Clues on the origin of thick disks in spiral galaxies

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Spiral galaxies have not only a thin disk of stars, but also a thick disk, which is less bright. The mechanisms invoked to form the thick disk range widely, from a turbulent initial phase in the galaxy formation, through radial migrations of stars due to bars, to mergers between galaxies. A team of astronomers from Paris Observatory has carried out numerical simulations to test whether minor mergers of galaxies with their small satellites could provide clues on this formation. They find a thick disk at the end of the simulation, formed from perturbed stars coming from the main galaxy disk. The thick disk is flaring with radius, and has a larger radial scale length than the thin disk. They also simulated the thick disk formation due to secular evolution, and do not find in this case a larger radial scale length for the thick disks. The different resulting characteristics indicate observations than can be made that could help to determine the actual formation mechanism(s).

Thick disks are ubiquitous features in disk galaxies and are observed all along the Hubble sequence â€" from lenticular early type spirals to ones that are bulgeless. As the name suggests, the thick disk is much thicker than the high surface brightness thin disk that make images of spiral galaxies so spectacular. Interestingly, even though the thin disk of galaxies show a wide variety of structural properties, thick disks seem to have many features in common no matter what the properties of their host disk galaxy. The stars in thick disks in galaxies are generally old, metal poor, and show a rotational lag, that is, they rotate around the galaxy center more slowly than the stars in the thin disk. In some galaxies a high fraction (up to 50%) of stars in thick disks counter-rotate compared to stars in the thin disk. Thick disks are seen in a majority of spiral galaxies, including our Galaxy. Its stellar mass is estimated to be about 10% of that of the thin disk, its stars have a lower rotational support than thin disk stars, they are old, enhanced in alpha-elements, and with average metallicities intermediate between those of thin disk stars and halo stars.

Figure 1 : Modeled scale heights as function of radius of various components in a galaxy with a thick disk. Note that the thick disk gets thicker with radius, while the stellar excess has a constant thickness. The scale heights z0 of the merger-induced thick disk and the stellar excess at great heights as function of radius in units of disk scale length, r/rd, for a range of dissipationless minor merger simulations. The shaded regions indicate the scatter in the scale heights, most of which is due to differences in initial orbital configurations. Also shown are the scale heights of the original stellar disk at the start (dotted line) and after its evolution in isolation for 3 Gyr (dashed line). The stellar excess has morphological and kinematical properties which are distinct from those of thick disk stars : its scale height is constant in radius, while that of the thick disk increases with radius â€" this disk flaring is a characteristic of thick disks formed by minor mergers.

Even though thick disks have been known and studied for over 30 years, their origin is still hotly debated, and many mechanisms have been invoked to explain their formation. It is well known that external mechanisms, like minor galaxy mergers, i.e., mergers of small satellites with a more massive galaxy, are viable processes to thicken a pre-existing thin stellar disk, although internal processes such as scattering of stars by spiral waves, by molecular clouds, or by massive clumps forming in unstable gas-rich disks in the early universe and radial migration of stars from the inner to the outer disk, are also able to heat a thin disk enough to produce a thicker component. How can we discriminate between these different processes for explaining the origin of the thick disk ? What are the typical and (perhaps) unique signatures that these processes leave in the stars â€" in their distribution, metal abundances and ratios, and kinematics ?

Figure 2 : So-called Toomre diagrams, comparing the total kinetic energy of stars with their rotational energy. The minor merger models agree with observations of the Milky Way ; in particular, the stellar excess stars lie exactly in the area of the Toomre diagram where alpha-enhanced stars are found. Toomre diagram of stars between radii of

2-3 times the disk scale length, rd, after a prograde minor merger simulation (left) and in an instable gas-rich clumpy disk evolved in isolation for 3 Gyr (right). The diagram shows the relationship between the total radial and vertical kinetic energy of stars and their rotational energy. In minor merger models the stellar excess stars lie exactly in the area of the Toomre diagram where .-enhanced stars are found (Nissen & Schuster 2010, A&A, 511, L10), thus strengthening the hypothesis that they may originally have been in the thin disk. Note that the clumpy disk model does not reproduce the Toomre diagram of the Milky Way, since it cannot heat disk stars as efficiently in the vertical direction as minor mergers do. In both panels, the dashed vertical line marks a total velocity of 180 km/s, which serves as a potential criteria to separate thick disk stars and halo stars (Venn et al. 2004, AJ, 128, 1177), and the dotted line is the Local Standard of Rest in these models. Also shown are the observed thick disk stars (triangles), halo stars with high [alpha/Fe] abundance (squares) and low [alpha/Fe] values (crosses) in the solar neighborhood, see Nissen & Schuster (2010) for further details. The halo stars in retrograde motion, against the sense of rotation of the bulk of the galaxy, are shown in green whereas those in prograde motion are in blue.

By means of tens of simulations, including gravity (from stars, gas and dark matter) and gas hydrodynamics, a group of researchers at the Paris Observatory have studied the imprints minor mergers leave on the distribution of stars in the vertical direction with respect to the galaxy mid-plane. Their results show that during the interaction with and subsequent merger of a satellite, stars in the original thin disk of the primary galaxy can be dynamically heated and scattered out to very large heights from the mid-plane. This leaves a unique signature in the vertical surface density profile of the post-merger disk galaxy : the thick disk formed during the merger has an ``excess'' in the regions furthest away from the disk mid-plane (z> 2 kpc). The distribution of stars in the thick disk appears to follow a double hyperbolic secant function. The first of these functions, necessary to fit the stellar distribution closest to the mid-plane is the classical thick disk, whereas the second component, necessary to fit the stars at the largest heights defines the excess. The scale height of the excess is larger than that of the main thick disk component. Stars in the excess have a rotational velocity lower than that of stars in the thick disk, and thus may be confused with stars in the inner galactic halo, which can have a similar lag.

Interestingly, some of the excess stars may already have been observed. Recently, Nissen & Schuster (2010, A&A, 511, L10) discovered the presence in the solar neighborhood of stars with halo kinematics, but [alpha/Fe] abundances similar to those of thick disk stars. These stars may well be part of the excess, as they show a significant rotational lag with respect to thick disk stars. If the Milky Way thick disk formed through the heating of a pre-existing thin component by minor mergers early in the universe, we would expect to find an inner halo population (the excess) with abundances similar to those of stars in the thick disk, but lagging rotationally behind them - just as observed.

Presently thus, observations seem to favour the minor mergers scenario for the formation of our Galaxy's thick disk.

References

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