PHYS 75800 - Galactic Phys I

Final Project Report

From Chaos to Cosmos:
Analyzing 13 Billion Years of Galaxy Formation
in the h277 Simulation

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1 Introduction

This project analyzes the h277 cosmological simulation to understand how galaxies form over cosmic time. We examine five snapshots spanning 9 billion years, tracking the transformation of a chaotic gas cloud into a mature spiral galaxy. The analysis provides the galaxy's morphology, mass evolution, rotation curves, and evidence for dark matter.

2 Motivation

Galaxies take billions of years to evolve, so we can't just watch one form. That's where computer simulations come in. The h277 simulation is a cosmological N-body + hydrodynamics simulation from the N-body Shop at the University of Washington. It tracks 30 million particles (dark matter, gas, and stars) over 13 billion years of cosmic evolution, including gravity, gas dynamics, star formation, and supernova feedback.

The key question: if you start with primordial gas and let physics run its course, do you end up with something that looks like the Milky Way?

3 The Setup

We analyze five snapshots:

- Snapshot 00144 (t = 3.8 Gyr): Early formation phase
- Snapshot 00252 (t = 6.9 Gyr): Active disk formation
- Snapshot 00336 (t = 9.1 Gyr): Mid-evolution
- Snapshot 00444 (t = 11.8 Gyr): Mature galaxy
- Snapshot 00492 (t = 13.2 Gyr): Present day

Each snapshot contains 3-7 million star particles, 5-11 million gas particles, and about 11 million dark matter particles. The workflow looks like this:

```
s = pynbody.load(path)
s.physical_units()
pynbody.analysis.halo.center(s.star, mode='ssc')
galaxy = s[pynbody.filt.Sphere('30 kpc')]
```

The centering step is critical. I initially tried centering on dark matter, which completely failed because dark matter extends way further than the visible galaxy. Centering on baryonic matter (stars + gas) using the shrinking sphere method works perfectly.

4 Numerical Methods: Pynbody Analysis

The main analysis uses pynbody's built-in tools. Pynbody handles calculating radial profiles, rotation curves, and surface densities.

4.1 Mass Profiles

To track mass evolution, we calculate enclosed mass as a function of radius:

```
p = pynbody.analysis.profile.Profile(galaxy,
    rmin='0.5 kpc', rmax='25 kpc', nbins=50)

radii = p['rbins'].in_units('kpc')
mass_enc = p['mass_enc'].in_units('Msol')
```

4.2 Rotation Curves

The rotation curve shows circular velocity versus radius. First, align the disk to the x-y plane:

```
pynbody.analysis.angmom.faceon(s)
```

Then calculate the profile:

```
p = pynbody.analysis.profile.Profile(galaxy,
    rmin='0.5 kpc', rmax='25 kpc', nbins=50)

v_circ = p['v_circ'].in_units('km s^-1')
```

The Profile class automatically computes circular velocity using $v = \sqrt{GM/r}$.

4.3 Decomposition

To see what's causing the rotation, we decompose into stars, gas, and dark matter:

```
p_total = pynbody.analysis.profile.Profile(galaxy, ...)
p_star = pynbody.analysis.profile.Profile(galaxy.star, ...)
p_gas = pynbody.analysis.profile.Profile(galaxy.gas, ...)
p_dm = pynbody.analysis.profile.Profile(galaxy.dm, ...)
```

The components combine in quadrature because gravitational potentials add: $v_{\text{total}}^2 = v_{\text{star}}^2 + v_{\text{gas}}^2 + v_{\text{dm}}^2$

5 Physics Verification: Manual Calculation

To verify we understand what pynbody is doing, we recalculate everything manually from first principles. The physics is simple: circular velocity comes from balancing gravity and centripetal force.

$$v_{\text{circ}} = \sqrt{\frac{GM(<r)}{r}} \tag{1}$$

5.1 Manual Implementation

Here's how we do it from scratch:

```
G = 4.302e-6  # kpc (km/s)^2 / Msol
```

```
radii = np.linspace(0.5, 25, 50)


x = galaxy.star['x'].in_units('kpc')
y = galaxy.star['y'].in_units('kpc')
z = galaxy.star['z'].in_units('kpc')
m = galaxy.star['mass'].in_units('Msol')


r = np.sqrt(x**2 + y**2 + z**2)
```

Loop through each radius and calculate enclosed mass:

```
for i, radius in enumerate(radii):
    M_enc = np.sum(m[r <= radius])

    if radius > 0:
        v_circ[i] = np.sqrt(G * M_enc / radius)
```

That's it. We count up the mass inside each radius and plug it into Newton's formula.

5.2 Verification Results

Comparing manual to pynbody:

- Total v_{circ}: Max difference 8.1 km/s, mean 5.2 km/s
- Stars: Max difference 10.6 km/s, mean 5.0 km/s
- Dark matter: Max difference 14.0 km/s, mean 1.6 km/s

This is excellent agreement. At typical velocities of around 200 km/s, these differences are only about 2-5%. The quadrature rule was verified to machine precision (0.0000000000 km/s difference), confirming that gravitational potentials add correctly.

6 Results

6.1 Morphological Evolution

The visual transformation shows clear progression from chaos to structure:

Early phase (3.8 Gyr): Chaotic, irregular blob with random stellar motions.

Formation (6.9 Gyr): Disk begins to emerge with preferred rotation plane.

Mid-evolution (9.1 Gyr): Clear disk structure with spiral arms and central bar.

Present day (13.2 Gyr): Fully-formed spiral galaxy resembling the Milky Way.

The disk thins from about 10 kpc to 2-3 kpc through dynamical relaxation as random motions convert to organized circular orbits.

6.2 Mass Evolution

Stellar mass: Doubled from 2.0×10^{10} to 4.1×10^{10} $M_\odot$ over 9 billion years.

Gas mass: Stayed constant at around 1.2×10^{10} $M_\odot$ due to continuous infall from the cosmic web replenishing star formation.

Star formation efficiency: Increased from 61% to 78%, peaking during active disk formation.

6.3 Rotation Curves and Dark Matter

The peak rotation velocity is about 220 km/s, matching the Milky Way. The curve stays flat across the disk, exactly what we see in real spiral galaxies. Total mass reaches about 2×10^{11} $M_\odot$ within 25 kpc.

Component decomposition:

Inner region (0-5 kpc): Stars dominate.

Transition (5-15 kpc): Dark matter rises, stars fall.

Outer region (15+ kpc): Dark matter completely dominates.

The flat rotation curve in regions with almost no stars is compelling evidence for dark matter. Without it, the curve would drop dramatically at large radii.

6.4 Disk Structure

The stellar surface density follows an exponential profile with scale length $R_d = 1.58$ kpc. This universal feature of disk galaxies emerged naturally from the simulation physics, not programmed in.

7 Discussion

The biggest challenge was coordinate centering. Centering on dark matter placed the galaxy at -3000 kpc from the origin. Switching to baryonic centering fixed this immediately.

The manual physics verification was straightforward once I understood it's just summing masses and applying Newton's law. The quadrature rule verified to machine precision confirms we understand how gravitational potentials combine.

8 Conclusions

This analysis demonstrates:

- Galaxies transform from chaotic gas clouds into organized spiral disks through dynamical relaxation
- Stellar mass doubles while gas mass stays constant due to cosmic inflows
- The final galaxy matches Milky Way observations in rotation curve, mass, and disk structure
- Dark matter is necessary to explain the flat rotation curve at large radii
- Manual verification confirms rotation curve physics from first principles (2-5% agreement with pynbody)

The success of h277 validates our understanding of galaxy formation and confirms the ΛCDM cosmological framework. We can simulate the universe and watch galaxies form from first principles.