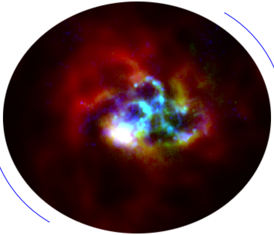
Chemical abundance mapping of PDRs and diffuse H I region envelopes in nearby galaxies

Vianney Lebouteiller

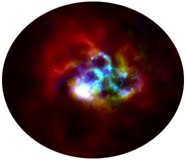
Laboratoire AIM - CEA, Saclay, France



FUV observations of the ISM in nearby galaxies

Measure elemental abundances in external galaxies

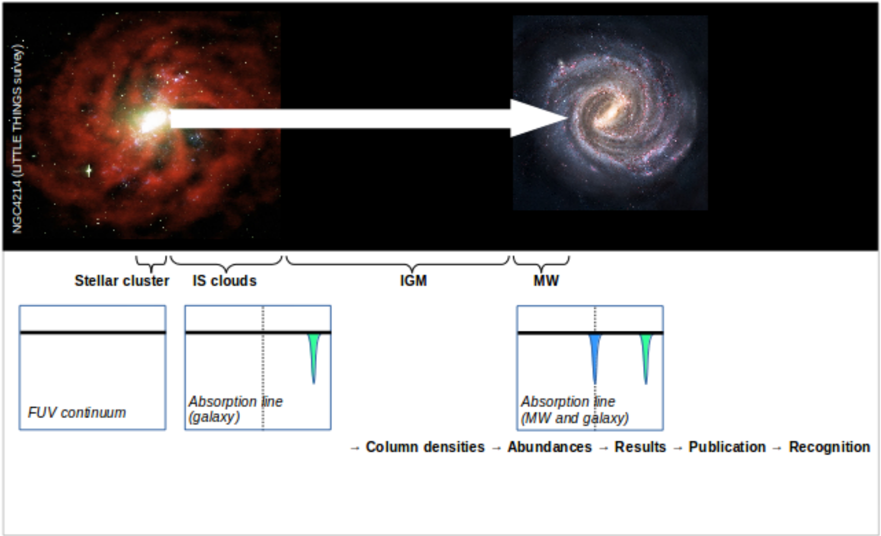
- Using far-UV absorption lines toward a FUV-bright source
- Complementary to abundances derived from optical emission-lines arising in the ionized gas of H II regions (T-dependence, ICFs)



Original motivations: fate of elements released by series of SF episodes

- **Galaxy evolution** & metallicity buildup, how is the ISM enriched?
  - Abundance discrepancy between neutral gas and H II region?
  - Existence of pristine gas pockets? Metallicity threshold due to IGM enrichment?
  - Abundance inhomogeneities between H II regions within a galaxy?
  - Role of outflowing galactic winds & infalling gas? Properties of infalling gas?
- **Conditions for star-formation process**
  - Heavy elements → dust production → H_2 formation & UV shielding
  - Cooling lines – opposes heating due to contraction/collapse in early phases
  - Indirect constraints on gas heating mechanisms

Observational technique



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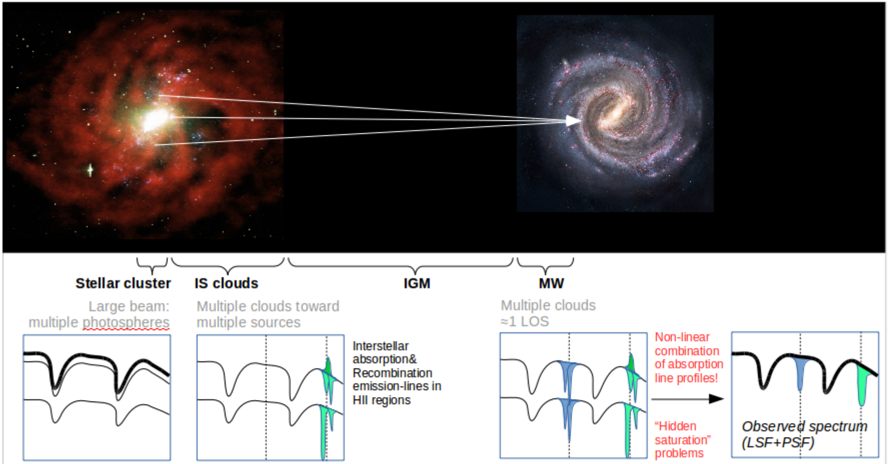

→ "Column densities" → "Abundances" → "Results" → Publication → Recognition

Examples

FUV ($\sim 900-2000$Å) IS absorption lines toward OB stellar clusters in nearby galaxies

- Metals (C II, N I, O I, Si II, S II, P II, Ar I, Fe II, Ni II, Mn II, Al II, Cl I...)
  - Wide range of oscillator strength (mitigates hidden saturation)
  - Fine-structure lines (e.g., C II*)
- + H I, H_2

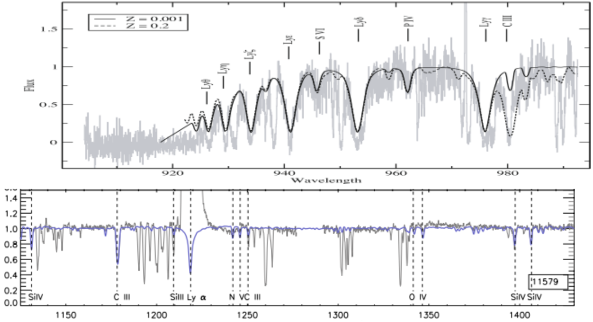

Fig.: *Top: FUSE spectrum of Pox 36, showing the Lyman H I series (Lebouteiller+ 2009). Bottom: HST/COS spectrum of I Zw 18 (Lebouteiller+ 2013).*

Abundances in Blue Compact Dwarf galaxies (BCDs)

Characteristics

- Family of nearby metal-poor dwarf galaxies ($\searrow$ 1/30 $Z_\odot$)
- UV-bright, H I gas rich

I Zw 18 as a testbed experiment

- **Pioneering study**: O I & Si II with HST/GHRS, H I Lyα with IUE *(Kunth+ 1994)*
  - Metal deficiency in H I region (/20), self-enrichment? *(Kunth & Sargent 1986)*
  - ⚠ Profile degeneracy due to saturation, S II 1250 – 9Å proposed as future alternative *(Pettini & Lipman 1995)*
- **The FUSE parenthesis**
  - *Aloisi+ (2003)*: metal deficiency but ⚠ issues with saturation and stellar features
  - *Lecavelier+ (2004)*: weaker O I lines used: no difference in metallicity, but some underabundant species
- **HST/COS** *(Lebouteiller+ 2013)*
  - Weak underabundance (factor < 1.5) using S II. Validates other FUSE results using same method

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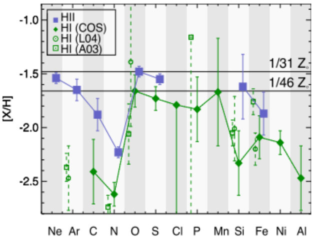

Fig.: *Comparison of H II region (blue; from optical emission lines) and H I region abundances (green; from FUV absorption lines) in I Zw 18 (Lebouteiller+ 2013).*

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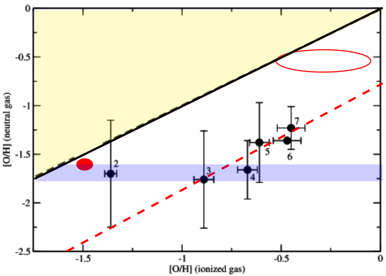
Few observations and many open questions

- Global metal underabundance in H I region of most BCDs (factor 1 – 10)
  - Self-enrichment of H II regions from current burst unlikely
  - Self-enrichment from previous bursts possible if small ($\lesssim 1\%$) fraction of metals mix locally
  - Dilution by metal-poor gas in halo more likely *(Cannon+ 2005; Lebouteiller+ 2009, 2013)*
  - No difference for the most metal-poor objects: minimal metallicity threshold? Set by IGM enrichment at $z = 0$? *Lebouteiller+ 2009*)

More tests

- Unique example of QSO sightline through a BCD: weak metallicity difference if any *(Schulte-Ladbeck+ 2004; Bowen+ 2005)*
  - Individual sightlines available in LMC/SMC but redshift too low for H I separation with MW



Other results (I): molecular gas

Absence of diffuse H_2

- Low $f(\mathrm{H_2})$ ($\lesssim 10^{-8}$) in BCDs *(e.g., Vidal-Madjar+ 2000)*
- Less diffuse H_2 in starbursts than expected from reddening $\rightarrow$ enhanced photodissociation *(Hoopes+ 2004)*
- Low dust abundance $\rightarrow$ enhanced photodissociation *(Sternberg+ 2014)*

Where is H_2? Role of H_2 for star formation?

- No CO detected below $1/8\,Z_\odot$ *(Schruba+ 2012)*
- Warm H_2 usually detected in NIR must exist in small dense clumps of $\sim$ parsec size *(Thuan+ 2004; Lebouteiller+ 2017)*

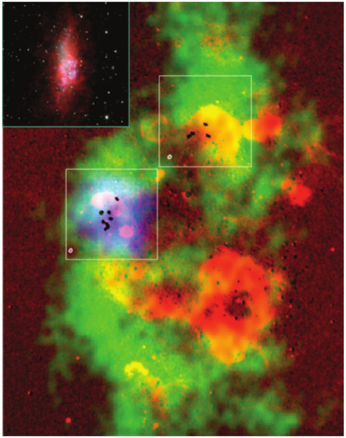


Fig.: *ALMA observations of CO in WLM at $1/8\,Z_\odot$ (Rubio+ 2015).*

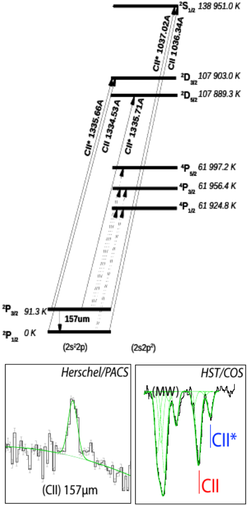
Other results (II): heating and cooling processes

Gas coolants

- Fine-structure line absorption, probing the population of important levels for gas cooling ([C II] 157 μm, [O I] 63 μm dominant/important coolants in WNM & CNM)
- Observed in (LIH)VCs around MW and in DLAs *(e.g., Lehner+ 2004; Wolfe+ 2003)*
- $\Rightarrow$ Cooling rate and physical conditions in H I reservoir for future SF episodes

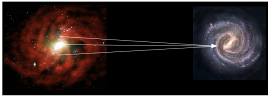
Heating mechanisms

- Detection of both C II* & [C II] 157 μm in an external galaxy *(Lebouteiller+ 2013, 2017)*
  - Large electron fraction due to photoionization by X-rays over potentially several kpc. Photoelectric effect heating negligible!
- n_e/n_{H}, T_{gas}, n_{H}: Si II* and O I* needed, as in MW *(Howk+ 2005)*.



Limitations & uncertainties

- Complex arrangement of LOS and absorption components with different properties (e.g., $v_{\rm turb}$, $v_{\rm rad}$, N, $[{\rm X/H}]$)
- Origin of absorption still uncertain due to poor spectral resolution
- LOS bias toward the brightest stars & with the most diffuse/dust-poor clouds
- Non-linear effects and spectral resolution effects (hidden saturation)
- Fine-structure lines Si II*, O I*, O I**... hard to detect



LUVOIR requirements well adapted to FUV absorption-line studies in extragalactic systems

- Ideal wavelength range 900 − 1400Å
- Sensitivity to detect lines with weak oscillator strength (prevent hidden saturation)
- $0.2''$ at 10 Mpc is 10 pc, $\sim$ 10 times smaller than COS aperture ($2.5''$) $\Rightarrow$ target individual sources, with help from high-angular resolution FUV imaging
- Spectral resolution 300 000 is 1 km s^{-1}, i.e., on the order of a single cloud component

(Some) applications

Chemical enrichment / fate of heavy elements

- Tomographic abundance mapping in the neutral gas envelope of nearby galaxies
  - + ionized gas abundance with MUSE/LUVOIR
- Self-enrichment around WR stars
- Metallicity evolution in a wide redshift range

Galaxy evolution and constraints for simulations

- Cooling rate via fine-structure absorption lines of C^+ and O^0
- Probing and characterizing infalling gas: Z, T, n, complementarity with SKA
- H_2 content: clump size and mass distribution, role of H_2 for star formation
  - Complementary UV and NIR observations of H_2 with LUVOIR
- Depletion patterns $\Rightarrow$ dust/gas (D/G) mass ratio, dust composition

Star-forming regions

- Enrichment level in SF regions
- Measure abundances & D/G in PDRs around molecular clouds