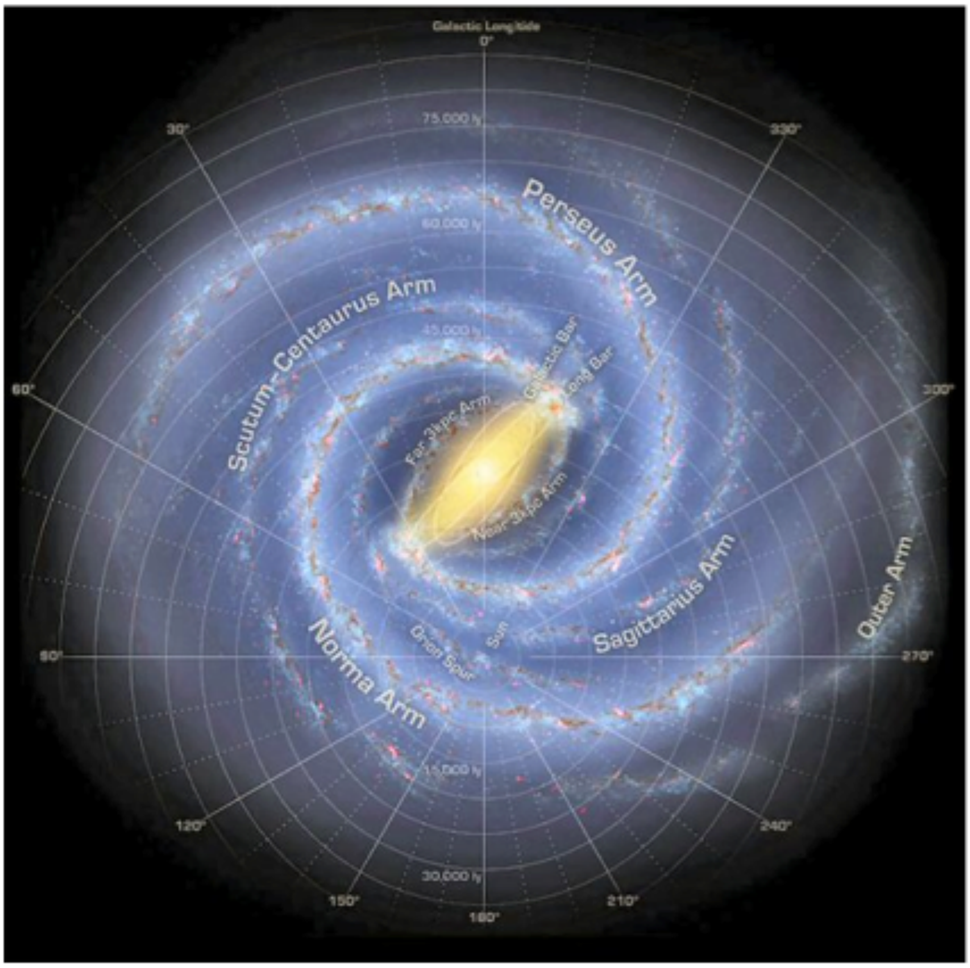
Lecture 1: Stellar formation in galaxies

I. General context

The topic of this course is the physics of the galaxies, which means that we will discuss physical properties of the galaxies taken as a whole (or Inside galaxies but on large scales), so we need to have in mind some numbers about galaxies.
We will focus on the Milky Way which is a large galaxy:

Here is the best representation we have of the Milky Way:

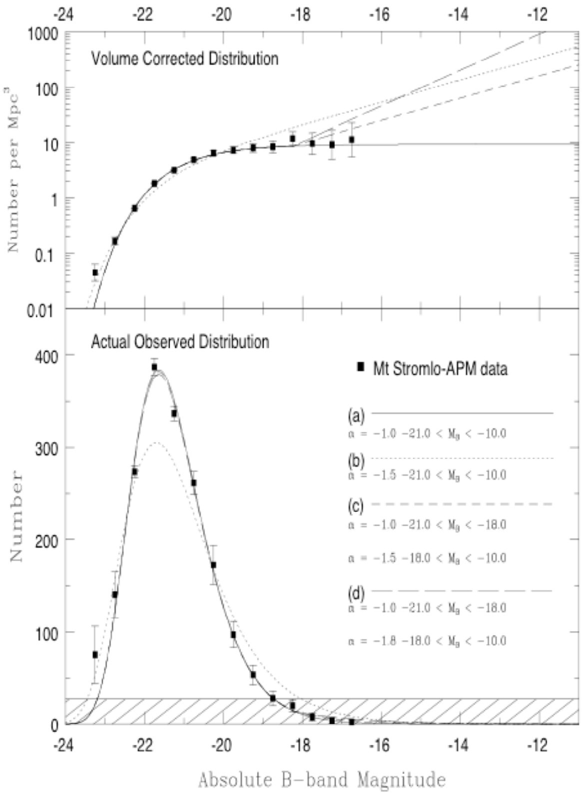


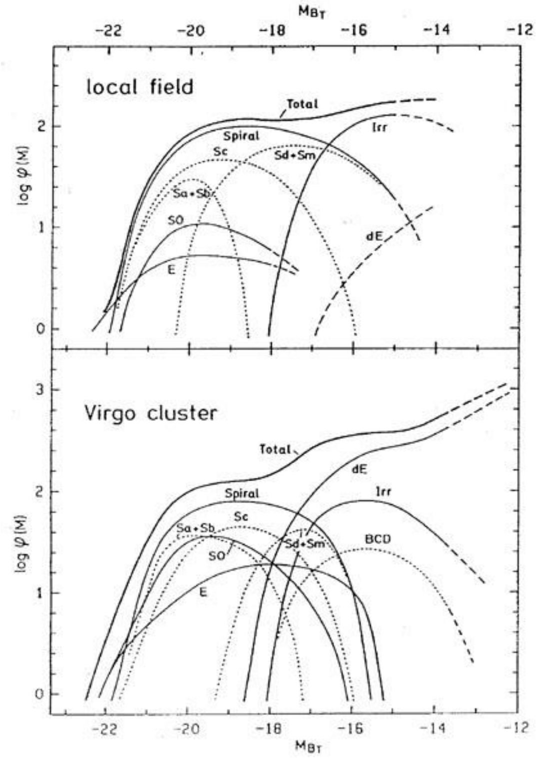
The stellar disk of the Milky Way Galaxy is approximately 30 kpc in diameter, and is, on average, 0.3 kpc thick. The Milky Way contains at least 10^{11} stars. The exact figure depends on the number of very low-mass, or dwarf stars which are hard to detect, especially at distances of more than 100 pc from the Sun. Both MW and is neighbour M31 (Andromeda) are giant regular spirals. The MW is a grand design, two armed, barred spiral (SBb). M31 is also a Sb spiral.
The Andromeda Galaxy is estimated to be 7.1×10^{11} M_{sun}.The mass of the MW is estimated to be similar or slightly less than that of M31. The two galaxies are expected to collide in 3.75 billion years, eventually merging to form a giant elliptical (as predicted for the merging of two spirals of similar size).

Below is a representation of the local group:

To have an idea of their luminosity as compared to those of other galaxies in the universe, let us consider the B luminosity function of galaxies in the nearby universe: the luminosity function is plotted in the top panel (the bottom panel represent the observations themselves).
The integrated magnitude of the Milky Way and M31 in the V band is estimated to be −20.9 mag. With an average B-V of 0.8 for Sb galaxies it leads to M_B ~-20 mag (B magnitudes are in the Vega system).
Therefore M31 and the MW appear to be systems of average luminosity.
However if one consider the luminosity function per galaxy type, they appear to be bright spirals, and a large fraction of ellipticals are not brighter than they are.

Figures from Bingelli, Sandage, and Tammann 1988 ARAA <u>*26*</u> *509 (right)*
And Driver & Philipps 1996 ApJ 469, 529 (left)





Question: Left panel: can you explain the strong difference between the observed distribution (lower panel) and the luminosity function (upper panel)?

The global luminosity functions in the optical (not in infrared) are usually represented by a Schechter function:

$$\Phi(L) = dn/dL = \Phi^*/L^* \exp(-L/L^*) (L/L^*)^{\alpha}$$

n is the galaxy density, Φ et Φ^* are in Mpc^{-3}
L et L* are expressed either in physical units or the solar luminosities.
α is named the faint end slope,
for local field galaxies :

Approximate Schechter values:
- $M^* \sim -20.5$ (in B)
- $L^* \sim 2 \times 10^{10} L_{sun}$ (~Milky Way)
- $\alpha \sim -1$ to -1.5

Beware of comparing these numbers, as M*and α are correlated. The Schechter function is just a parametric description and the determination of the parameters is not easy.

II. Large scale star formation

Stars form within molecular clouds. For star formation at small scales we refer to the lecture « fundamental astrophysics ». Here we will focus on the laws driving stellar formation at the scale of galaxies.
In order to describe star formation quantitatively, a formalism has been developped :
Stars form according to an initial mass function usually expressed as:
$\Phi(M) = dN/d\log M$. One also defines a lower and upper limit for the stellar mass : M_{low} and M_{up}.
The initial mass funtion is often described by several power laws and supposed to be universal even if there are some claims for a variable IMF especially at high redshift or in extreme media. We will go back to the topic when studying star formation calibrations.
Let us assume that the IMF is known and universal:

<u>The star formation rate (SFR)</u> is defined as dM_*/dt in $M_{sun}\ yr^{-1}$ (or sometimes $M_{sun}\ Gyr^{-1}$).
Its meaning depends on the spatial and temporal average assumed (or imposed by the observations).
Sometimes (for resolved galaxies) surface densities of SFR are defined.
<u>The efficiency of star formation</u>, ε, is measured in different ways. It is usually defined as:
$\varepsilon = SFR/M_{gas}$ and the depletion time is $t_{dep} = 1/\varepsilon$.
It is often compared to the free fall time t_{ff} or the crossing time through the galaxy or the galaxy orbital time.
A very common quantity is the <u>specific star formation rate</u> defined as $SSFR = SFR/M_{star}$.
Whereas ε quantifies the future evolution of the galaxy the SSFR is related to its past history.

Question: How to relate the SSFR to the birthrate parameter defined as the ratio of the present to past averaged SFR?

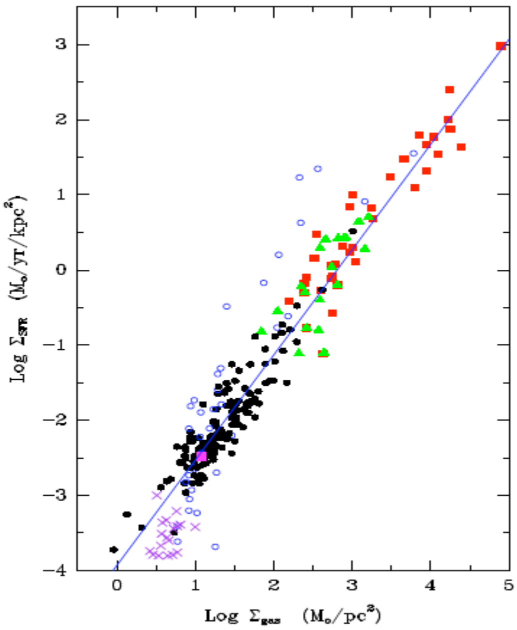
A. Star formation relations
The current paradigm is that the presence of giant molecular clouds is a prerequisite to star formation.
Once molecular clouds are formed part of them are transformed into stars over short timescales as compared to the age of the universe (and of the galaxies). So the problem of star formation can be reduced to that of forming molecular gas.
In galaxies (at low and high redshift) the SFR is found to correlate with the neutral gas content.
This law is expected, the gas being the driver of star formation, but the tightness of the relation, its mathematical form as well as the efficiency of star formation deduced from it are intensively studied at every redshift and for different types of galaxies illustrating different regimes of star formation.
The concept of a power-law relation relating SFR and gas surface densities dates to Schmidt (1959)
The law is now commonly called 'Schmidt-Kennicutt' and proposed by Kennicutt (1998, ApJ 498, 541) averaged over whole galaxies :

$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{1\ M_\odot\ \mathrm{pc}^{-2}}\right)^{1.4\pm0.15} M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$$

$\Sigma_{SFR} \propto \Sigma_{gaz}^{\ n}$ with $n \approx 1.4$, gas is for $HI+H_2$: the relation is non linear
The value of n remains discussed : from 1.4 to 1.9.

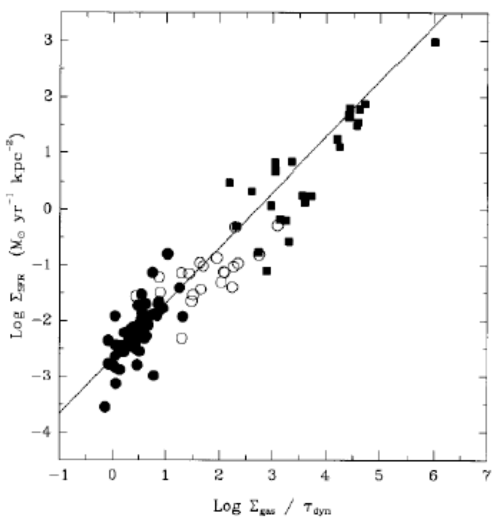
Kennicutt & Evans 2012
Black points: normal galaxies
Red points: IR selected galaxies
Green points: starbursting galaxies
Blue open squares: low mass galaxies
Purple crosses: low surface brightness galaxie
Magenta square: Milky Way

Blue line: n=1.4

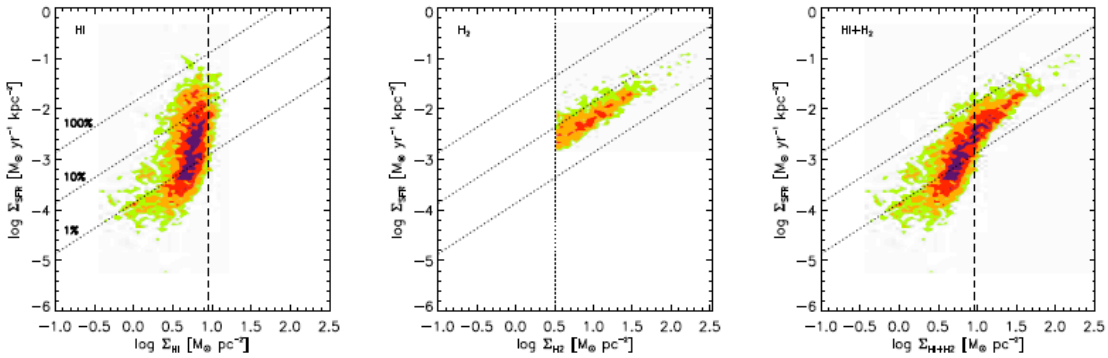


This relation can be easily interpreted if one assume that the SFR is proportional to the gas density and inverse proportional to a characteristic timescale for star formation. Let us consider the free-fall time t_{ff}
$t_{ff} = (3\pi/(32\ G\ \rho))^{0.5}$ (see appendix).
and SFR $\propto \rho_{gaz}/\tau_{ff} \propto \rho^{1.5}$ which is a good approximation of the Schmidt-Kennicutt law.

It is not the only relation found in galaxies to relate the SFR to the gas content. The SFR surface densities also correlate with the ratio of the gas surface density to the local dynamical time, defined as the orbital time :
$\sum_{SFR} \propto \sum_{gas} /t_{orb} \propto \sum_{SFR}\ \Omega$
This dependence of the star formation on the orbital frequency is expected if star formation is enhanced when the gas crosses the arms. However other possible scenarios like a self regulated star formation related to the gas dispersion also lead to this relation (Boissier 2012, figure on the right)
There is no observational reason to prefer one model to another one. On the right figure the dynamical timescale τ_{dyn} is proportional to Ω^{-1}.



Recent studies were devoted to studies at the sub kiloparsec scale and as a function of the gas phase (atomic or molecular). The best correlation was found with the molecular gas with a slope equal to 1. It corresponds to a H_2 depletion timescale of ~2 Gyr, a value also found at high redshift
There is no clear relation with HI but a saturation. The combination of both trends creates the non-linear relation found with total gas content (Bigiel et al 2008, AJ, 136, 2846).



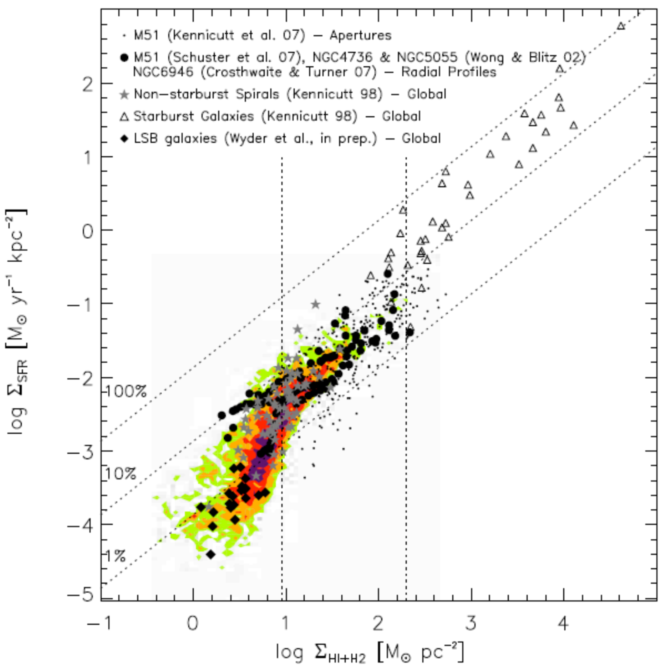
The truncation above might correspond to the surface density where HI converts efficiently into H_2 One must now understand the evolution of $R_{mol} = \sum_{H2}/\sum_{HI}$ et to produce some analytical formulae that theoreticians of galaxy formation can put into their models.

Note that the relation between SFR and M_{gas} depends necessarily on the scale used for the analysis. If we start with the solar neighbourhood (SN): within 100 pc around the sun there is no H_2 and no star formation measured from Hα for example. At the scale of 500 pc, Orion HII region enters the SN area, but the number of O stars is too small to give a reliable SFR from the Hα line again and the SFR is under-estimated by a factor of 10.

B. Efficiency of star formation

This efficiency is defined in different ways:

- For nearby clouds (usually inside the MW) it is based on the comparison between the mass turned into stars and the total mass of the cloud: $\varepsilon = M^*/(M^* + M_{gas})$. A time scale must also be chosen over which this quantity is calculated (stars continue to form until the cloud is disrupted or the density is too small). Over 2 Myr ε is 2-8 %: star formation is a very inefficient process.
- An other definition, currently used in extragalactic studies is based on the comparison between the current SFR and the mass of gas available $\varepsilon' = SFR/M_{gas}$ (SFR = dM*/dt) A related quantity is the depletion time $t_{dep} = 1/\varepsilon'$. For local clouds again, t_{dep} is found of the order to 50 Myr which is much longer than the 2 Myr used to calculate ε, much longer than the free fall time for the cloud (1.4 Myr) or that of a typical cloud lifetime (less than 10 Myr), confirming that star formation is inefficient at the scale of molecular clouds. At the scale of the entire Galaxy (MW) the depletion time is of the order of 1-2 Gyr.



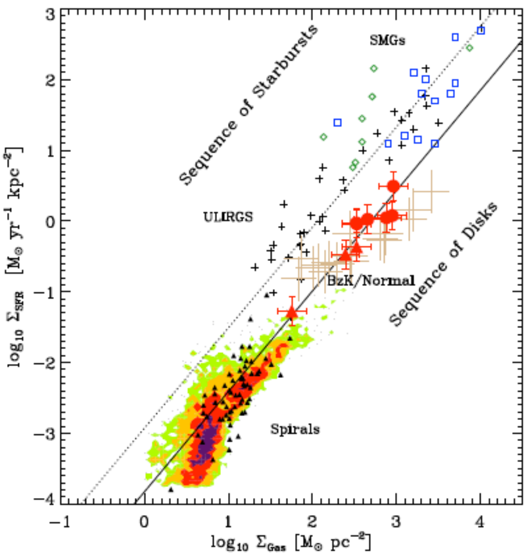
At the scale of whole galaxies (not only the MW), which is the topic of this course, the efficiency is found almost constant inside nearby galaxies (when the H_2 phase only is considered or when the total gas mass is dominated by the molecular phase) and increases for starbursts.

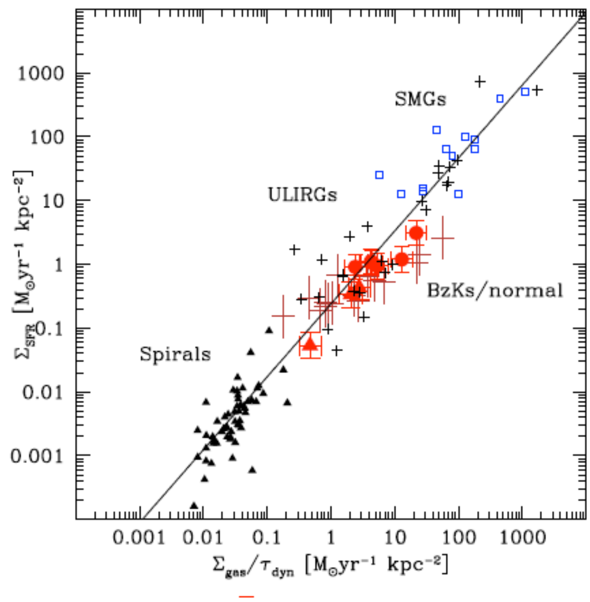
From Bigiel et al. 2008, ApJ 136, 2846

The diagonal lines represent the values of Σ_{SFR} needed to consume 1%, 10% and 100% of the gas in 10^8 years. They correspond to constant depletion times of 10^8, 10^9 and 10^{10} years

In average the star formation efficiency measured with the molecular gas content was found to be $\sum_{SFR} / \sum_{H2} = (5.25 \pm 2.5)\ 10^{-10}\ yr^{-1}$ (Leroy et al. 2008, AJ 136, 2782)

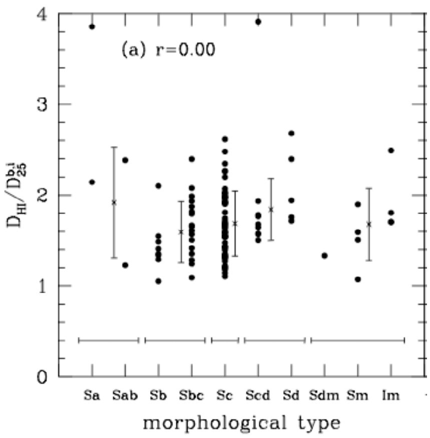
In high redshift galaxies (as well as in local starbursts), the star formation efficiency is found to increase (Daddi et al. 2010, ApJ). These analyses remain controversial given the uncertainty on the determination of the molecular gas surface density but are not surprising. One question is if two sequences have to be defined or a continuum of star formation efficiency from normal to extreme regimes of star formation. When Σ_{gas}/τ_{dyn} is considered the relation becomes unique for all star formation regimes, it is due to the shorter timescales found in starbursts , related to a higher density of the gas and a higher star formation efficiency.





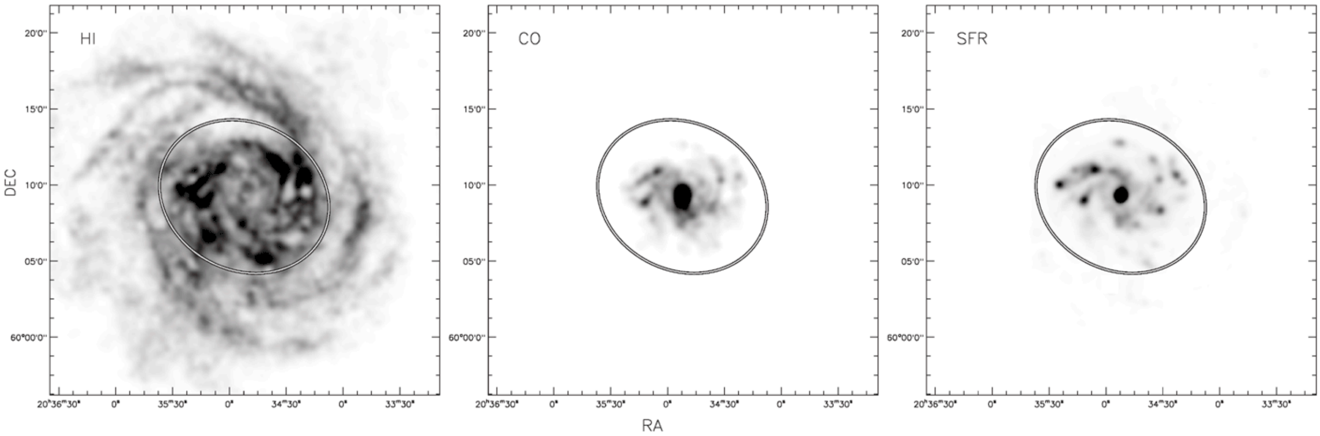
C. Gas distributions and gas tracers

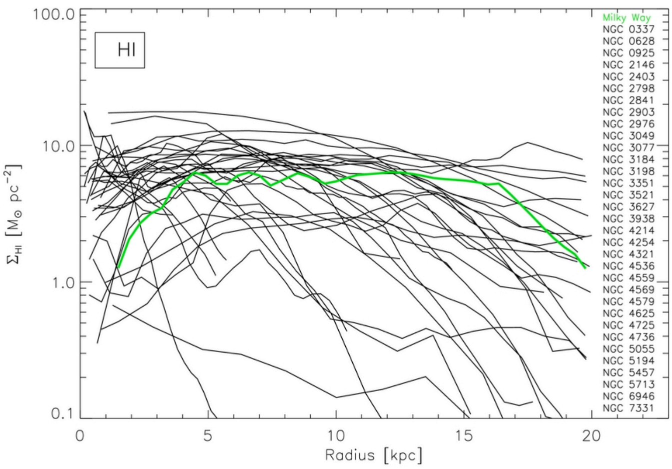
Gas distribution in galaxies strongly depends on the gas phase, as shown by Bigiel and Blitz (2012, ApJ 756, 183) for 33 nearby galaxies including the Milky Way. The HI gas has a flat and extended distribution (see diameters below) whereas the molecular and total neutral gas exhibit an average exponential distribution.
The dispersion found from one galaxy to another one illustrates the scatter found for any average relation among galaxies.
The molecular distribution is found to follow the SFR distribution in agreement with the average relations discussed above (for NGC 628 from Schruba et al, 2011, AJ, 142, 37)

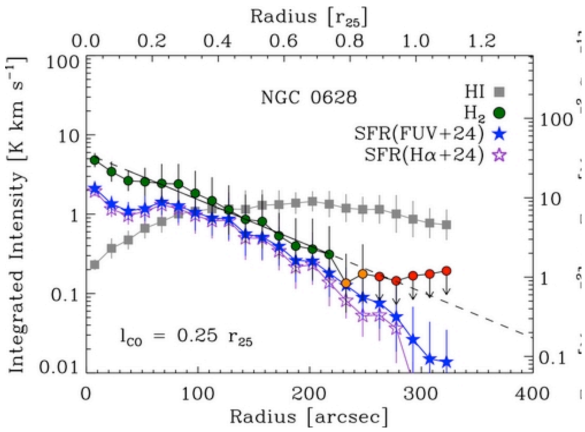


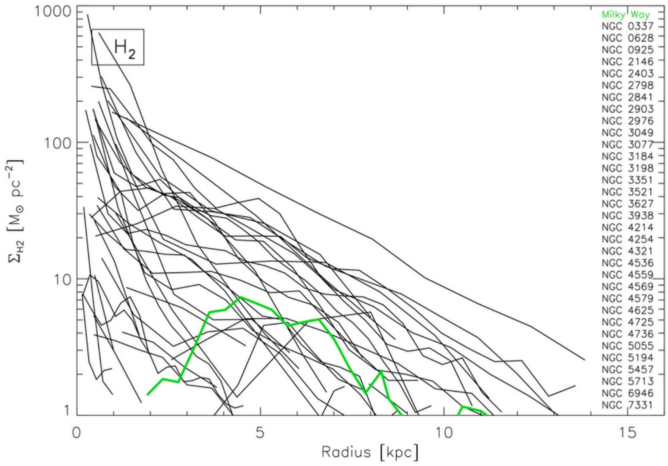
HI diameters in galaxies : Broeils & Rhee, 1997, A&A 324, 877

Bigiel et al. 2008, AJ 336, 2846

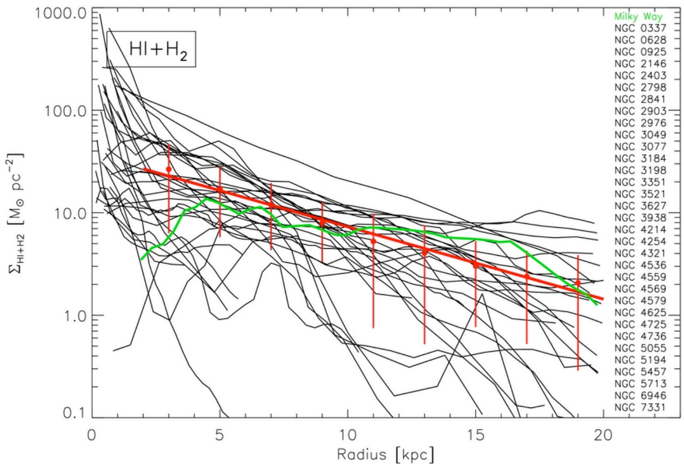








Bigiel & Blitz 2012 (33 galaxies)
Schruba et al 2011 (NGC 628)



III. Chemical evolution

A. Closed box model

The global evolution of metal content in galaxies can be easily calculated with a closed box model, even if it is not realistic as discussed below.
The **metallicity** (also called **Z**) of an object is the proportion of its matter made up of chemical elements other than hydrogen and helium.
Hydrogen and helium are estimated to make up roughly 74% and 24% of all baryonic matter in the universe respectively. Despite comprising only a very small fraction of the universe, the remaining "heavy elements" can greatly influence astronomical phenomena. Only about 2% (by mass) of the Milky Way galaxy's disk is composed of heavy elements. The evolution of Z is due to star formation and evolution, as a consequence star formation and chemical histories are closely linked.

It is convenient to define the fractions by mass of hydrogen X, of helium Y , and of heavy elements Z. Therefore, Z = (mass of heavy elements)/(total mass of all nuclei)
We therefore have **$X + Y + Z = 1$**

Under the hypothesis of a **closed box model** :
$M_{tot} = M_{gas}+M^* = Cte$

$dM_{gas}/dt = -SFR(t)+E(t)$ (1)

SFR(t) corresponds to the reduction of M_{gas} due to stellar formation, E(t) is the increase of M_{gas} due to recycled gas (ejected from stars) or return rate. The calculation is made under **the hypothesis of instantaneous recycling**
E(t) depends on SFR(t), IMF and stellar tracks. If these two last quantities are fixed then $E(t)= R\ SFR(t)$, R is the recycling factor comprised between 0.3 and 0.4 for usual IMF and stellar tracks.

Eq. 1 becomes $dM_{gas}/dt = - (1-R)\ SFR(t)$

We define $Z = M_Z/M_{gas}$, the metallicity of the gas.
In a similar way as for (1) we can write
$d(M_Z)/dt = d(Z\ M_{gas})/dt = -Z\ SFR(t)+E_z(t)$ (2)
$E_z(t)$ is the production of metals disseminated in the ISM due to the instantaneous return rate and to the production of metals into newly formed stars.

One defines the yield y_z= (mass of newly formed metals ejected in the ISM)/(total mass locked into stars)

$$y_Z = M_{new\ metals}/M^*$$

$M^* = M_{stars\ formed} *(1-R)$ since only a fraction (1-R) of all stars formed remains into stars.

Then $dM_{new\ metals}/dt = y_Z\ (1-R)\ SFR(t)$.

And $E_z(t) = y_Z\ (1-R)\ SFR(t)+ Z(t)\ R\ SFR(t)$
The first term corresponds to the global metal production due to the nucleosynthesis into stars, the second one corresponds to the instantaneous recycling

The combination of Eq(1) and Eq(2) gives:

$d(ZM_{gas})/dt = dZ/dt\ M_{gas} + Z\ dM_{gas}/dt = -Z\ SFR(t) + y_Z\ (1-R)\ SFR(t) + Z(t)\ R\ SFR(t)$
and
$dZ/dt\ M_{gas} = -y_Z\ dM_{gas}/dt$

Which gives: $\mathbf{Z(t) = Z(0) - y_Z \ln(M_{gas}(t)/M_{tot})}$ since at t=0 all the mass is gaseous.
$M_{gas}(t)/M_{tot}$ is often noted $\mu(t)$

This equation can be applied to every heavy element.

The same equations can be used to link metallicity and stellar mass in a galaxy:

$M^* (<Z) = M_{tot} - M_{gas} = M_{tot} - M_{tot} \exp((Z(t)-Z(0))/y_Z)$

The abundances in the ISM of galaxies are in reasonable agreement with the prediction of this model.
The prediction of the mass of stars (or number of stars) less metallic than Z can also be compared to observations.
G- or K-type main sequence stars can conveniently be used in these studies because their lifetimes are sufficiently long that they will have survived from the earliest times to the present: these stars are known as G and K dwarfs. G dwarfs have generally been used because of the advantage of their greater luminosity and because the techniques of estimating metallicities have been well calibrated. The metallicity distribution observed for metal-poor globular clusters gives a tolerably good fit to the above model prediction . However, matters are very different for the stars in the solar neighbourhood, within the disc of the Galaxy. The model predicts a far larger proportion of metal-poor stars than are actually found. This has become known as the G dwarf problem.

Questions:

1. Show that the combination of a closed box model and of a linear relation between the SFR and the gas mass leads to an exponential decrease of the SFR of a galaxy and a linear increase of the metallicity with time. Express the decreasing rate in terms of star formation efficiency and return rate
2. How does the IMF be modified in the earlier phases of the Galaxy to predict a lower number of G-dwarfs ?

B. Models with inflow and outflow

The current understanding we have of galaxy evolution is not consistent with a closed box model, infall of new gas and outflows are needed to reproduce the general evolution of galaxies in a cosmological context. Inflows may solve the G-dwarf problem
In this case the total mass of the system is no longer a constant but changes with time
$dM_{tot}/dt = A(t) - W(t)$
A(t) is the inflow rate and W(t) the outflow rate of gas mass

$dM_{gas}/dt = -SFR(t) + E(t) + A(t) - W(t)$
and in the same way for the metallicity of the gas:
$dZM_{gas}/dt = -Z\ SFR(t) + E_Z(t) + Z_A\ A(t) - Z\ W(t)$

This equation can only be solved if A(t) and W(t) are known.
The infall rate is often taken exponential. The prediction of the variation of Z(t) and M*(t) compared to observations is a way to constrain the amount of inflow and/or outflow.

Appendix

Temps caractéristique de chute libre (t_{ff})

C'est le temps que met une particule donnée pour tomber sur la masse M qui l'attire (durée donc de l'effondrement gravitationnel). Ce temps se calcule en faisant le raisonnement suivant : on part de la troisième loi de Kepler reliant période P et demi grand axe de l'ellipse a:
$P^2 = (4 \pi^2 / G M) a^3$.
Cette formule ne dépend pas de l'excentricité de l'ellipse. Pour modéliser la chute on suppose une ellipse infiniment fine (excentricité maximale) et dans ce cas a=r/2, r étant la distance initiale entre la particule et la masse (donc la taille de la perturbation gravitationnelle).
On écrit ensuite $M = 4/3 \pi r^3 \rho$.
Le temps de chute libre est P/2 (une demi période) soit
$\tau_{ff} = (3\pi/(32 G \rho))^{0.5}$

Mesure du contenu en gaz atomique et moléculaire

a. Gaz atomique

Le contenu en gaz HI provient de la mesure de la raie de structure hyperfine à 21 cm, optiquement mince. Le gaz HI est le constituant majeur du gaz interstellaire dans l'univers local

$$\frac{M_{\rm HI}}{M_\odot} = 2.36 \times 10^5 \times \frac{S_{\rm HI}}{\rm Jy\,km\,s^{-1}} \left(\frac{D_1}{\rm Mpc}\right)^2 ,$$

b. Gaz moléculaire

La mesure du contenu en gaz H_2 des galaxies n'est qu'indirecte, Elle est basée sur celle de la molécule CO, molécule la plus abondante après H_2 ($[CO]/[H_2] = \sim 10^{-5}$). En effet la molécule d'hydrogène étant symétrique seules les transitions électroniques sont autorisées. Dans les cas de très fortes excitations (par collisions par exemple) des raies interdites de transitions ro-vibrationnelles dans le proche IR peuvent être observées mais on ne peut pas s'en servir pour des mesures systématiques.
On utilise donc les transitions rotationnelles de basse énergie de CO qui ont le mérite de se produire dans le millimétrique, donc observable depuis le ciel.
Cependant la justification de l'usage de CO pour mesurer l'abondance en H_2 est difficile et fortement remise en question dans certains cas.
Etant donnée l'abondance de la molécule CO, les raies de ^{12}CO sont optiquement épaisses, il est alors impossible d'obtenir directement la densité de H_2 de l'analyse de la raie, comme on le fait avec la raie de HI à 21cm.
On fait alors appel à des méthodes alternatives. En pratique quatre approches différentes du problème existent :

- Etude des raies de plusieurs isotopes de CO, certaines de ces raies sont optiquement minces. Grâce à des modèles de transfert radiatif on estime la densité de colonne de ^{13}CO

ou ^{18}CO qui sont optiquement minces. Avec une connaissance de l'abondance absolue $^{12}CO/H_2$ (~8 10^{-5}) on en déduit la densité de colonne H_2
Quand seule l'observation de la molécule ^{13}CO qui donne des raies optiquement minces est possible, on mesure $^{13}CO/H_2$ qui est calibré dans notre galaxie.. Reste à admettre que ce rapport est universel pour l'appliquer à d'autres galaxies.

- Utilisation du rapport gaz/poussières (supposé constant). Il existe aussi une relation entre l'extinction A_V et la densité de colonne $N(H_2+HI)$ connue pour la Voie Lactée. On mesure le contenu en poussières ou l'extinction et on en déduit $N(H_2+HI)$, $N(HI)$ est en général connu et on en déduit $N(H_2)$. On tente de mesurer les rapports gaz/poussières et extinction/gaz dans les galaxies extérieures pour en vérifier l'universalité
- Emission diffuse des rayons gamma dans notre galaxie encore. Ces photons interagissent avec la matière et donc le gaz moléculaire. De la distribution spatiale et spectrale de l'émission gamma peut être déduite la distribution de la composante moléculaire
- Enfin, la méthode la plus populaire est celle basée sur l'équilibre statistique (« virialisation ») des nuages moléculaires. Détaillons la méthode :

On cherche à justifier l'universalité d'un rapport de l'intensité de la raie de CO à la densité de colonne de H_2 : $I(^{12}CO)/N(H_2)$.
Cette justification est basée sur le théorème du viriel appliqué à l'ensemble des nuages moléculaires observés dans le lobe du télescope. Elle est basée expérimentalement sur la corrélation trouvée avec la masse issue du viriel d'un ensemble de nuages moléculaires et leur luminosité dans la raie ^{12}CO (Solomon et al. 1987).

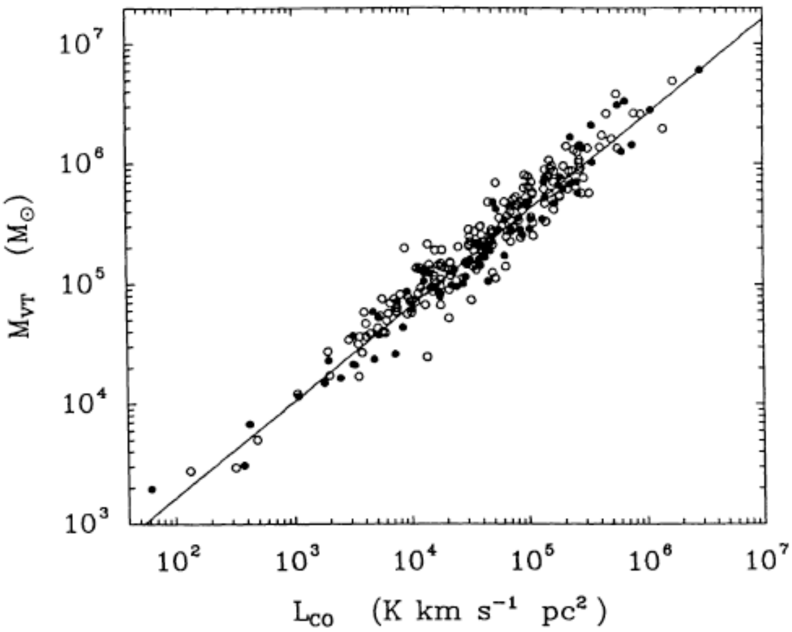


Figure 3. The virial mass–CO luminosity relation for real molecular clouds. The fit is $M_{VT} = 39(L_{CO})^{0.81}$. The closed circles are the calibrator clouds, the open circles the non-calibrators.

Ainsi l'émission CO d'une galaxie est supposée être la somme de l'émission de nuages indépendants, ne se recouvrant pas (faible taux de remplissage), ces nuages étant en équilibre du viriel. Cela est justifié par l'étude des nuages de notre Galaxie qui présentent des relations entre leur masse, leur rayon et leur dispersion de vitesse caractéristiques de l'équilibre du viriel.

Soit A l'aire observée par le télescope projetée sur le ciel. Chaque nuage a une aire $a=\pi d^2/4$, d étant le diamètre des nuages.

Chaque nuage a une dispersion interne de vitesse Δv et une température de rayonnement (ou de brillance) T_b. La dispersion de vitesses internes se traduit par un élargissement de la raie par effet Doppler $\Delta\nu$

L'intensité de la raie de CO peut alors s'écrire

$I(CO) = N\, a/A\, T_b\, \Delta v$ (K km s^{-1}) où N est le nombre de nuages, a/A le facteur de dilution

Cette relation appelle quelques commentaires:
Les intensités en radio-astronomie s'expriment en temperature, ce sont des temperatures de brillance définies à partir de la formule du corps noir appliquée dans l'approximation Rayleigh-Jeans soit $I_\nu = 2\, h\, \nu^3/c^2\, k\, T/h\nu$ (en W m^{-2} sr^{-1} Hz^{-1}). Même lorsque le rayonnement n'est pas celui d'un corps noir on écrit: $I_\nu = 2\ k\, T_b\, \nu^2/c^2$, T_b est la temperature de brillance. A noter que les measures se font en temperature d'antenne qui dans un cas ideal (antenne parfaite, source uniforme sur le ciel) serait égale à la temperature de brillance. Dans la pratique on applique des coefficients de correction.
Enfin on n'utilise généralement pas toutes ces constants pour exprimer directement I_ν en K soit I(CO) en K km s^{-1} car on multiplie par la largeur de la raie (exprimée en vitesse plutôt qu'en fréquence: $\Delta\nu/\nu = \Delta v/c$). Pour plus de details voir Kütner & Ulrich 1981,ApJ 250, 341.

$N(H_2)$, la densité de colonne en H_2 est donnée par :
$N(H_2) = 4/3\ \pi\ (d/2)^3\ n\ N/A$, n est la densité ($mol/cm^3$) de H_2 donc $4/3\ \pi\ (d/2)^3\ n$ est le nombre de molécules pour un nuage. $N(H_2)$ s'exprime en mol/cm^2 et
$N(H_2) = \pi\ d^3/6\ (nN/A)$

Des deux expressions de I(CO) et de $N(H_2)$ on déduit :
$I(CO)/N(H_2) = 3/2\ T_b\ \Delta v/nd$
Il s'agit d'exprimer Δv. On suppose chaque nuage virialisé : $2T+\Omega=0$ $T=1/2\ M\ \Delta v^2$ et
$\Omega \sim -GM^2/d$ soit
$\Delta v \sim (GM/d)^{0.5}$ et puisque $M \sim d^3 n$ alors $\Delta v \sim n^{0.5}\ d \sim \Delta\nu$

et $I(CO)/N(H_2) \sim T_b/n^{0.5}$

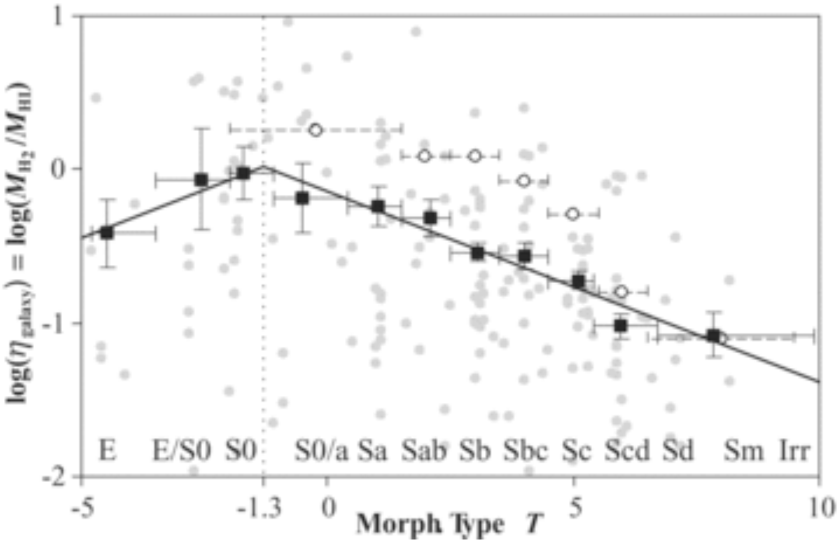
Si on suppose une même température ainsi qu'une même densité pour tous les nuages alors le rapport est constant.
Usuellement on adopte $T_b = 10K$ et $n = 200\ cm^{-3}$ et on obtient

$N(H_2) = 2.8\ 10^{20}\ cm^{-2}/(K\ km\ s^{-1})$, en accord avec la relation observée

Malheureusement, et comme on pouvait s'y attendre la métallicité va jouer un rôle important, l'abondance de CO lui étant reliée. Ainsi ce rapport ne reste vrai que pour des abondances à peu près solaires. Dans les nuages de Magellan, qui contiennent moins de métaux que la Voie Lactée le rapport $I(CO)/N(H_2)$ pourrait bien être 10 fois plus faible.

Malgré cette limitation majeure, des études statistiques du contenu en gaz moléculaire des galaxies ont été faites :$M(H_2)/M(HI)$ est inférieure ou au plus égale à 1, suivant les études.
Une forte dépendance avec le type des galaxies est observé (figure ci dessous d'après Obreschkow & Rawlings 2009), les galaxies de type tardif ayant moins de gaz moléculaire

mesuré par CO. Mais comme ces galaxies sont aussi moins métalliques, il faut être très prudent dans les conclusions.



La variation radiale des phases gazeuses est très différente, comme déjà souligné plus haut (ci-dessous variation radiale de diverses composantes d'après Bigiel et al. 2008). Notez la distribution « plate » et large du HI , et celle exponentielle des quantités liées à la formation stellaire, H_2 et SFR

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- Numerous references in the text