Gas in External Galaxies

Interstellar Medium -- Lecture 2
Françoise Combes
The gas component is essential for the star formation and dynamics

Morphological type
Gas fraction along the Hubble sequence
Dwarfs, LSB

Radial distribution, spiral structure
ISM and bars
Fueling of nuclei

Polar rings
E-galaxies, CO in shells
Tidal dwarfs

Dynamical triggering of Star Formation
AGN feedback
Hubble sequence

Sequence of mass, concentration

Gas fraction
HI and $\text{H}_2$ content vs morphological types

HI gas fraction increases for late types

The $\text{H}_2$ mass is comparable in average to the HI mass in spiral galaxies
Varies with morphological type, by a factor $\sim 10$

$\text{H}_2$ to HI mass ratios versus type
According to mass
For galaxies of high masses, there is no trend of decreasing $H_2$/HI with type

The dependence on type could be entirely due to metallicity

The conversion factor CO-$\rightarrow$H$_2$ can vary linearly (or more) with Z

Dust depleted by 20 $\Rightarrow$ only 10% less H$_2$ but 95% less CO (Maloney & Black 1988)

Environment: HI deficient for galaxies in clusters (interactions, ram pressure)
There is no CO deficiency in galaxy clusters
Dwarf galaxies

Taylor et al 98

$O/H$ is the main factor (below 7.9, galaxies are undetectable)
But other factors, too; like the SFR (UV)
Low Surface Brightness LSB

Large gas fraction (up to $fg=95\%$ LSB dwarfs Shombert et al 2001) and dark matter dominated $\Rightarrow$ unevolved objects

Low surface density of HI, too, although large sizes

Un-compact

Resemble the outer parts of normal HSB galaxies

15 LSB, Matthews et al 2005
LSB on the same Tully-Fisher relation
(for the same $V$, galaxies twice as large) $M \sim V^2 R$
$M/L$ increases as surface density decreases

Low efficiency of star formation (Van Zee et al 1997)
Gas $\Sigma_g$ below critical

A gas rich galaxy is stable only at very low $\Sigma_g$

Galaxy interaction, by driving a high amount of gas
$\Rightarrow$ trigger star formation
LSB have no companions (Zaritsky & Lorrimer 1993)
Tully-Fisher relation for gaseous galaxies works much better in adding gas mass

Relation $M_{\text{baryons}}$ with Rotational $V$

$M_b \sim V_c^4$

Radial Distribution in Spirals

HI versus H\textsubscript{2}
The H\textsubscript{2} is restricted to the optical disk while the HI extends 2-4 x optical radius

HI hole or depression in the centers, often compensated by H\textsubscript{2}
Radial distribution in NGC 6946

The HI is the only component not following star formation
Exp. Scale-lengths optical and CO are similar

Bima SONG  (Regan et al 2001)
Spiral Structure

The H$_2$ component participates even better than the HI and stellar component to the density waves due to its low velocity dispersion.

Larger contrast than other components streaming motions, due to the spiral density wave.

- Formation of GMC in arms
- Formation of H$_2$? Chemical time-scale $10^5$ yrs
- HI is formed out of photo-dissociation of H$_2$
- CO exist also in the interarms in CO-rich galaxies
M51 spiral + nuclear ring
Tilanus & Allen 1991

Pearls on string

GMC complexes

More recent map
From Aalto, Hüttemister et al
Full map of M31 with IRAM 30m

CO and dust coinciding

$M(\text{H}_2) \ll M(\text{HI})$

$M_{\text{virial}} > M(\text{CO})$

Müller & Guélin 2003

On the Fly map of M31 at IRAM 30m, Neininger et al (1998)
M31 On the Fly
IRAM CO
Nieten et al 2005

Arm-interarm Contrast

=20 in CO
=4 in HI
Gas to dust ratio distribution

CO → H2 yields only 7% of the neutral gas

Nieten et al 2005
Gas in Barred Galaxies

Bars are non-axisymmetric perturbations that create tangential forces and torques on the gas.

The main direction of orbits are parallel or perpendicular to the bar, and change at resonances.

The sign of torques change at resonances.

Inside corotation (encircling the bar) the torques are negative, and the gas is driven towards the center.
Gravity Torques

Gravity torques dominate over viscous torques in simulations

NGC 7479

Gravity torques derived from red image (potential) and Hα gas distribution

Rate of gas infall
With gas accretion (and star formation)

Without gas accretion
Bars destruction and reformation

Dynamical instabilities are responsible for evolution
With self-regulation

- Formation of a bar in a cold unstable disk
- Bar produces gas inflow, and
- Gas inflow destroys the bar
  + gas accretion

Accumulation of mass in the center creates a Central Mass Concentration (CMC)
May destroy the bar, through scattering of orbits
Role of gas in bar destruction

Gas is driven in by the bar torques

The angular momentum is taken up by the bar wave

⇒ This destroys the bar

Central Mass Concentration, Plays only a small role
⇒ It is then more easy to reform a

(Bournaud & Combes 02, 05)
Embedded bars are frequently observed: above a nuclear bar (*right*, field of 36") included inside the primary bar (*left*, field of 108"). The secondary bar rotates faster than the primary bar.

1/3 of barred galaxies have nuclear bars

NGC 5728
DSS
+CFH
Adaptive Optics
NIR
Inflow with two embedded bars

Cumulated gas inflow (70pc)

Inflow rate in 20pc and in 200pc
Evolution along the Hubble Sequence

Bulge to disk ratio is an essential parameter of the sequence: although it generally increases through evolution, it can also decrease → cycle
Quantification of accretion rate

Block, Bournaud, Combes, Puerari, Buta 2002

Observed

Doubling mass in 10 Gyr

No accretion
CO images
Searching for observational evidences of ‘ongoing’ feeding...

**NGC6951**: barred spiral prototype of Seyfert 2

**Molecular gas** distribution inside 700pc suggests gas along x2 orbits in bar potential: gas piles up in highly contrasted *nuclear spiral arms* (~4x10⁸ Mₜₚ) feeding starburst while little molecular gas 200 pc from the AGN.
Gravitational Torques in NGC6951

Torques Map

Efficiency of stellar torques
Schematics of secular evolution

- Bar strength
- Bar destruction
- Viscous overtake

- Gas inflow ➔ ring
- AGN phase
- Disk replenishment

- New Bar
- Gas inflow ➔ ring, etc

- Gas accretion ➔ replenishment
Polar Ring Galaxies (PRG)

Good examples of gas accretion

PRG are composed of an early-type host surrounded by a gas+stars perpendicular ring.

The polar ring is akin to late-type galaxies with a large amount of HI, CO, young stars, and blue colors.

Unique opportunity to check the shape of dark matter halo.

Formation scenarios.
Formation of Polar Rings

By accretion?

By collision?
Formation of PRG by collision
Formation of PRG by accretion
Cold accretion from cosmic filaments

Maccio & Moore 2005
Molecular gas in Ellipticals

Most E-galaxies possess accreted gas, already detected in HI (van Gorkom et al 1997)

Either the remnant of the merger event at their birth, or accretion of small gas-rich companions

No correlation with the stellar component ➔ accretion

Elliptical galaxies have a lot of gas, but in the hot phase (heated by shocks in the merger, emitting X-rays)
Shells around ellipticals

The merging events giving birth to ellipticals are also forming shells

**Stellar shells** discovered by Malin & Carter (1983)
Ripples like waves generated by the collision

HI gas detected in shells (Schiminovich, 1994, 95)
Normally, the diffuse gas condenses to the center in the merger

CO is now also detected in shells (Charmandaris et al 2000)
Star shells in yellow
HI white contours
CO points in red
Radio jets in blue

Charmandaris, Combes, van der Hulst 2000
Gas dragged outside galaxies

Interactions of galaxies, formation of tidal tails
Gravitational collapse in the tail → tidal dwarfs

CO detected in these small dwarfs, supposed to be formed in the interaction

Is the molecular gas dragged with the tidal tail gas and reclump in the tidal dwarf, or the molecular gas re-formed in the collapse? Trigger some star formation, but in general insufficient to have solar metallicity
More likely that the gas and metals come from the main galaxies

Fate of these tidal dwarfs? In general, they are re-accreted and merge
Braine et al 2000, 01
Star formation
Is it triggered by the dynamics?

The biggest starbursts (ULIRGs, 1000 M⊙/yr)
are all mergers of galaxies (e.g. Sanders & Mirabel 1996)
but they are rare (more gas, dust, young stars)

Interacting galaxies don't show intense starbursts
(Bergvall et al 03), or only in their centers

→ Interactions: necessary condition, but not sufficient
Another necessary condition: the presence of gas
Star Formation History in SMC

Star formation history in SMC reveals some bursts corresponding to pericenters with the Milky Way (Zaritsky & Harris 2004)

Between 10-70% tidal

\( \Rightarrow \) fit possible with gas infall at least 50%
The Antennae HST SSC formation (Super Star Clusters)

The Antennae, HI

Contours obtained with VLA +BVR colors
Dynamical processes

SFR/area ~ $\Sigma^n$  \( n=1.5 \) (global, not local, Schmidt law)
\( \Rightarrow \) Same for interacting and non-interacting

**Processes:** Jeans instability, dynamical time $\rho^{3/2}$
or Cloud-cloud collisions *(Elmegreen 1998)*
+SF contagion + Feedback (\( \Rightarrow \) chaotic conditions..)

Without dynamical trigger, episodic bursts with feedback
*(Köppen et al 1995; Pelupessy et al 2004)*

**Radial gas flows due to bars, or spirals**
Molecular gas concentrations, and circumnuclear starbursts
Ultra-Luminous Galaxies

ULIRGs have enhanced amounts of gas (CO-rich), $10^{11}$ Mo but also enhanced star formation efficiency (SFE).

Most of their light is in the Far Infrared

$$\text{SFE} = \frac{L_{\text{FIR}}}{M(\text{H}_2)}$$

This can be explained by the gravitational torques of the interactions driving gas very quickly to the centers.

Gas is concentrated in central nuclear disks or rings \cite{Downes et al 98}

The condition of starburst: accumulating gas in a time short enough that feedback mechanisms have no time to regulate.
Interactions between galaxies

Ultra-luminous galaxies are always mergers
Compressive tidal forces

For a spherical density profile in a power-law $\rho (r) \sim r^{-\alpha}$, then the acceleration is in $r^{1-\alpha}$, so the attraction can increase with distance, if $0 < \alpha < 1$

$\Rightarrow$ the tidal force is compressive $F_{\text{tid}} \sim (1-\alpha) r^{-\alpha}$

In particular, for a core density (rotation curve $V$ is in $r^{1-\alpha/2}$)

Molecular clouds inside the core are then compressed, and SF can be triggered

Can also explain the formation of nuclear starbursts and young nuclear stellar disks

Revealed by velocity drops at galaxy centers

Mihos & Hernquist 96

Simulations of disk/halo galaxies

Gas and young stars are plotted
Star formation Recipes

Numerical simulations use recipes, for the sub-grid physics Schmidt law with threshold, with exponent $n=1.5$

Results depends on disk stability

Without bulge, disk more unstable
At the end, the same SFR
Influence of velocity dispersion

Star formation in $\rho^n \sigma^\beta$
could take into account shock-induced SF

Applied by Barnes (2003) to the
Mice simulations
Better match of the observations,
when $\beta = 0.5$

Star formation
and $M_{\text{gas}}$ remaining
solid line $n=1.5 \beta =0$
dash $n=1 \beta =0.5$
dotted $n=1 \beta =1$

t=0= pericenter
The Mice
Contours: old stars
grey scale: gas

Points: New stars
Red: youngest age, then green, blue

$\beta=0$  $\beta=0.5$

(Barnes 2004)
Importance of gas infall: Constant SFR for intermediate Hubble types

Galaxies in the middle of the Hubble sequence have about constant Star formation rate (Kennicutt et al 1994, Brinchmann et al 04)

- Galaxies must accrete large amounts of gas mass along their lives

Required for bar reformation:
- a source of continuous cold gas accretion from the filaments in the near environment of galaxies

- Cosmological accretion can explain bar reformation
4 « phases »

4 Zoom levels from 20 to 2.5 Mpc.

$z = 3$. (from $z=10$.)
History of star formation

- **Isolated galaxy**
- **Galaxy with accretion and mergers**

⇒ Accretion is compatible with doubling the mass in 10 Gyr
Galaxies and Filaments

Gas is accreted from the Cosmic filaments

Multi-zoom
(Semelin & Combes 2003)
Active Galactic Nuclei feedback

Supermassive black holes exist in every galaxy
When they accrete mass, they can inject large energies in the surrounding

Feedback due to the AGN:
Reheating processes,
shocks, jets,
acoustic waves, bubbles...

Works only for the largest masses

In particular Clusters
Self-regulated to a lower cooling rate

Croton et al 05
Abell 1795 cooling flow

Very hot gas dominates the visible mass in galaxy clusters
Should be cooling only in the center, where the density is sufficient

Cooling time 300 Myr
200 Mo/yr in R < 200kpc

60kpc Hα filament at V(cluster) ➔ Cooling wake
The cD has V=374km/s w/o cluster
Abell 1795: CO with IRAM interferometer

CO(1-0) 3.8'' IRAM PdB CO(2-1) 1.8''

Cold gas coincident with cooling flow, not with any galaxy (Salomé & Combes 2003)  

$z=0.06326$  Cont-3mm = 7mJy  

$4.8 \times 10^9 \, M_\odot$
Close correspondance between the CO(2-1) emission and the Hα +[NII] line emission (gray scale)
6cm contours van Breugel et al 1984
Cold gas may have deflected the expanding radio lobes?
⇒ The jet creates a hole (bubble) in the hot gas, which is compressed at the boundaries, and cools
NGC 1275  Hα (WIYN) and CO (IRAM)

Hα, Conselice 01

Salome, Combes, Edge et al 05
Perseus Cluster

Salome et al 2006
Some conclusions

Star formation depends **essentially on the gas supply**
Gas accretion is essential for the efficiency of dynamics

Galaxy interactions help to drive the accreted gas radially inwards and trigger central starbursts

- In the field, accretion is dominant, and explain bars and spirals, and the *constant star formation* rate for intermediate types

- In rich environments: quicker evolution, much more importance of mergers, secular evolution of galaxies is halted at z~1, since galaxies are stripped from their gas