Detailed formation history of the shell galaxy NGC 474

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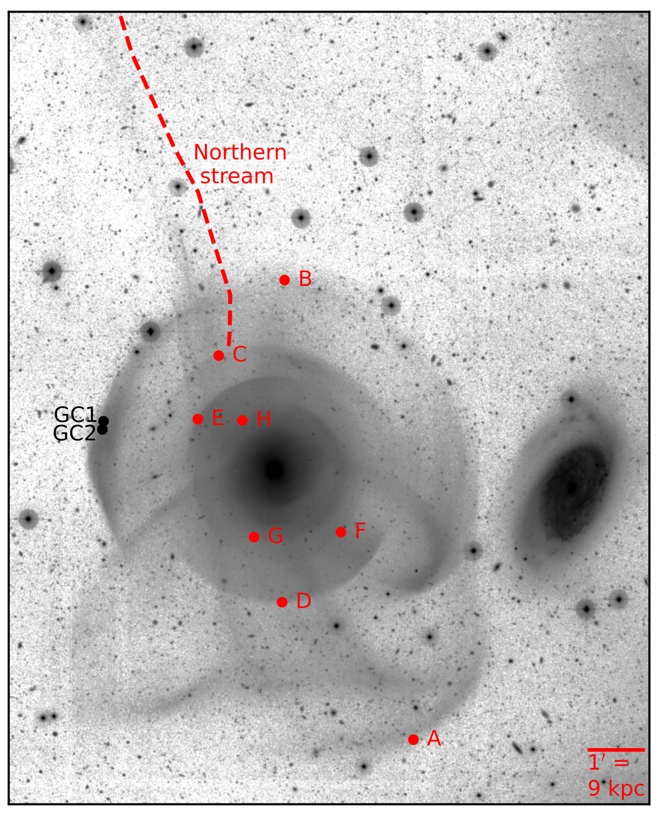
Abstract

NGC 474 is a nearby lenticular galaxy famous for its dramatic system of low-surface-brightness tidal shells and streams. Recently, the shells have been studied spectroscopically as the first shells in history. We contributed to the investigations of this prominent galaxy by applying the analytical shell identification method to estimate the time since the collision from the observed sizes of shells. Moreover run N-body simulations that reproduce much of the morphology of the galaxy employing either dark matter halos or the MOND gravity. We built a scenario of the formation of the galaxy that accounts for all observational constraints. We found that all of the tidal features in the galaxy were created by one accreted spiral galaxy that made two passages through NGC 474 before the galaxies merged ca. 1 Gyr ago. The timing derived from tidal features agrees with the ages of young stellar populations. There are hints that the merger was invoked by a three-body interaction involving NGC 470, which is the neighbor of NGC 474. This work indicates that it is possible to reconstruct the formation shell galaxies in surprising detail by combining their deep images with spectroscopy of their centers. Such data can now be routinely obtained. In the future, more elaborate simulations of this nearby well studied galaxy might help to distinguish between dark matter and MOND.

Introduction



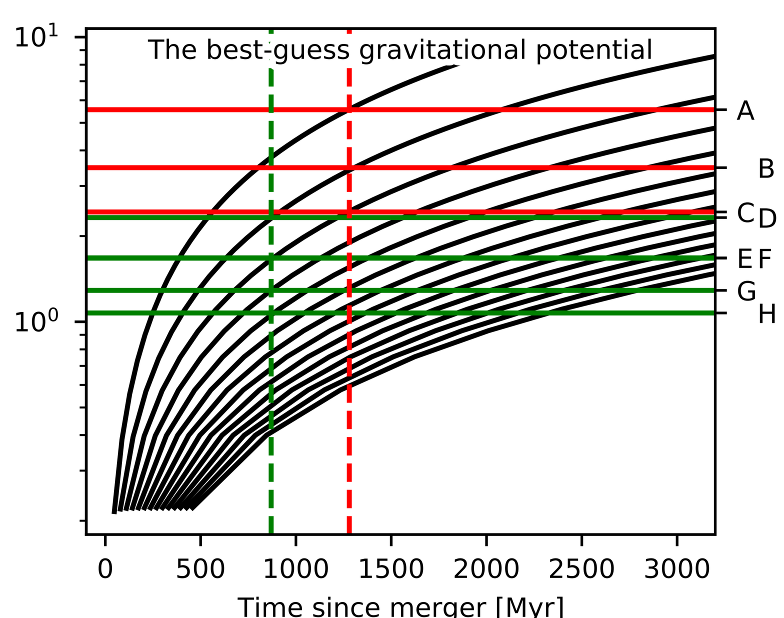
NGC 474 (left in the image) is nearby a Milky-Way mass lenticular galaxy forming a pair with the spiral NGC 470 (right). It hosts many bright tidal features, witnessing about past interaction with other galaxies. It contains at least ten shells (the circular features in the image). 10-20% of elliptical and lenticular galaxies host shells. The shell B of NGC 474 is one of the brightest shells known. Its spectrum has been published by Fensch et al. (2020) and Alabi et al. (2020) as the first shell spectrum ever. They found that the star formation history of the shell peaked about 2 Gyr ago. They discovered two young globular clusters in it, GC1 and GC2, with the ages of 1.4 and 0.5 Gyr, respectively. Moreover, they found a 0.9 Gyr old stellar population in the center of the galaxy, overlaid on an old stellar population typical for a lenticular galaxy. The observations opened the question of whether and how are these stellar populations and tidal features causally related and whether all the numerous tidal features originate from an interactions with only one companion. We investigated these questions in **Bílek et al. (2022)**.

The origin of the shells in NGC 474

Shells seem to usually form in nearly radial collisions of galaxies with different masses. The shells are made of stars of the smaller galaxy, which had been disrupted by tidal forces. The edges of shells are made of stars which reach the apocenters of their nearly radial orbits. Several shells are formed each time the two galaxies go through their orbital pericenter. The shells gradually increase their size in time.

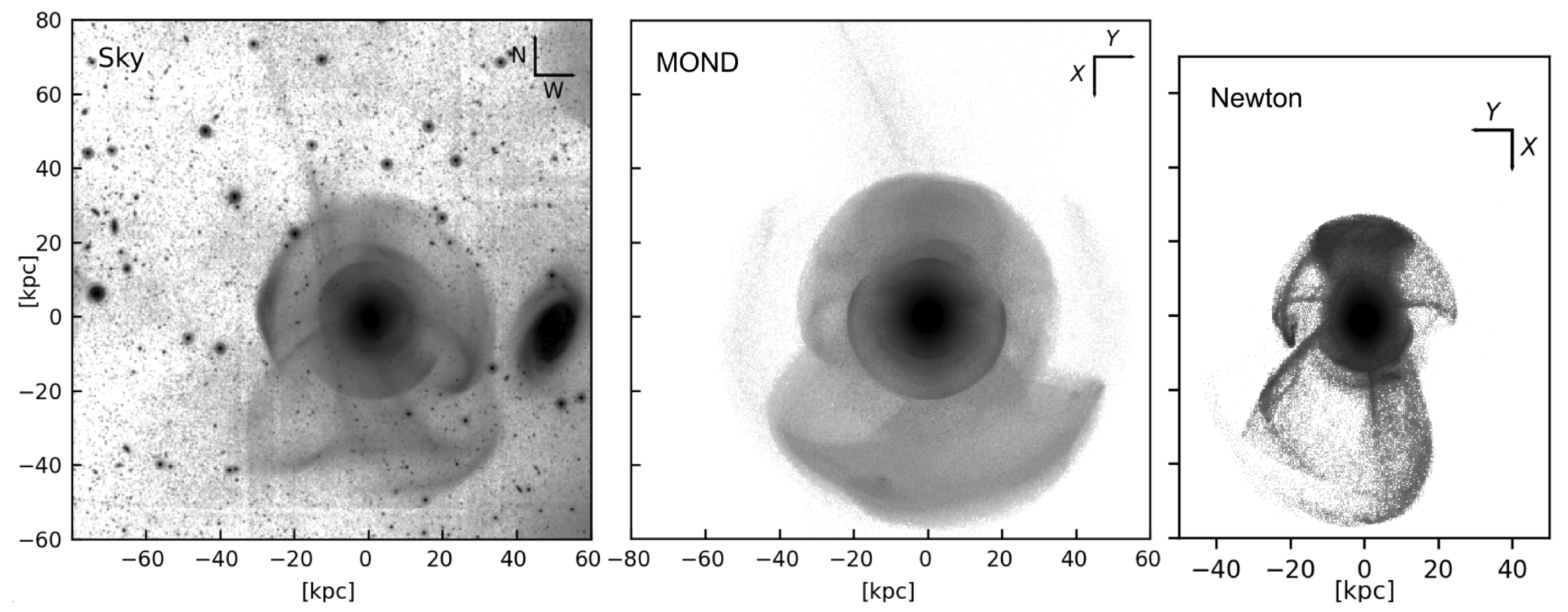
There are clues that the shells in NGC 474 formed by accretion of a smaller spiral galaxy: there are unrelaxed dust patches in the galaxy, HI gas emission and the young stellar population in the center. The fact that the material in the shell was forming stars until recently indicates the same. Finally, shells and streams resembling those in NGC 474 can be seen in a simulation by Dupraz and Combes (1987), where they were formed in a merger of an elliptical and a spiral. Photometry and spectroscopy of the shells indicate that the merging galaxies had a mass ratio of 1:4-1:40.

Estimating the ages of the shells



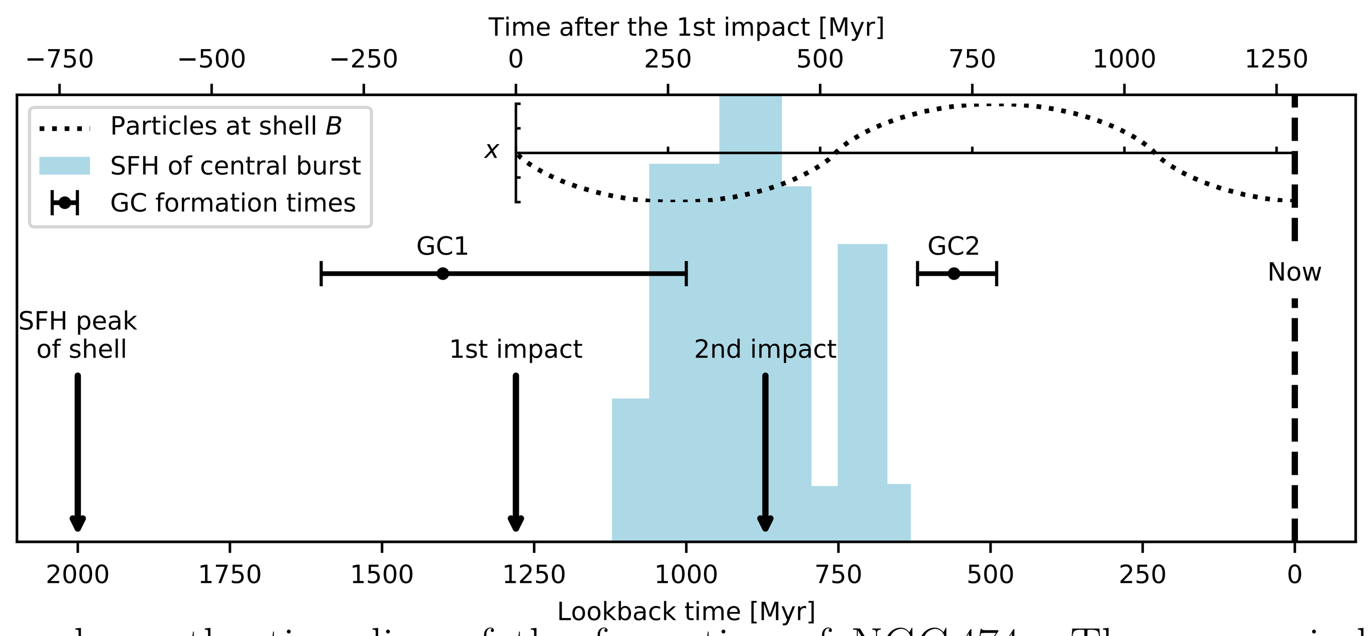
It is possible to estimate the age of the shells using the shell identification method (Bílek et al. 2013). It is based on the fact that the shell radii depend primarily on the gravitational potential of the host galaxy and the time since the stars making the shells were stripped from the satellite. Currently, MOND (Milgrom 1983) is the most reliable way to estimate the gravitational potentials of galaxies similar to NGC 474 (Bílek et al., 2019). In the figure, the curved lines show the modelled evolution of radii of the shells of NGC 474. The radii of the observed shells are marked by the horizontal lines. The observed shells can be divided by two groups, as indicated by the colors, such that each group is reproduced by the model at a certain time. We interpret this such that the stars forming the shells were stripped from the satellite during its two pericentric passages around NGC 474. This agrees with what we see in our simulations and it can explain the ages of the different stellar populations in the galaxy, see below.

Simulation of the collision



We made Newtonian and MOND self-consistent N-body simulations of merging galaxies that lead to formation of objects similar to NGC 474. Gas was not included. The simulations suggest that all tidal features in NGC 474 were formed from one accreted spiral that arrived to NGC 474 in the plane of the sky from the south and its rotation axis pointed to the Earth. Hinted by observations, we used the stellar mass ratio of the merging galaxies of 1:6.

Explaining the ages of young stellar populations



The figure shows the time line of the formation of NGC 474. The arrows indicate the recovered peak of star formation history of the shell, and the times of the two impacts of the accreted galaxy as deduced from the positions of the shell. The histogram of the ages of the young stars in the galaxy center is shown in blue. We can see that the central starburst began shortly after the first impact, where we expect it. The age of the young globular cluster GC1 agrees with the time of the first impact, which suggests that its formation was initiated by a tidal shock during the pericenter of the merging galaxies. The progenitor gas cloud of second globular cluster, GC2, survived the first impact of the accreted galaxy, but became detached from it. The cloud made a swing in the potential well of NGC 474 and formed the cluster when it reached the center of NGC 474 again. The peak of the star formation history of the shell B is likely not related to the merger. The shape of star formation history of the shell agrees with the shapes we observe other galaxies that have masses similar to the one that was accreted by NGC 474 (Sánchez et al., 2019). Gravitational potentials predicted by other algorithms than MOND lead to ages of shells that do not agree with the star formation events that well.

Does NGC 474 prefer between dark matter and MOND?

Our MOND and Newtonian simulations each reproduce certain features of the galaxy better than the other. The MOND simulation reproduces better the sizes of the tidal features and the presence of the Northern Stream. The Newtonian simulation rather reproduces better the internal structure: the disjoint appearance of the shell A and the filamentary density enhancements at the bottom borders of the shell B. The advantage of each was a persistent disadvantage of the other in all simulations we made. Nevertheless, we varied mostly the orbital configuration. Exploring the influence of the initial internal structure is necessary before drawing conclusion which gravity model works better.

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