The Universe on a Computer



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Where (and what) are we?

Our Solar System



What's a Galaxy?

Today (13,700,000,000 yrs old)



Our solar system



~100,000,000,000 stars!



A lot that we can't see with our eyes (but can with the right telescope)

(Dust and gas)

Even more that we just can't see (dark matter)

The Dark-Ish Side

Billions of Stars we can barely see... but we're working on it



So what is the "recipe"?

Composition of the Cosmos (ingredients)



"Baby" Universe (400,000 yrs old)



Today (13,700,000,000 yrs old)



Add Gravity and "Cook" (ON A COMPUTER)



The "Cosmic Web"

Observations versus Models



Paint some galaxies on there...





The Universe is a Big Place



Stars, black holes, protostellar disks



Add some fluid dynamics and chemistry, and go!

The Basic Picture:



The Inter-Stellar & Inter-Galactic Medium

- WHERE STARS & PLANETS FORM



Star & Planet Formation

- WHAT'S HAPPENING ON SCALES CLOSER TO OUR OWN?

David Guszejnov



Collapse of a disk around a young star to form a planet



Done!

Not so fast...

Problem: WHY SO FEW GALAXIES & STARS?





Problem: WHERE ARE THE "MISSING SATELLITES"?



Predicted structure (dark matter) Observed around us

Problem: WHY ISN'T THERE MORE DARK MATTER? ("CUSP-CORE" or "TOO BIG TO FAIL")



What did we miss?

What Actually Happens? STARS *SHINE*, HEAT UP GAS AROUND THEM



Xiangcheng Ma

Star-forming cloud:

If stars were passive ("no feedback")

Realistic (stellar winds & radiation included)

What Actually Happens? STARS *SHINE*, HEAT UP GAS AROUND THEM





Spitzer Space Telescope • IRAC + MIPS







Scaled Up: Stars Matter!



Nature Hates Theorists...



~0.00001 light-years (100,000,000 km) Stars, protostellar disks

Cores, clusters, Supernovae blastwaves Molecular clouds, Star-Forming Regions Ok, how do we deal with this?

Previous "State of the Art"

Resolution: ~10,000 ly ~10⁶ M_{sun}

Interstellar Medium: single, ideal fluid

Winds? "sub-grid" (cheat a bit)

turn off coolingthrow out mass "by hand"

 $M_{\rm wind} = ({\rm fudge}) \times M_{\rm stars}$



e.g. "Illustris", "OWLS," "EAGLE,"anything I wrote before 2012...

The FIRE Project

Feedback In Realistic Environments



• Resolution ~ 1-10 ly Cooling & Chemistry ~10 - 10¹⁰ K

Feedback: \bullet

- SNe (II & Ia)
- Stellar Winds (O/B & AGB)
- Photoionization (HII regions) & Photo-electric (dust)
- Radiation Pressure (IR & UV)

- now with...
 - Magnetic fields
 - Anisotropic ulletconduction & viscosity
 - Cosmic rays •

Yellow: hot (>10⁶ K) Pink: warm (ionized, ~10⁴K) Blue: cold (neutral <10-8000 K)

New Generations of Models: PUTTING IT ALL TOGETHER

Xiangcheng Ma (arXiv:1706.06605)





(Animation: J. Wise)





So What Comes Out?

The Inter-Stellar Medium - WHERE STARS & PLANETS FORM







LMC

- Gravity
- Turbulence (super-sonic up to Mach~100)
- Magnetic Fields
- Cosmic Rays & relativistic particles
- Radiation
- Cooling processes & molecular chemistry
- Star & Black Hole Formation/Growth
- "Feedback": Stars, supernovae, black holes

Galaxies are Violent Places!



Stars (Hubble image): Blue: Young star clusters Red: Dust extinction

Gas: Magenta: cold $(< 10^4 K)$ Green: warm (ionized) Red: hot $(> 10^6 K)$

Galaxies are Violent Places!

Kareem El-Badry



Gyr = 1,000,000,000 years (a billion years!)
 kpc = 3000 light-years (20,000,000,000,000,000 miles!)

The Inter-Galactic Medium

(movies at www.tapir.caltech.edu/~phopkins)



Does It Work?

This Works (More or Less) if You Resolve Key Scales GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

PFH et al. (arXiv:1311.2073)



Thin Disks Emerge Naturally

Garrison-Kimmel et al., in prep



+ baryons & feedback (stars)

10 kpc

10 kpc

10 kpc





Failures No More FEEDBACK EXPLAINS WHY SATELLITES ARE "MISSING"

Andrew Wetzel (arXiv:1602.05957)

Dark matter only simulation (dark matter)



+ baryons & feedback (dark matter)

Tidal destruction (e.g. Zolotov et al.) + Feedback-induced "dissipation" + baryons & feedback (stars)



600 kpc

Failures No More FEEDBACK EXPLAINS WHY SATELLITES ARE "MISSING"









New Classes of Galaxies ULTRA-DIFFUSE SYSTEMS: THE NEW "NORMAL"

TK Chan (prep)





Galaxies from a computer:

What Didn't I Tell You?

Super-Massive Black Holes - THE "MONSTERS" AT **GALAXY CENTERS**





- How do they accrete material? How does this radiate and "shine"? How can we observe it?
- > How does the black hole (and its relativistic jets, accretion disks) interact with the galaxy?

0 Myr

Gas Daniel Angles-Alcazar Gas disk in galaxy center sees 10 pc the "photon wind" from black hole Gas in Perseus Cluster ~ millions of light years "blown out" by a single black hole!

Conclusions



Star formation is feedback-regulated

Feedback naturally predicts masses, KS law, scaling relations without fine-tuning

There are no major astrophysical challenges to ΛCDM

- Cusps to cores: no exotic dark matter needed!
- Missing satellites, "too big to fail," thin disks, Tully-Fisher relation, flat rotation curves, etc — all fall out
- Violent "burstiness" visible in abundances, SFHs, kinematics

AGN feedback is real and here to stay

- Fueling: gravitational instabilities, not Bondi (factor 100,000,000 wrong)
- Accretion disk winds & radiative feedback: *probably* the "quasar mode"
- Jets & cosmic ray bubbles: *probably* the "radio mode"



My own life-changing render

