Lecture 2: Spectral energy distributions of galaxies

From the observations to the physical content of galaxies

Galaxies are huge systems (as seen in the first lecture for the Milky Way) but most of the time, and especially in modern astrophysics, they are very distant. As a consequence we have only access to a very limited information: some photometric data and sometimes some spectra.

Most of the studies of the distant universe are performed on a small sky area and with only a few observations (at different wavelengths). In cosmological studies, the approach becomes statistical, the detection of faint, very distant sources is privileged. To get the highest possible exposure time only one or very few filters are used. Such data are not sufficient to pursue a physical analysis of the galaxies. We will see that a large wavelength coverage is necessary to get information on the main galaxy components.

The best information we have on galaxy physics come from the nearby universe. As a matter of fact, most of the examples used in this lecture will be taken from studies of nearby galaxies.

A. Galaxies observed at different wavelengths: stars, gas and dust

1. Stars

Stars, gas and dust (in a decreasing order of mass) are the main observable components of the visible part of a galaxy (excluding dark matter). The original Hubble classification was based on images taken in the visible, therefore by stars emitting mainly in visible, whose distribution varies from ellipticals to spirals and irregulars.

However, a galaxy hosts stars at very different temperatures as we will see and its observed morphology will depend on the stellar content and on the wavelength of observation.

Stars are formed in a galaxy from the gravitational collapse of molecular gas. People assume that they are distributed at birth according to an Initial Mass Function that is considered as universal as a first approximation and most of the time. Therefore the lifetime and stellar mass of all stars is different, as well as their emission.

Below is a figure representing the flux as a function of wavelength for different stars: O stars emit most of their energy in the UV-blue, and the peak of emission is shifted towards the red going from O to M stars according to the Wien law (stars are assumed to be black bodies)

$$\lambda T = \mathrm{cte}$$

Varying the wavelength of observation from the UV to the NIR is equivalent to shift from young hot stars to old, colder ones. **The stars emit their light from the Lyman limit (91.2 nm) to the Near-IR (3 to 5 µm)**

It is illustrated in the 3 images of Messier 81, a very close galaxy classified as Sab (i.e. with a large bulge), try to identify the wavelength domain of each observation

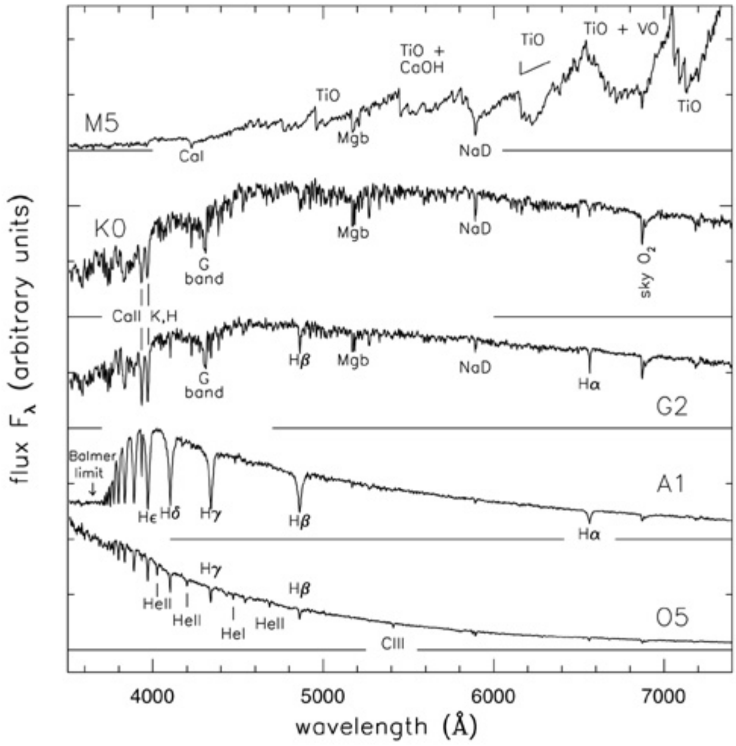
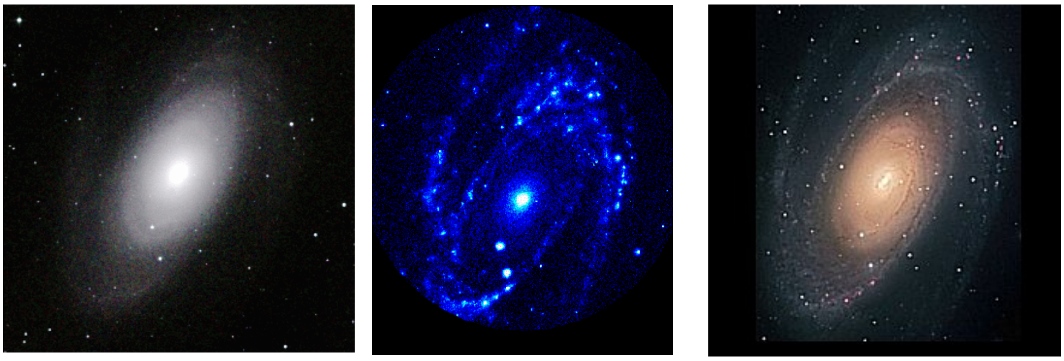


Fig 1.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



When observed with **large filters** in the photometric mode (resolution $\lambda/\Delta\lambda < \sim 10$), the stars behave as black bodies since the spectral resolution is not sufficient to detect detailed features of the spectrum.

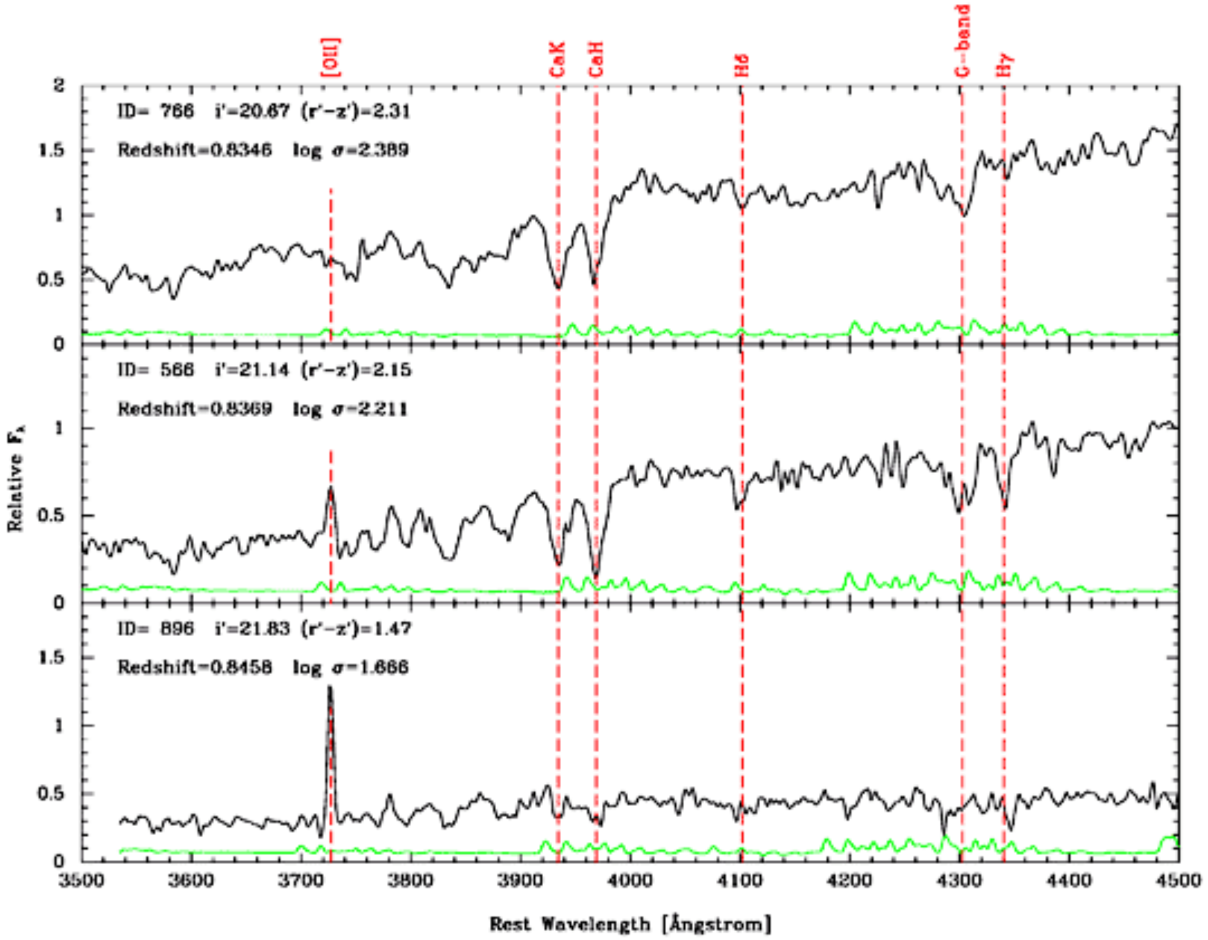
When **spectroscopy** is used, stars are seen as a **continuum with absorption lines,** as in the above figure.

Describe the main features present in the spectra of stars

In visible a galaxy is seen as a collection of stars, and the same features as those seen in stars spectra can be detected:

The absorption lines seen in a galaxy spectra are direct signatures of its stellar content

Below large band filters are shown to measure the broad continuum (i.e. the black body emission) whereas lines are observed on the spectra.



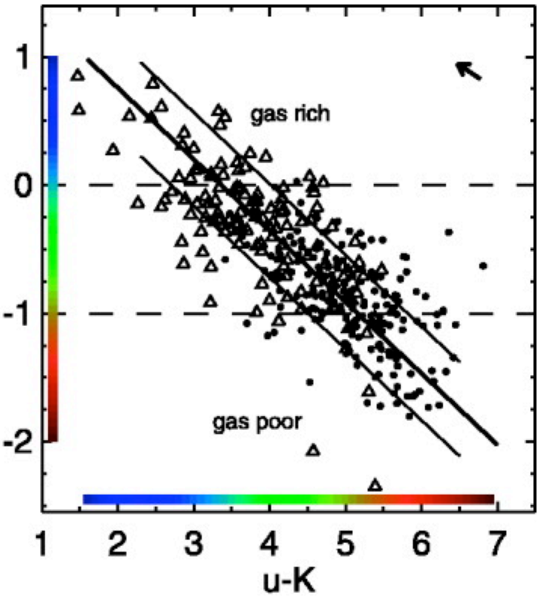
2. Gas

Some emission lines are visible in the above spectra, they are due to the gaseous component. Interstellar gas is diffuse and the corresponding emission lines are thin as compared to the absorption lines due to the stars

The gas is essentially hydrogen (~75%) and ~25% is Helium, 1 or 2% is formed of heavier elements.

The fraction of the mass in gaseous form varies among galaxies.

The gas to stellar mass ratio (logarithmic units) is plotted as a function of the u-K color and varies from 1% to more than 50%



Gas to stellar mass ratio,

Adapted from Cortese et al. 2012

For the Milky Way:

M(baryons) = 9.5 10^{10} M_{sun}
M(atomic gas) = 8 10^9 M_{sun}
M(ionized gas) = 2 10^9 M_{sun}
M(molecular gas) = 2.5 10^9 M_{sun}
Gas-to-baryons ratio = 0.13

Can you interpret the x axis in terms of morphological type?

a. Neutral atomic and molecular gas

The atomic phase is detected with the 21 cm line (hyperfine structure of hydrogen)

(see Phillips 1996)

The HI distribution in galactic disk was described in Lecture 1.

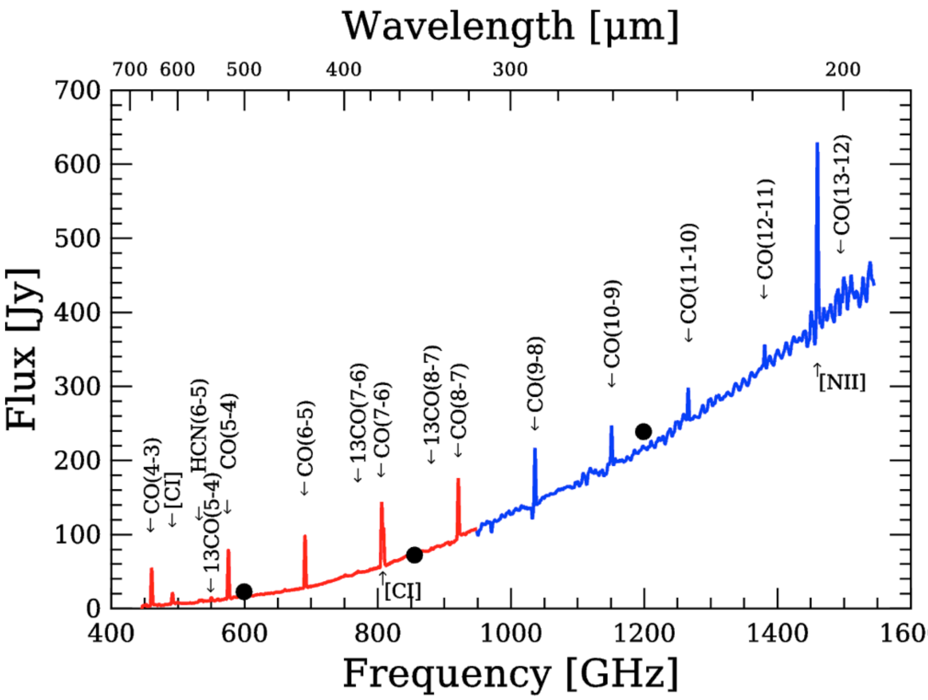
The H_2 molecule is symmetrical and has no dipolar momentum, only quadripolar transitions (rotation and ro-vibration) can be observed in the near-IR, but must be excited with UV photons and are intrinsically weak. Electronic transitions are observable in far UV, difficult to observe.

Moreover all these lines need a high excitation and only molecular gas close to young stars can be detected directly. Since we know that stars form in molecular clouds, it is mandatory to be able to detect cold molecular gas.

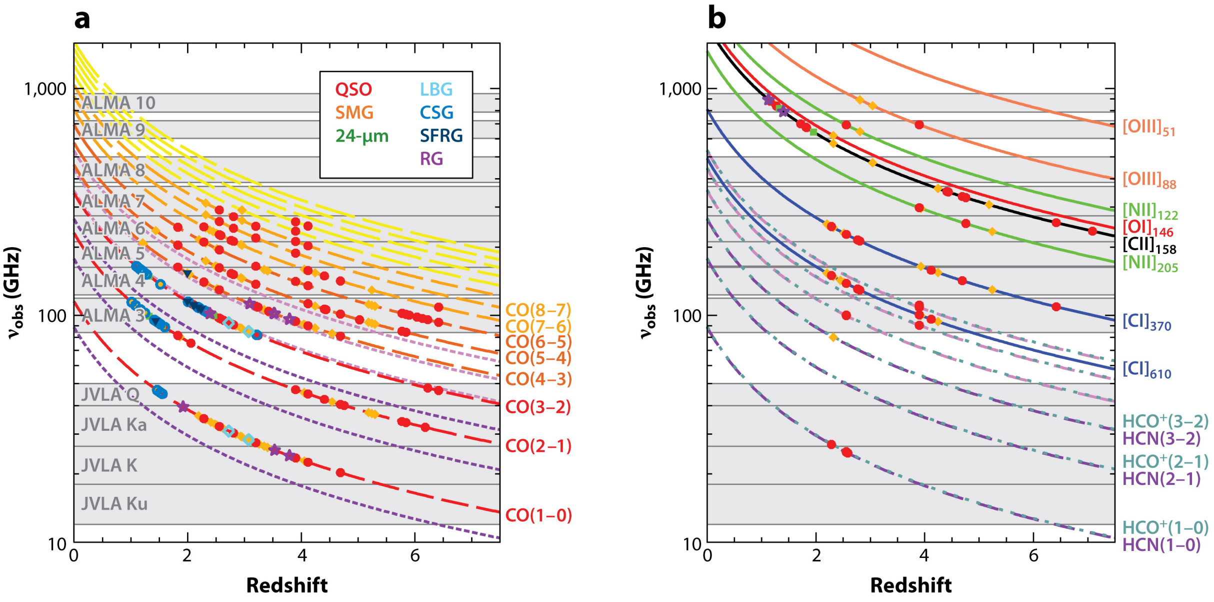
Given the impossibility to detect directly H_2, astronomers use the CO molecule which is abundant and have a large dipolar momentum. **The J=0-1 transition at 115 GHz (2.6**

mm) is commonly observed. Anyway a CO/H_2 ratio has to be assumed to derive the molecular content. The abundance ratio between CO and H_2 is of the order of $[CO]/[H_2] = \sim 10^{-5}$

Molecular lines are mostly observed in the far infrared, sub-mm and radio domain., as illustrated by the sub-mm spectrum of the nearby galaxy Messier 82 (Herschel-FTS observations, Panuzzo et al. 2010)



With the new generation of centimeter and millimeter telescopes, molecular and atomic far-IR and sub-mm transitions are now reachable at high redshifts



Carilli CL, Walter F. 2013.
Annu. Rev. Astron. Astrophys. 51:105–61

The measure of the molecular content

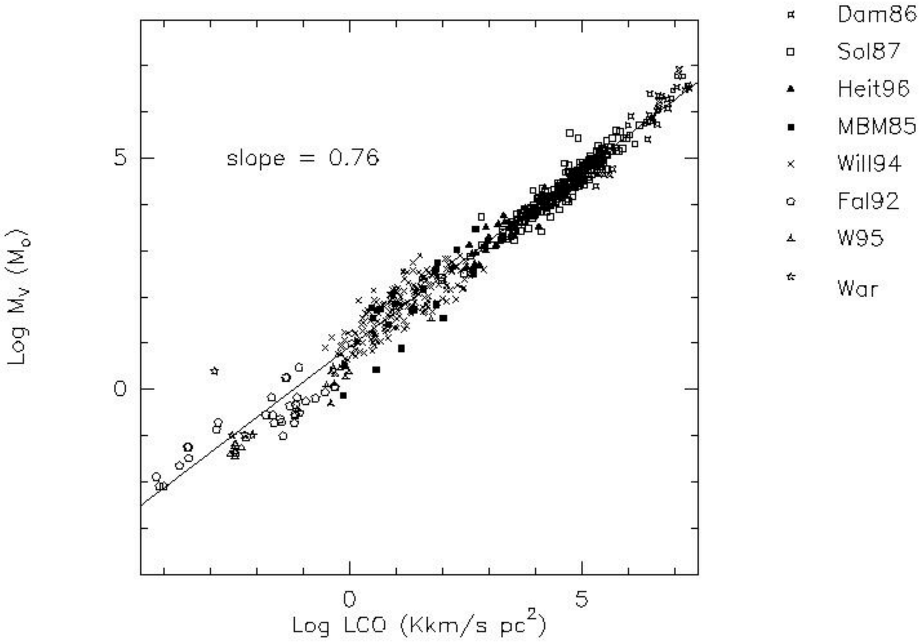
Since the CO molecule is abundant the CO lines are optically thick and the density is not directly deduced from the observed emission lines.

Alternative methods are thus used:

- Using isotope of oxygen or carbon (^{13}CO ou C ^{18}O) which are less abundant and thus optically thin. The column density is measured and provided that the isotopic ratio is known (or assumed to be known) the column density of ^{12}CO can be inferred, however they are poor tracers of the molecular content since they only trace the dense cores.
- Using the dust to gas ratio (supposed to be constant among galaxies). The dust content is measured from far-IR and submm data (as described in another section) and the total gas content is deduced (discussed later)
- The most popular method is based on the virialisation of molecular clouds as described here:

The CO lines do not give the column densities but the velocity width of the all the clouds observed in the beam of the telescope.

A correlation is found between the mass of a cloud measured with the virial theorem and the intensity of the CO line. It is this correlation which justify the universality of I(^{12}CO)/N(H2). The figure below is for individual clouds in the Milky Way (adapted from Solomon et al. 1987)



For external galaxies for which individual clouds are not resolved the observed CO emission is the sum of the emission of independent clouds, which do not overlap (the filling factor is small enough to make this assumption). These clouds are supposed to be virialised, similarly to the individual clouds of the MW.

Let A be the projected area observed by the telescope. Each cloud covers an area $a=\pi d^2/4$, d being the cloud diameter.

The velocity dispersion of " an average cloud " is Δv and the brightness temperature is T_b. The width of the CO line is due to this velocity dispersion (Doppler effect).

The intensity of the CO line is:

$I(CO) = N\, a/A\, T_b\, \Delta v$ (K km s^{-1}) N is the number of clouds into the beam, , a/A the dilution factor.

Some explanatory comments:

Radio-astronomers use temperature to measure intensities, called brightness temperature. They are defined from the black body and the Raylleigh-Jeans approximation (at high wavelength)

$I_\nu = 2\, h\, \nu^3/c^2\, k\, T/h\nu$ *(en* $W\, m^{-2}\, sr^{-1}\, Hz^{-1}$*).*

Even if the data are not fitted by a black body

$I_\nu = 2\ k\, T_b\, \nu^2/c^2$ *and* T_b *is the brightness temperature*

I is expressed directy in K (units of Tb) and I(CO) in K km s^{-1} *since the width of the line is expressed in km* s^{-1} *(*$\Delta\nu/\nu = \Delta v/c$*). For more details see Kutner & Ulich 1981,ApJ 250, 341.*

The column density $N(H_2)$ in the beam is given by:

$N(H_2) = 4/3\, \pi\, (d/2)^3\, n\, N/A$, n is the molecular density (mol/cm^3)

→ $4/3\, \pi\, (d/2)^3\, n$ is the number of molecules for a single cloud of diameter d and

$N(H_2) = \pi\, d^3/6\, (nN/A)$ (mol cm^{-2})

From the two above expressions of I(CO) and $N(H_2)$ one deduces :

$I(CO)/N(H_2) = 3/2\, T_b\, \Delta v/nd$

We have to relate Δv to the mass M of an "average cloud".

The virial theorem gives : $2T+\Omega=0$

$T=1/2\, M\, \Delta v^2$ and $\Omega \sim -GM^2/d$

then

$\Delta v \sim (GM/d)^{0.5}$, since $M \sim d^3 n \rightarrow \Delta v \sim n^{0.5}\, d$

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

If one assume a similar temperature and density for each cloud then the ratio becomes constant

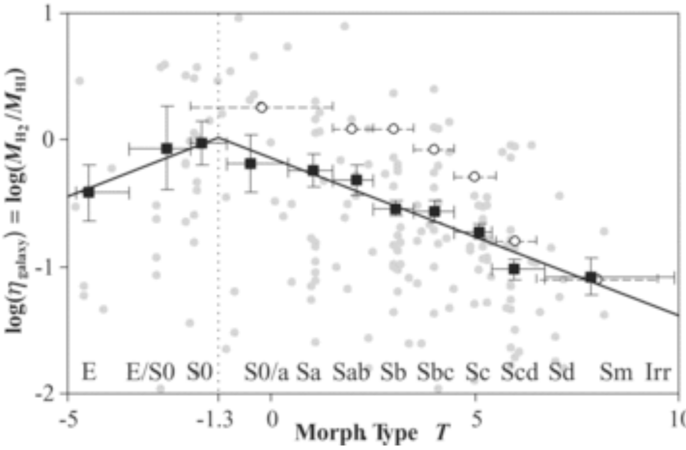
Usually $T_b = 10K$ et $n= 200\ cm^{-3}$ and

$N(H_2) = 2.8\ 10^{20}\ cm^{-2}/(K\ km\ s^{-1})$

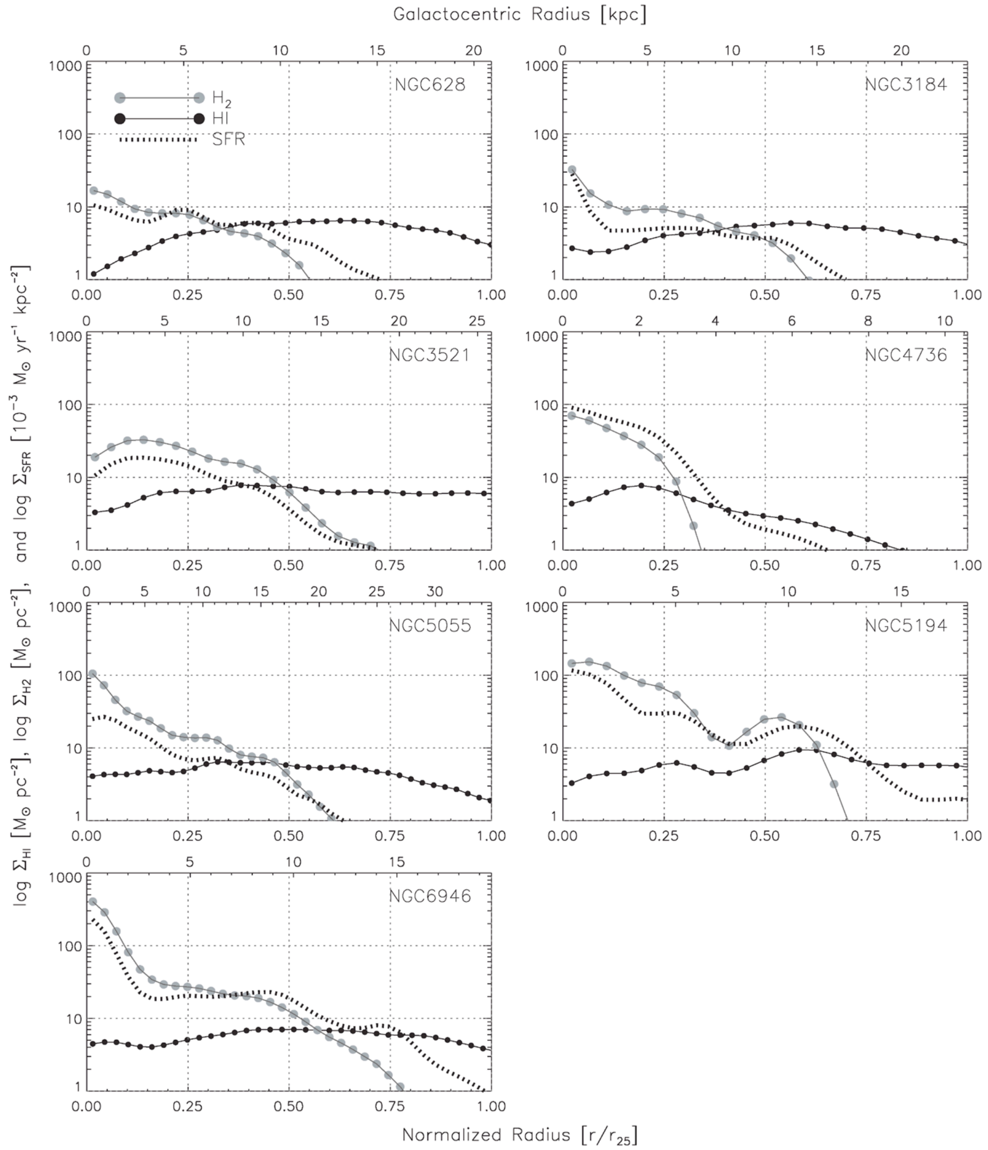
Unfortunately, the real situation is different and the ratio will depend on several factors, including metallicity (as expected). The above ratio is valid for solar abundances. In the Magellanic clouds the abundances is lower than for the MW and I(CO)/N(H_2) is lower by a factor 10 (see below).

M(H_2)/M(HI) is found <= 1 in most of the studies.

A trend is found with the morphological type (Obreschkow & Rawlings 2009). Late-type galaxies host less molecular gas but since these galaxies are less metallic one must be cautious with the result.



The radial variation of gaseous phases is very different as seen below. The HI gas has a flat and extended distribution whereas the H_2 radial variation is close to an exponential one (Bigiel et al. 2008)



b. Ionised gas

The ionised gas is located around hot and young stars, which emit ionizing photons. A large number of recombination lines are observed in visible and NIR.

Since the H atom is the most abundant these regions of ionized gas are called HII regions. They can be either radiation bounded (all the ionized photons are captured) or density bounded (when the density is too low ionizing photons can escape).

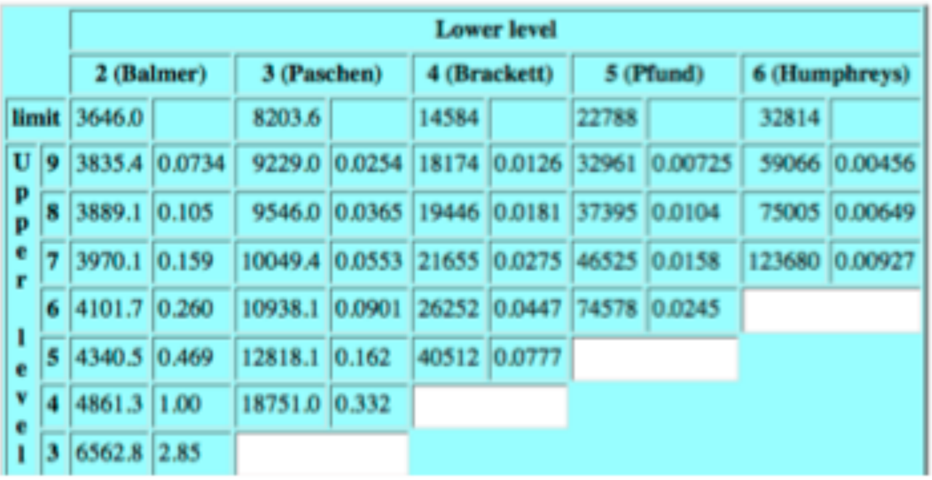
The case B of recombination is assumed, and well verified:

All Lyman line photons are re-absorbed by other hydrogen atoms

Every decay must eventually go to n=2, counting **the Balmer photons** gives access to the number of Lyc photons, Balmer photons leave the nebula and the galaxy.

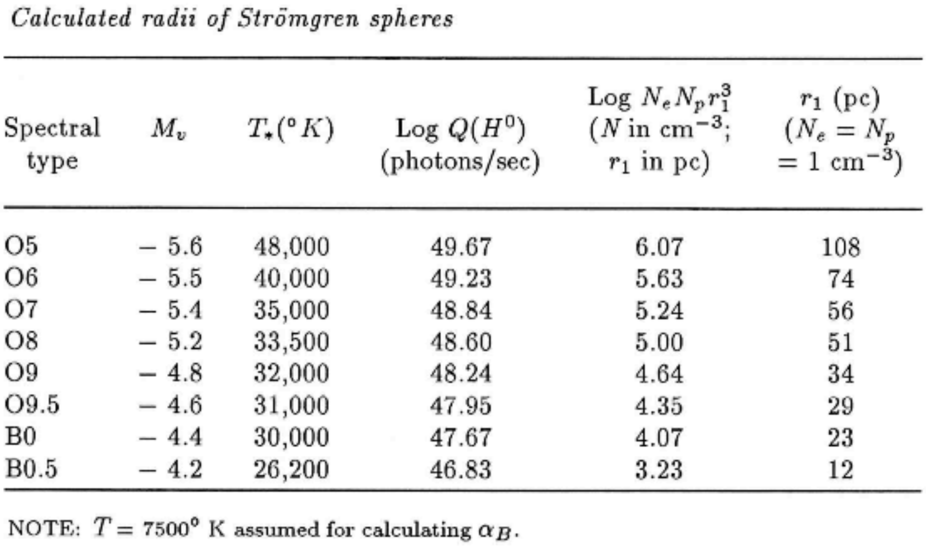
Lyman α photons are produced by the decay from n=2 to n=1 to gether with the 2-photons decay and can leak out of the nebula if their wavelength is slightly shifted or when they arrive at the edge of the nebula (no HI to absorb them) (assuming no dust**)** **Lyα/Hα=8**

(Osterbrock, Astrophysics of gaseous nebulae)



		Lower level									
		2 (Balmer)		3 (Paschen)		4 (Brackett)		5 (Pfund)		6 (Humphreys)	
limit		3646.0		8203.6		14584		22788		32814	
Upper level	9	3835.4	0.0734	9229.0	0.0254	18174	0.0126	32961	0.00725	59066	0.00456
	8	3889.1	0.105	9546.0	0.0365	19446	0.0181	37395	0.0104	75005	0.00649
	7	3970.1	0.159	10049.4	0.0553	21655	0.0275	46525	0.0158	123680	0.00927
	6	4101.7	0.260	10938.1	0.0901	26252	0.0447	74578	0.0245		
	5	4340.5	0.469	12818.1	0.162	40512	0.0777				
	4	4861.3	1.00	18751.0	0.332						
	3	6562.8	2.85								

The rate of ionizing photons decreases strongly when the spectral type of the stars go from O to B, practically only O stars and early B ones are able to ionize efficiently the HI gas.

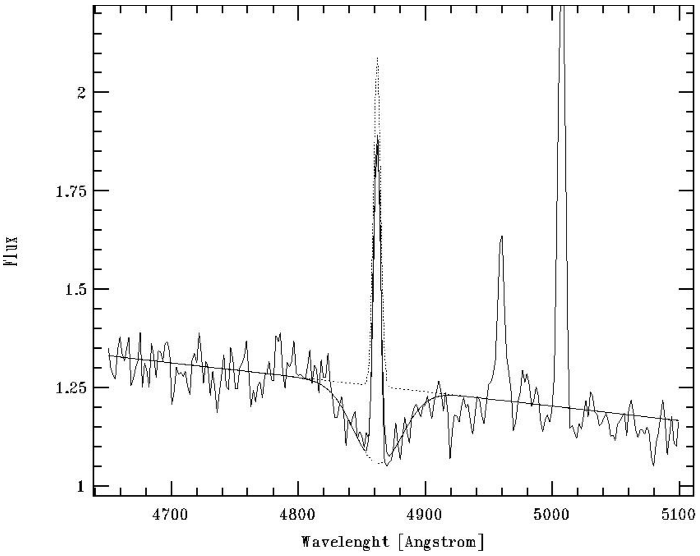


Calculated radii of Strömgren spheres

Spectral type	M_v	$T_*(°K)$	Log $Q(H^0)$ (photons/sec)	Log $N_eN_pr_1^3$ (N in cm^{-3}; r_1 in pc)	r_1 (pc) ($N_e = N_p = 1$ cm^{-3})
O5	− 5.6	48,000	49.67	6.07	108
O6	− 5.5	40,000	49.23	5.63	74
O7	− 5.4	35,000	48.84	5.24	56
O8	− 5.2	33,500	48.60	5.00	51
O9	− 4.8	32,000	48.24	4.64	34
O9.5	− 4.6	31,000	47.95	4.35	29
B0	− 4.4	30,000	47.67	4.07	23
B0.5	− 4.2	26,200	46.83	3.23	12

NOTE: $T = 7500°$ K assumed for calculating α_B.

The observation of emission lines is not always easy as illustrated below for an Hβ line seen in emission.



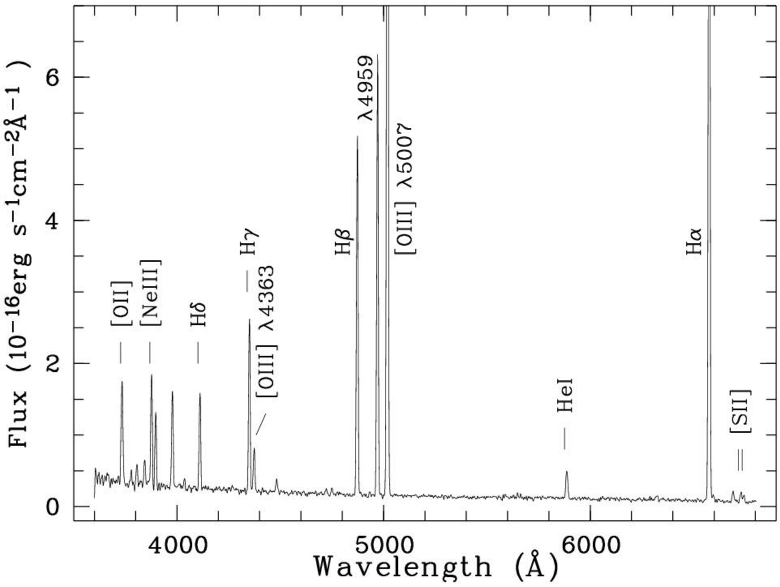
Explain the shape of the continuum and of the emission line

Other lines from heavier elements are also observed, whose intensity is linked to the ionization level and to the metallicity of the gas.

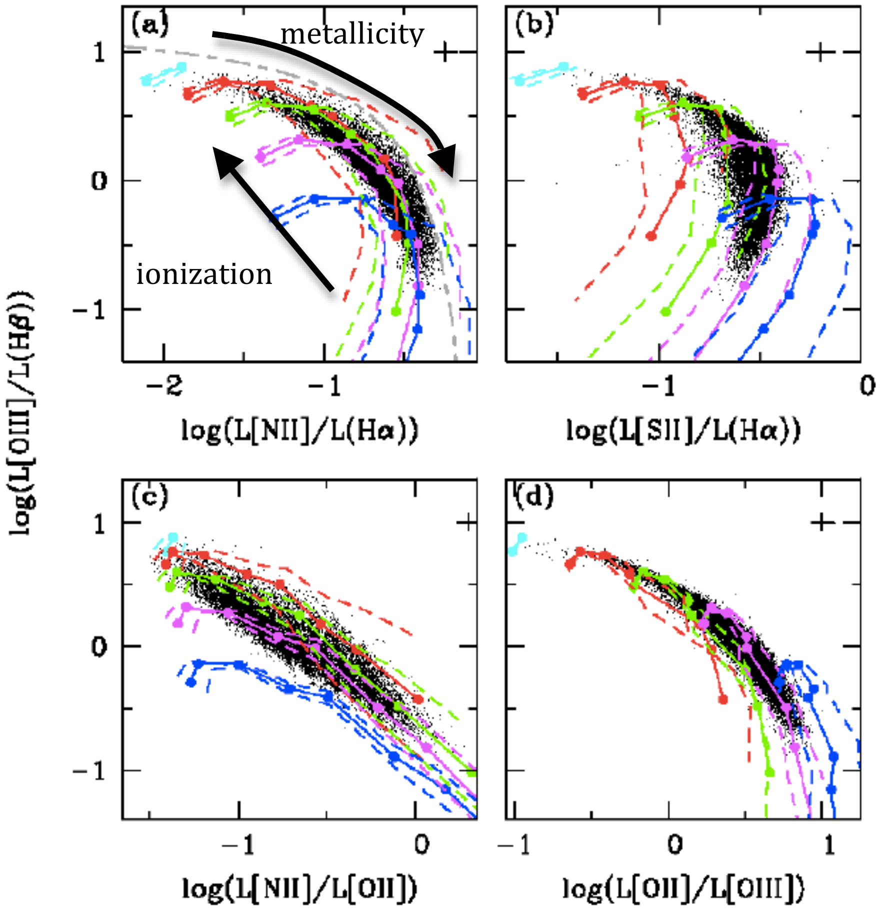
The main lines are due to oxygen ionized one or two times (OII, OIII) and some other species depending on the local conditions in the galaxies.

These lines are most of the time forbidden, but the huge column densities found in the interstellar medium allows their emission.

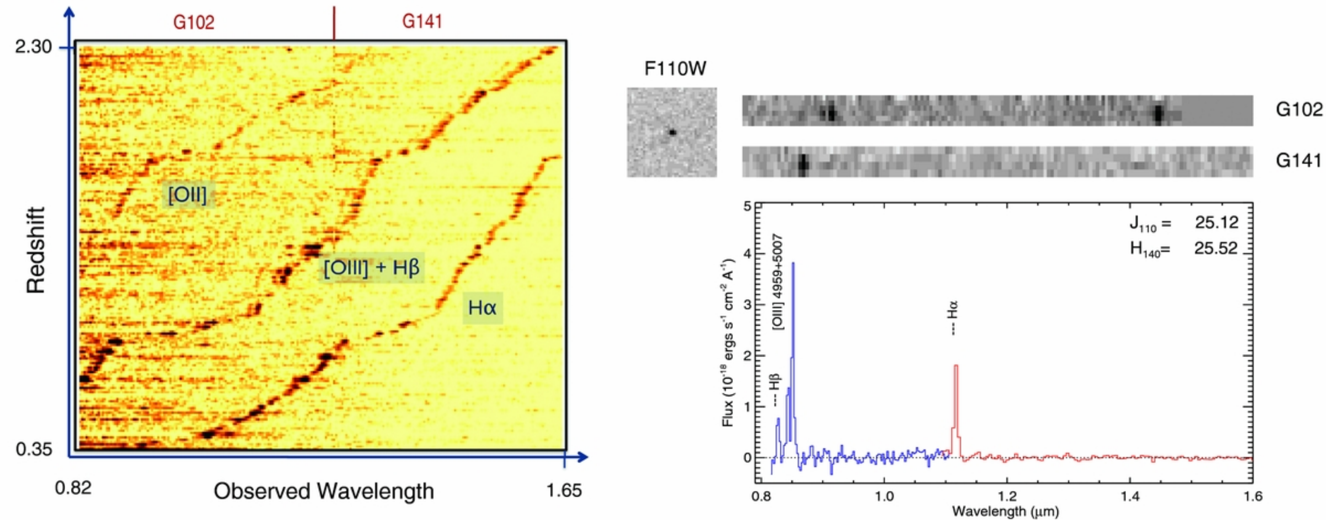
Below is an example of emission lines in a nearby galaxy very active in forming stars



The main parameters acting on the relative strength of line emissions are the metallicity of the gas and the ionization spectrum



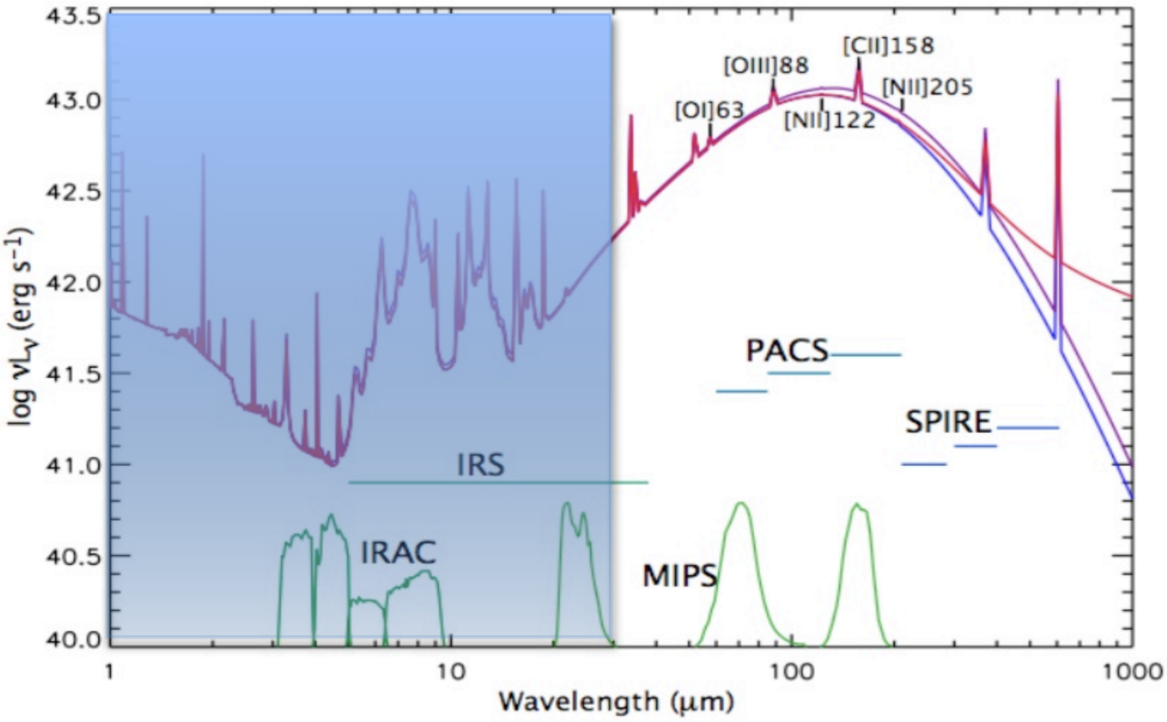
At high redshift the lines are redshifted and fall in the NIR, more difficult to be observed from the ground than the visible, they also become fainter and simpler indicators have to be defined



At high redshift the most prominent line are [OIII] and Hα

What is the redshift of the source whose emission is reported above?

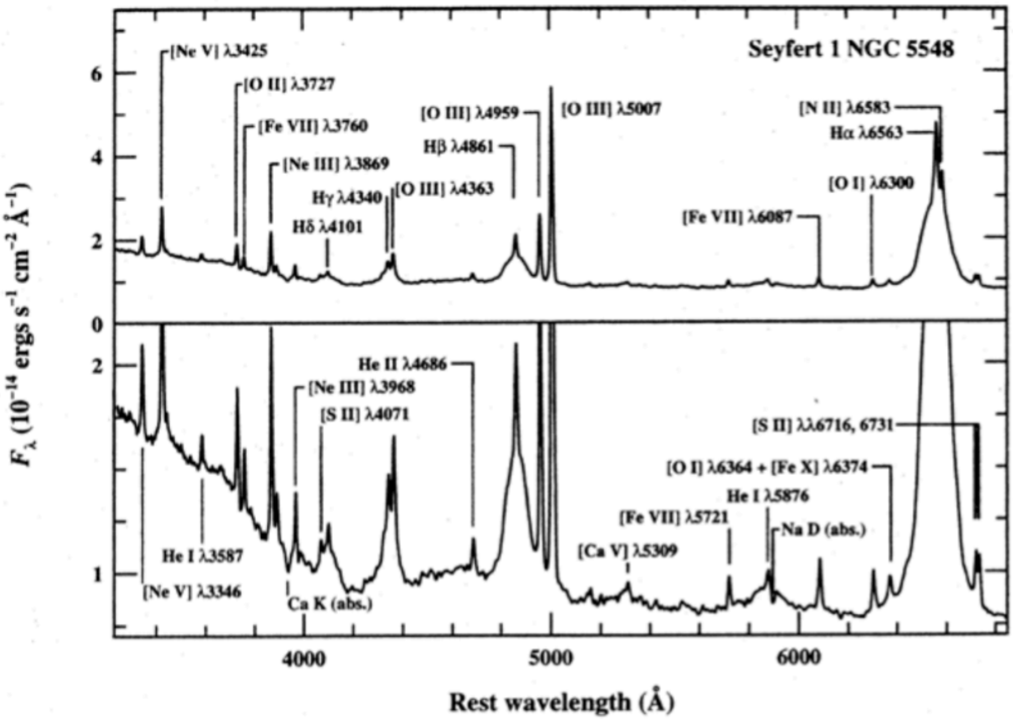
Far-IR emission lines also come from ionized gas, Oxygen and Carbon lines and are very useful to trace the young stellar populations ionizing the gas. Up to now they have not been observed for very distant and/or faint galaxies but the situation rapidly changes with ALMA for very high redshift sources. Ironically, the situation is more difficult at intermediate redshift and one must wait for a new generation of FIR space telescopes.

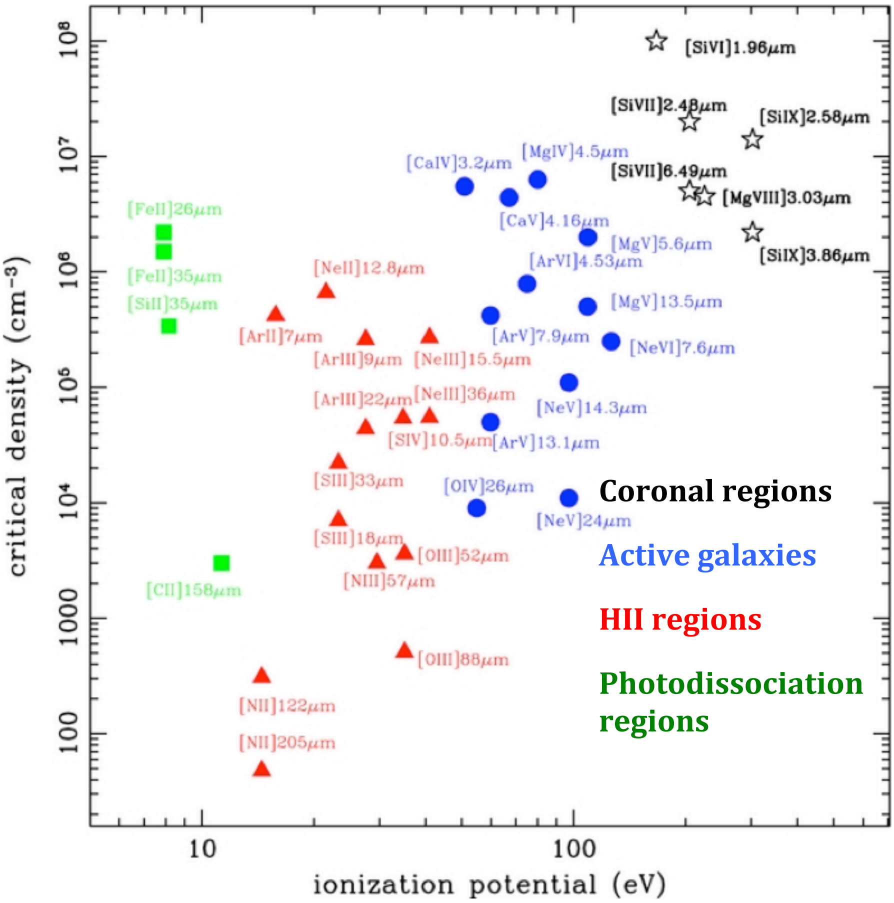


c. Emission lines in active galaxies

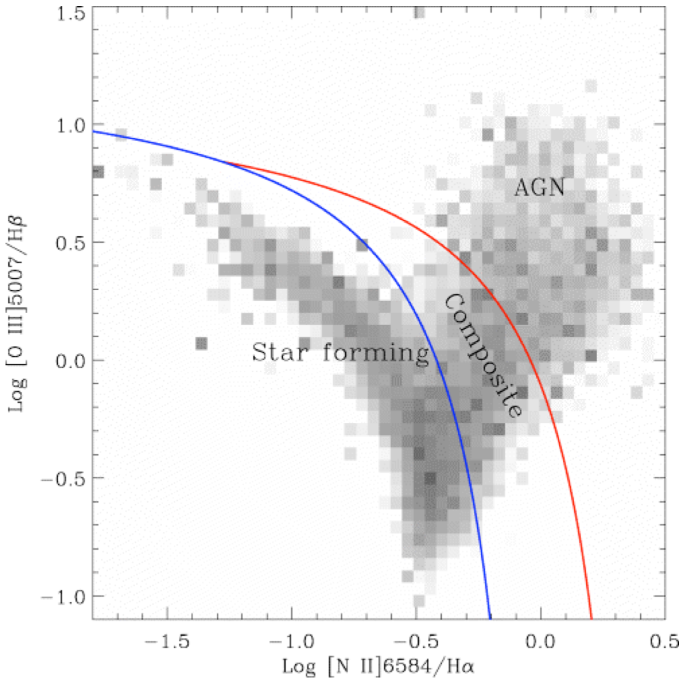
Active galaxies are galaxies which host a giant active black hole. For these objects, the ionizing source is not only young stars but also the energy released by the accretion process.

These galaxies exhibit very different spectra in visible with lines which are largely broadened, and highly ionized species are present (Spinoglio et al. 2012)





Line diagnostics are developed to separate sources dominated by stellar or non thermal ionization, the line ratios are similar to those used in the above plot for star formation alone



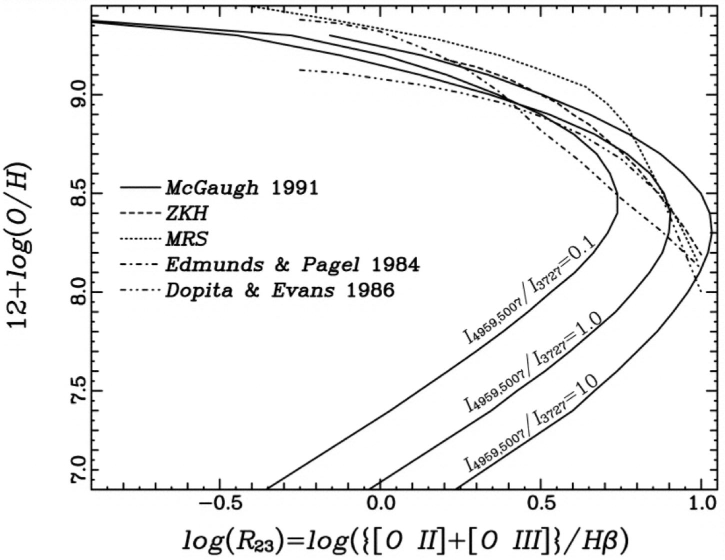
d. Metallicity

Metallicity (i.e. measure of the quantity of species heavier than H and He) is usually measured by using the most prominent oxygen lines.

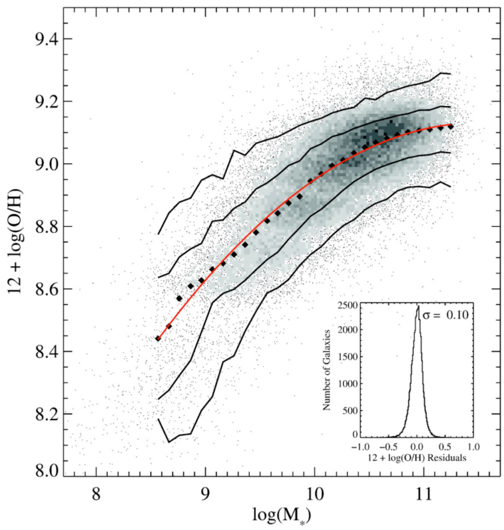
The R_{23} ratio is defined as:

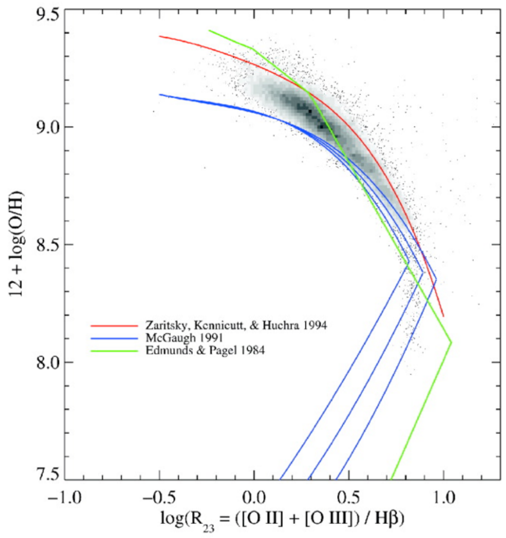
R_{23} = log(([OIII]λ5007+[OIII]λ4959+[OII]λ3727)/Hβ)

The calibration of this parameter in terms of O/H ratio is obtained by modeling, depending on the assumed ionizing parameter.



The solar abundance corresponds to 12+log(O/H) = 9.7 (corresponding to Z=0.02)





In the study of 53 000 galaxies for the nearby universe (SDSS), the metallicity remains high enough to avoid problems in the calibration (Tremonti et al. 2004) . The situation may be quite different in the early universe

The metallicity is found to increase with the stellar mass of the galaxies

Is such a relation expected?

3. Breaks in galaxy spectra

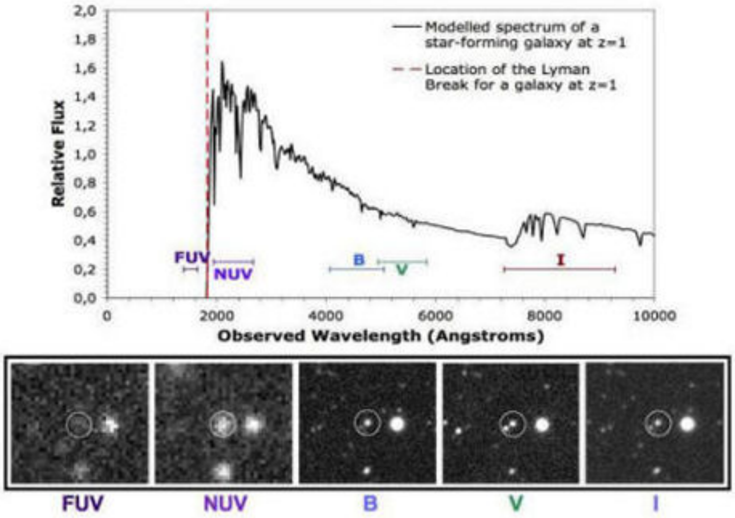
Breaks are particularly interesting since they are easily identifiable and do not need high resolution spectroscopy, imaging may even be sufficient with well chosen filters. Moreover, they are not heavily affected by dust attenuation (as we will see in the next lecture). They are due either to the stellar continuum or to gaseous transition lines.

a. Lyman break

It is the major break found in a galaxy spectra. Unfortunately it is not observable in nearby galaxies since it occurs at 91,2 nm. Practically the spectrum decreases below the Lyman α line (121,6 nm) because of the Lyman series, and, at large redshift, of the intergalactic absorption. Indeed, these signature is very useful at high redshift when it is shifted in the visible or the NIR for very distant objects.

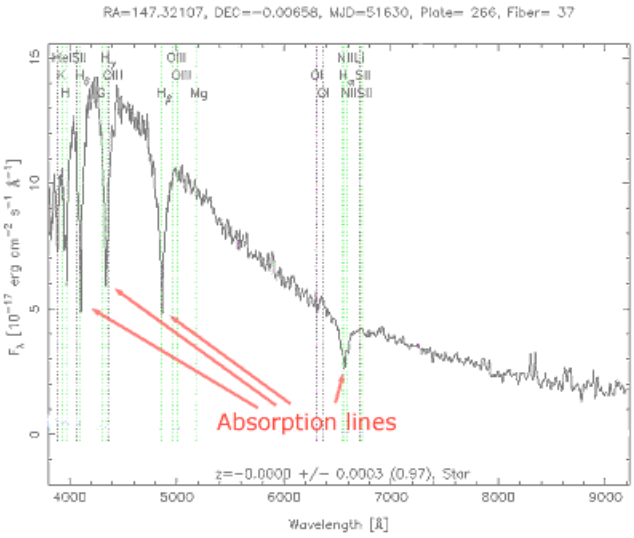
The Lyman Break Galaxies (LBG) are a class of objects detected thanks to their break, they are active star forming galaxies since their UV rest-frame continuum is intense.

Example of a LBG selection around z=1, imaging in FUV (153 nm) and NUV (231 nm) allows to locate break between these two bands (Burgarella et al. 2006)

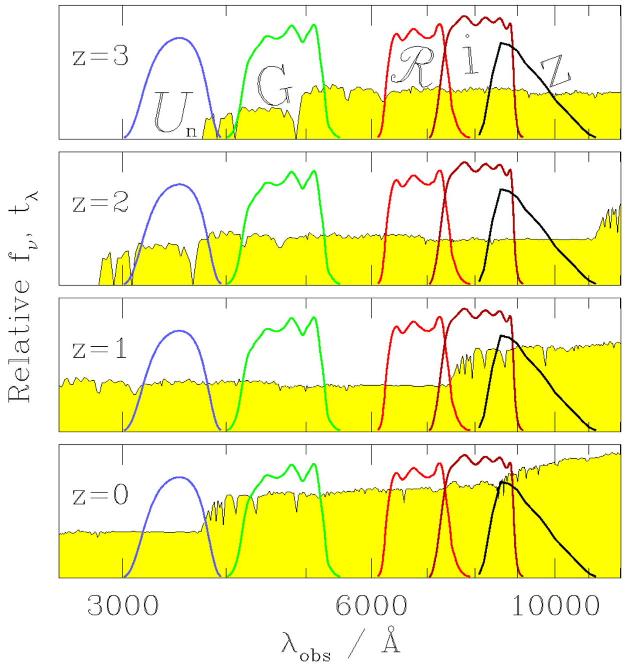


b.Balmer break

We have already seen that the Balmer Break is mainly due to B stars, it is an indicator of young (but not very young) stars.

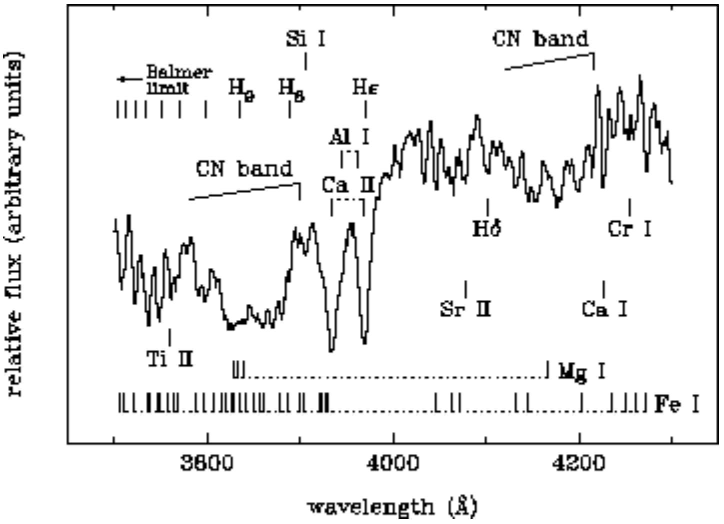


It can be detected at different redshift by combining filters of increasing wavelength.



c. D4000 break

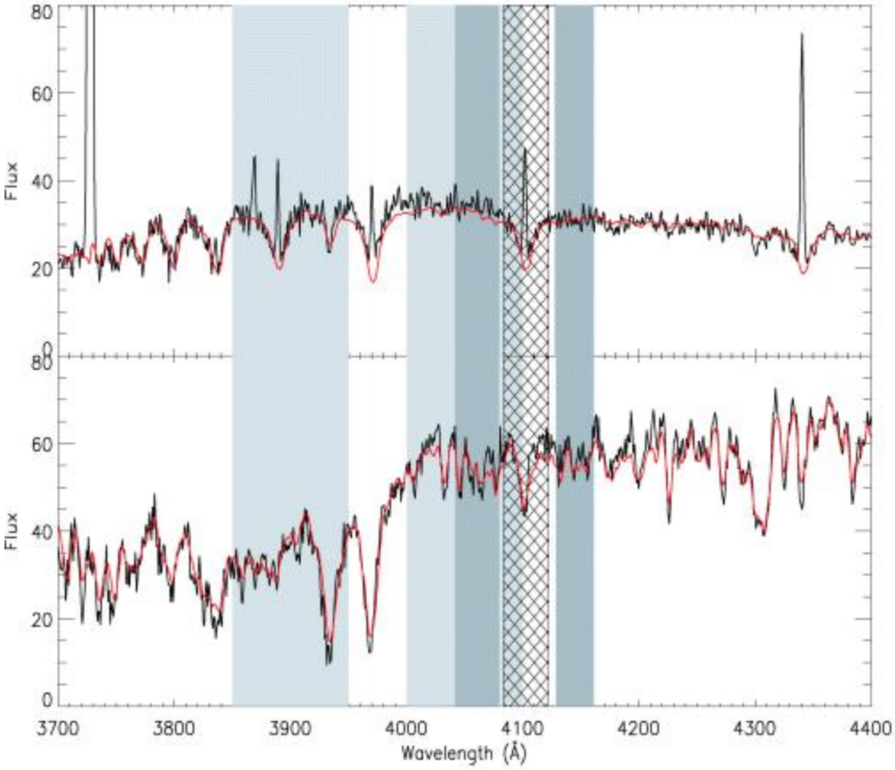
The D4000 feature or break is a well known indicator of the presence of old stars. Cold stars show a large depression in their spectra below 4000 A due to the opacity of metal lines, which increases with the spectral type of the stars (shown below the spectrum of a G9 star)



The D4000 break is commonly used to measure the average age of of a stellar population. A spectrum of a late-type galaxy exhibits a lowD4000, an early type galaxy will be found with a larger D4000 feature

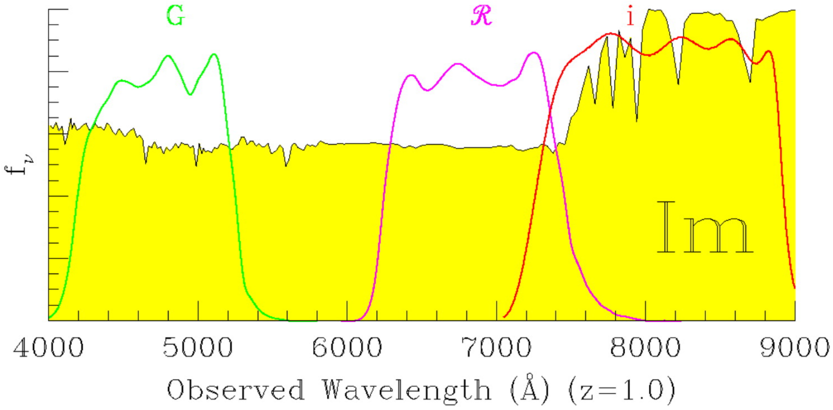
Kauffmann et al. 2003, MNRAS 341, 33 (late-type(upper panel) & early-type (lower panel), the range to search for the Hδ line is also indicated.

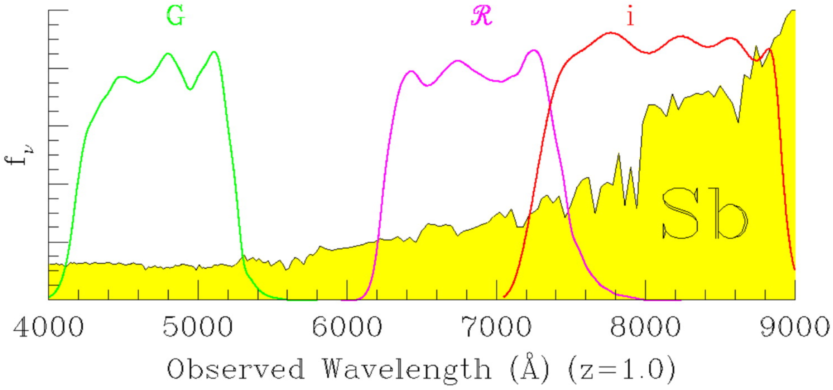
Comment on the difference on the Hδ line detection in both cases: explain the difference



All breaks are used at high redshifts.

Given the proximity of the Balmer and D4000 breaks, they are often associated in a single feature, even if their physical meaning is completely different, as illustrated below for a z=1 galaxy.

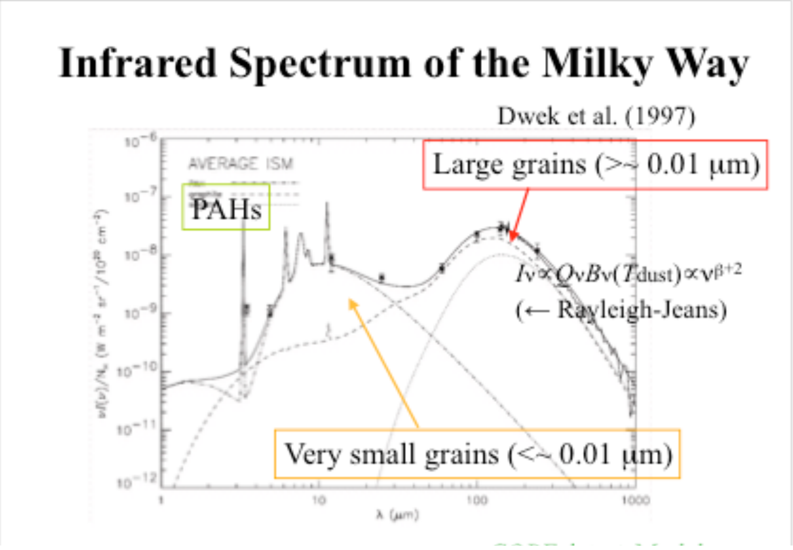




3. Dust emission.

The Milky Way is the best laboratory to measure dust properties and the modeling of both dust emission and stellar extinction has led people to a unified view of the dust content

a. Different dust components



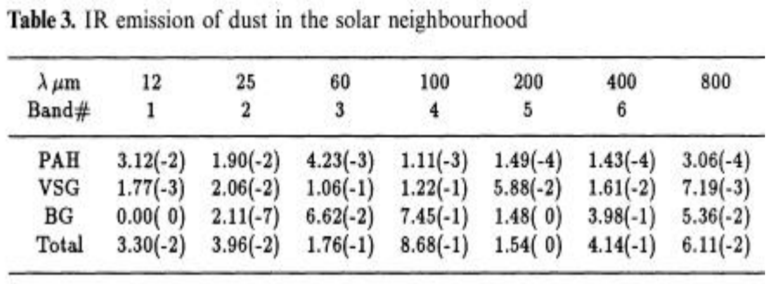


Table 3. IR emission of dust in the solar neighbourhood

λ μm Band#	12 1	25 2	60 3	100 4	200 5	400 6	800
PAH	3.12(-2)	1.90(-2)	4.23(-3)	1.11(-3)	1.49(-4)	1.43(-4)	3.06(-4)
VSG	1.77(-3)	2.06(-2)	1.06(-1)	1.22(-1)	5.88(-2)	1.61(-2)	7.19(-3)
BG	0.00(0)	2.11(-7)	6.62(-2)	7.45(-1)	1.48(0)	3.98(-1)	5.36(-2)
Total	3.30(-2)	3.96(-2)	1.76(-1)	8.68(-1)	1.54(0)	4.14(-1)	6.11(-2)

b. Dust masses, temperatures and dust to gas ratios

Dust masses:

This is a crucial parameter for the study of chemical evolution and extinction in galaxies.

It is most of the time introduced through the Gas to Dust Ratio (GDR) whose value is around one hundred in nearby galaxies.

Dust emission is studied in IR (up to the sub-mm). From these observations a dust mass has to be measured.

The classical approach assumes a modified Black Body B(ν,T) emission of the dust with an emissivity Q(ν) varying as ν^{α} with α=1-2. Note that there is a degeneracy between the temperature T and the coefficient α.

Let us consider a cloud at a distance D made of N spherical dust grains at temperature T with an emissivity Q(ν) and a cross-section s

The flux of the cloud can be expressed as:

$F(\nu) = N (s/ 4\pi D^2) Q(\nu)\ 4 \pi B(\nu,T)$ (W $m^{-2}Hz^{-1}$)

Soit $F(\nu) = N (s/ D^2) Q(\nu) B(\nu,T)$ et $N = F(\nu) D^2/(B(\nu,T) Q(\nu) s$

$B(\nu,T)$ is expressed in W $m^{-2}sr^{-1}Hz^{-1}$

The total colume of the dust grains is $V = N v$

$V = N v = (F(\nu) D^2/B(\nu,T) Q(\nu)) (v/s)$

With $v=4/3 \pi a^3$ et $s = \pi a^2$

And $M_{dust} = V \rho \rightarrow M_{dust} = (F(\nu) D^2/B(\nu,T)) (4a\rho/3)/Q(\nu)$

To measure M_{dust}, a grain size and density must be assumed

Typical values are $a=0.1\ \mu m$ et $\rho = 3000 kg\ m^{-3}$ (**Hildebrand 1983, QJRAS 24, 267)**

Dust temperature

it is not realistic to assume a single temperature for dust. Some models combine several modified black bodies. More physical and sophisticated models are developed but are not related to any well defined temperature.

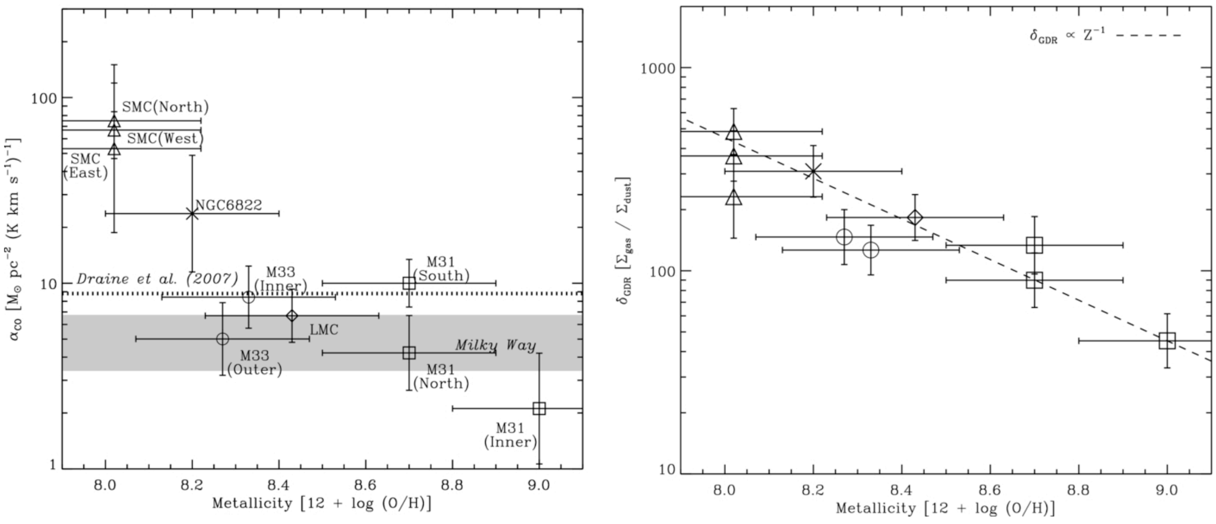
People wanting to measure dust masses either assume a single temperature or implement sophisticated models, it clearly depends on the number of available data. It is also important to compare quantities measured in a similar way.

Gas to Dust ratio (GDR)

If a Gas to Dust ratio is known and universal, measuring the dust mass gives access to the gas mass. However a universal value is not ensured, and may vary with the metallicity, as shown in the nearby universe.

$\delta(GDR)^* \Sigma(dust) = \alpha(CO)^*I(CO)+\Sigma(HI)$, $\delta(GDR)$ and $\alpha(CO)$ can be estimated

from Leroy et al. 2011



B. The whole FUV to IR emission of galaxies

1. The building of the whole SED

Dust is heated by young stars,

There is an energy balance

between the absorbed stellar

emission (difference between

blue and black lines) and the

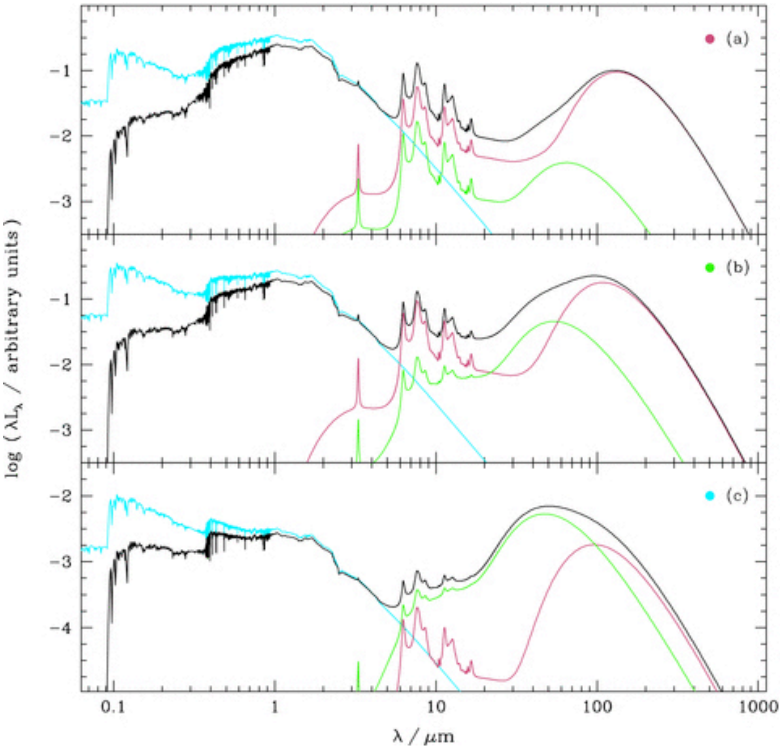
re-emission in infrared.

Here are models of galaxies

built with this energy

conservation

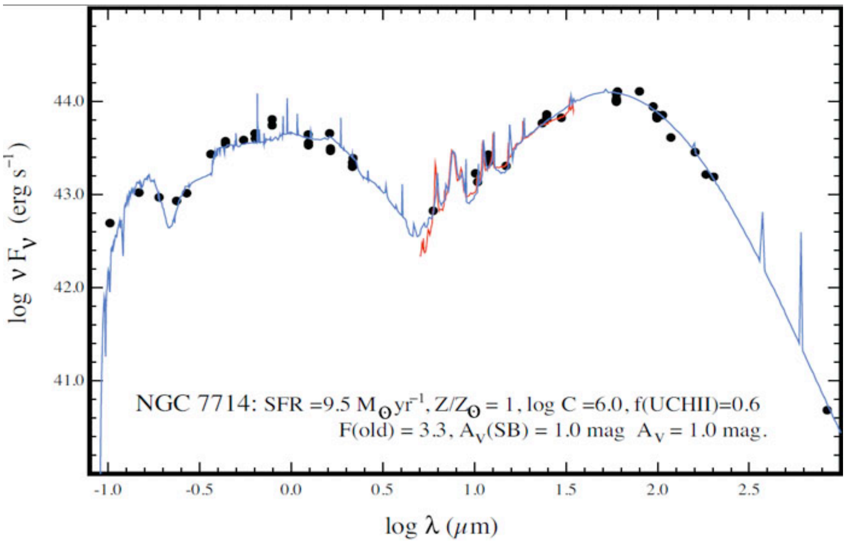
(da Cunha et al. 2008)



Here is the case of NGC 7714, a small nearby galaxy, very active in star formation, the wavelength coverage is large, combining several surveys, mostly from the space.

Indicate the contribution of stars, dust and gas

Groves et al. 2008

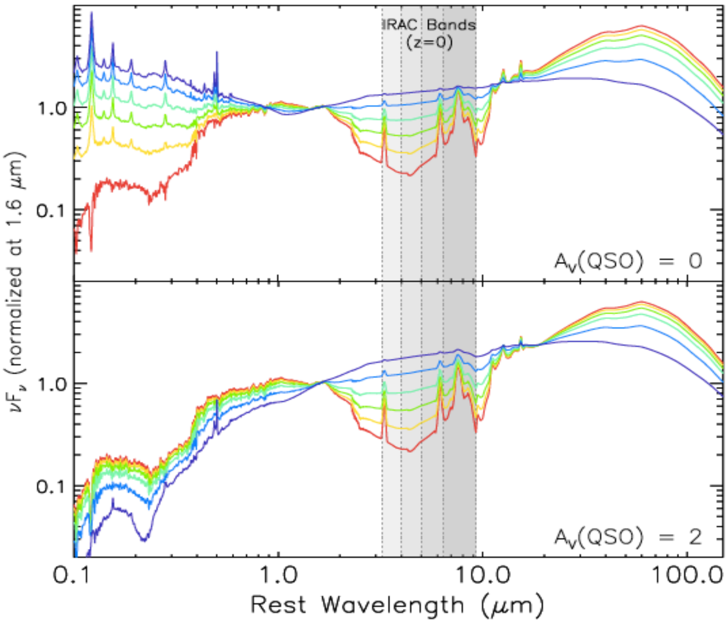


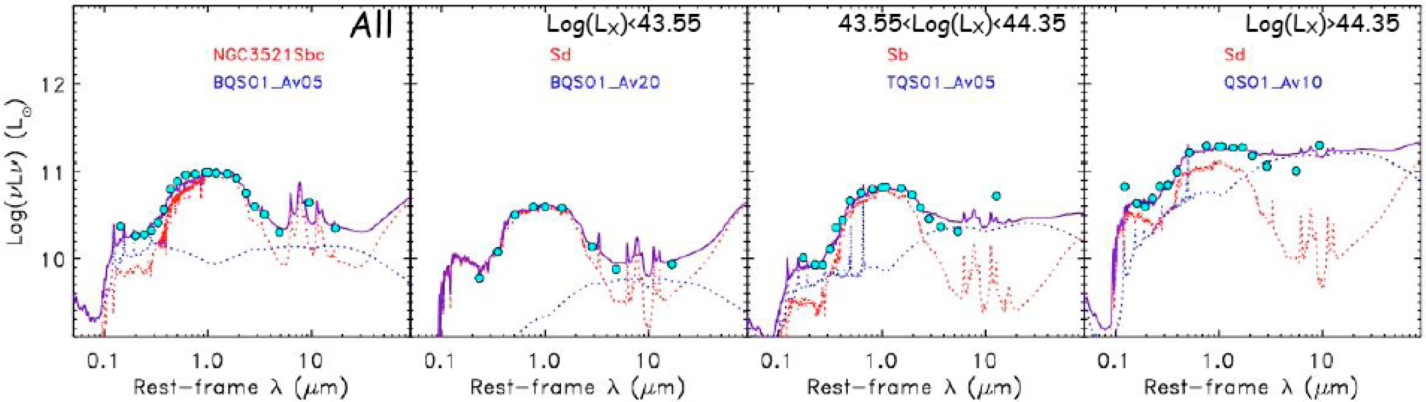
2. The Spectral Energy Distributions of active galaxies

In galaxies hosting an active nucleus, the total emission is the combination of the nucleus emission and of the stellar (and dust) one.

It is a very complicated topic, mostly due to the fact that the modeling of the whole SED of an AGN has still to be made and that we rely on empirical templates.

The combination of spectra is illustrated on the right side (from Donley et al. 2012) where a stellar component (red) is combined with the spectrum of a quasar (blue line: 95% due to the quasar emission).





This decomposition is performed on real data (Poletta et al. 2008)

Describe each panel: which component (stars or nucleus) dominates?

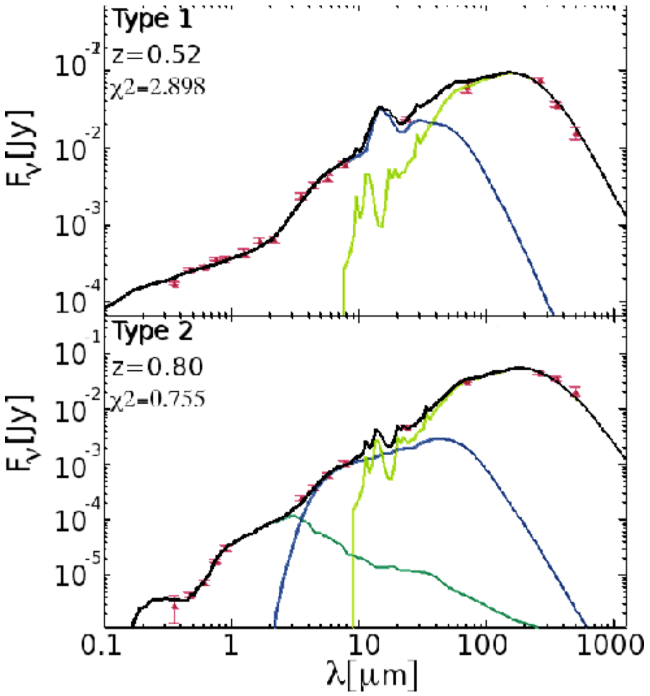
In far-IR, the emission is dominated by the stellar component, as illustrated below

(Hatziminaoglou et al. 2010)

For type 1 AGN, the AGN dominates in the UV optical up to the mid-IR

For type 2 AGN, the stellar component is seen in optical and its imprint through PAH emission is seen in the mid-IR

In both cases the far-IR emission (λ > 100 μm) is completely dominated by the stellar emission re-processed by dust.



3. The distant universe: redshifting the galaxy emission

The SED of nearby galaxies are mostly built with the aim to be compared to those of more distant objects. In this cases, there is a redshifting of the spectrum.

Practically if a galaxy is a luminous distance D

$F(\nu_{obs}) = L(\nu_{ém})(1+z) / 4\pi D^2$ (W/m^2/Hz)

$\nu_{obs}=\nu_{ém}/(1+z)$ and $\Delta\nu_{ém} = \Delta\nu_{obs}(1+z)$, therefore the flux per Hz is multiplied by (1+z) (the same energy is put in an observed band whih is narrower than the emitted one)

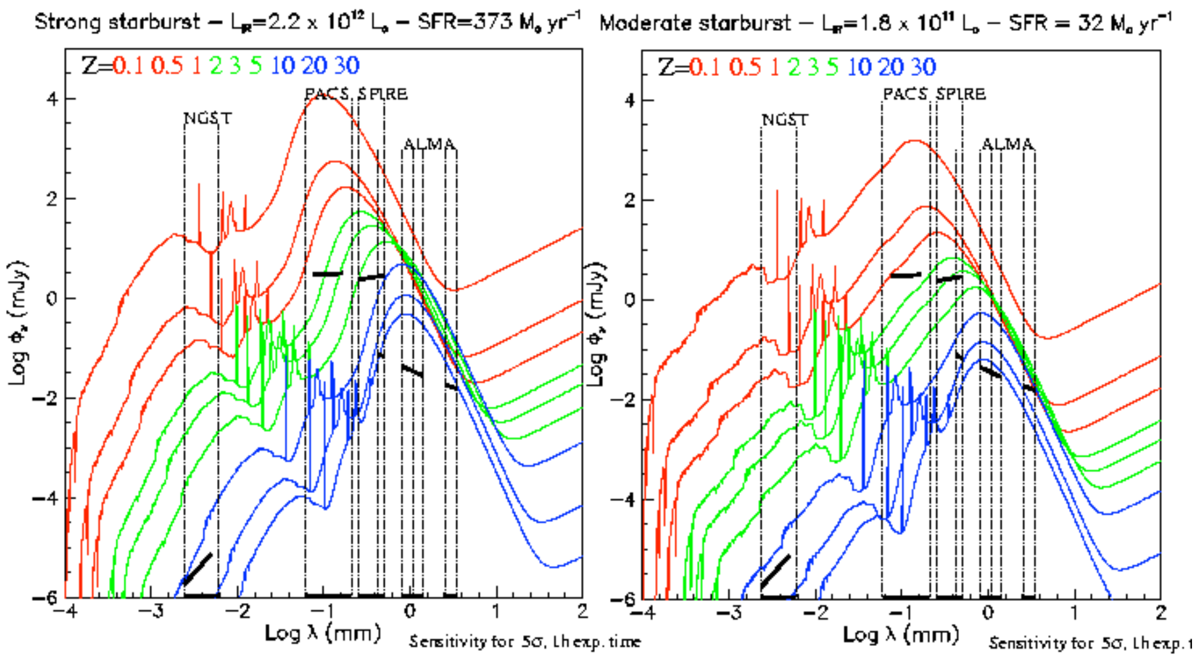
Note :

1. The most popular unity is the jansky: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}
2. If the flux was expressed in W m^{-2} A^{-1} the flux would be reduced by (1+z)

Accouting for the distance of a source is usually called “K correction”: it includes the wavelength redshift and of the modification of the wavelength or frequency intervals.

In a global sense a distant galaxy must be fainter than its nearby sibling. It is observed in the UV-optical-NIR as shown below

Positive K-correction: in far-IR (submm at high redshift) the redshift associated to a modified Black Body induces a “positive K correction”: at wavelength larger than the peak emission (Rayleigh Jeans regime) the dimming is compensated by the shift making distant galaxies as luminous as closer objects. This property is a powerful way to detect high redshift systems in the sub-mm (Herschel, Scuba).



Application :

A galaxy forming stars actively emits a continuum flux in the ultraviolet (120-250 nms) following approximately the law: $f(\lambda) = A\,\lambda^{-\text{ß}}$, $f(\lambda)$ is expressed in erg $cm^{-2}\,s^{-1}\,nm^{-1}$

1. Give the expression of the law $f(\nu)$ as a function of ν (i.e in the units oferg $cm^{-2}s^{-1}Hz^{-1}$) and then in logarithmic units. Discuss the case $\beta=2$
2. The quantity $\lambda\, f(\lambda)$ is commonly used to plot the spectral energy distributions of galaxies

a. Show that $\lambda\, f(\lambda) = \nu\, f(\nu)$

b. Justify the wording " spectral energy distribution of galaxies"

3. The galaxy is now at a redshift $z > 0$

a. What is the wavelength range of observations of the rest-frame ultraviolet continuum? N.A. $z=1$

b. Let us call λ_{obs}, λ_{em},ν_{obs},ν_{em} the wavelengths and frequencies observed and emitted.
Give the expression of $f(\lambda_{obs})$ as a function of $f(\lambda_{em})$ and z, and show that the quantity $\lambda\, f(\lambda)$ does not depend on z.

c. Same question with the frequency

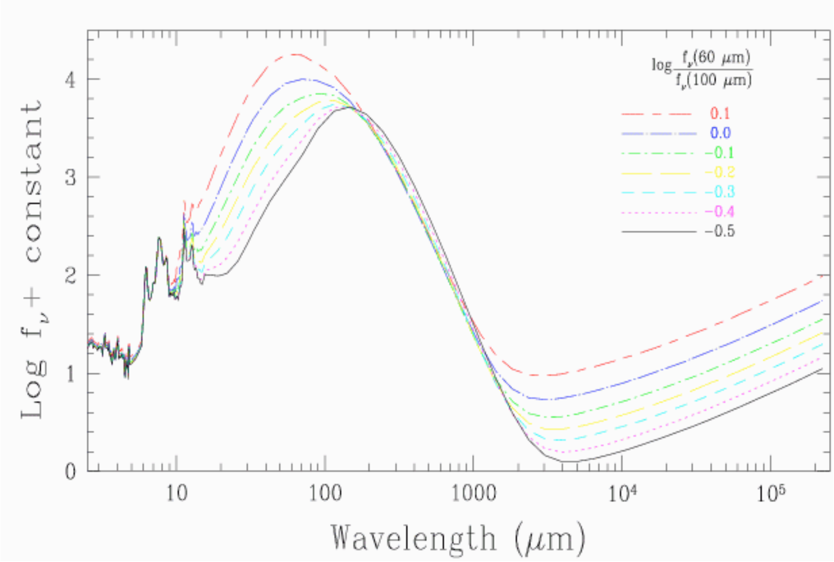
4. Radio emission of normal galaxies

The radio emission of galaxies arises from two physical processes : the synchrotron radiation from the cosmic-rays generated by supernovae evolving in galactic magnetic fields and the free-free emission of ionized gas. The latter is directly related to the ionizing flux of stars and should be a quite good indicator of the Young stellar content of galaxies. Unfortunately is represents only ~10% of the total radio emission, 90% coming from synchrotron emission.

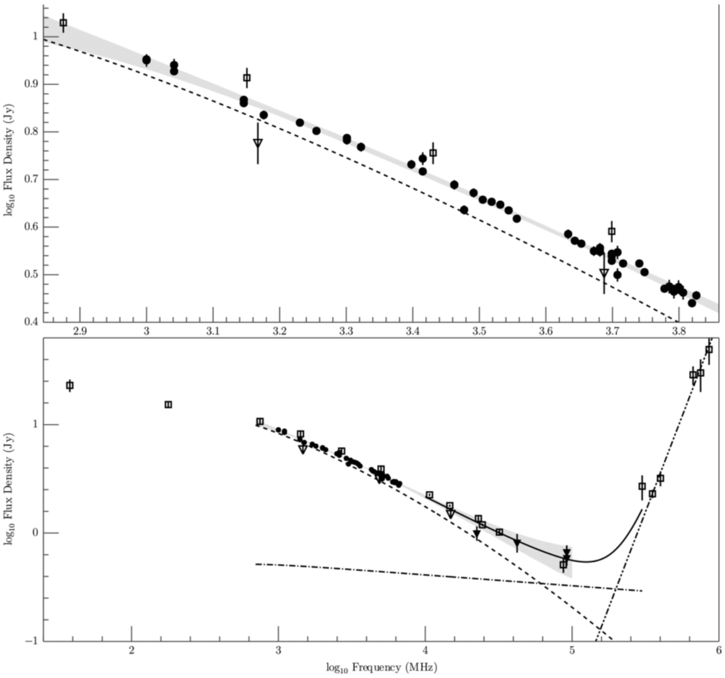
The spectrum of the thermal, free-free emission is almost flat ($f(\nu) \sim\nu^{-0.1}$) and the non-thermal emission is steeper ($f(\nu) \sim\nu^{-0.8}$)

The whole SED of a normal (non active) galaxy must account for this emission

(Dale & Helou, 2002)



It is a zoom of the radio range for the starburst galaxy M82 and the different components (see Boselli, 2012).



Identify the different components and the wavelength range: free-free, synchrotron and modified Black-body