Astronomy 218

Colliding Galaxies
Examine any sample of galaxies and two observations become apparent.

1) The **distance** between galaxies is often not much larger than the **size** of the galaxies themselves.

2) A significant fraction of galaxies seem to be **interacting** with their neighbors.

The Cartwheel galaxy ($d \sim 130$ Mpc) is the result of another galaxy **passing through the galaxy** $\sim200$ Myr ago, creating a **shockwave** that moved outward.
Such galaxy collisions are frequently accompanied by bursts of star formation in both galaxies, leaving the galaxies bluer than normal for tens of Myr.

X-ray observations of the nucleus of NGC 2207 suggests it is a highly absorbed, low luminosity AGN.
Unoccupied Volume

In stellar systems, we know that collisions are rare. Even in the high stellar density confines of a globular cluster, the blue stragglers that signal a merger are rare.

A typical star \( R \sim 10^6 \text{ km} \sim 3 \times 10^{-8} \text{ pc} \) is separated from its neighbors by a distance \( D \approx n^*^{-1/3} \). In the solar neighborhood, \( n^* \approx 0.1 \text{ pc}^{-3} \), thus \( R/D \approx 10^{-8} \), so stars occupy \( \approx 1/10^{24} \) of the space in the Galactic Disk.

Even in the core of a globular cluster \( n^* \approx 1000 \text{ pc}^{-3}, R/D \approx 3 \times 10^{-7} \) or the Galactic center \( n^* \approx 10^7 \text{ pc}^{-3}, R/D \approx 6 \times 10^{-6} \) stars occupy \( > 1/10^{18} \) of the available space.

In contrast, the typical size of a galaxy \( R \sim 10 \text{ kpc} \) is a much larger fraction of the galactic spacing. \( n_{Gal} \approx 10 \text{ Mpc}^{-3} \) in a group or \( \approx 1000 \text{ Mpc}^{-3} \) in a rich cluster, thus \( R/D \approx 0.02 \) for a group or \( R/D \approx 0.1 \) for a rich cluster.
The chances of a collision also depends on the star’s motion. A star of radius $R$ and relative velocity $v$ over time sweeps out a volume $V(t) = vt (4\pi R^2)$. If the local density of stars is $n_\star$, then the star will experience $N_\star = n_\star V(t) = n_\star vt (4\pi R^2)$ collisions in time $t$. This leads to a rate of collisions $dN_\star/dt = n_\star v (4\pi R^2)$ or a collision timescale of $t_\star = 1/n_\star v (4\pi R^2)$. In solar units, 

$$t_\star \approx 5 \times 10^{10} \text{Gyr} \left( \frac{R}{R_\odot} \right)^{-2} \left( \frac{v}{30 \text{ km s}^{-1}} \right)^{-1} \left( \frac{n_\star}{0.1 \text{ pc}^{-3}} \right)^{-1}$$

In the Sun’s lifetime, there is $1/10^9$ chance of collision. For globular cluster ($v \approx 10 \text{ km s}^{-1}$), $t_\star \approx 10^7 \text{ Gyr}$. For the Galactic Center ($v \approx 200 \text{ km s}^{-1}$), $t_\star \approx 80 \text{ Gyr}$.
**Galactic Pinball**

The identical expression applies to galaxies.

\[ t_G \approx 5 \times 10^{10} \text{Gyr} \left( \frac{R}{R_\odot} \right)^{-2} \left( \frac{v}{30 \text{ km s}^{-1}} \right)^{-1} \left( \frac{n_G}{0.1 \text{ pc}^{-3}} \right)^{-1} \]

While the Milky Way is \( R \approx 15 \text{ kpc} \), most galaxies are smaller, \( R \approx 3 \text{ kpc} \approx 1.3 \times 10^{11} R_\odot \).

For a rich cluster like Coma, the relative speed \( v \approx 3^{1/2} \sigma \approx 1500 \text{ km s}^{-1} \).

For Coma, roughly \( \frac{1}{2} \) of galaxies lie within \( r_h \approx 1.5 \text{ Mpc} \), thus

\[ n \approx \frac{N/2}{(4\pi/3) r_h^3} \approx \frac{5000}{(4\pi/3) 1.5^3 \text{ Mpc}^3} \approx 350 \text{ Mpc}^{-3} \approx 3.5 \times 10^{-16} \text{ pc}^{-3} \]

The result for Coma is \( t_G \approx 17 \text{ Gyr} \approx 1.2 H_0^{-1} \) implying collisions are likely. Note that even when galaxies collide, stars rarely do because \( t_\star \approx 5 \times 10^8 \text{ Gyr} \).
For every head-on collision, there are many galactic close encounters. As the galaxies make their closest approach to each other, tidal bulges grow on near and far sides of each interacting galaxy.

For a strong enough tidal interaction, stars are unbound from their parent galaxy. Stars from the near side tidal bulge will stream ahead of their galaxy, while the far side stars will trail.
Direct collisions can also show tidal tails, but the real fireworks happen within the galaxies.

The Antennae galaxies, NGC 4038/NGC 4039, \((d \sim 14 \text{ Mpc})\) represent an ongoing collision, sparking stellar formation.

Originally a pair of spiral galaxies, which had a close encounter 200-300 Myr ago forming their tidal tails, they are now merging.
Much of our understanding of galaxy collisions comes from computer simulations. Referred to as N-body simulations, the galaxies are sub-divided into sections that interact only via gravity. These simulations allow us to perform experiments impossible in reality.

The earliest N-body by Erik Holmberg in 1941 used $N = 74$ lightbulbs on a table to reproduce tidal tails, but modern supercomputer simulations use $N = 10^6 - 10^9$. 
While the original simulations of galaxy collisions considered only the mass (dark & light), modern simulations consider also the gas and dust. Such simulations help explain the strange geometry of remnants like the Leo Ring.
**Starbursts**

While the tides raised by near misses can cause considerable star formation, it is collisions that give rise to the most spectacular starbursts. With radii millions of times those of stars (~ 10 pc), giant molecular clouds are almost guaranteed to collide, resulting in billions of stars being formed over the course of a few Myr.

The result is bright, both in the UV from new O & B stars and also the infra-red from protostars of all masses, creating ultra-luminous infrared galaxies (ULIRGs).
While density wave theory shows us how a spiral wave develops, it does not explain the initial perturbation that begins the process.

Numerical simulations demonstrate that near miss interactions with a smaller galaxy can excite a spiral wave in a larger disk galaxy.

Once excited, the density wave propagates unabated.
Inelastic Collisions

Simulations teach us that galactic collisions are inelastic, with some of the galaxies’ kinetic energy converted into internal energy by dynamical friction. This internal energy takes the form of stellar motions.

Ordered systems like spirals can be disordered by the collision. Mergers of two spiral galaxies often results in an elliptical galaxy.

A spiral galaxy generally survives a merger with a dwarf galaxy, cannibalizing the smaller galaxy.
Galactic Cannibalism is an ongoing process. The Milky Way Galaxy is currently **tidally disrupting** the Sagittarius and Canis Major dwarf galaxies. The Milky Way also contains **streams of stars** in its halo that result from previous captures.

Some of the larger MW **globular clusters** (like ω Cen) may be the remnants of galaxies.

Galactic Cannibalism also explains why **giant cD ellipticals** haunt the centers of rich clusters, growing at the expense of passing galaxies.
Not just the stars are incorporated into merging galaxies, but also their central black holes.

**X-rays** reveal that the starburst galaxy NGC 6240 has two supermassive black holes orbiting one another at $d \sim 1$ kpc.

They are expected to merge in about 400 million years, releasing a tremendous burst of gravitational radiation.
Cluster Dynamics

Spiral galaxies can suffer only minor collisions before becoming either a small elliptical galaxy by having their disks stripped or a large elliptical galaxy by merging. This explains the preference for ellipticals in the centers of rich clusters but spirals in poor clusters and groups. The observation that spirals in Virgo have a larger velocity can be explained by the loss of galactic kinetic energy in the merger process that created the ellipticals.
The importance of collisions to current galaxy evolution suggests a historical role.

Observations support this notion, with the most distant galaxies appearing bluer and more irregular than the present day.

In fact collisions seem to be more important in the past.
When we look deep into the past to find the earliest galaxies, we find that large galaxies ($M \sim 10^{10-12} M_\odot$) are dramatically outnumbered by smaller clusters of stars with $M \sim 10^{6-8} M_\odot$.

This suggests a **hierarchical merger model** where large galaxies are progressively assembled from smaller ($M \sim 10^{6-8} M_\odot$) clusters of stars in a small-to-large process.
One of the most striking features of the Milky Way is the differences in the stellar populations of the kinematic components. The halo has only old metal-poor stars while the disk has metal-rich stars.

To explain these differences, Eggen, Lyden-Bell & Sandage in 1962 formulated a top-down model for the formation of the Milky Way. An initially spheroid proto-galactic nebula collapses rapidly (~200 Myr) to form a disk.

The first stars formed, prior to the nebula’s organization into a disk, now constitute the halo, while ongoing star formation occurs only in the disk.
While the ELS model was successful at explaining the basic features of the Galaxy, it failed in some specifics.

For example, in the ELS model, the halo on average should be rotating in the same direction as the disk. While this is true for the inner halo, the outer halo shows no overall rotation.

The ELS model also cannot explain the observed preference for older, but more metal-rich globular clusters in the inner galaxy.

Such problems can be resolved by the continued accretion of star clusters. Many halo stars, especially in the outer halo, and globular clusters are the result of later mergers.
Now it is possible to build simulations of the evolution of galaxies, which support the bottom up scenario.

Simulations show significant collisions over several billion years, with mergers of small galaxies persisting until today.
Galaxy clusters are also observed to collide. The members of the cluster are largely unaffected. Like the stars in a galactic merger, they may gain some velocity.

The intercluster media of the colliding clusters are strongly affected, directly colliding with each other.

This image shows two clusters of galaxies colliding, with the galaxies and dark matter (blue) separate from the intracluster gas (pink).
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