Multi-Line Spectroscopy

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Facts with modern radio-telescopes:

1. Broad instantaneous bandwidth

   In the mm/sub-mm most of the observations will include several lines, even with a single frequency setup.

   - multiplets of hyperfine transitions with fixed intensity ratios
   - multiplicity of molecular species

2. High sensitivity $\Longrightarrow$ more lines

   For some sources (extragalactic) the detection limit will reach the confusion limit

3. Limit of confusion $\Longleftrightarrow$ angular resolution

4. Scientific goals relying on line ratios

   obtained using one or several receiver bands

5. Stacking lines:

   e.g. λ_{cm} RRLs , to enhance the S/N

6. Identification of molecular species

   require observations of many transitions

7. With high resolution and sensitivity complex velocity structures will be more effectively revealed for some types of sources

   multiple velocity components: from few to all directions in an image (more details in general)

We are not yet well prepared to process optimally and efficiently such use-cases!

Artefacts, different resolutions & samplings, ...

Examples:

1. calibration: *e.g.* bandpass: spectral dynamic range

   - *e.g.* line to continuum ratios for λ_{cm} RRLs

   - weak lines and thermal continuum at λ_{sub-mm}

2. imaging: chromatic effects (large instantaneous bandwidth)

   - varying angular resolution through the set of base-bands

   - varying UV sampling (coverage)

3. Different contexts for multi-line:

- within a spectral window of an EB
- with multiple spectral windows of an EB
  e.g. for transitions involving different isotopes
- switching between pre-loaded frequency setups in an EB
- with several array configurations
  for line ratios to achieve common spatial resolution for different transitions of a molecular specie *e.g.* ^{12}CO(1-0), ^{12}CO(2-1), ^{12}CO(3-2), ...)

Software tools:

- Data-reduction tools
  - Regularization
  - Inversion: towards global solutions
- Data-analysis tools
  - Multi 3D image viewer
  - Multi-line profile analysis
    - velocity component models
    - co-constrained spectral profile decomposition
- Data-mining tools

A concrete example.

M82 (HI, RRLs, HCN, HCO^+, ...)

Property of the multi-line data set:

- High S/N HI in absorption with a complex velocity structure (VLA)

- Low spectral resolution (50 kms^{-1}) H92α RRLs (VLA)

- Low spatial (3") resolution and S/N H40α RRLs (PdB 3mm)

- Low spatial (3") resolution HCN... (PdB 3mm)

Co-constrained algorithms:

Image formation:

Example:

- Imaging of low S/N line data: (H40α)
- Low S/N at full resolution (2.7") but high S/N on short spacings (multi-configuration use-case)
- Two fields mosaic

$\Longrightarrow$ multi-field-multi-resolution inversion with multi-line regularization

Algorithm: MFRC (MFCLEAN + MRC)

- **multi-field** MFCLEAN, a clean-based algorithm (FV 1992 unpublished).
  It includes the two gain level optimization path (relevant for poor UV coverage, Schwarz, A&A 65, p.345 (1978)).

- **multi-resolution** MRC (Wakker and Schwarz, 198?). MFRC, a procedure integrating a small variant of the original MRC

- **multi-line** Regularization: high S/N data (12μm NeII line) to constrain the 3D search area for the clean components.

Results:

- A procedure fully automated

- Reliability: main final uncertainties come from the uncleaned low resolution residuals

  Must save the residual images of MFRC

  $\Longrightarrow$ *inputs (with dirty beams) in methods for flux measurements*

  $\Longrightarrow$ *must be components in the data model for the reduced data*

  N.B.: Magnitude of these uncertainties directly related to the properties of the transfer functions

- The two-line regularization:

  1. a method to draw the attention on peculiar features.

- separation in 3D of regions with different spectral line properties (kinematics)

- revealing confusion with nearby molecular line(s)

2. a method useful in case of weak S/N for automated processing

Remarks:

- An iterative procedure may be required when "peculiar" features are important relative to the "normal" features

- By experience the image products need a visual inspection for control (adjustment of parameters, adapting the choice for the companion line information in the regularization: line specie, resolution, cut-offs, ...)

- Comparison of results using other algorithms (WCLEAN (FV), MR_CASA Clean, ...) not yet done.

Image analysis

Scientific context:

- **Comparison between different lines:** at 3" resolution, in M82, there is a remarkable correspondence in 3D between tracers of dense gas (HCN,HCO^+) with H40α line (H RRLs of low quantum numbers come from dense plasma).

- **Complex velocity structure:** Whatever the line specie, the profiles in the nuclear region of M82 are very complex having a multiplicity of components (up to 5).
  This has been interpreted by the presence of 2 families of non-circular orbits (x_1 and x_2) and the fact that M82 is observed nearly edge-on. Furthermore this nuclear region is the base of outflows in the halo.

$\Rightarrow$ high spatial and velocity resolutions are critical to identify the state of the ISM in the mechanisms at work responsible of the star-burst activity.

The primary question was *"what is the origin of the λ_{mm} RRLs emission? compact HII regions?*

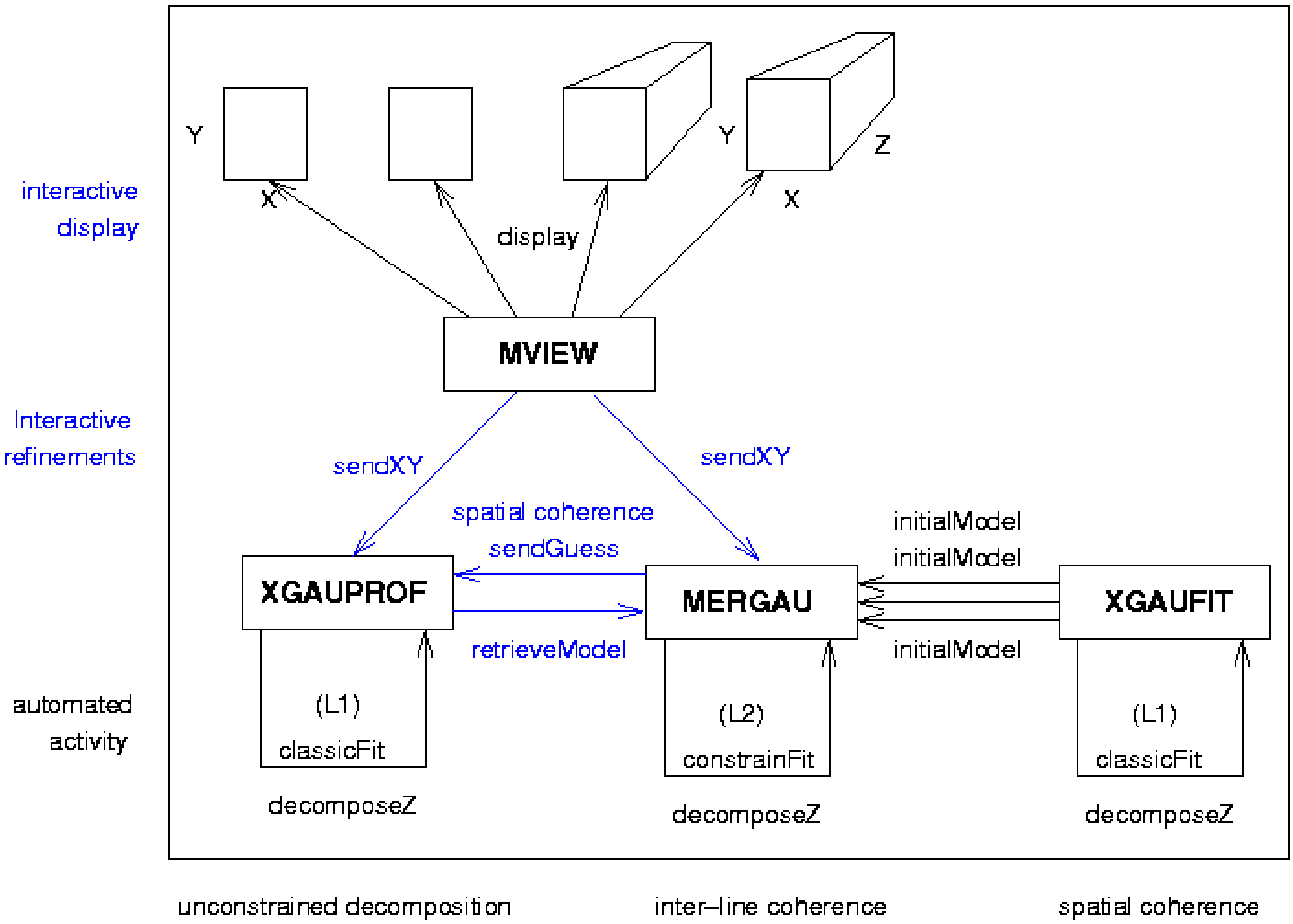
Experimental context:

- **multi-resolution data set:** very heterogeneous! .5" to 3" and ~10 to 50 kms^{-1}.

- **velocity components model:** a source model build from the decomposition of the high (for λ_{mm} observers) quality HI profiles.

- **co-constrained multi-line profile fitting:** reveal the nature of the RRL H92α emitters at 1" resolution

- **association** to the λ_{mm} RRL and molecular lines.



Tools:

XGAUPROF XGAUFIT MVIEW and MERGAU:
a set of tasks working in collaboration

MERGAU has for inputs:

- A set of component models parametrized by their number of components, this for every directions.

  These are produced by XGAUFIT, a task for automated model constructions. Several model are entered because there is not always unique solutions.

- A set of 3D line images for co-constrained line fitting.

- Events published by MVIEW for interactive refinements to enhance the quality of the input models.

  The main difficulty is at the intersection of position-velocity 'tracks', the automated fitting giving artificially broad component width discontinuities.

(There is room for improvements to better account for the spatial coherence.)

- Parameters to define a *strategy* to select the best input model this being direction dependent.

  A strategy is a sequence of "AND/OR" conditions; required to be able to **process all the spectra automatically**.

- Parameters to control the amount of co-constraints

  e.g. set the fixed & free parameters, ...

- Parameters for telling when a component found with no co-constraint can be associated to a component from the input model.

MERGAU has for outputs:

- Files which host the input models refinements performed interactively, if any, to be reuse from one session to the next

- 3D images corresponding to the co-constrained fitted profiles.

Status and comments:

It is an experimental task implemented in C++. It uses the **Gipsy** Data Structure, a generic model, and the event driven mechanism available in that environment.

For the development of such kind of tools it is essential to be confronted to very concrete real cases and learn by processing portions of the data-base interactively. This is a necessary step triggering the emergence of new concepts with the perspective of developing a more advanced multi-line analysis tool.

Results with the M82 use-case:

- 95% of the RRL H92α emission in the image can be associated to HI components.

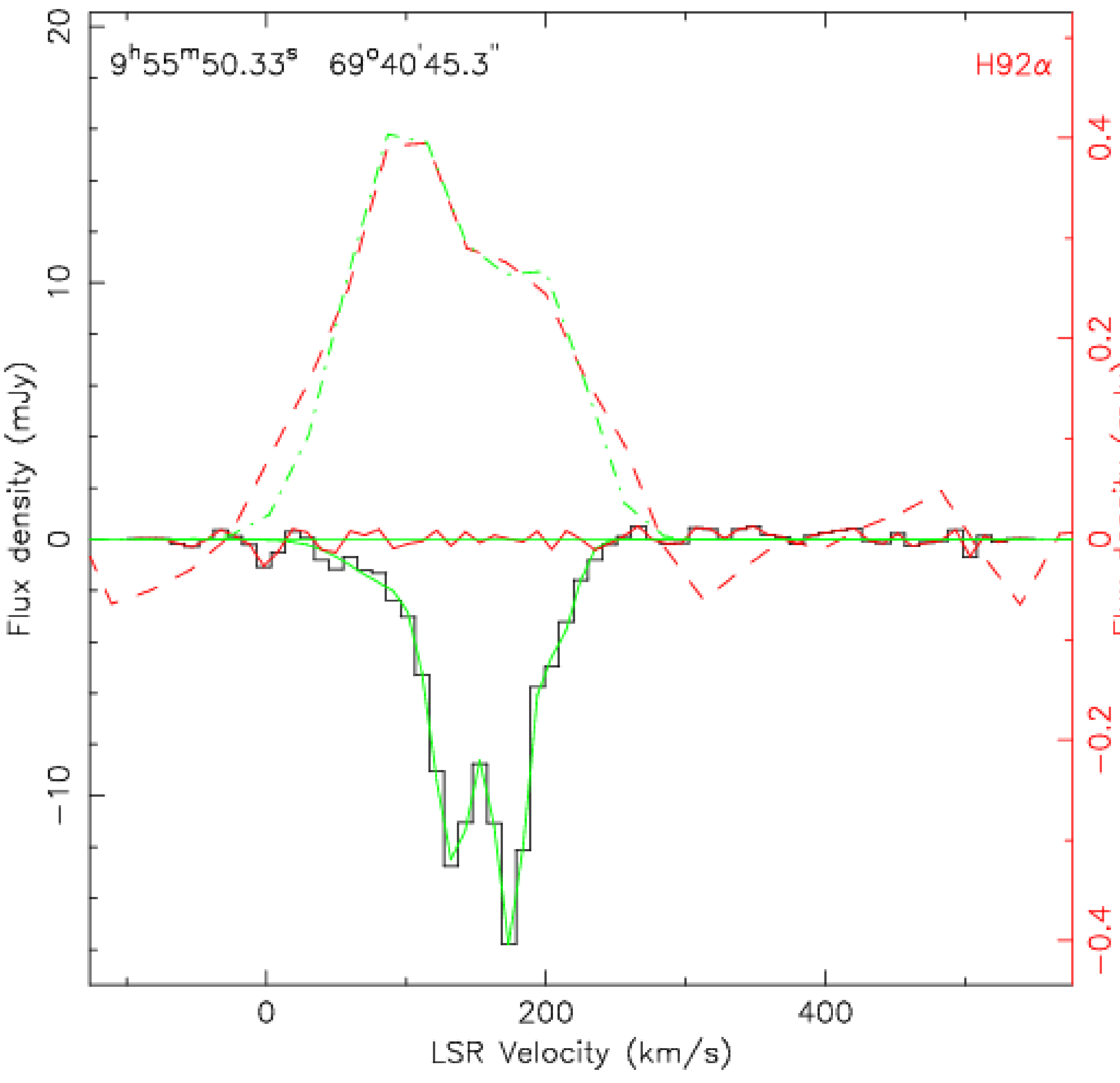
- The two constraints, the velocity positions and the widths of the HI components are sufficient conditions.

- Most of the remaining 5%, the H92α with no HI counterpart is distributed over a giant arc at an extrem velocity (35 km s $-$ 1

- There are HI components with no H92α counterpart; this is expected.

Example of graphic output from MERGAU:

The following figure shows a H92α profile (dashed red) fitted (dashed-dot green) using the velocity positions and widths of the HI component model (green continuous) as fixed parameters. The only free parameters are the amplitudes.



9h55m50.33s 69°40'45.3"
H92α
Flux density (mJy)
Flux density (mJy)
LSR Velocity (km/s)
20
10
0
−10
0.4
0.2
0
−0.2
−0.4
0
200
400