thesis work, and the main caveats due to the approximations done for the simulations, and also the limited capacity of the instruments to resolve the velocity profile of the shells. May be the main limitation comes from the hypothesis of a radial merger, since considering a non-zero impact parameter will imply an important angular momentum of the shells, and therefore a tangential component of the stellar velocity in addition to the radial one. This adds a degeneracy in the velocity profile, which is quit complex, since the dynamical friction plays a different role in the radial and tangential motions of the satellite. Ivana Ebrova discuss with realism the uncertainties, not only in the potential of the primary, but also in the age of the merger event, etc..
All the work is published in one paper in Astronomy & Astrophysics, and in several proceedings to conferences. Videos are also supplied, which illustrate scientifically but also esthetically the simulations.

In summary, the work of Ivana Ebrova is a very detailed and deep study of the dynamics of shell formation, and will be very useful to interpret future observations with high spectral resolution and high sensitivity. The work is going farther than the previous work, in showing that the velocity profile of a shell is not split into a double, but into a quadruple component. Ivana Ebrova has acquired a deep understanding of the galaxy dynamics, and has mastered the techniques of numerical simulations. I have much appreciated the writing of the manuscript, which is very pedagocical for future students working in the domain. The thesis with no doubt proves the author ability to creative scientific work. I fully support that Ivana Ebrova can defend her thesis and obtain her PhD in astrophysics.

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