Galaxy-Wide Star Formation Processes (and a brief conference overview)

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Galaxy Formation: An International Conference

...and a not-Festschrift for our conference co-organisers
"Gang of Four" Receives $500,000 Gruber Cosmology Prize for Reconstructing How the Universe Grew

THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

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ABSTRACT

We present the results of numerical simulations of nonlinear gravitational clustering in universes dominated by weakly interacting, “cold” dark matter (e.g., axions or photons). These studies employ a high resolution N-body code with periodic boundary conditions and 32,768 particles; they can accurately represent the theoretical initial conditions over a factor of 16 in length scale. We have followed the evolution of ensembles of models with \( \Omega = 1 \) and \( \Omega < 1 \) from the initial conditions predicted for a “constant curvature” primordial fluctuation spectrum. We also ran one model of a flat universe with a positive cosmological constant. Large filamentary structures, superclusters of clumps, and large low-density regions appear at certain times in all our simulations; however, we do not find large regions as extreme as the apparent void in Boötes. The evolution of the two-point correlation function, \( \xi(r) \), is not self-similar; its effective power-law index becomes more negative with time. Models with \( \Omega = 1 \) are inconsistent with observation if galaxies are assumed to be unbiased tracers of the underlying mass distribution. The peculiar velocities of galaxies are predicted to be much too large. In addition, at times when the shape of \( \xi(r) \) matches that observed, the amplitude of clustering is inferred to be too small for any acceptable value of the Hubble constant. Better agreement is obtained for \( \Omega = 0.2 \), but in both cases the rms relative peculiar velocity of particle pairs decreases markedly with pair separation, whereas the corresponding quantity for galaxies is observed to increase slowly. In all models the three-point correlation function \( \zeta \) is found to fit the observed form, \( \zeta \propto Q^2 \), but with \( Q \) depending weakly on scale. On small scales \( Q \) substantially exceeds its observed value. Consistent with this, the mass distribution of clusters is very broad, showing the presence of clumps with a very wide range in mass at any given time. The model with a positive cosmological constant closely resembles an open model with the same value of \( \Omega \). If galaxies are a random sampling of the mass distribution, none of our models is fully consistent with observation. An alternative hypothesis is that galaxies formed only at high peaks of the initial density field. The clustering properties of such “galaxies” are biased; they appear preferentially in high-density regions and so are more correlated than the overall mass distribution. Their two- and three-point correlation functions and their relative peculiar velocity distribution may be consistent with observation even in a universe with \( \Omega = 1 \). If this is an appropriate model for galaxy formation, it may be possible to reconcile a flat universe with most aspects of the observed galaxy distribution.

Subject headings: galaxies: clustering — galaxies: formation — numerical methods
Simulating the joint evolution of quasars, galaxies and their large-scale distribution

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The cold dark matter model has become the leading theoretical paradigm for the formation of structure in the Universe. Together with the theory of cosmic inflation, this model makes a clear prediction for the initial conditions for structure formation and predicts that structures grow hierarchically through gravitational instability. Testing this model requires that the precise measurements delivered by galaxy surveys can be compared to robust and equally precise theoretical calculations. Here we present a novel framework for the quantitative physical interpretation of such surveys. This combines the largest simulation of the growth of dark matter structure ever carried out with new techniques for following the formation and evolution of the visible components. We show that baryon-induced features in the initial conditions of the Universe are reflected in distorted form in the low-redshift galaxy distribution, an effect that can be used to constrain the nature of dark energy with next generation surveys.

Subject headings: cosmology: theory — dark matter — galaxies: halos — methods: numerical

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Causes for Celebration: Theory and Simulation

• A single model/paradigm which extends from inflation, CMB, and large scale structure to the formation and evolution of galaxies(!)
• Steady progress in resolving the challenges and “crises” of earlier years
  – N-body achieving state of the art(?)
  – “concordance cosmology” eliminated much room for mischief and solved some problems (e.g., “faint blue galaxy problem”)
  – incorporation of gas physics, cooling
    • direct treatment of “bias”
    • importance of accretion modes
    • “cooling” and “angular momentum” crises partially resolved?
  – semi-analytical framework for incorporating star formation, feedback, and confronting models with observations
Causes for Celebration: Observation

- Extraordinary observational progress
  - a fully filled, dust-corrected cosmic SFR history
  - resolution of most of the cosmic background
  - major progress toward cosmic histories of (stellar) masses, galaxy sizes, metal abundances, environmental evolution
  - statistical power of mega-surveys, especially in low-z observations, and a new quantitative framework
  - growing inventory of detailed stellar pops histories locally
  - beginnings on histories of cold baryon masses and kinematics
  - steady progress toward quantifying “sub-grid” scaling laws
Assurances of Steady Work Ahead

• The foundation of our theoretical construct is still largely based on unobserved (or ill understood) phenomena
  – dark energy, dark matter, dark baryons, cold accretion, stellar feedback, NFW profiles, AGN feedback

• Uncomfortable reliance on primitive “subgrid” ingredients
  – IMF, cooling prescriptions, SF laws, feedback recipes
  – connection of galactic-scale to SMBH-scale processes embryonic

• Some problems just don’t seem to go away
  – overcooling/angular momentum; dwarf galaxy deficit; rapid growth of massive galaxies, SMBHs, metals, dust; reionising background

• Lack of information on cold baryon evolution a major handicap, but that is about to change

• The devil may live in the details of the sub-grid processes
Galaxy-Wide Star Formation: 
the case study of the Schmidt law

Kennicutt & Evans, ARAA, in prep
But what does it mean, and where can it be applied?
- spatially resolved and gas phase-resolved studies needed
\[ \frac{\Sigma_{\text{SFR}}}{\Sigma_{\text{gas}}} \sim \Sigma_{\text{gas}}^{0.5} \]

But what does it mean, and where can it be applied?

SFR/M(HCN) \sim \text{const}

Kennicutt 1998

Gao, Solomon 2004
Obs. and Data Reduction in Progress

- CARMA: 10 completed + 3 half done.
- Nobeyama 45m telescope: 17 observed

by Misty La Vigne; Fumi Egusa; Rieko Momose; Masahiro Fujishita; Guolin Liu; Jin Koda

Nobeyama CO survey of M33

HERACLES CO 2-1 survey (IRAM)
Multiwavelength observations provide dust-free SFR tracers

Kennicutt et al. 2009
Consistent Results (mostly)

- Global non-linear Schmidt law confirmed \((N = 1.4-1.5)\)
  - threshold present at low density (e.g., LSB’s, outer HI discs)
  - non-linear behaviour seen in total and molecular gas laws (latter somewhat dependent on \(X_{\text{CO}}\))
  - low-metallicity dwarf galaxies deviate from main law \((X_{\text{CO}}?)\)
- Low-density thresholds seen in \(\Sigma_{\text{SFR}} vs \Sigma_{\text{gas}}\) relations
- Local SFR uncorrelated with HI gas density
Confirming Evidence for SF Thresholds

Bigiel et al. 2010

Martin, Kennicutt 2001

Wyder et al. 2009
Kennicutt et al. 2007 (M51)

Biegel et al. 2008 (THINGS)
Inconsistent Results

• Several studies of the local SF law suggest a constant ratio of SFR to molecular gas density from CO(2-1)
  – implies that any non-linearities in global SFR law arise from HI – H₂ conversion
  – implies constant dense core (HCN) fraction everywhere

• Results inconsistent with very high SF efficiencies in starbursts
  – requires a second mode, with either non-linear high-density regime or a separate high-efficiency regime
  – transition density near point where global SF density approaches that in GMCs

• Or problem could be observational--other groups find non-linear SF law in CO. Differences coupled to method used to measure SFRs

Bigiel et al. 2011
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Two Ways to Reconcile

thresholds from UV shielding, not gravity

Krumholz et al. 2009

Genzel et al. 2010
The Challenge: Spatially-Resolved SFRs

• the robustness of galaxy-wide SFRs rests several approximations:
  – averaged over full range of region ages
  – IMF is fully populated, well represented
  – dust geometry effects average out
  – SFR averaged over a galaxy roughly steady with time, so age sensitivity of tracers (Hα, UV, IR) can be ignored

• extending this approach to a “SFR map” uncovers several systematic effects:
  – local emission dependent on small number statistics of individual stars, “cosmic variance” (especially for Hα, other ionised gas tracers)
  – variations in dust geometry add scatter to “SFRs”
  – age of stellar population varies locally, altering Hα/UV/IR emission per unit SFR
  – Hα and dust emission trace gas, not stars
  – diffuse emission produces false “star formation” signal far away from any young stars
  – meaning of “SFR” itself ill defined on local scales
Contamination by diffuse emission

- Difficult problem that requires masking out of clustered regions of star formation (HII regions/clusters) and separate diffuse SF-associated PAH emission associated from non-SF diffuse PAH emission (Crocker et al., in prep.)
The “SF Law” Within Clouds

Fit with broken powerlaw with slopes of 4.6 below and 1.1 above a turnover $\Sigma_{\text{gas}} = 129\pm14 \, M_{\odot} \, \text{pc}^{-2}$. (see Lada et al. 2010)

Gutermuth et al. favor continued rise with $\Sigma_{\text{SFR}} \sim \Sigma_{\text{gas}}^2$ throughout.

All agree: well above all exgal relations except for dense gas relation.

Heiderman et al. 2010
Lessons

- Current measurements of the local Schmidt law are limited by systematics, esp. $X_{CO}$ and mapping of “SFRs”
- Studies to date suggest that the local form of the SF law may differ dramatically from the simple global relation – apply cautiously.
- A clearer observational picture will be needed to discriminate between physical mechanisms and models for the large-scale SFR (e.g., roles of gravity, neutral phase instabilities, atomic/molecular transitions, pressure, dense core formation, self-regulation)