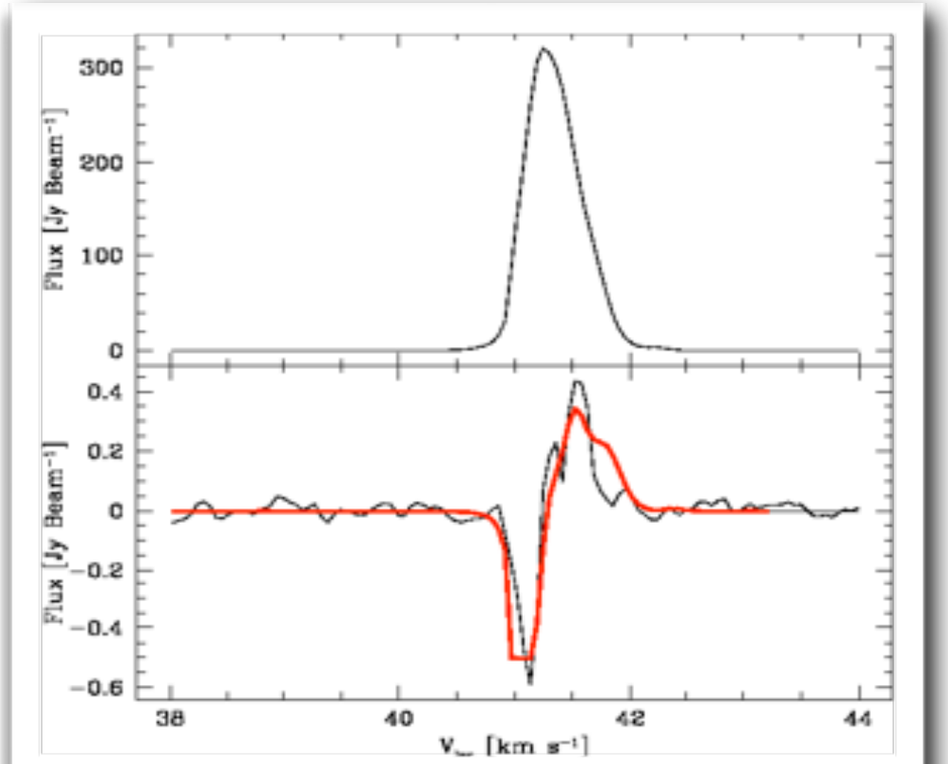
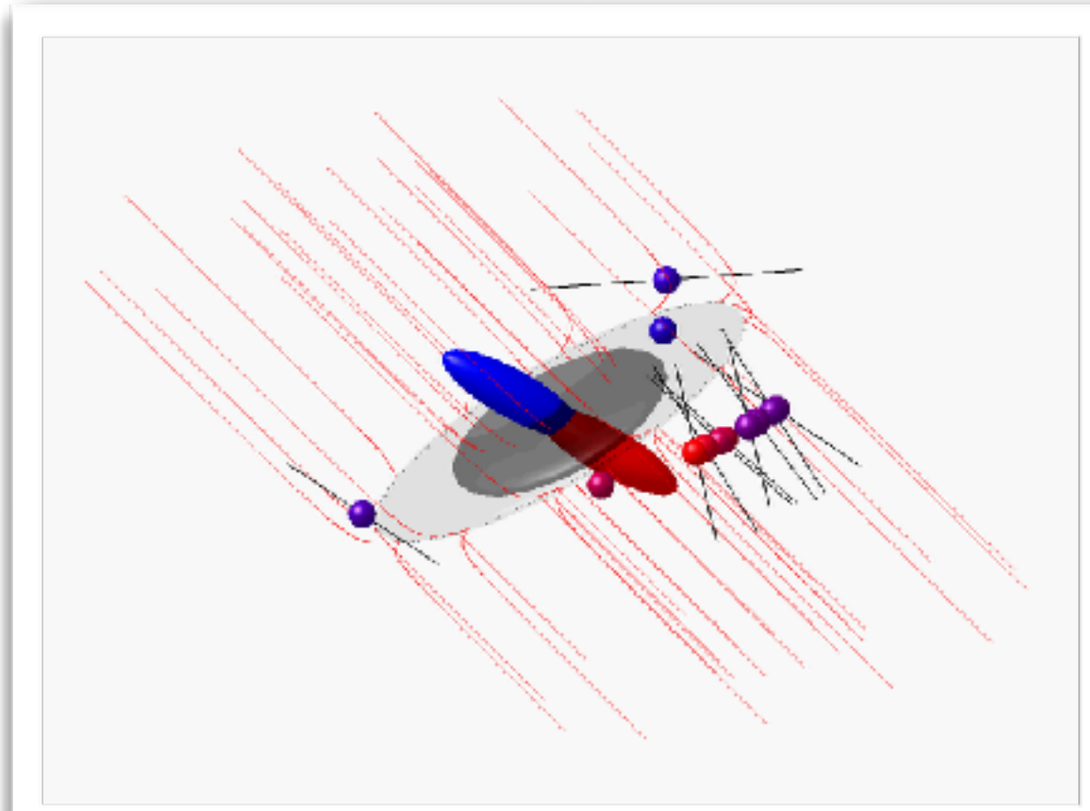
Characterizing methanol as a magnetic field tracer in star forming regions





Boy Lankhaar, Wouter Vlemmings, Ad vd Avoird (RU), Gabriele Surcis (INAF-OAC) et al.

Cagliari, 4 September 2017

Onsala Rymdobservatorium, Chalmers Tekniska Högskola

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Vetenskapsrådet

Re-interpreting maser observations

- Class II: 6.7 GHz

  Vlemmings et al. 2008, 2011

  - radiatively pumped
  - occur in accretion disk close to protostar

    $n_{\mathrm{H_2}} \approx 10^{8}\ \mathrm{cm}^{-3}$

- Class I: 44 GHz, 36 GHz

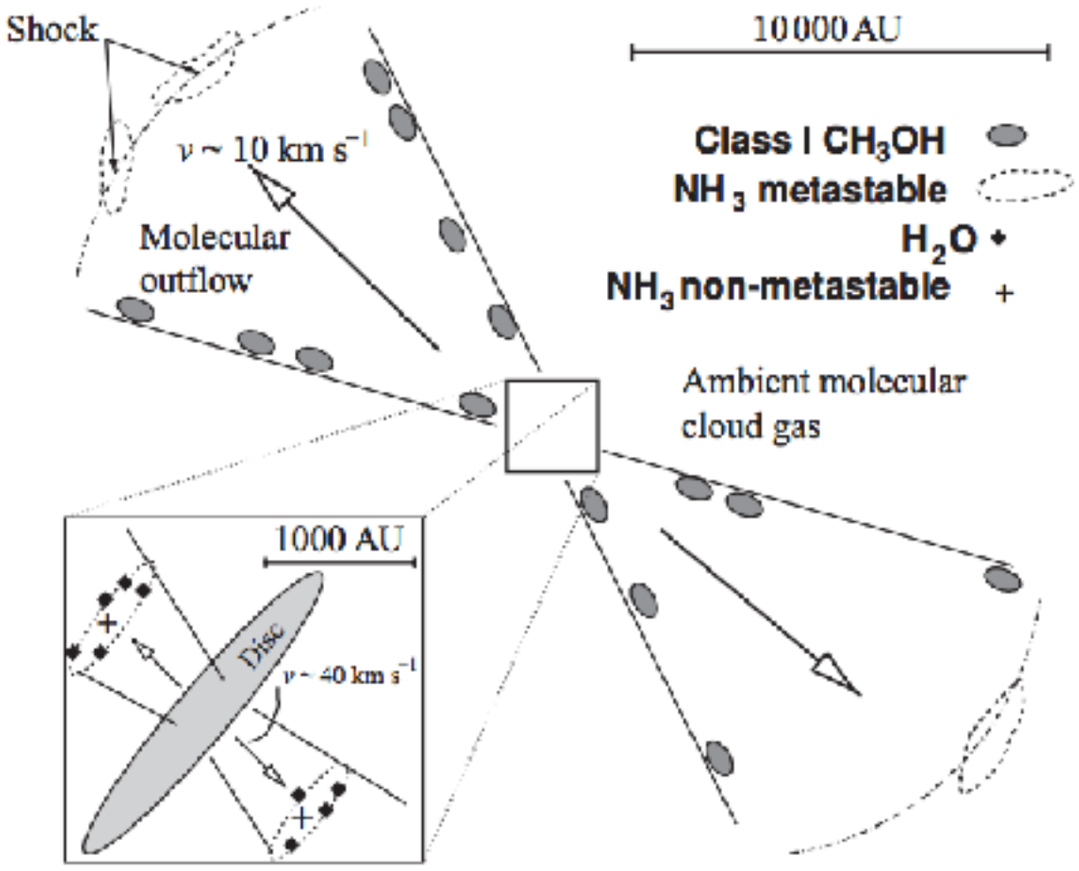
  Sarma and Momjian 2009, 2011 and 2017

  - collisionaly pumped
  - occur in outer regions of the molecular outflow

    $n_{H_2} \approx 10^{7-8}\ \mathrm{cm}^{-1}$

- Maser observations can extend $\langle |\boldsymbol{B}| \rangle \propto n_{\mathrm{H_2}}^{1/2}$ relation Crutcher et al. 2012

High-mass star forming region

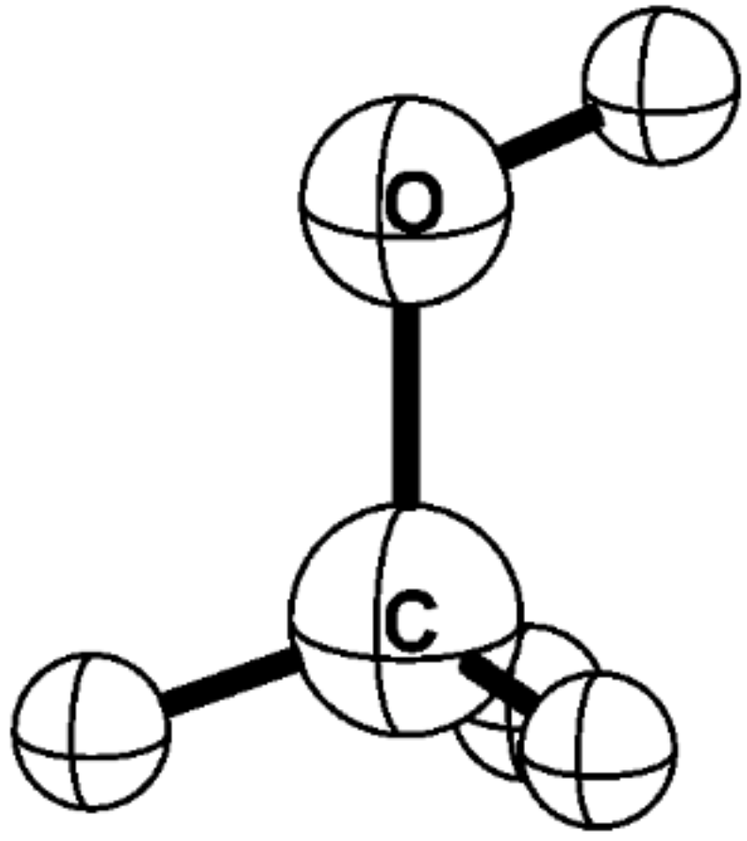


Gray 2012

Vlemmings et al. 2006ab
Surcis et al 2011, 2012, 2013, 2014, 2015
Momjian and Sarma, 2012ab
Stack and Ellison 2011
Fish et al. 2011
Sanna et al. 2010

Zeeman effect

- Rotational Zeeman effect
  - rotational part: g-tensor (ab-initio)
  - torsional part: d-tensor (estimate*)
  - requires torsion-rotation structure: Xu et al. 2011



* Engelbrecht et al. 1972

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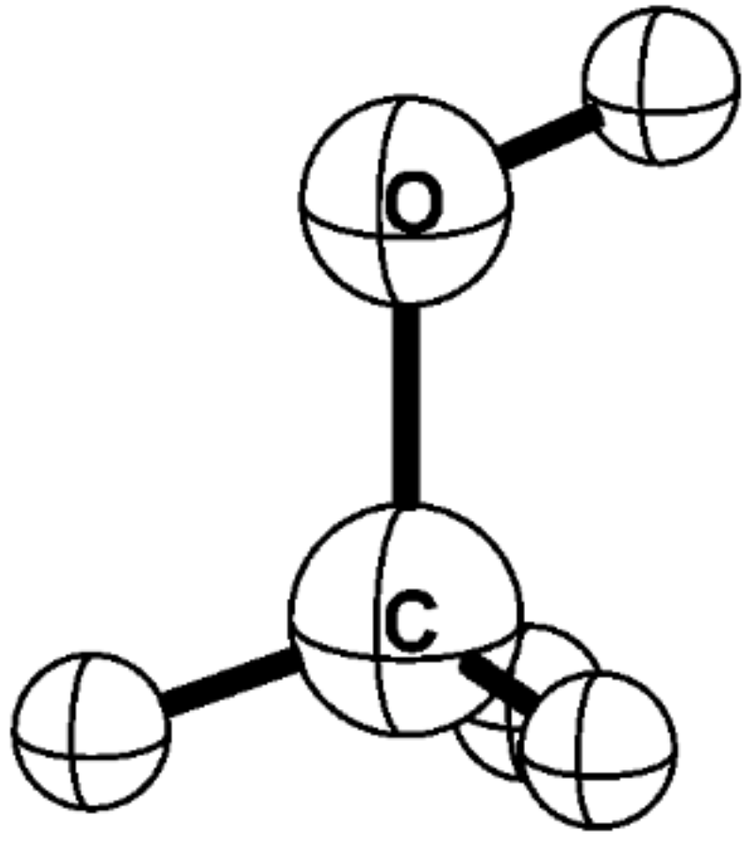
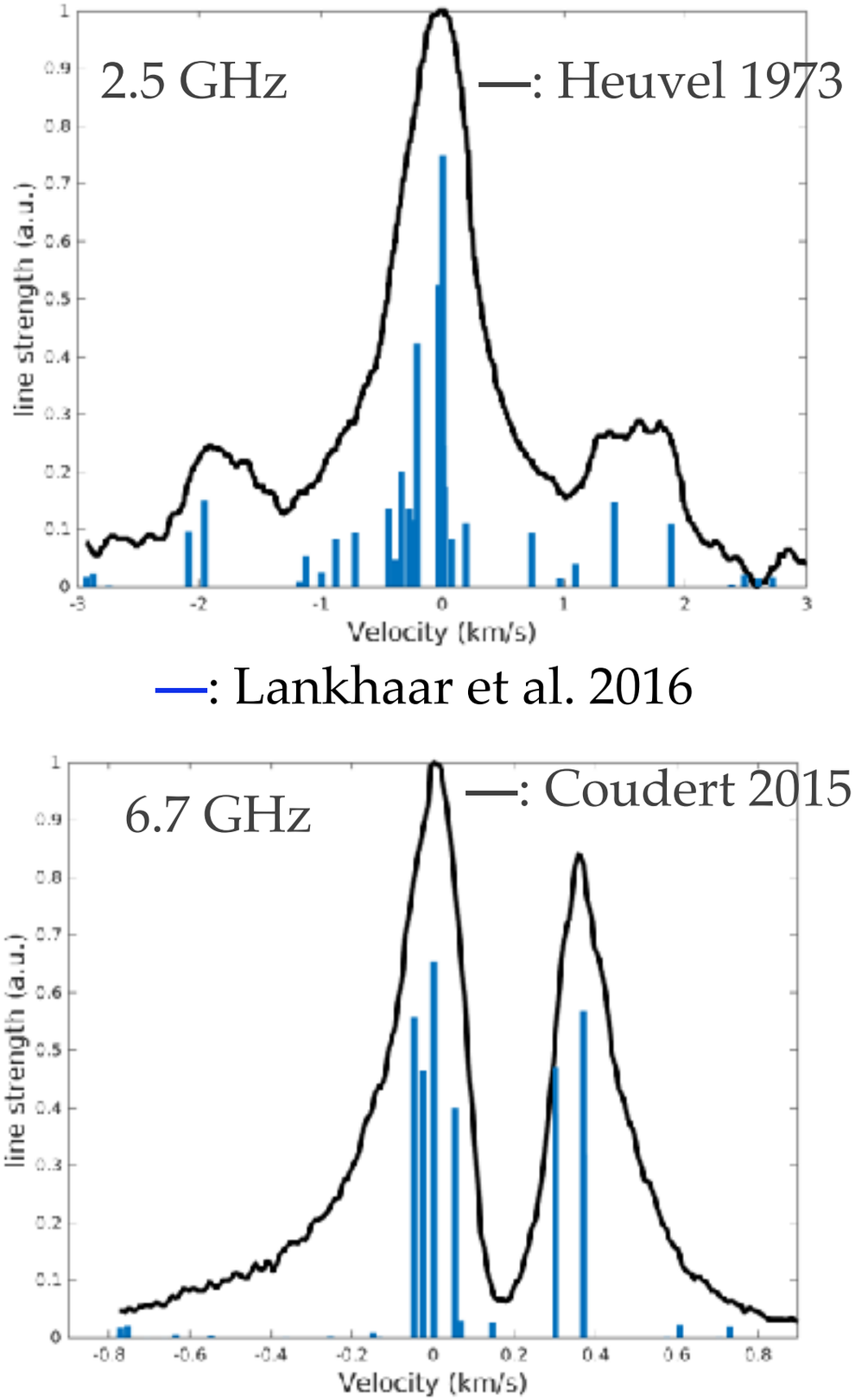


- Nuclear Zeeman effect
  - calculable from hyperfine structure

* Engelbrecht et al. 1972

Hyperfine structure: improved fitting model

- Spin-rotation interaction
  - ab-initio data
- Spin-torsion interaction
  - adjusted Thomas precession correction
  - reformulation torsion operator
  - improved fitting parameters
- Improved fit: no need for unphysical parameters



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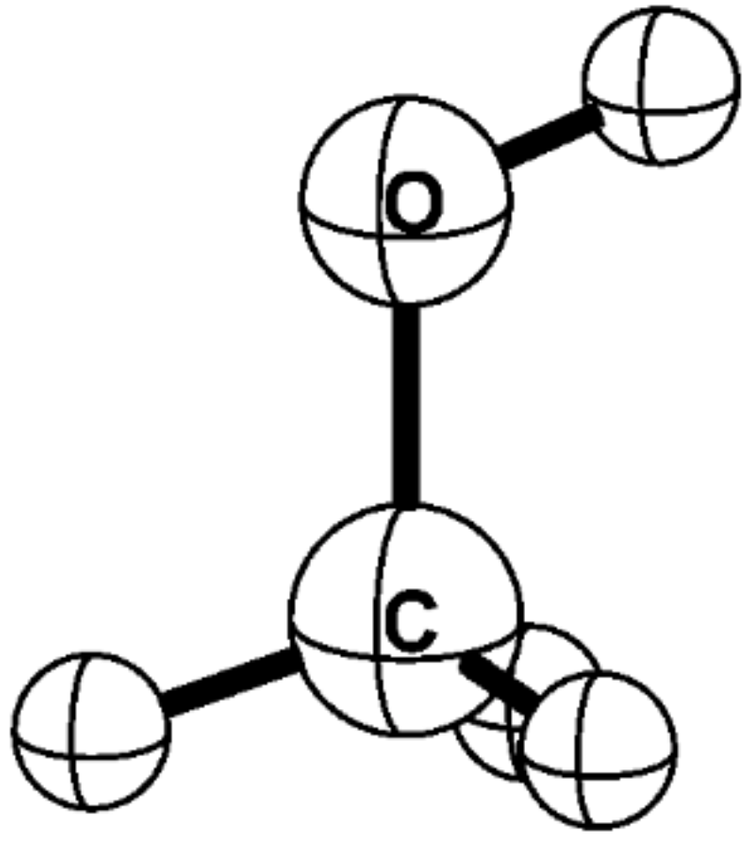

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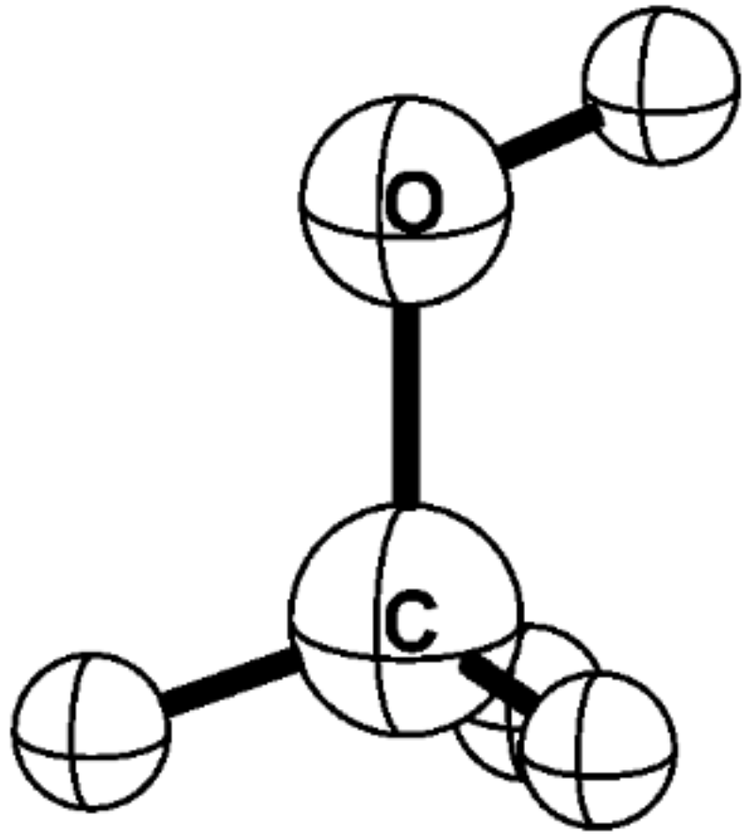
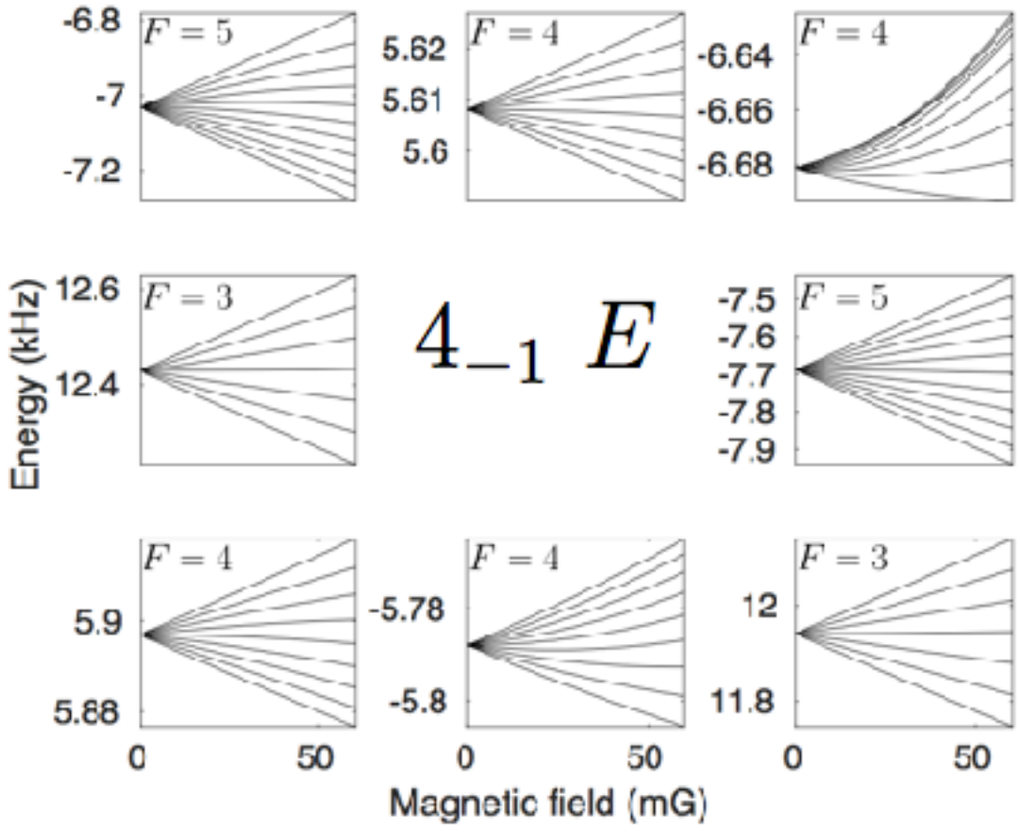


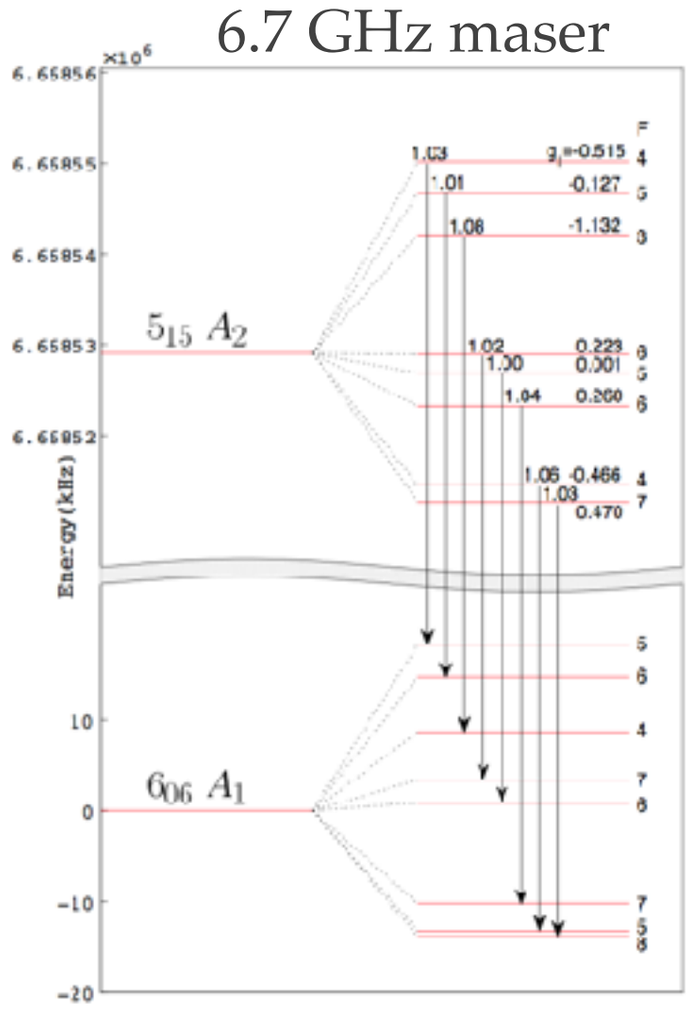


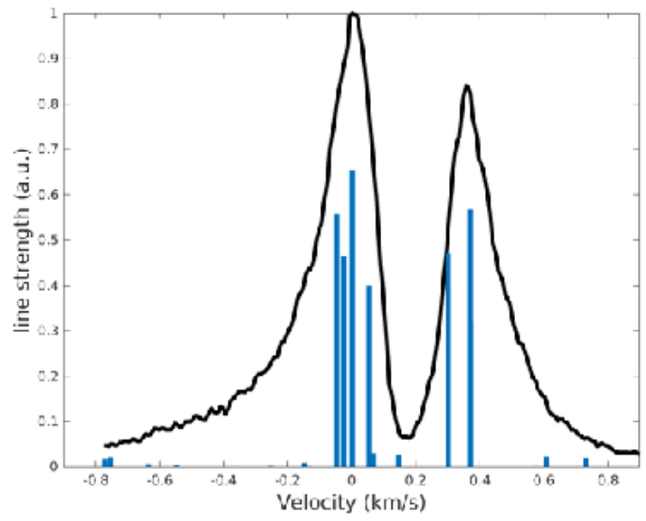
Lankhaar et al. 2017 (submitted)

Re-interpreting maser observations

- Every hyperfine transition has its own g-factor!

- Preferred hyperfine transition masing
  - varying radiative rates
  - kinematic effects
  - hyperfine specific pumping
    - radiative and collisional decay favor high F hyperfine states





Re-interpreting maser observations

- Class II: 6.7 GHz

  (Vlemmings et al. 2008)

  - $\langle |B| \rangle \approx 12$ mG

    $n_{\mathrm{H_2}} \approx 10^8$ cm^{-3}
  - Implies dynamically important magnetic field

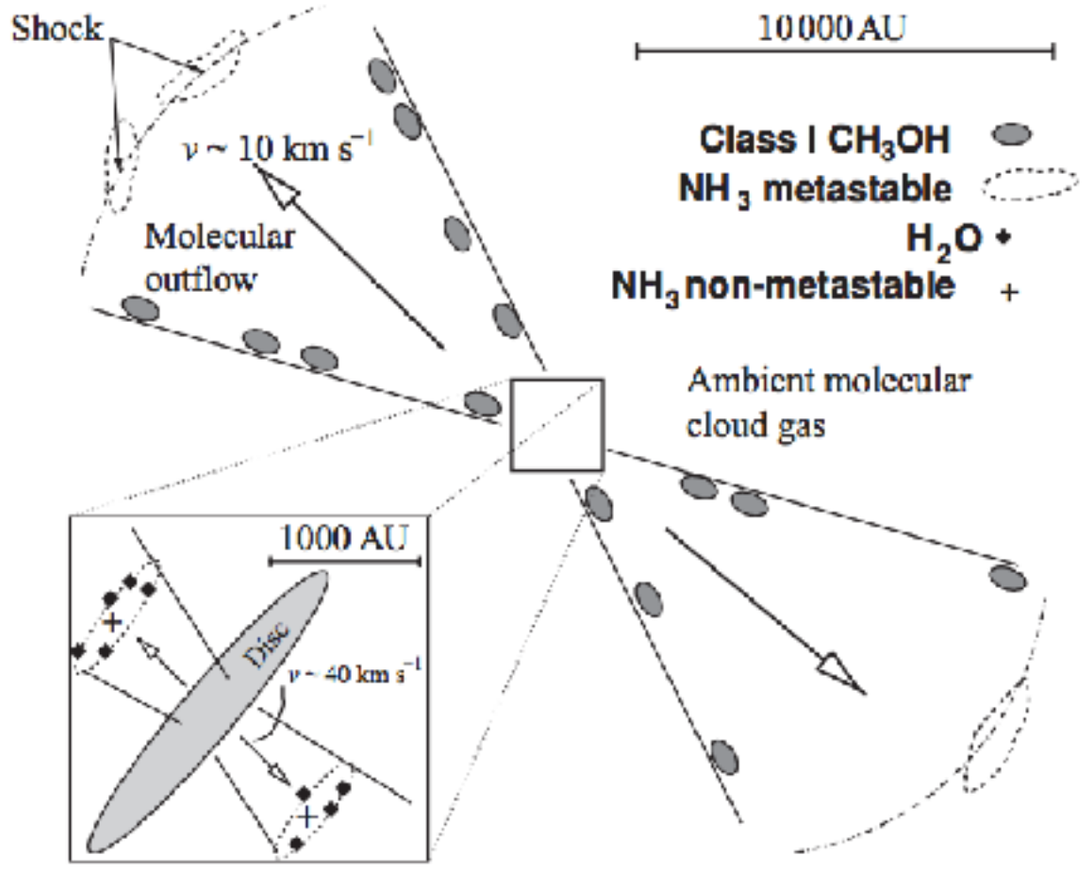
- Class I: 44 GHz, 36 GHz

  (Sarma and Momjian 2009, 2011 and 2017)

  - $|B| \approx 20 - 75$ mG

    $n_{H_2} \approx 10^{7-8}$ cm^{-1}
  - Tracer of the shocked region

High-mass star forming region

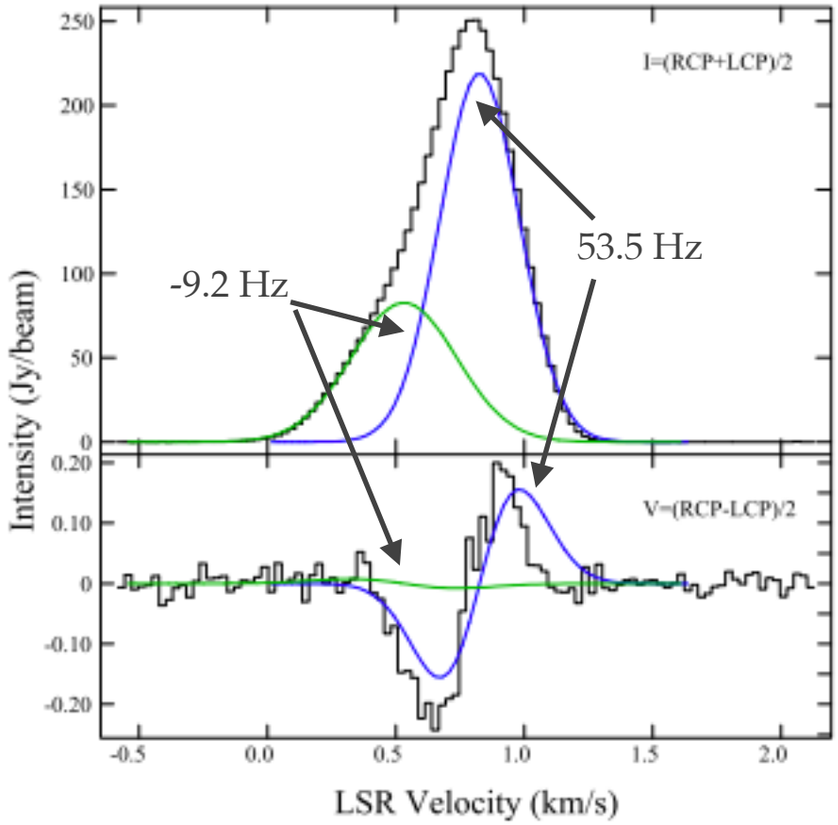


Gray 2012

Re-interpreting maser observations

Recalcitrant masers

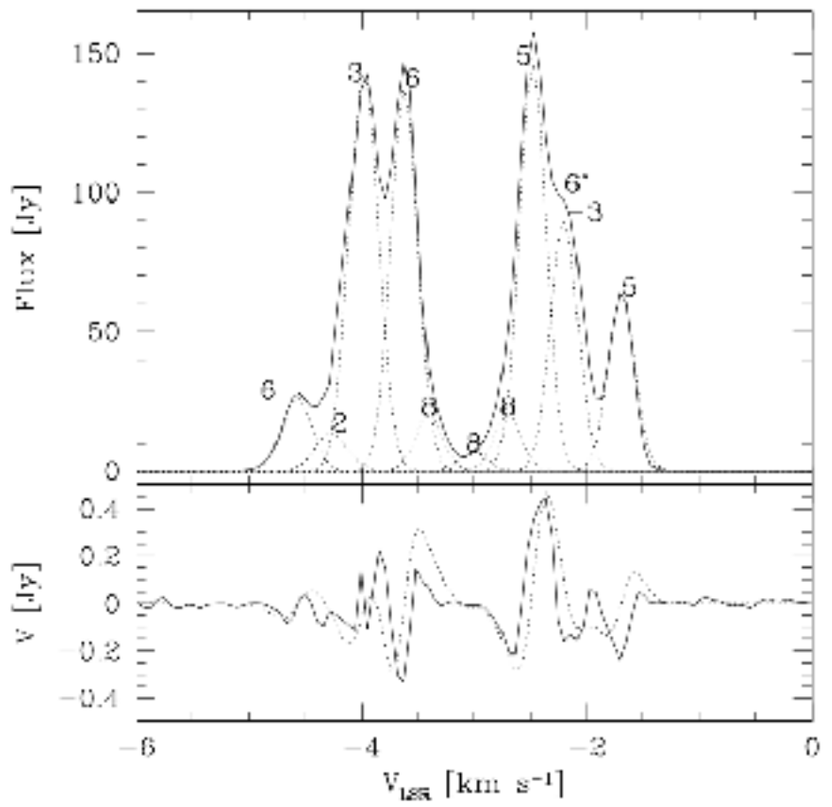
- Oppositely polarized masers along l.o.s.
  - Current analysis: B flips sign
  - But if we assume maser action favors different hyperfine transition: similar B



53.5 Hz -> B = -58.15 mG

-9.2 Hz -> B = 10 mG

B = -45.32 mG

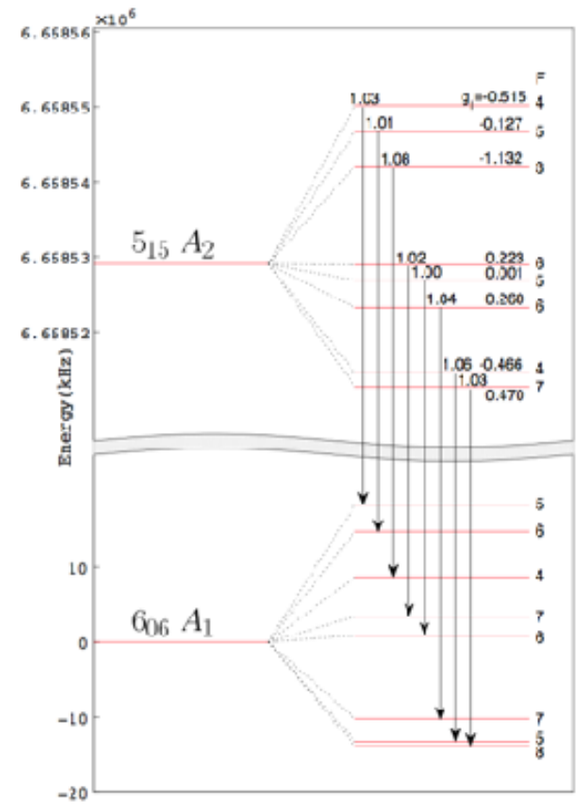


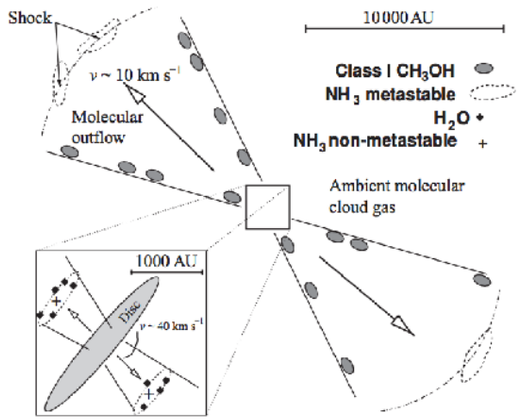
Momjian and Sarma 2017

Vlemmings et al. 2010

Summary

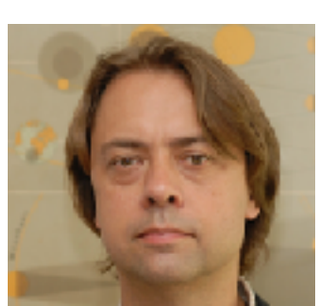
- Methanols magnetic field dynamics
  - hyperfine structure
    - fit requires no unphysical paramaters
    - compares well to experiment
  - Zeeman effect
    - ab-initio calculations
    - estimation from experiments
    - magnetic field characteristics available for all transitions
- Re-interpretation of maser observations
  - Class II: Dynamically important magnetic field around protostar
  - Class I: trace shocked region of outflow












Onsala Rymdobservatorium, Chalmers Tekniska Högskola

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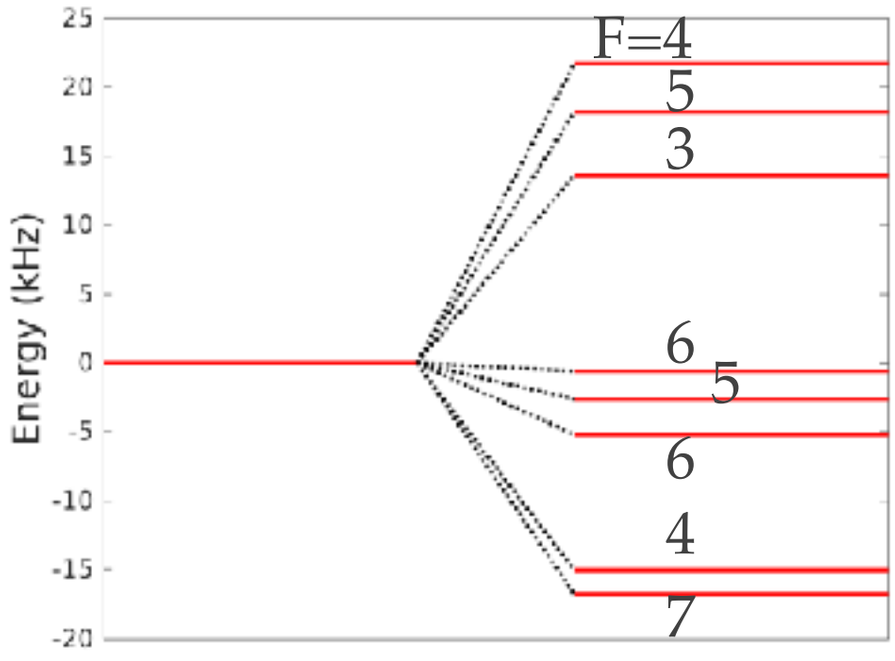
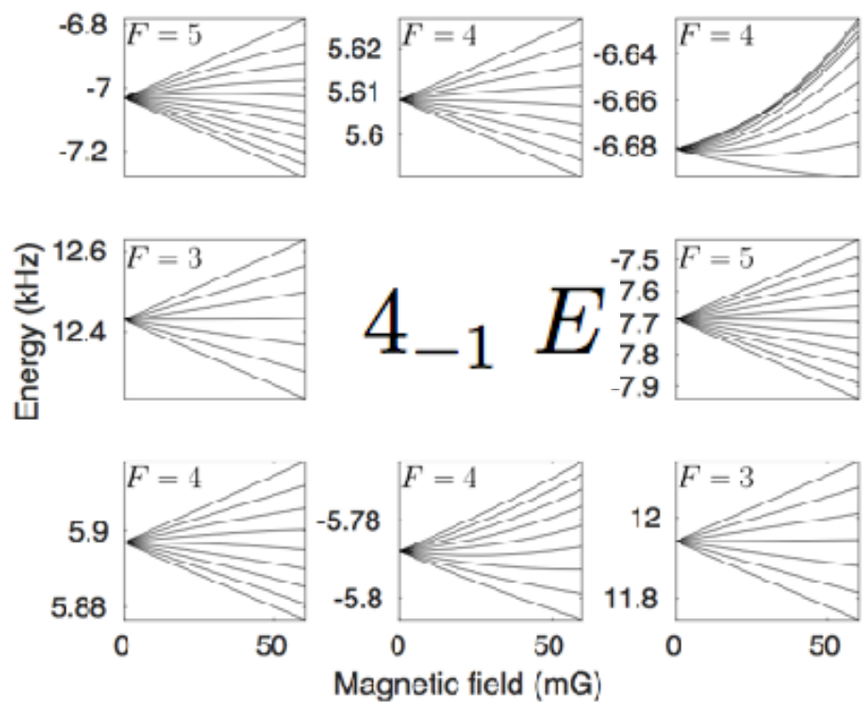
Zeeman effect



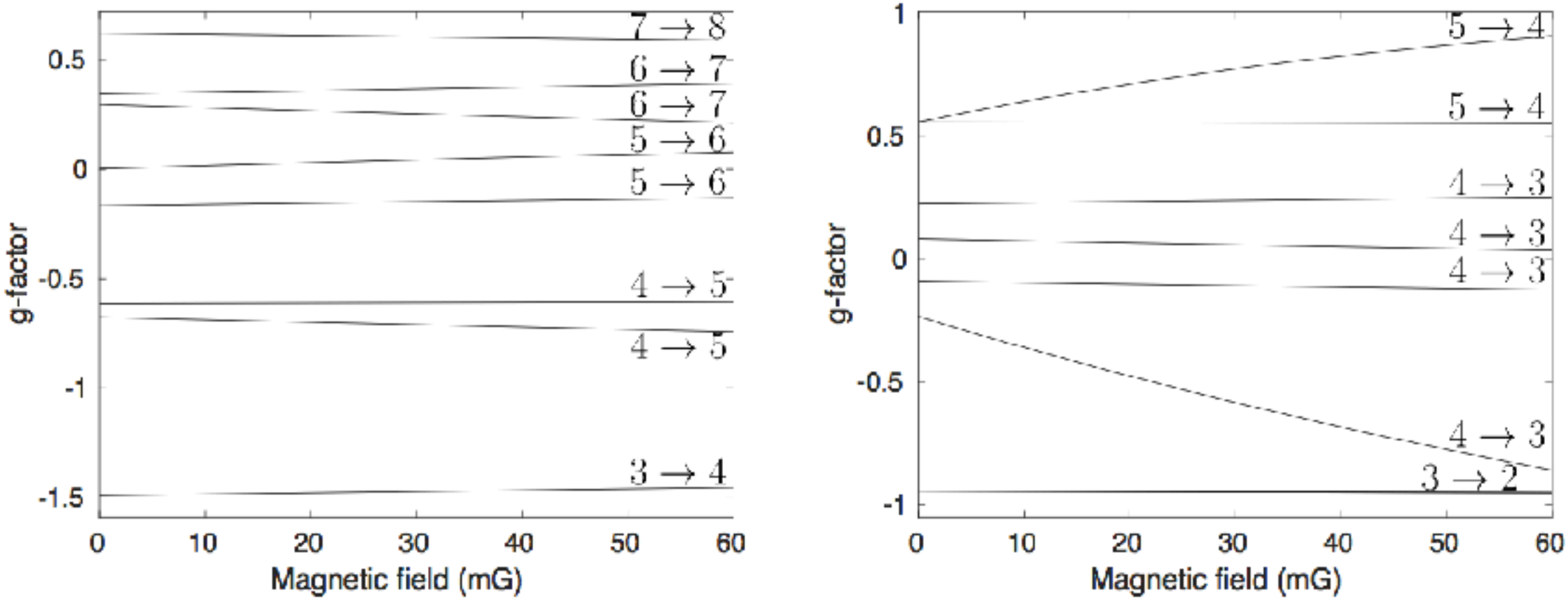
Radiative transfer modeling

- Hyperfine structure
  - narrow (proximate energy-levels)
  - I: no good quantum number
- Zeeman effect
  - exhibits non-linear behavior
- Radiative transfer modeling needs to be done rigorously!





Deguchi and Watson 1990
Neduloha and Watson 1994



(a) (b)

FIG. 1: Magnetic field dependence of the g-factors of the strongest hyperfine transitions within the 6.7 GHz ($5_{15}\ A_2 \rightarrow 6_{06}\ A_1$) (a) and 36 GHz ($4_{-1}\ E \rightarrow 3_0\ E$) (b) methanol maser lines. The different components are labeled $F \rightarrow F'$ with their initial and final F values, which are good quantum numbers for $B = 0$.

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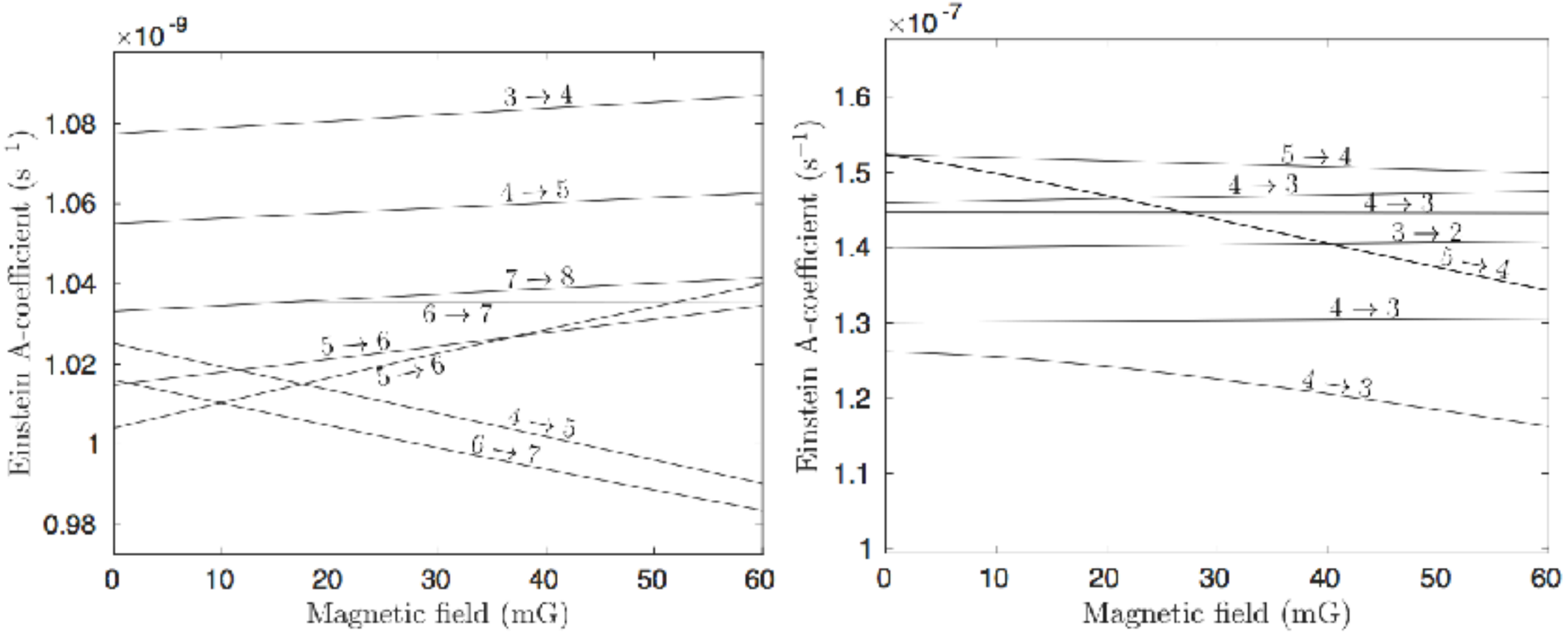

FIG. 2: Magnetic field dependence of the Einstein A-coefficients of the strongest hyperfine transitions within the 6.7 HGz ($5_{15}\ A_2 \rightarrow 6_{06}\ A_1$) (a) and 36 GHz ($4_{-1}\ E \rightarrow 3_0\ E$) (b) methanol maser lines

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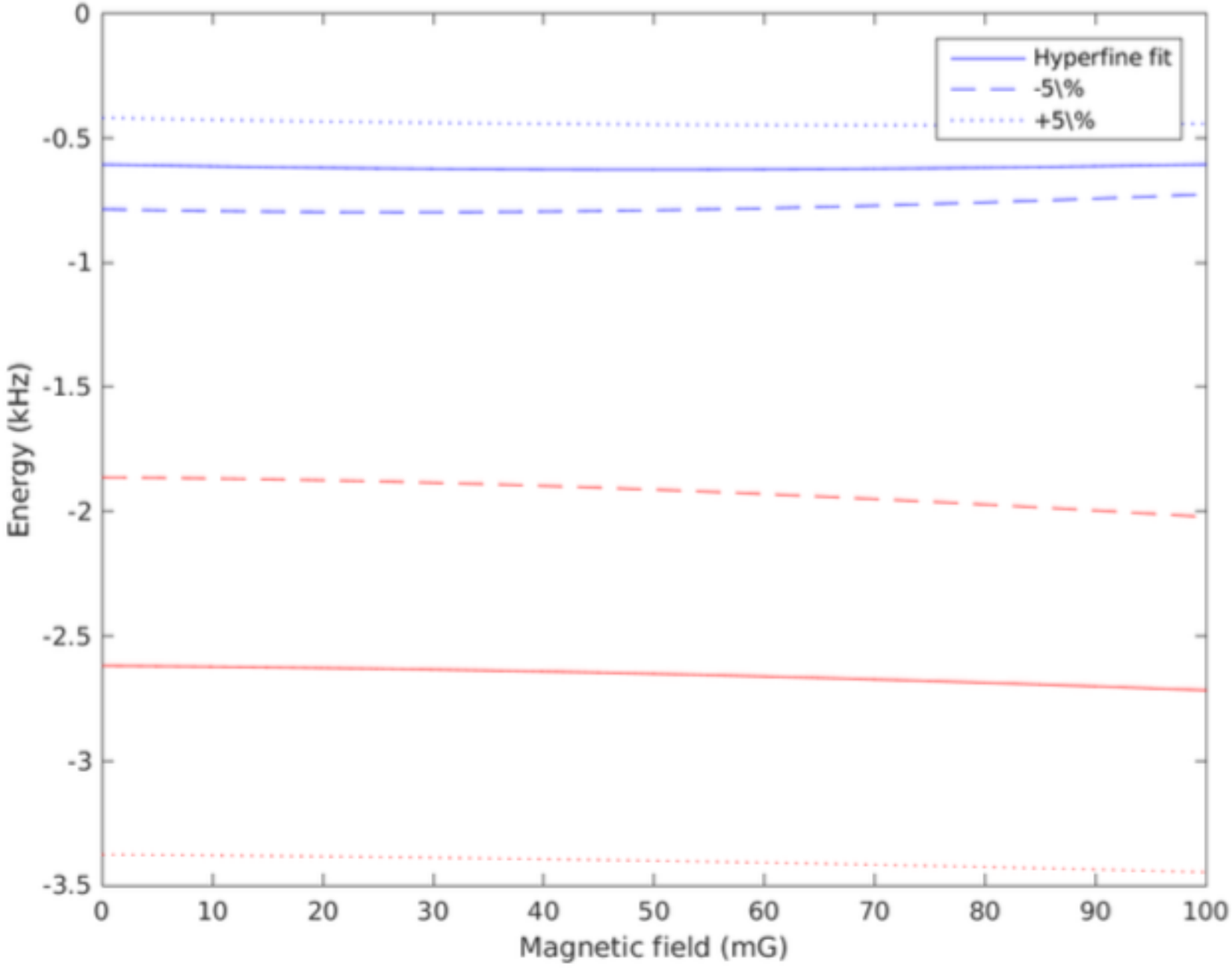

FIG. 4: The splitting of hyperfine levels of the rotational 5_1 A^- state as a function of the magnetic field strength for different values of the d_z^4 coupling tensor.