Lyman-α Radiation Transfer effects in galaxies

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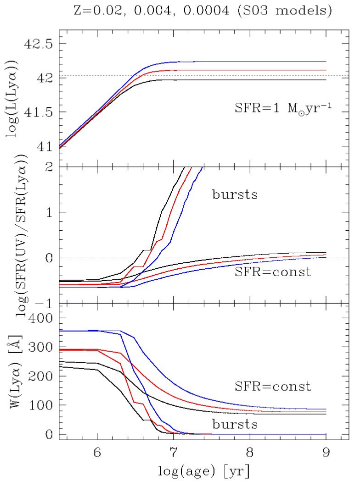
Outline

1. Lyα : an interesting tool to study star-forming galaxies
   - Star-forming galaxies are Lyα emitters
   - Diversity of observed Lyα profiles in starburst galaxies
2. Alteration of the Lyα line by hydrogen
   - Microscopic scale
   - macroscopic scale
3. Alteration of the Lyα line by dust
   - Homogeneous medium
   - Inhomogeneous medium
4. Other possible alterations
5. Numerical approach
6. Conclusions

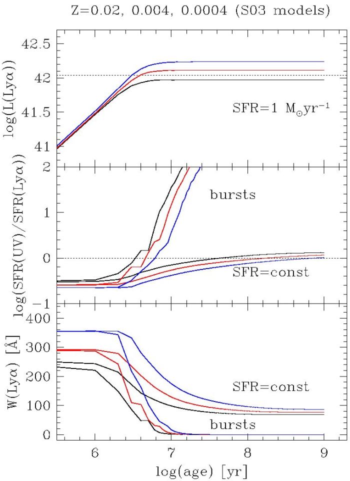
Star-forming galaxies are Lyα emitters



Intrinsic Lyα spectrum from a starburst

- mechanism : ionisation from young massive O-B stars
  $\Longrightarrow$ Lyα emission by recombination of hydrogen atoms

Star-forming galaxies are Lyα emitters



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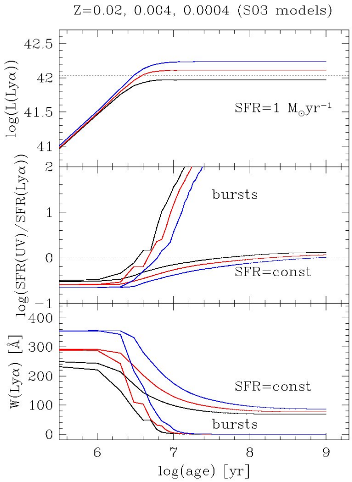
Partridge & Peebles 1967 ; Schaerer 2003

Star-forming galaxies are Lyα emitters



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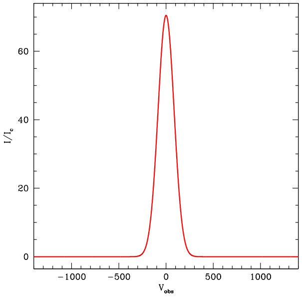
  Partridge & Peebles 1967 ; Schaerer 2003
- EW$>$ 100 Å $\Longrightarrow$ young starbursts
- low metallicity $\Longrightarrow$ strong emission
- EW$\sim$ 0 Å $\Longrightarrow$ bursts
- for SFR=cst over 100 Myr, EW(Lyα)=cst$\sim$ 80 Å

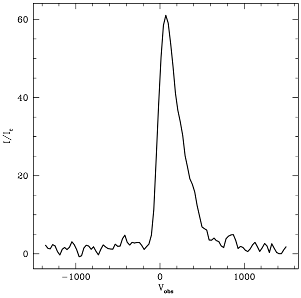
Diversity of observed Lyα profiles in starburst galaxies

Lyα puzzle

How to reconcile predictions with observations ? what governs Lyα escape from a starburst ? what shapes the Lyα profile ?
Lyα *resonnance* line VERY optically thick $\Longrightarrow$ radiation transfer



$\Longrightarrow$



Alteration of the Lyα line by hydrogen

Microscopic scale

detailed description of one interaction between Lyα and HI :

1. absorption
2. re-emission direction
3. re-emission frequency

Macroscopic scale

cumulative effect of multiple interactions :

1. in a static and homogeneous medium
2. influence of HI geometry
3. influence of HI kinematics

Microscopic scale : Absorption

Lyα optical depth is a Voigt profile

- atomic cross-section :

$$\sigma(\nu) = \frac{\pi e^2}{m_e c} f_{12} \frac{\Gamma/4\pi^2}{(\nu-\nu_0)^2 + (\Gamma/4\pi)^2} \sim 7 \times 10^{-11} [\mathrm{cm}^2]$$

10^4 times higher than other recombination lines ! !

- Lyα optical depth :

$$\tau_x(s) = \frac{\sqrt{\pi} e^2}{m_e c} \frac{f_{12}}{\Delta\nu_D} H(a,x) \int_0^s n_H(l) dl \sim 3.31 \times 10^{-14} T_4^{-1/2} N_{\mathrm{H}}$$

with H(a,x) the Voigt function :

$$H(a,x) = \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2} dy}{(x-y)^2 + a^2}$$

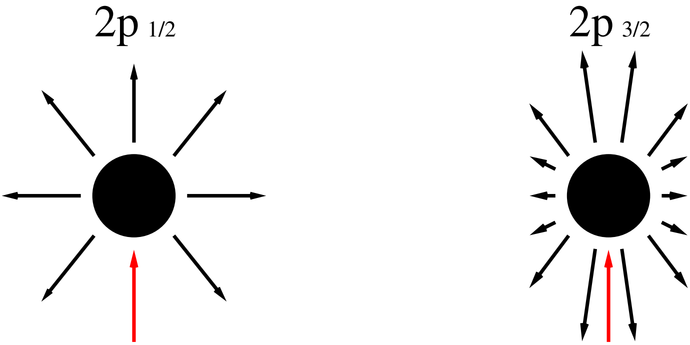
Microscopic scale : Re-emission (1/3)

Re-emission direction

Angular redistribution depends on :

- atomic levels ($2p_{1/2}$ or $2p_{3/2}$)
- absorption frequency

$\Longrightarrow$ polarisation of the Lyα line (cf Mark's talk)



Microscopic scale : Re-emission (2/3)

Re-emission frequency in atom's frame

Coherence :

$$\nu_{after} = \nu_{before}$$

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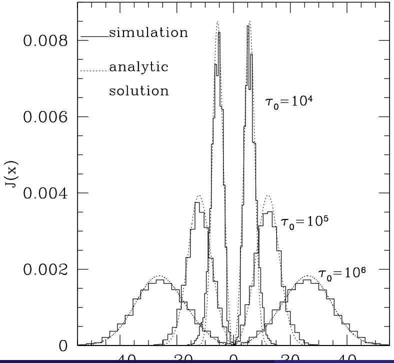
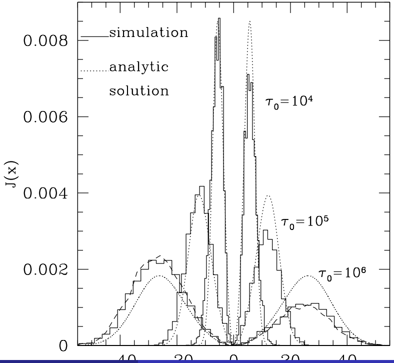
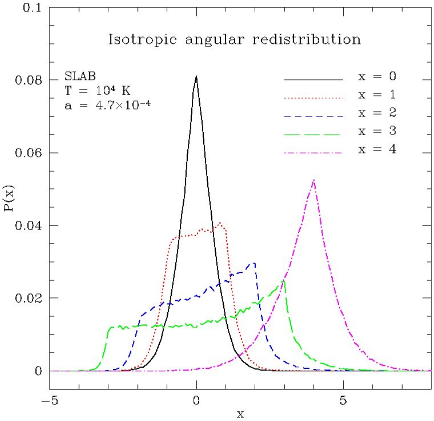


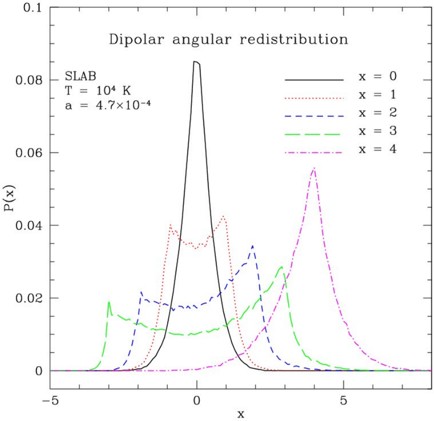


Microscopic scale : Re-emission (3/3)

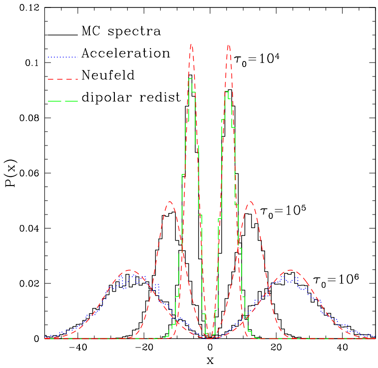
frequency redistribution in external frame

- in the line core : redistribution over [-x,x]
- in the wings : coherent diffusion





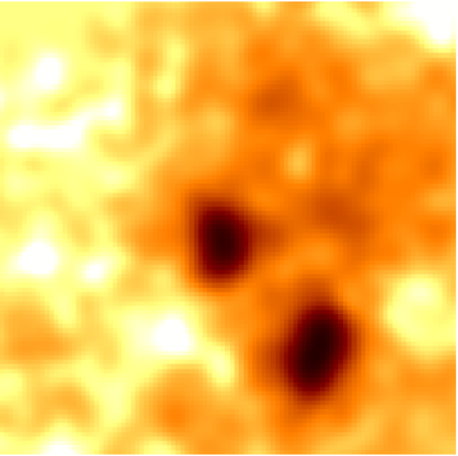
macroscopic scale : multiple scatterings



static and homogeneous medium

- huge number of scatterings before escape
- emergent spectrum : symetric double peaked profile
- calculated analytically

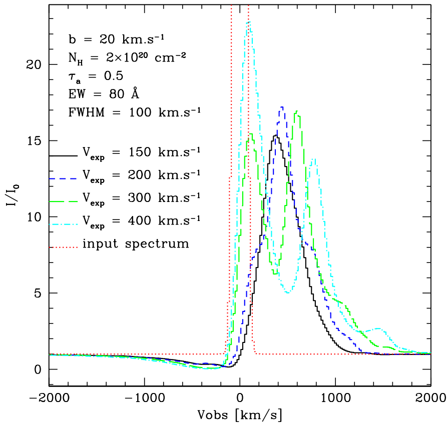
  Neufeld 1990 ; Dijkstra et al. 2006
- random walk => prediction of mean number of scatterings, and mean escape frequency



non-homogeneous medium

- Lyα photons escape through holes => resolved spectra can be very different from integrated spectra
- spectral shape also affected : Lyα can be boosted compare to continuum (cf after)

macroscopic scale : HI kinematics



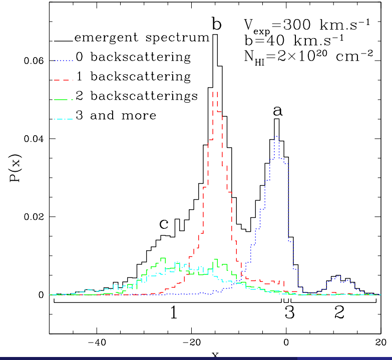
non-static medium

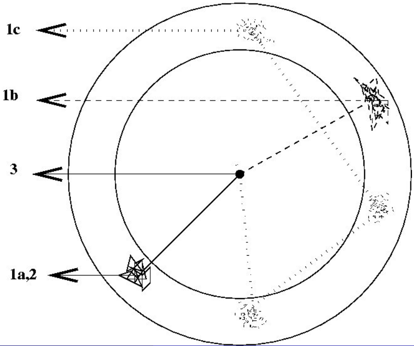
- Lyα photons escape through high velocity gas => resolved spectra can be very different from integrated spectra
- spectral shape strongly affected by velocity fields : symetry broken

macroscopic scale : HI kinematics

spherically expanding shell

- main peak at twice the expansion velocity
- spectral features due to back-scattering



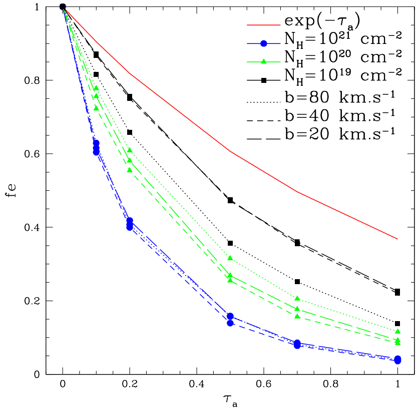


Summary of interaction with HI

Summary of interaction with HI

- a huge scattering cross-section => a huge optical depth => multiple scatterings
- complex redistribution in direction and frequency after each scattering => alteration of the spectrum and polarisation of the Lyα line
- HI geometry and kinematics give an imprint on the Lyα line

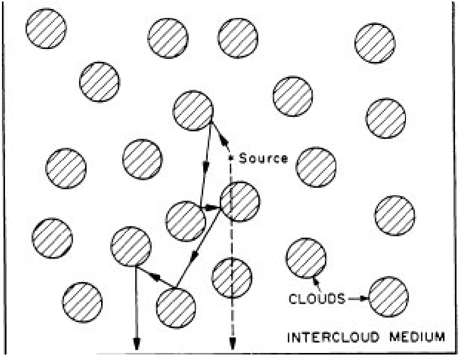
Alteration of the Lyα line by dust



in a homogeneous medium

- UV photon $\Longrightarrow$ interacts with dust $\Longrightarrow$ either absorbed or scattered
- coherent and isotropic re-emission
- proba to interact with dust + albedo $\Longrightarrow$ escape fraction
- multiple scatterings $\Longrightarrow$ Lyα more attenuated than continuum

Alteration of the Lyα line by dust

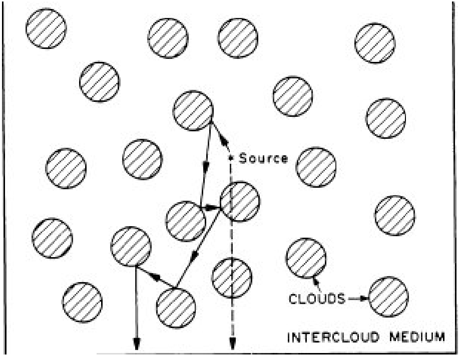


in an inhomogeneous medium

- *Neufeld 1991, ApJ 370 85*

  Hansen & Oh, 2006, MNRAS 367 979
- medium with 2 phases
- Lyα+continuum source in the diluted phase
- Lyα less attenuated than continuum

Alteration of the Lyα line by dust



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$\Rightarrow$ Lyα escape fraction either decreased or boosted by dust compare to the continuum depending on HI geometry

Other possible alterations

Other possible alterations

- Deuterium : 10^5 times less abondant than Hydrogen
- H_2 pumping : presence of H_2 molecules in starforming regions
- Collisions in a very dense medium : can transform 2p into 2s
- Evolution with time

MCLya : 3D Lyα radiation transfer code

General description of the code

- Monte Carlo technics, 3D, cartesian grid *Verhamme et al. 2006*
- physics included : HI, dust, Deuterium
- coupled with photoionisation code *Pierleoni et al. 2008*

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Inputs

- distribution of sources
- HI and dust geometry
- temperature distribution
- velocity field

Outputs

- integrated or resolved spectra
- Lyα images along any line of sight
- number of (back-)scatterings
- escape fraction

Revue of Lyα radiation transfer codes

Team	Numerical	Interaction with H			Other	Geometry		Applications	Limita
affil. date	Technics	recoil	redist.	polarisation		Dim.	clump.		
Ahn&Lee Korea 1998-2002	MC	no	distinguish wing/core redist	yes	no	1D	no	ISM expanding shell	limited t rical geo
Loeb&Rybicki USA 1999	analytic + MC	no	distinguish wing/core redist	yes	no	1D	no	Hubble flow	limited t rical geo
Richling&Meinköhn Germany 2001-2003	Finite Elements	no	isotropic	no	dust	3D	yes	ISM of high-z galaxies	low opt. $\tau <$
Zheng&Miralda-Escudé USA 2002	MC	yes	dipolar	no	no	3D	no	external fluorescence from DLAs	no d
Cantalupo Switzerland 2005	MC, hydro+ cont coupling	no	isotropic or dipolar	no	no	3D	no	fluorescence from proto-gal.	no d
Hansen&Oh USA 2006	MC	no	dipolar	no	dust	3D	yes	clumpy, dusty, moving ISM	no polar
Tasitsiomi USA 2006	MC + paral. hydro coupling	yes	dipolar	no	no	3D AMR grid	no	Lyα from a simulated $z \sim 8$ LAE	no d
Dijkstra USA 2006-2008	MC	no	distinguish wing/core redist	yes	Deuterium	1D	no	collapsing proto-galaxies	limited t rical geo
Semelin France 2007	MC, hydro +cont coupling	no	isotropic	no	no	3D AMR grid	no	reionisation Lyα-21cm coupling	no d
Laursen Denmark 2007	MC hydro coupling	yes	dipolar	no	no	3D	no	Lyα from a simulated $z \sim 3$ LBG	no d
Verhamme&Schaerer Switzerland 2006	MC +parallelization	yes	distinguish wing/core redist	no	dust Deuterium	3D	no	ISM exp. shell	no polar

Conclusions

Lyα radiation transfer effects in LAEs

- interpretation of a Lyα line => radiation transfer effects
- multi-parameter problem => numerical approach necessary
- more information in the Lyα line than in optically thin lines
- see Daniel's talk for illustration !