# Galactic "rocket engine" explains unusual stellar motion in galaxies

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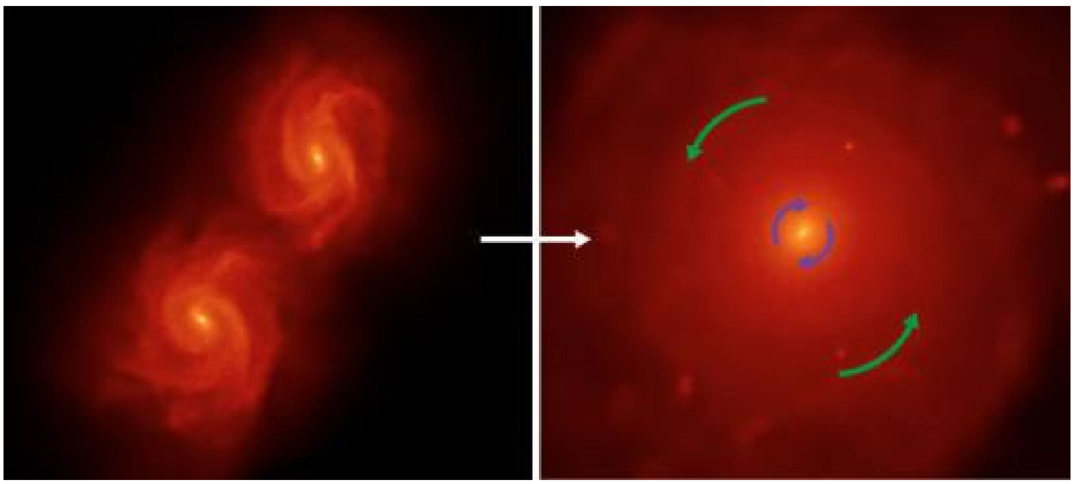


Snapshots from the simulation where Tsatsi made her discovery of the "galactic rocket engine". Left: the two galaxies before the merger; right: the resulting elliptical galaxy after the merger. Credit: B. Moster / MPIA

A discovery by MPIA graduate student Athanasia Tsatsi has changed astronomers' understanding of how mergers of two galaxies can produce unusual stellar motion in the resulting elliptical galaxies, with the central region rotating in the direction opposite to that of the galaxy's other stars. Previously, such differences had been thought to be the result of an opposite ("retrograde") orientation of the galaxies prior to their merger. Looking at a simulation of a galaxy merger, Tsatsi discovered a different way of bringing about such counter-rotating cores, which involve mass loss from the bodies of these galaxies acting as a primitive galactic "rocket engine."

In so-called elliptical galaxies (which are shaped like somewhat flattened spheres), the movement of stars can show an intriguing pattern, with stars in the outer regions all rotating around the center in one way, while stars in the core region jointly rotate in a completely different direction.

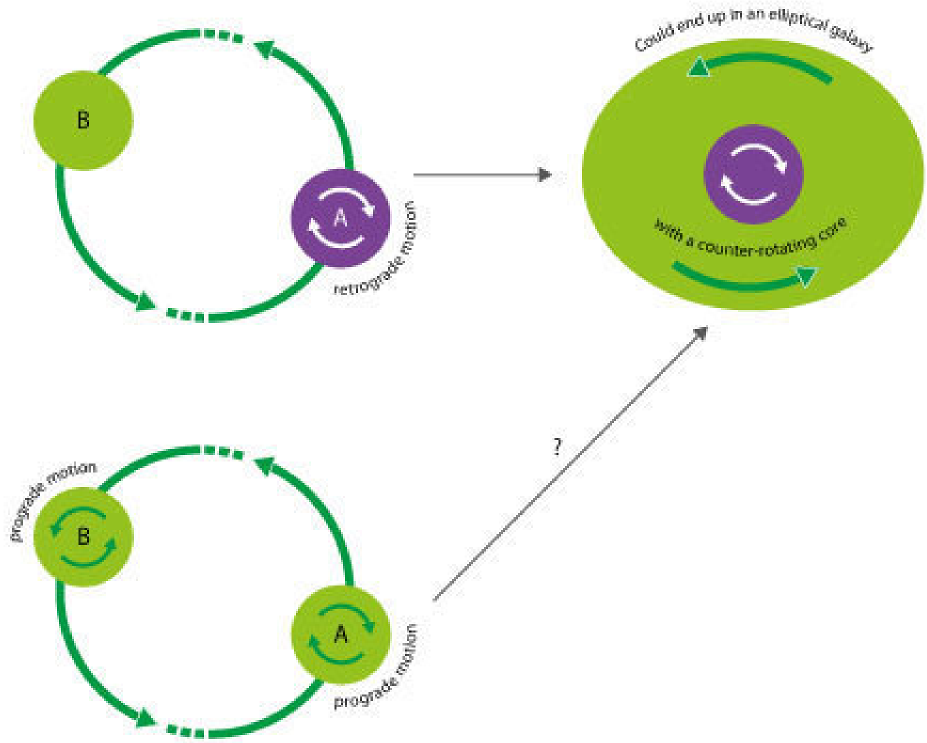
Elliptical galaxies are the result of the collsion and merger of two or more disk galaxies (such as our home galaxy, the Milky Way). Previous explanations had assumed that counter-rotating (or, more generally, "kinematically decoupled") cores can form if one of the merging galaxies has a tightly bound core region, with just the right orientation relative to the galaxies' orbit during the merger. However, this explanation predicts fewer counter-rotating cores than are actually observed.

That was the situation when Athanasia Tsatsi at the Max Planck Institute for Astronomy began to look at computer simulations of galaxy mergers. Tsatsi's aim was to find out how the resulting galaxies would look through astronomical instruments – but when looking through one such "virtual instrument" at one of the simulations, she made an unexpected discovery: The elliptical galaxy that resulted from the simulated merger contained a counter-rotating core. But the merger certainly did not have the specific ("retrograde") orientation required by the usual explanation of how such cores form!

A more detailed examination showed that the counter-rotating motion is directly linked to a change of direction of the galactic central regions during the merger due to the so-called Meschchersky force, or more prosaically: due to gigantic galactic rocket engines. As the galaxies merge, the central regions lose mass which, just like the gas expelled by a rocket engine, can cause their motion to change.

The result of the simulated merger was consistent with the observed examples for such counter-rotating cores: With 130 billion times the mass of the Sun, this was one of the more massive elliptical galaxies, where such cores were known to be more common. In the simulation, the counter-rotating core remains distinct from its surroundings for 2 billion years after the coalescence of the two galaxies, making for a phenomenon sufficiently persistent as to be observable in real galaxies. Finally, the counter-rotating stars consisted mostly of older stars that had been present before the collision, not the new generation of stars produced during the merger; this, too, was what observations of such systems had shown.

Tsatsi's discovery concerns a single case. But that is sufficient to serve as a proof of concept, showing that the Meshchersky mechanism of producing counter-rotating galactic cores is indeed feasible. Next, the astronomers will need to show the likelihood of this kind of interaction by varying the initial conditions of their galaxy collision simulations. Should these systematic tests show that the Meshchersky mechanism for producing counter-rotating cores is common, they would resolve a long-standing discrepancy between the observed prevalence of such counter-rotating cores and their assumed modes of production. But, even now, Tsatsi's discovery has had an impact on the way future astronomers will look at counter-rotating cores and galactic mergers – knowing that it doesn't necessarily take special, retrograde configurations of colliding galaxies, but that "galactic rocket engines" could do the job just as well.




Different orientations for galaxy mergers: retrograde motion (top left) means that stars in one of the progenitor galaxies (shown in dark purple) rotate in one direction, while before the merger, the two progenitor galaxies orbit each other in the opposite direction. The existing model posited that elliptical galaxies with counter-rotating cores (right) can form only in situations like this, but not in the case of prograde motion (botto left), where both galaxies rotate, and orbit each other, in the same direction. Credit: MPIA

**Questions and Answers**

## In what ways is the research described here new / important?

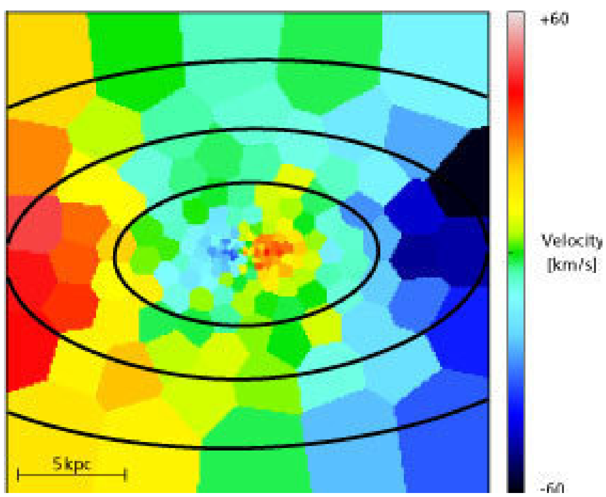
Tsatsi's discovery points to a solution of a long-standing problem: How do counter-rotating cores in elliptical galaxies form? Previous explanations could not account for the prevalence of such unusual patterns of stellar motion; with the "galactic rocket engine", the new discovery posits an attractive new mechanism that could help explain the discrepancy. It will, however, take more systematic studies to find out whether or not the new mechanism can indeed account for the observed number of counter-rotatig cores.

## What is unusual about stellar motions in some elliptical galaxies – and what was unexplained?

Spiral galaxies such as our own Milky Way galaxy present a stately stellar dance, with all stars orbiting the center of the galaxy in the same direction, at a stately pace (it takes our Sun about 250 million years to complete one orbit around the galactic center). But for a different species, so-called elliptical galaxies, the situation can be more complex. As the name indicates, these galaxies are shaped like ellipsoids, and at least some of them exhibit a two-fold rotation pattern: While the stars in their outer regions have a common preferred direction of rotation, stars in the core region can jointly rotate in a completely different direction – a "counter-rotating core", or more generally a "kinematically decoupled core", which is apparently completely independent from the motion of the majority of the galaxy's stars.

The best available explanations link the existence of such counter-rotating cores to a galaxy's formation history. Elliptical galaxies are thought to be the result of the merger of two or more sizable galaxies ("major merger", see figure 1) . There is one immediately plausible scenario for how counter-rotating cores could form in such a merger. Imagine that at least one of the galaxies has a core region that is fairly tightly bound by the galaxy's gravity. Furthermore, imagine that the direction in which the two galaxies orbit each other before merging is opposite to the direction of rotation of stars in that tightly bound core ("retrograde merger", cf. figure 2). In that case, it is likely that, after the merger, the tightly bound core will end up as the core of the new, larger galaxy, while retaining its original sense of rotation. The surrounding stars, on the other hand, will rotate in a different way dictated by the orbital motion of the galaxies around each other, before the merger.

While this is a plausible scenario, it can only explain some of the counter-rotating cores. In total, more than half of the more massive elliptical galaxies contain kinematically decoupled central regions. This is significantly more than the retrograde merger scenario can explain. After all, by pure chance, one would expect a retrograde motion for the more tightly bound of the two galaxies in only about half of the cases – and only some of those mergers are thought to result in a counter-rotating core.

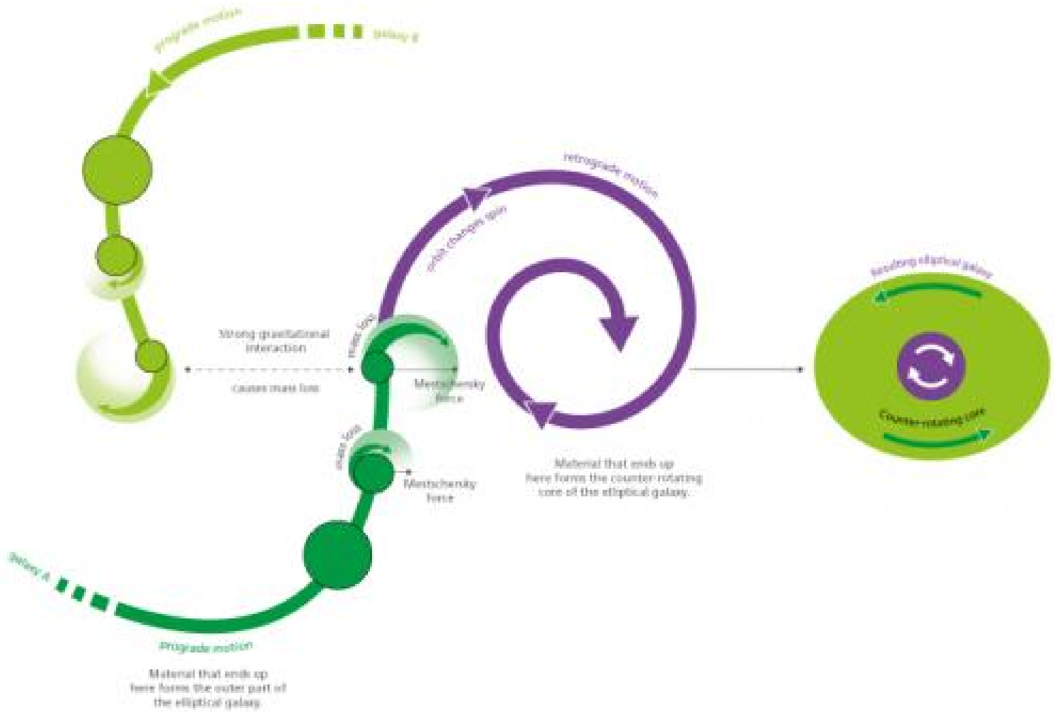



In this simulated integral field spectroscopic image, colors represent motion parallel to the line of sight: from blue (fastest motions toward us) to red (fastest motion away from us). The different types of motion in the inner and outer regions are clearly discernible. This is how Tsatsi first realized the simulation had produced a counter-rotating core. Credit: A. Tsatsi / MPIA

**How did Tsatsi's discovery of an alternative production mechanism for counter-rotating cores come about?**

Tsatsi's aim was to analyze simulations that show the formation of an elliptical galaxy by the merger of two spiral galaxies, and to reconstruct how the resulting galaxy would look to astronomical observers: What would such observers find if they analyzed their astronomical images and spectroscopic measurements? Such a reconstruction is a key step if one wants to compare predictions from these simulations with observations of actual galaxies. The simulations in question were created by Benjamin Moster, then also graduate student at MPIA and now at Cambridge University. They are based on the cosmological simulation code GADGET developed by Volker Springel and colleagues, which simulates a galaxy as a collection of a great many particles representing the galaxy's stars, gas and dark matter content. The code is particularly suitable for running in parallel, on a great number of processors at once, enabling detailed, yet large-scale simulations.

The main observational technique featured in Tsatsi's program is known as integral field spectroscopy. This type of observation allows astronomers to take spectra of many different regions of a galaxy, splitting light from each region into myriads of different colors. As stars move towards or away from the observer, the starlight is shifted towards shorter or longer wavelengths, respectively (a Doppler shift, more concretely a blueshift or redshift). Such a wavelength shift can be identified in a star's spectrum. In this way, integral field spectroscopy allows astronomers to reconstruct which parts of the galaxy are, on average, moving towards us and which parts are moving away. Based on such observations, astronomers can reconstruct stellar motion within a galaxy, which in turn gives them valuable information about the distribution of the galaxy's mass.




Schematic diagram of the Meshchersky mechanism: As the core regions lose mass during the merger, the reaction force ("rocket drive") changes their orbits; that way, the material that ends up in the center of the resulting elliptical galaxy rotates in the opposite way to the matter in the outer regions. Credit: MPIA

When Tsatsi reconstructed integral field spectroscopic observations for one particular simulation, she noticed an unusual fact. The kinematic map showing stellar motion within the galaxy indicated that the central region was moving in a different way from the rest of the galaxy (cf. figure 3). In other words: the galaxy evidently contained a counter-rotating core. But this had been a merger in which the two colliding galaxies rotate in the same direction as that of their orbit around each other – a prograde merger, and thus a merger of a kind deemed incapable of producing a counter-rotating core (see figure 2). When Tsatsi had a closer look, she could see directly what had escaped the attention of all previous astronomers who had looked at the simulation: As the core regions of the two galaxies orbit each other, there is a particular time at which their orbital direction changes. This change in direction happens just as the galaxies are shedding mass in the form of stars while they interact via their mutual gravitational attraction (cf. figure 4).

## What is the Meshchersky mechanism?

While searching the available scientific literature, Tsatsi realized that there was a precedent for the effect she had observed in the simulated galaxy collision. It is closely related to a special case of a problem studied intensively by the Russian mathematician Ivan Vsevolodovich Meshchersky (sometimes also spelled "Mestschersky"): point-like bodies, whose masses can change over time, moving under each other's gravitational influence. In such a situation, the influence of lost mass can change a body's direction of motion – resulting in the so-called Meshchersky force. The best-known example is rocket propulsion, where the rocket's loss of mass as it expels hot gases in one direction is accompanied by a reactive force (and hence an acceleration) in the opposite direction (see figure 3). That was why, even in ordinary (prograde) collisions, counter-rotating cores could form: the mass loss experienced by the galactic bodies acted like a gigantic rocket engine, and could be sufficiently strong so as to change the direction of rotation for the stars in the new galaxy's core (the remnant of the two colliding galaxies' central region). Tsatsi dubbed this way of producing counter-rotating cores the Meshchersky mechanism.

**More information:** "A New Channel for the Formation of Kinematically Decoupled Cores in Early-type Galaxies" *Astrophysical Journal Letters*, Volume 802, Issue 1, article id. L3, 7 pp. (2015). DOI: 10.1088/2041-8205/802/1/L3