**Chemo-dynamical Evolution of Galaxies**

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Lecture Nov. 2014: XIXth CCE, Rio de Janeiro

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**Content**

I. Introduction/Motivation: Observational signatures of connected dynamical and chemical evolution

II. Gas-phase interaction processes, star formation and stellar feedback

III. Cosmic chemistry and stellar yield

IV. Chemo-dynamical prescription and modeling
I. Introduction and Motivation

✓ Galaxies consist of gas and stars, the latter formed from the cold gas.

✓ Stars release radiation and ejecta (= stellar feedback), both heating the gas.

✓ Gas “phases” with different states (n,T) develop and evolve dynamically.

✓ Stars pump chemical elements into the ISM, differently into the different gas phases according to the energy.

✓ Gas mixing effects exchange gas properties.

✓ Gas develops dissipatively, while stars continue their dynamics and witness their original conditions.

1. Zoo of galaxies

Galaxies exhibit a broad variety of parameter combinations. But:

• parameters are correlated,
• environment matters.
**Panchromatic View of Normal/Ordinary Galaxies**

**Dwarf Galaxies**

DGs are smaller editions of massive galaxies:

\[10^6-10^{10} \, M_\odot, \, 2-20 \, \text{kpc}, \, M_V > -16^m\]

*Ferguson & Binggeli 1994, A&ARev 6, 67*
Smaller editions of Hubble-type galaxies? 
$10^9 - 10^{10} \ M_\odot$, 
1-10 kpc, $M_V > -16$ m

Transformation paths from one morphological type to the other are proposed.

NGC 205       NGC 4214
M32            Antlia

Sandage & Binggeli (1984)

2. Correlations of structural parameters for different galaxy types

Issues:
- Hubble-type gas-rich vs. gas-poor separate in $M_V - \mu_V$
- dIrr-dE-dSph sequence vs. UCDs and GC
6 Gyr ago: z=0.65

Faber et al. 2005
3. Gas-rich Galaxies

M58

M74

M101


The fundamental properties of galaxies

Mass

Star Formation

Interactions

Merger Induced Starbursts

Figure 11. The three-dimensional classification scheme proposed in this paper to account for all known galaxies. The three parameters used are the mass, recent star formation and interaction properties of galaxies. Several well-known galaxy types are labeled in their appropriate locations in this space. As the top of the classification axis is filled with galaxies with no recent-star formation, across the middle axis we progress from dEs to Scs in giant ellipticals. Any galaxy with a recent interaction/no merger would be found further into the third dimension. As we go further into the other three axes we find systems with a higher contribution of recent star formation or the stellar mass. Low-surface brightness orals would be found in a region of this space where the star formation is episodic, high and/or interactions occur. Merger induced starbursts are located to the high star formation, high-interaction part of the diagram, while irregulars and the are located towards the bottom right-hand side of the cube, as these are typically lower mass and evolving galaxies. The Hubble sequence is a two-dimensional projection of the star formation and interaction axes on to the mass sequence. This will offer a visually recognizable Hubble sequence by different galaxies that are not always easy to reconcile, but in principle are reasonable for all observable galaxies.
**Disks and Bulges**

Bulges are ellipsoidal centrally concentrated stellar populations of disk galaxies, older (~12 Gyrs) but as metal-rich.

**Multi-spectral observations**

IC5333 in Hα gives star formation, follows gaseous spiral arms.
Bright stars follow the molecular gas

NIR (2MASS) and Mid-IR (ISOCAM) of M51
4. Star formation

Formation of clumpy interstellar clouds in filamentary structures

Trigger of Star Formation?
or Self-gravitation?

Small-scale clumpiness crucial for ISM components!

FIG. 3. High-resolution CO map of a 10.6°×8.4° portion of the sky centered on (l=112°, b=1°). From the Five College Radio Astronomy Observatory (FCRAO) CO survey of the outer Galaxy (see Heyer et al., 1998). Figure courtesy of M. H. Heyer. [Color]
Gas-SFR correlation must be understood!

\[ \Sigma_{SF} = (2.5 \pm 0.7) \times 10^{-2} \left( \frac{\Sigma_g}{M_\odot \text{pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot \text{yr}^{-1} \text{kpc}^{-2} \]

\[ \Sigma_{SF} \propto \frac{\Sigma_g}{\tau_{\text{dyn}}} = 0.017 \Sigma_g / \Omega_g \]

5. The local Cosmic Matter Cycle

- Stars form from interstellar gas;
- Star formation is mostly self-regulated by energy feedback;
- Stars “live” only a finite time;
- During their “lifes” stars release stellar material (largely unprocessed) by means of winds;
- Their final evolutionary phase is determined by mass ejecta (with processed matter);
- Gas has to cool again and forms mol. clouds
Massive stars affect their environment:
stellar winds (partly C, N, O), radiation, explosions (nucleosyn. prod.s)
Abundance and energy release by supernovae

Supernovae release metals to the ISM!

Small-scale processes in a multi-phase ISM

Different Phases of the Interstellar Medium:
- cool clouds (CM, CNM)
- warm partly ion. medium (WNM, WIM)
- hot gas (HIM, ICM)
  (dust + Cosmic Rays)

Interact dynamically, energetically and materially:
- turbulence
- instabilities
- interfaces
- phase mixing

Effects for gal.evol.:
- Cooling
- Element mixing
- Gas outflow/infall
Why is it important to understand the Cosmic Matter Circuit?

At present:
- Chemical abundances: Diff.s related to system parameters,
- Distribution of metals; gas-phase mix. processes + dynam.
- Star-formation rates vary strongly: SF self-regulation
- Distribution and kinematics of gas and stars: Dynamics

In the past:
- First star formation
- Star-formation history
- Mass assembly in galaxy evolution vs. mass loss
- (early) metal enrichment
- Down-sizing of structure formation

The 3d Cosmological Structure Model!

Density enhancements at filamentary knots lead to mass concentrations by streaming motions
6. How do galaxies get their gas?  

Cold accretion

Dekel et al. (2009) Nature, 457:  
Colours refer to inflow rate per solid angle of point-like tracers at the centres of cubic-grid cells. Box side length is 320 kpc.


Figure 1: Surface brightness and velocity of the [OIII] 5007 Å line, and metallicity maps.  
The data for SSA22a-C6 (z = 3.219, a) and SSA22a-M18 (z = 3.286 c) were obtained with the SINFONI spectrograph using the 0.125' × 0.125' pixel scale in seeing-limited conditions, resulting in a spatial resolution of ~0.5'' (full-width at half-maximum (FWHM) of the point spread function). The maps were extracted from the SINFONI datacube after a Gaussian smoothing with FWHM = 3 pixels (0.375''). The left panels in each row show normalized surface brightness in the [OIII] 5007 Å emission line. The same line has been used to derive the velocity maps shown in the middle panels; the observed gas kinematics is compatible with a rotating disk, with no evidence of merger-induced complex dynamics. The right panel shows maps of gas-phase metallicity, as relative abundances of oxygen and hydrogen parameterized in units of 12 + log(O/H). Lower metallicity regions, corresponding to a higher [OIII]/[OII] ratio, are surrounded by a more enriched disk. The crosses in each panel mark the position of the continuum peak.

Signatures as local metal deficiency in high-z galaxies are indicating low-Z primordial gas infall.
Accreting Low-Metallicity Gas happens all the time, depend. on the environment – and let them grow

Gas Infall everywhere?
The case of NGC 2403

Fraternali et al. (2002)

HI gas with different velocity
Star formation is self-regulated!

\[ \tau_{SF} = \tau_{g \_cons} = \frac{M_g}{\Psi} > \tau_{\text{Hubble}} \]

or

\[ s\text{SFR} := s\Psi = \frac{\Psi}{M_\text{gal}} \approx 0.01 \text{ Gyr}^{-1} = 10^{-11} \text{ yr}^{-1} \]

What triggers high star-formation rates?

\[ \Rightarrow \text{Gas Infall?} \]

Consider the effects of external gas infall vs. outflow!

\[ \Rightarrow \text{Both act simultaneously:} \]

\[ \text{e.g. at high } z \sim 2-3: \text{ Erb (2008) ApJ, 674} \]

Infall+outflow make the job!


Fig. 2.—Time evolution of the star formation rate as predicted by the K-S law for a variety of initial gas masses \( M_\text{g} \). From top to bottom, the solid lines show \( M_\text{g} = 10^6 M_\odot \) (dark blue), \( M_\text{g} = 10^7 M_\odot \) (light blue), \( M_\text{g} = 10^8 M_\odot \) (yellow), and \( M_\text{g} = 10^9 M_\odot \) (red). The dashed lines show intermediate values. Data points are from Erb et al. (2006b). The left panel shows a closed box model with no inflows or outflows; the right panel shows an outflow rate equal to the star formation rate and a gas accretion rate 1.9 times the SFR, such that the accretion rate is 99% of the gas processing rate.
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- at low \( z \leq 1 \): Lehner et al. (2013) ApJ, 770

Differences in metallicities of outflow vs. infall

Metal content of the cool (~10^4 K) circumgalactic medium around 28 HI-selected LLS at \( z \leq 1 \) observed in absorption against background QSOs
Star formation is self-regulated!

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present: starburst DGs

A counter-rotating HI envelope around NGC 4449 is dynamically perturbed by the passage of DDO 125 and is condensed(?).

**Metallicity of infalling Gas?**

Hunter et al. (1998)
**Gas infall triggers Starburst**

The case of NGC 1569:
- HI clouds (each ~$10^6 M_\odot$) fall towards in from a disk
- 2 huge super star clusters are formed.

The proto-typical SBDG NGC 1569

X-ray in colors according to hardness (blue: hard, red:)

The O+Fe abundances in the hot outflow (~1-2 Z_\odot) demonstrates that mass loading in the wind has reduced the SNII yields!
7. Mass and element loss by Galactic Winds

An almost normal spiral with a huge hot halo

2MASS mosaic of NGC253 shows also extranuclear SB

XMM EPIC pn: Soft X-ray halo of NGC253 (0.2 – 0.5 keV)

Pietsch et al. 2001
Galactic Winds at high z

Figure 1: Part of the data cube obtained from integral field spectroscopy for the z = 3.09 galaxy LBG-2, showing the Lyman emission line. The absorption feature, interpreted as due to foreground H\(^+\), is indicated. A data cube is a three-dimensional structure for spectroscopic data from integral field spectrographs. Here the long axis corresponds to the dispersion axis and the other two axes represent spatial dimensions on the sky, that is, the data cube stores a spectrum for each point in a two-dimensional region of sky. With visualization software, the data cube representation can provide useful qualitative insights into complex data sets, \(\lambda\), wavelength.

Metal loss through galactic outflows!

Effective yields \(\gamma_{\text{eff}}\) of dIrrs < solar! Outflow of SNII gas reduces e.g. O. but:

simple outflow models cannot account for gas mixing + turb.

heating

Garnett (2002)
8. Metallicity as the crucial marker of galactic evolutionary processes

**M-Z relation:**
Z is not constant in galaxies though their gas mass fraction is equal, but depends on mass.

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**The N/O Problem**

**N/O production:**
- O is produced in **massive stars** (HMS) and released by WR winds and SNeII (hot gas);
- N is mainly produced in **intermediate-mass stars** (warm gas);
- HMS stars live shorter than IMS;
- N is also from HMS as primary and secondary element.
- Constant low N/O for young stellar pop., but **most dIrrs** (red) contain old SPs.
**Chemical enrichment in the Milky Way**

**The G-dwarf Problem**

\[ P = y \text{ represents the yield.} \]

The actual yield for a \( Z_\odot \) stellar population with a Salpeter IMF amounts to \( y \approx 2 Z_\odot \).

This slope is only fulfilled in the Bulge, but smaller in the solar neighbourhood \( \Rightarrow \text{effective yield } y_{\text{eff}} < y \).

Conclusions: gas infall or/and outflow.
9. Diversity of gas-rich Hubble galaxies

NGC 5055:
Largely extended disk; Warps in the outermost gas disk.

HI Disks

Usually, the gas disk is extended as far as the stars.
10. Galaxies in Cluster environments

Gas-disk sizes smaller towards the cluster center!

Chemin et al. (2004)

Gas-free galaxies dominate in clusters and are concentrated to the center


Figure 1: The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of log(M/L) is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dotted lines. In addition to the LF of all spirals, the LFs of the subtypes Sa, Sbc, Sb, and Sc are also shown as dotted curves. The LF of Irr galaxies appears for the first time in a paper on galaxy clustering; in the case of the Virgo cluster, the BCDs are also shown separately. The curves dE, ddE, and dE in 'dE' are not discussed. They are, however, included in the total LF over all types (broken line).
HI-deficient spirals with truncated HI disks in the outskirts of the Virgo cl.

VCC 655

Not frequently enough observed, but should exist in the field!

VCC 1730

VCC 1118

The case of VCC1217

Transformation by RPS

RGB

UV,U,B,V

Hα-off

not new HII

Hα-on

not new HII
Galaxy transformation by gas loss due to ram pressure at cluster infall

Recently, a huge HI filament was detected by Oosterloo & van Gorkom (2005, A&A, 433) close to the Virgo Cluster center, probably a residual of gas ram-pressure stripped from NGC 4388.
Cluster-gas abundances from X-ray spectra

A1413: z=0.143

(Pratt & Arnaud, 2002)

Galaxy-cluster gas is metal enriched to 1/3 $Z_\odot$

Fe line already in the hot gas of a high-z galaxy
11. Chemical abundances at high $z$

Figure 1: Keck/ESI spectrum of QSO PS0209 + 0517 showing the Ly$\alpha$ forest, a pair of damped Ly$\alpha$ systems, and a series of metal lines. The schematic labeling in the figure identifies several high-$z$ Damped Ly$\alpha$ systems at $z = 3.864$. The absorption trough at $\lambda = 5674$ Å corresponds to the damped Ly$\alpha$ line at $z = 3.667$.

The rapid decline of $Z$ in high-$z$ DLAs

Figure 3: Left: DLA metallicity vs. redshift, showing a sharp decrease in metallicities at high redshift. The blue crosses show the cosmic metallicity ($Z$) analysis. The black dotted line is a linear fit to the $Z$ data points in redshift space. Right: Density of metals as a function of redshift for DLAs and LBGs per redshift interval. The black squares are $\rho_{\text{DLA}}(z)$ produced by LBGs, the blue filled circles are $\rho_{\text{DLA}}(z)$ for DLAs, and the brown triangle is $\rho_{\text{DLA}}(z)$. This shows that DLAs are an important contributor to the total metal budget at $z > 4$, and that $\rho_{\text{DLA}}(z)$ may begin to decrease at $z > 4.7$. 

THE ASTRONOMICAL JOURNAL LETTERS, 782.129 (opp), 2014 February 20
The early metal enrichment of galaxies

High-z galaxy spectra also reveal the chemical evolution of the early universe.

Galaxies at $z \approx 1.0$ (upper) and $z \approx 1.5$ (lower);

O abundance determination with different methods:

O3N2 (top), N2 (bottom)

Shapley et al. (2005)
TWO QUESTIONS:

What determines galaxy evolution

1. globally?
   - mass
   - angular momentum
   - environment

2. intrinsically?
   - gas content, state, and dynamics
   - star formation
   - stellar feedback (incl. stellar evolution)
   - mixing processes

So far galaxy evolution can be followed by purely dynamical simulations, partly with stellar lifetimes (SNe for dE) + Chemistry:

Mostly a single gas phase with a plausible star-formation recipe, stellar feedback descriptions; star clusters as particles

Processes on unresolvable scales = so-called “subgrid physics” neglected or parametrized
If energetic and dynamical processes are intimately coupled, but only partly dominated by gravitational energy.

To study the chemical abundances in stars and gas phases and their dynamics simultaneously, the chemo-dynamical treatment is ultimately required.
THIS LECTURE CONTAINS NOTHING ABOUT:

**Dark Matter content**

**Galaxy formation and conditions in the early universe**

**Galaxy mergers**

**Galaxy interactions with cluster environment**

**Central BHs and AGN feedback**

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**Requirements for Modelling Galaxy Evolution**

- *self-consistency*: lowest number of free parameters
- *represent* kinematics and energetics of galactic components most realistically: decoupling of components
- *include* most actual astrophysical processes (stellar evol., gravitation, yields, etc.)
- *trace* chemical enrichment by processes and timescales!
- *treat* dynamical, energetic and materialistic plasmaphysical processes properly and inherently: coupling of components
  - heating
  - different cooling timescales
  - large-scale streaming motions
  - gas-phase mixing processes
  - star-gas interactions
- *include* environmental effects!

*Requ.: self-consistent chemo-dynamical treatment*