Recombination Line Studies with LOFAR

A Theoretical Perspective

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The Radio Universe @ Ger's (wave)-length

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Motivation



Different Phases of the ISM



Motivation





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RRLs & 4C41.17

Motivation



Questions:

- 1 How do you go from measured spectrum to gas properties?
- 2 How tight are the constraints on the gas properties?
- 3 Can we expect to obtain detections at z > 0?

Recombination Lines



Hydrogen



Rydberg Atom



- Outermost electron in high-n state
- Sees nucleus with +1 charge
- "Hydrogenic"



Rydberg Atom



- Outermost electron in high-n state
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Dielectronic-like Recombination



Dielectronic-like Recombination

 ${}^{2}\mathrm{P}_{3/2}$

 $^{2}P_{1/2}$



Free e⁻ can give $\Delta E = 0.0079 \text{ eV}$ to ${}^{2}P_{1/2}$ and still recombine with negligible binding energy

 $\Delta \mathbf{E} = 0.0079 \text{ eV}$ = 92 K

Building the Non-LTE Model



1. Set ${\rm T}_{\rm e}$ and ${\rm n}_{\rm e}$

2. Populate levels up to $\mathbf{n}=2000$ assuming LTE

$$N_n^* = n_e N_{ion} \left(\frac{h^2}{2\pi m_e k T_e}\right)^{3/2} \frac{w_n}{2} e^{\chi_n}$$

3. Define ambient radiation field $(S_{\nu} \propto \nu^{-\alpha})$

4. Populate / depopulate levels

- Collisional: level transitions, recombination, ionization
- Radiative: recombination (+ cascade downwards)
- Spontaneous: emission
- Induced: emission, absorption
- Dielectronic-like recombination
- 5. Calculate departure coefficients
- 6. Calculate optical depth

S
$$N_n = b_n N_n$$
 $u \propto rac{\mathrm{d} \, \mathrm{ln} b_n}{\mathrm{d} n}$

 $\int \tau_{\nu} d$

Model Results





Model Results



















Column Density





Line intensity







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Line intensity + width





Line intensity + width



RRLs in Extragalactic Sources



Unique probe of the cold Interstellar Medium



Observe ISM in radio galaxies up to $\mathbf{z} = \mathbf{4}$

RRLs in Extragalactic Sources





RRLs in Extragalactic Sources



Summary



1. Recombining $\rm C\,II$ can be successfully modelled as a Rydberg atom

2. $\mathbf{T}_{e}, \mathbf{n}_{e}$ can be constrained to within an order of magnitude

- By combining line width and intensity constraints

3. Look forward to exciting extragalactic results!

Questions?

Line Width





An additional constraint