Coronal Magnetic Field Measurements from EUV wavelengths

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Collaborators:

Atomic method, theory and calculations:

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Queen's University Belfast: Connor Balance

Laboratory measurement:

Fudan University: Roger Hutton and Shanghai-EBIT laboratory

Solar observations and applications:

Peking University: Hui Tian group
High Altitude Observatory: Philip G. Judge
University of Michigan: Enrico Landi

Outline

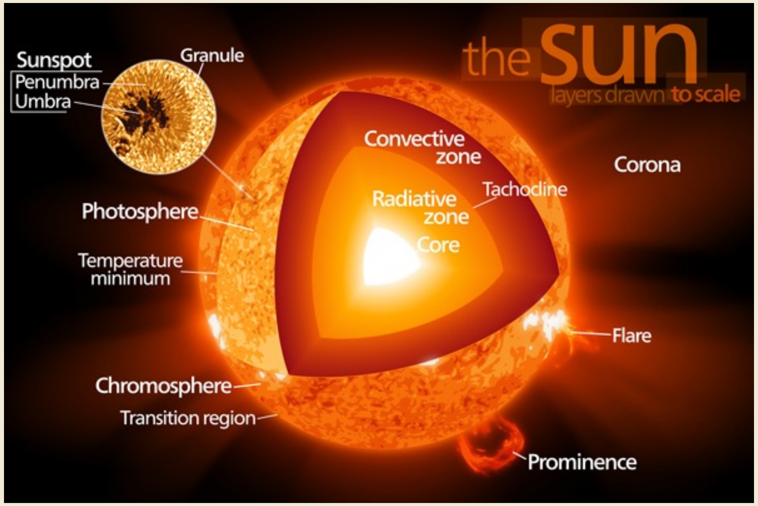
- **Coronal Magnetic Fields**

- **Magnetic-field Induced Transitions (MITs)**
  - Introduction to MIT
  - MIT in Fe X

- **Applications of Fe X MIT in solar/stellar coronal magnetic field measurements**
  - Methodology
  - Forward modeling with 3D MHD model
  - Application to Hinode/EIS observations

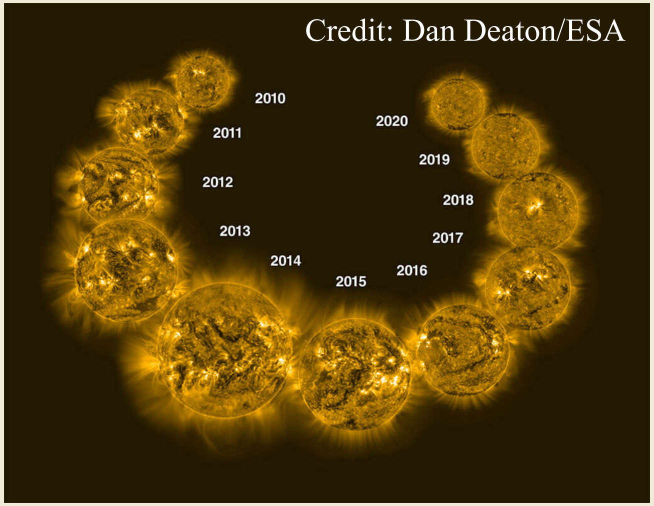
- **Discussions and Summary**

Magnetized solar atmosphere

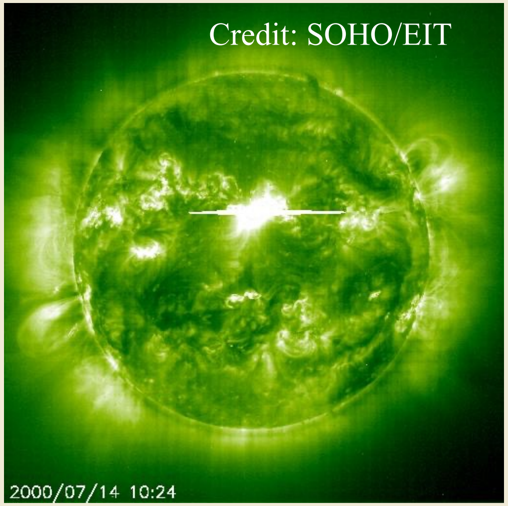


If the Sun did not have a magnetic field, it would be as uninteresting as most astronomers consider it to be.
——Robert Leighton

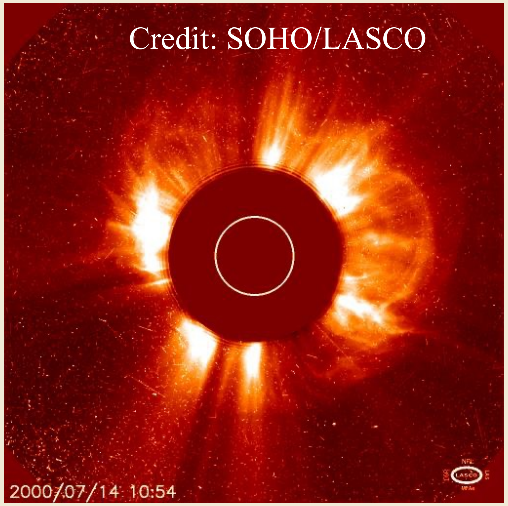
solar cycle, structuring, solar eruptions, coronal heating ……



Credit: Dan Deaton/ESA

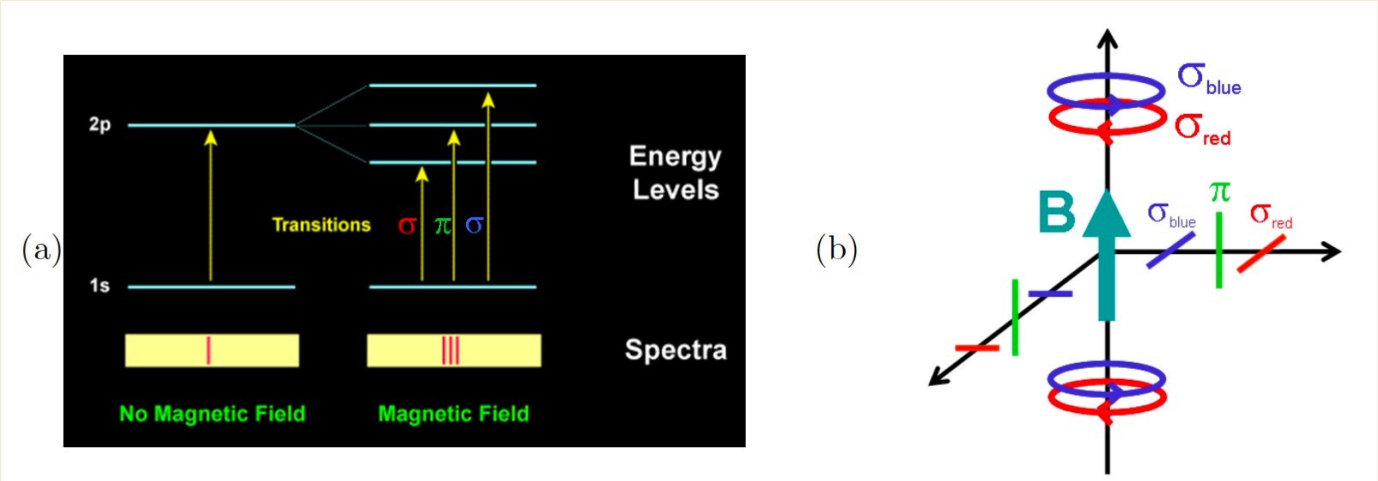


Credit: SOHO/EIT

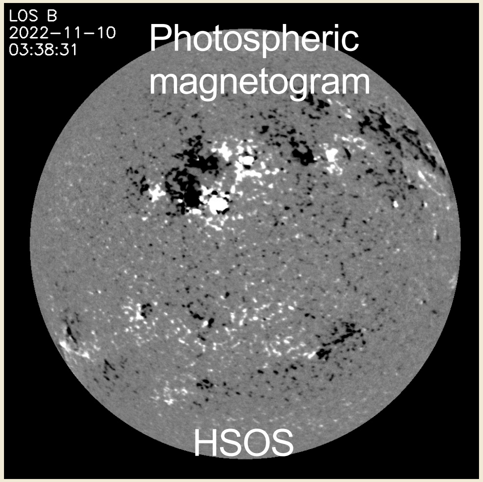


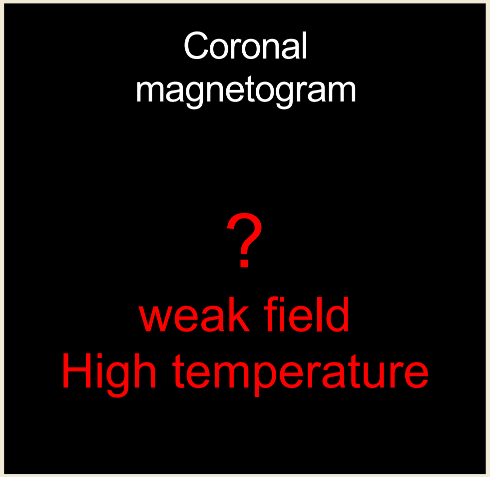
Credit: SOHO/LASCO

Schematic of Zeeman splitting and polarization of the π and σ components (Reiners, LRSP, 9,1, (2012))



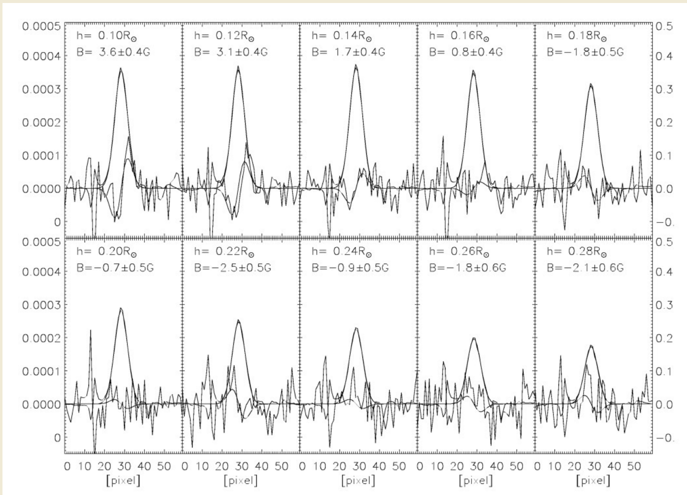
Accurate and routine measurements of solar magnetic field achieved at the photospheric level (e.g., HSOS, SDO/HMI, ASOS-FMG)



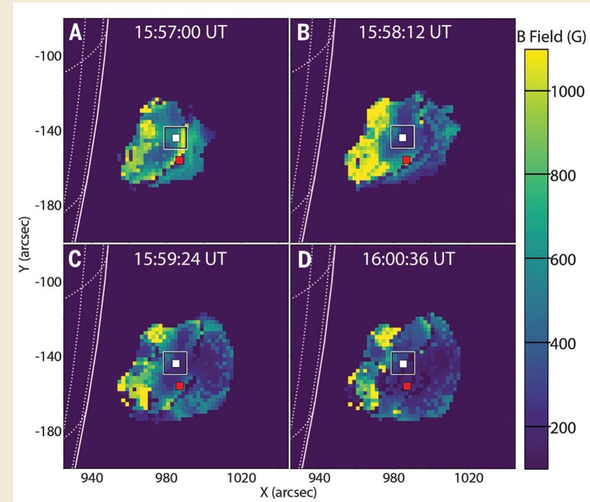


How to measure the coronal magnetic field?

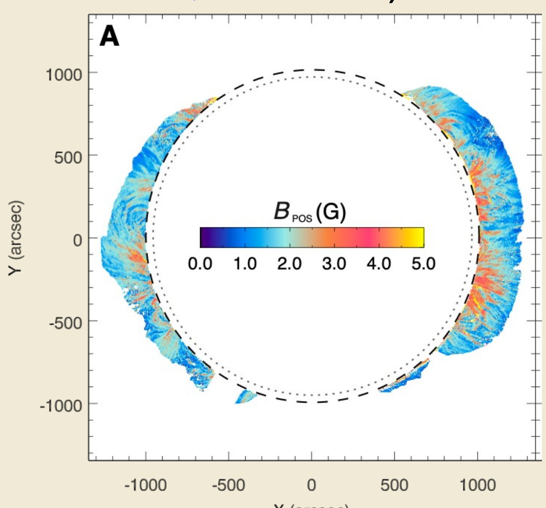
Spectropolarimetry of the visible and near-infrared coronal emission lines (Lin et al. 2004, ApJL)



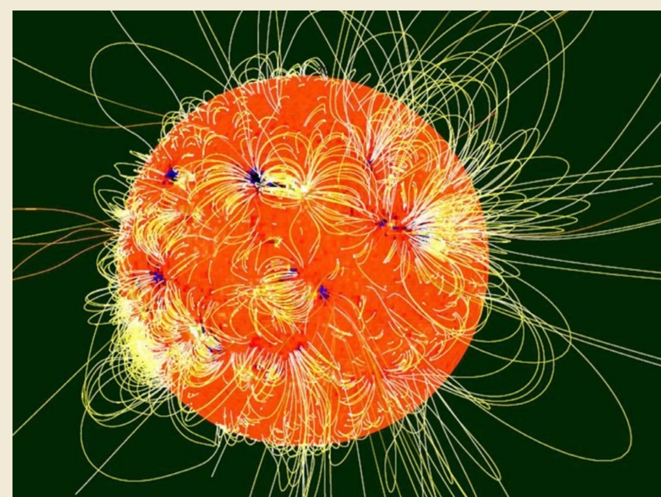
radio imaging observations (Fleishman et al. 2020, Science)



magnetoseismology (Yang et al. 2020, Science)



Extrapolation from photospheric magnetic field (Wiegelmann and Solanki 2004)



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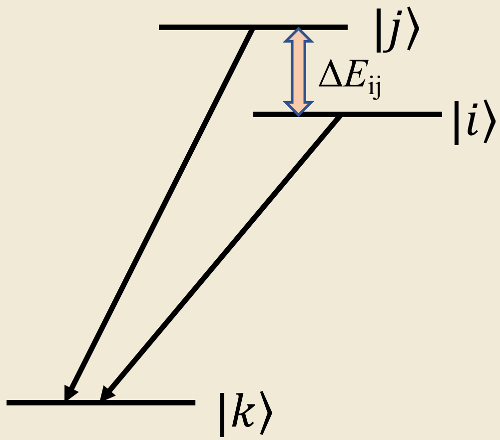
Magnetic-field Induced Transitions, MITs



A simple three-level system (Grumer et al. 2014)

- State *j* has a "fast" decay channel to the ground state *k*; strong spectral feature
- State *i* is metastable; small transition probability $A(i \rightarrow k)$

$$H = H_{fs} + H_m = H_{fs} + (N^{(1)} + \Delta N^{(1)}) \cdot B$$

$$\Psi_i = \sum_j c_j^i \Phi_i \qquad c_j^i \approx \frac{\langle \Psi_j^0 | H_m | \Psi_i^0 \rangle}{E_i^0 - E_j^0}$$

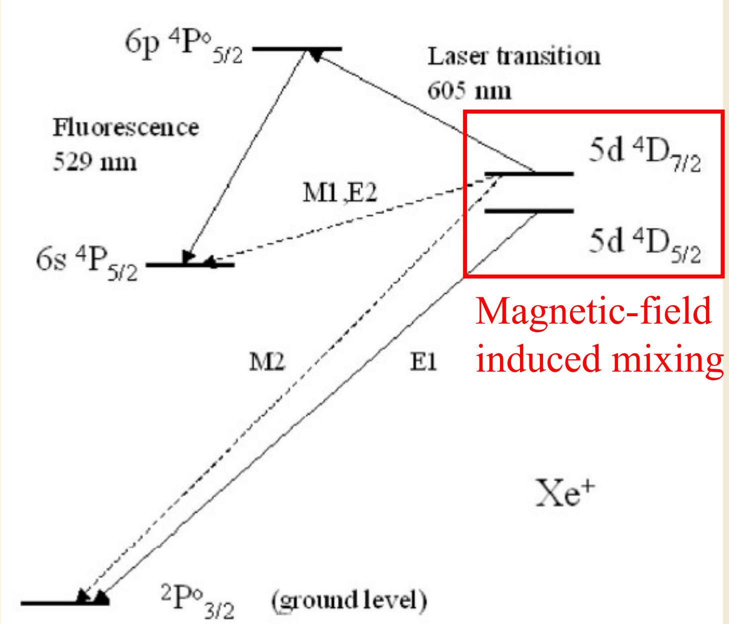
- External magnetic fields mix states *i* and *j*; a "new" transition channel $i \rightarrow k$: magnetic-field induced transition (MIT)

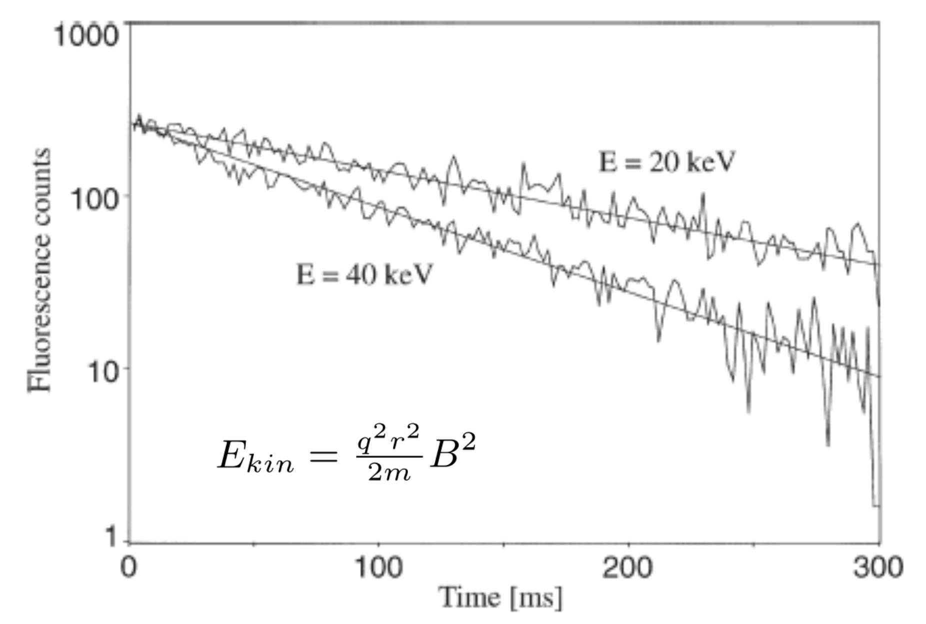
$$A_{MIT}(i \rightarrow k) \approx \left| c_j^i \right|^2 A(j \rightarrow k)$$
$$\propto A(j \rightarrow k) \frac{B^2}{\lambda^3 (\Delta E_{ij})^2}$$

GRASP(Jönsson et al. 2023)+HFSZEEMAN (Li et al. 2020)

Zeeman quenching: shorten the lifetime of long-lived levels (Feldman et al.,1967; Balling et al.,1992; Andersen et al.,1993; Mannervik et al. 1997; Schef et al. 2005)

Schef et al. 2005: lifetime measurement of metastable states in Xe II in Ion Storage Ring + laser probing

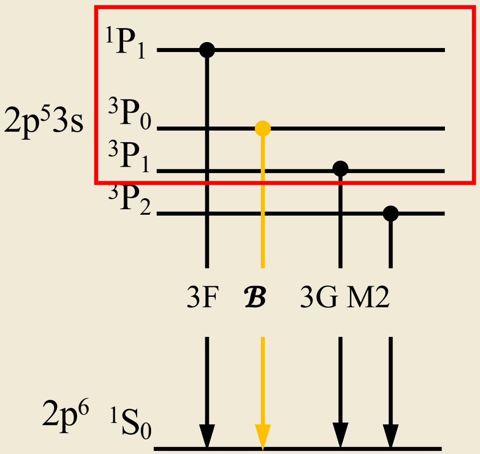




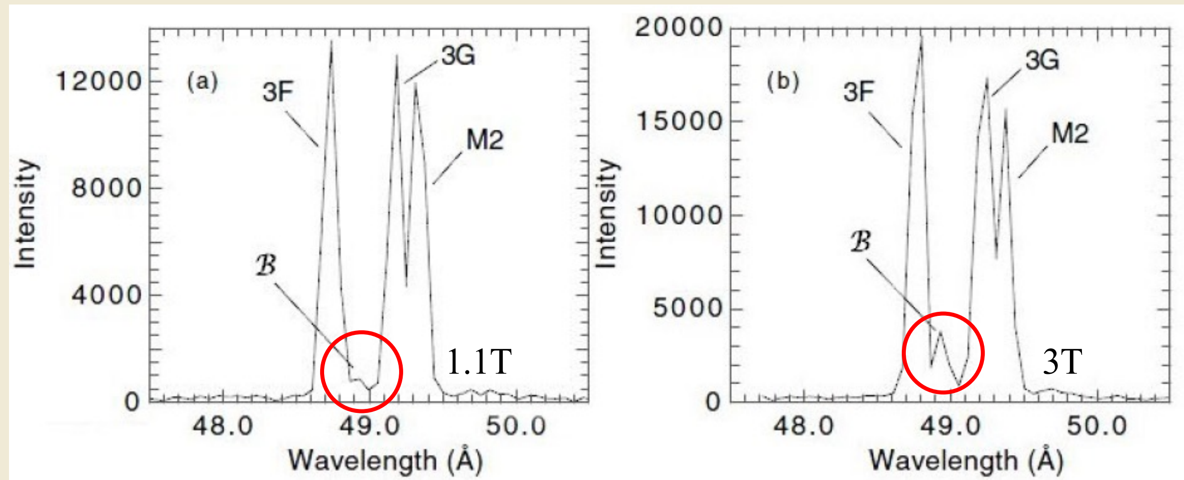
Lifetime curves of the 5d $^4D_{7/2}$ level in $^{132}Xe^+$ recorded at different beam energies.

Measurement of MIT in the Laboratory

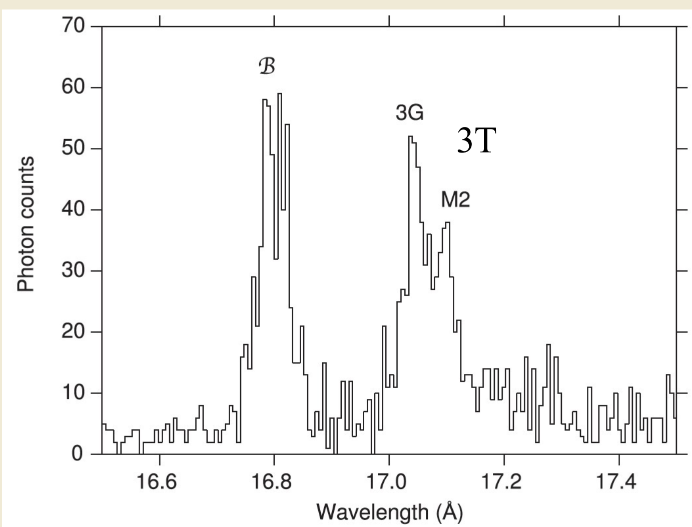
Ne-like ions in Electron Beam Ion Trap (EBIT)



Ar IX: Beiersdorfer et al. PRL, 2003



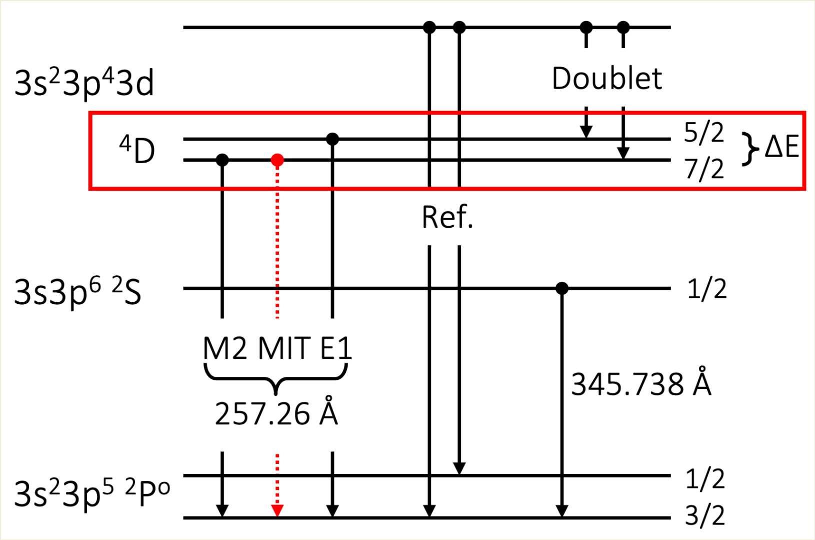
Fe XVII: Beiersdorfer et al. ApJ, 2016



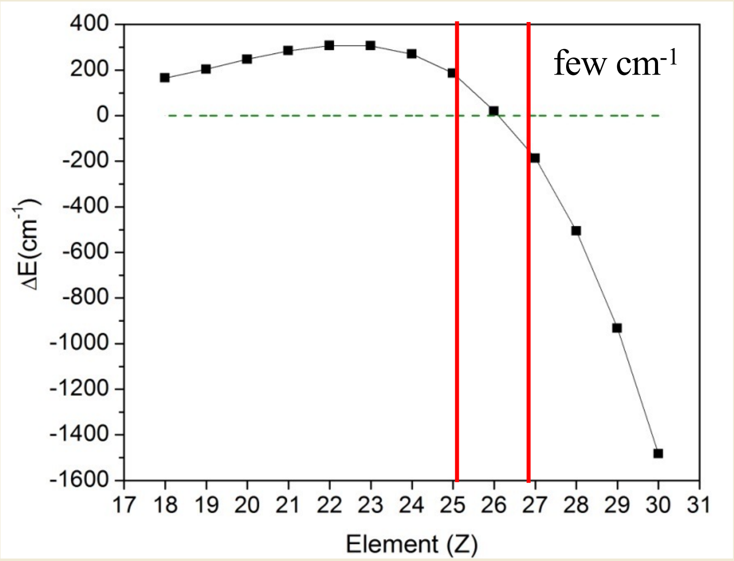
- Potential for magnetic field strength diagnostics
- Be-, Ne- and Mg-like ions: MITs are generally very weak for small external fields.

MIT in Fe X

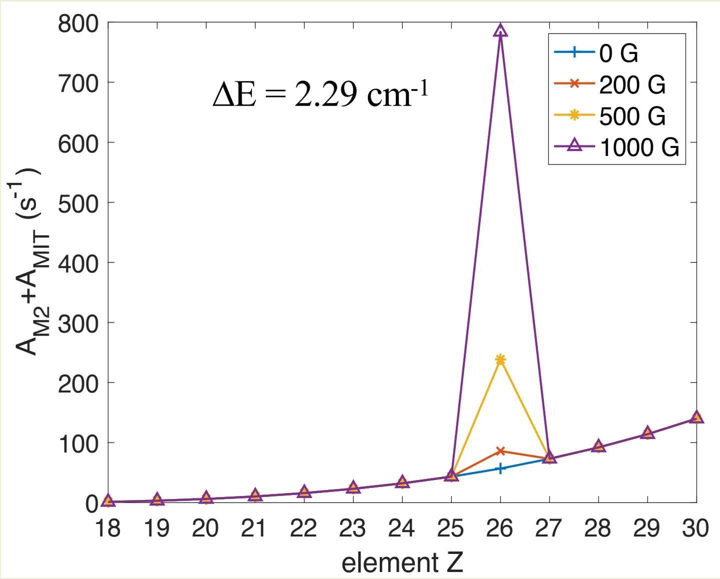
Li et al. ApJ, 2015, 2016, 2021



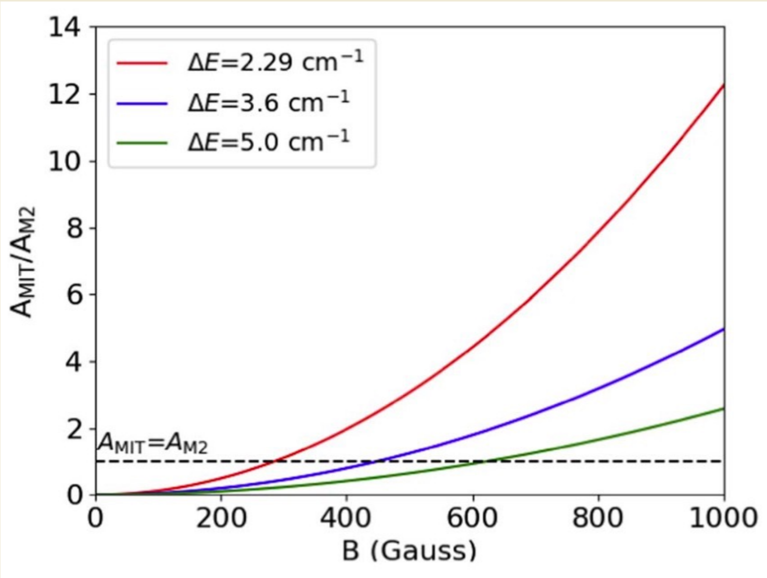
Schematic energy diagram of Fe X



Energy difference as a function of *Z*



$A_{MIT}+A_{M2}$ as a function of Z

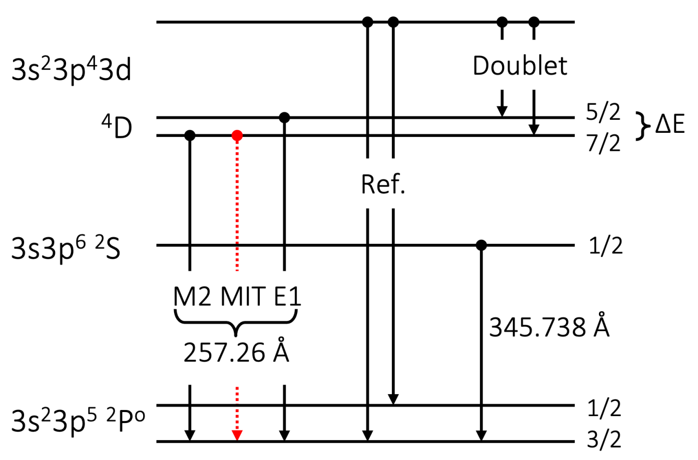


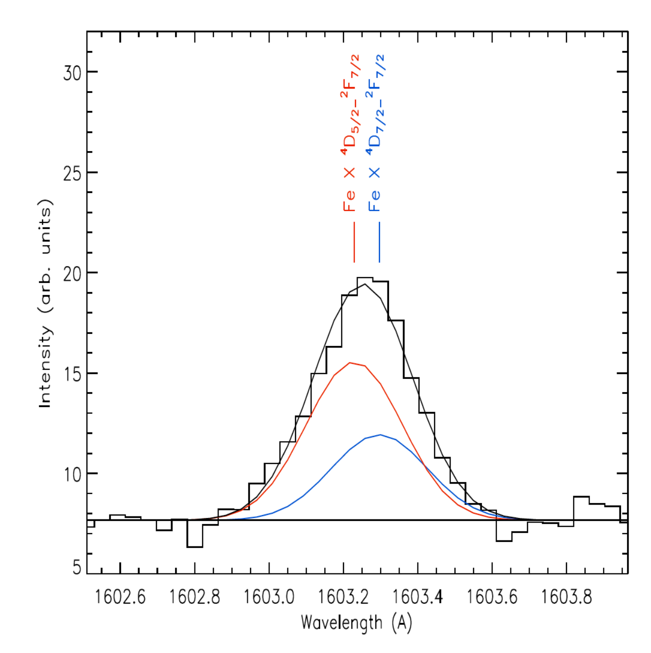
A_{MIT}/A_{M2} as a function of B

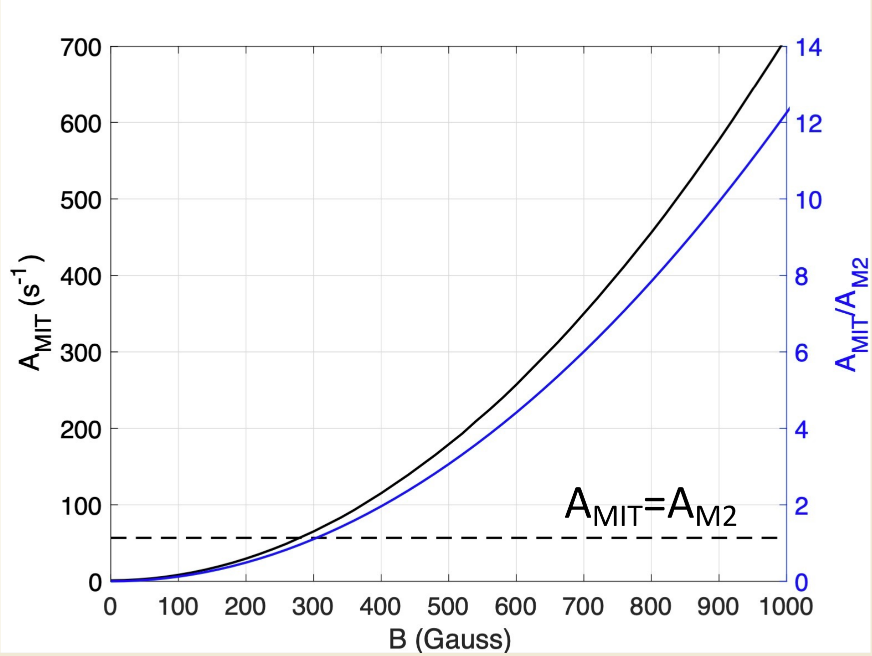
- ΔE from EBIT measurements: 3.5 cm^{-1} with upper limit of 7.8 cm^{-1} (Li et al. ApJ, 2016)
- double Gaussian fit for lines from the same upper level to $^4D_{7/2,5/2}$

✓ SO82-B/SKYLAB spectra: 3.6 ± 2.7 cm^{-1} (Judge et al. ApJ, 2016)

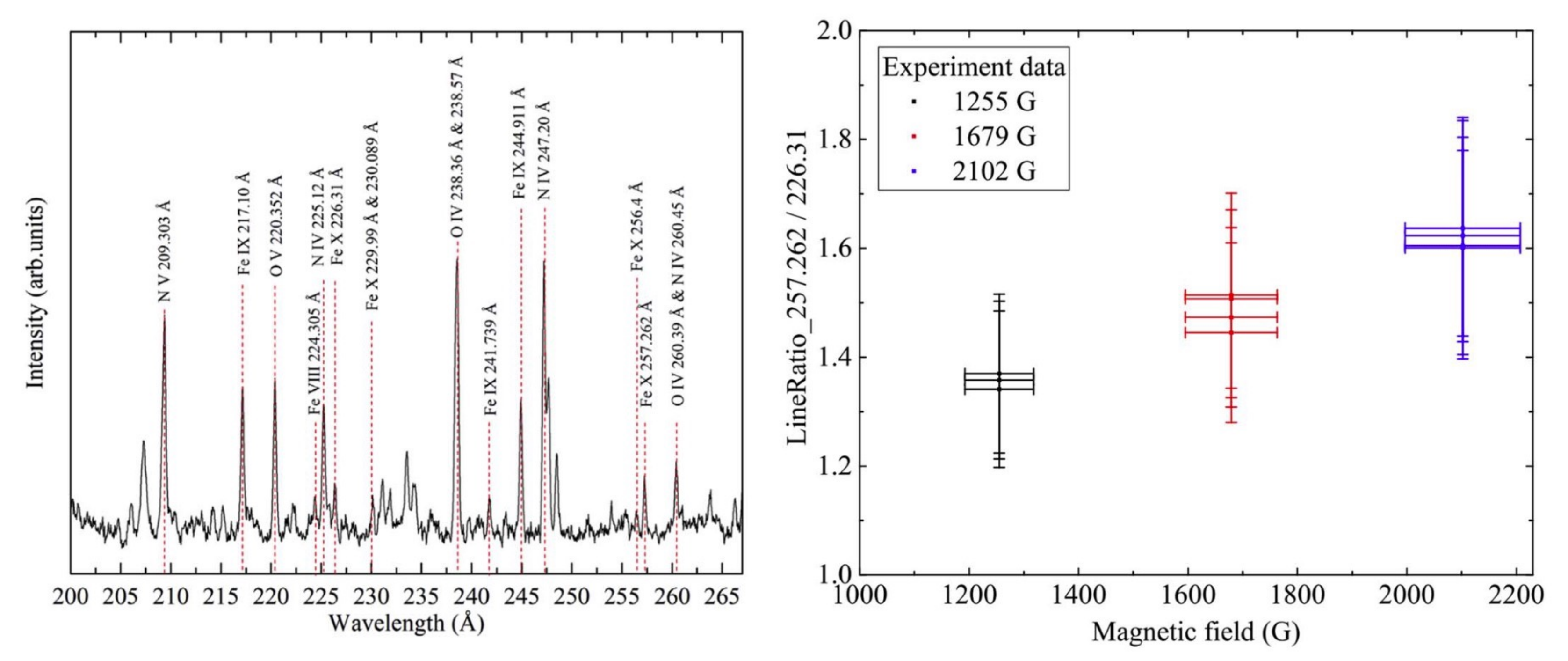
✓ SoHO/SUMER spectra: 2.29 ± 0.5 cm^{-1} (Landi et al. ApJ, 2020)







Laboratory measurement of MIT in Fe X at different magnetic fields@ SH-Htsc EBIT (Xu et al. 2022, ApJ)



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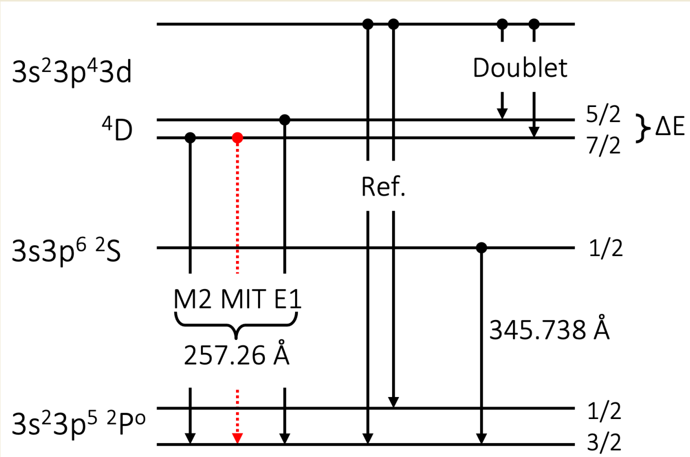
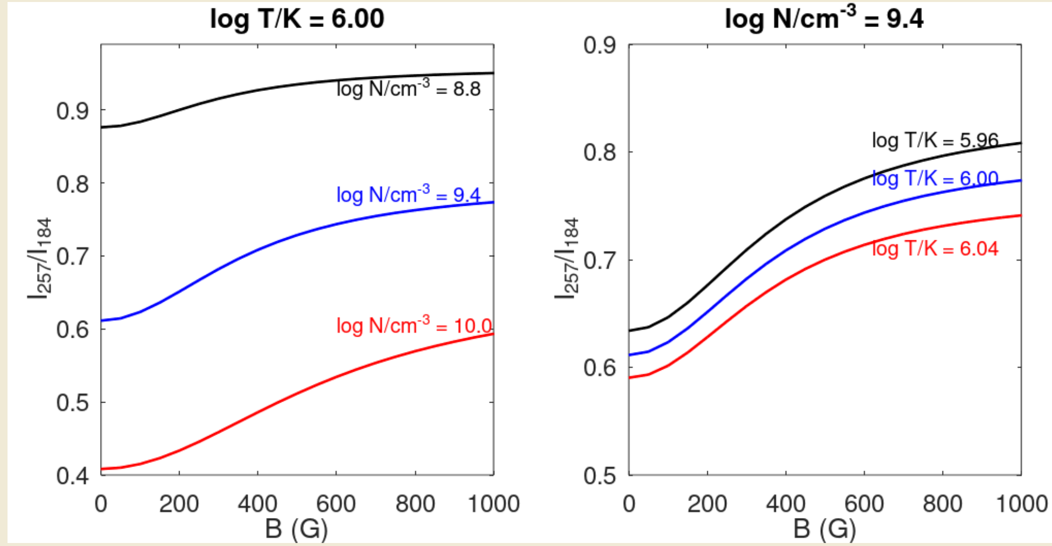
Coronal magnetic field diagnostics using MIT method





compare the observed 257/Ref. with theoretical predictions LR(T,N,B)

- Reference line: insensitive to B
- Density diagnostic: intensity ratio with Fe X 174/175
- Temperature diagnostic: intensity ratio with Fe X 184/345
- Spectral modelling: CHIANTI database, Int(T,N,B)

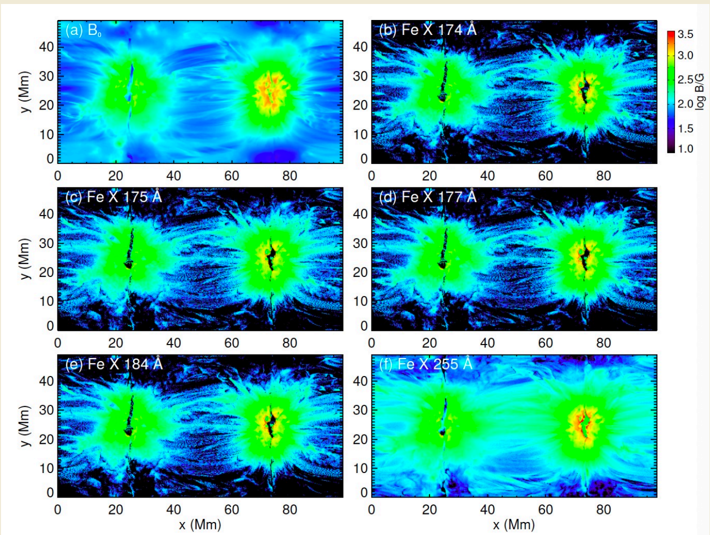
Forward modeling with a 3D MHD model (Chen et al. 2021, ApJ)

- Construct MHD models of solar corona for a range of activity levels
- establish an atomic database of the Fe x ion (Chianti+MIT)
- synthesize the emissions of Fe x lines from 3D MHD model
- Density diagnostics: Fe X 175/174 ratio
- Temperature diagnostics: constant or Fe X 184/345 ratio
- Derive the magnetic field strengths using the intensity ratios 257/Ref.
- compare the derived field strengths with those in the models

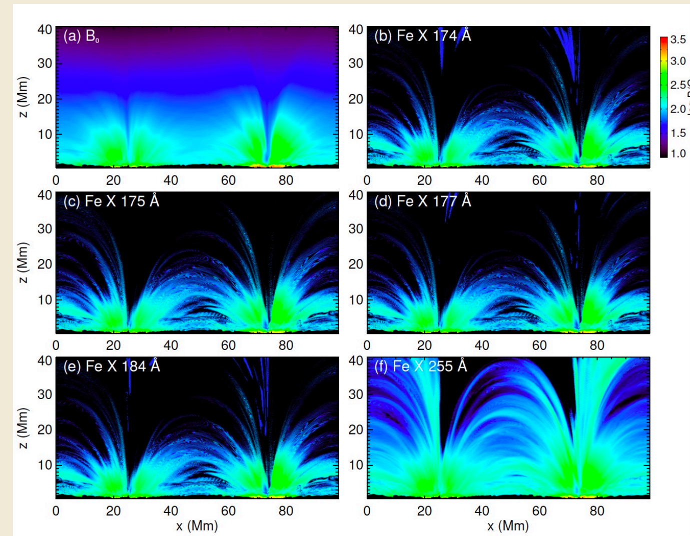
$$B_0 = \frac{\int_{LOS} \epsilon_{174}(s) \cdot B(s) ds}{\int_{LOS} \epsilon_{174}(s) ds}$$

Forward modeling with a 3D MHD model (Chen et al. 2021, ApJ)

Disk-center observations

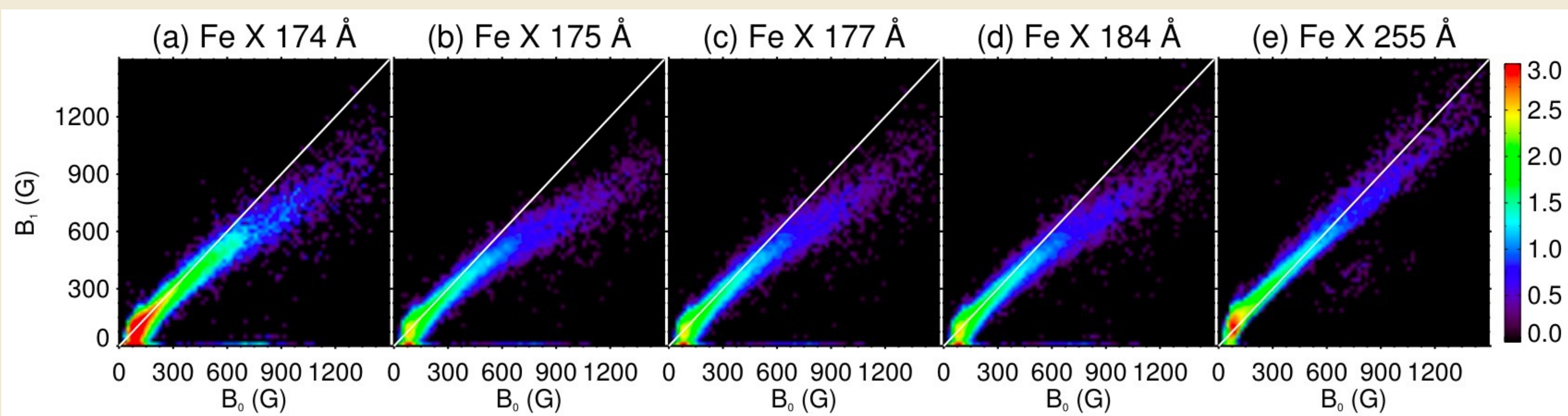


Off-limb observations



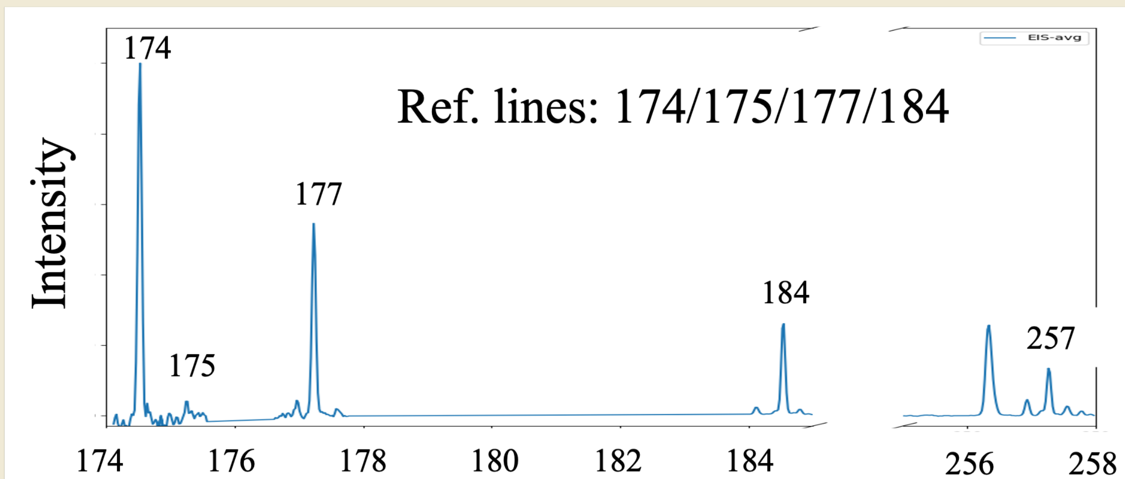
(a): B_0

(b)-(f): B_{MIT}



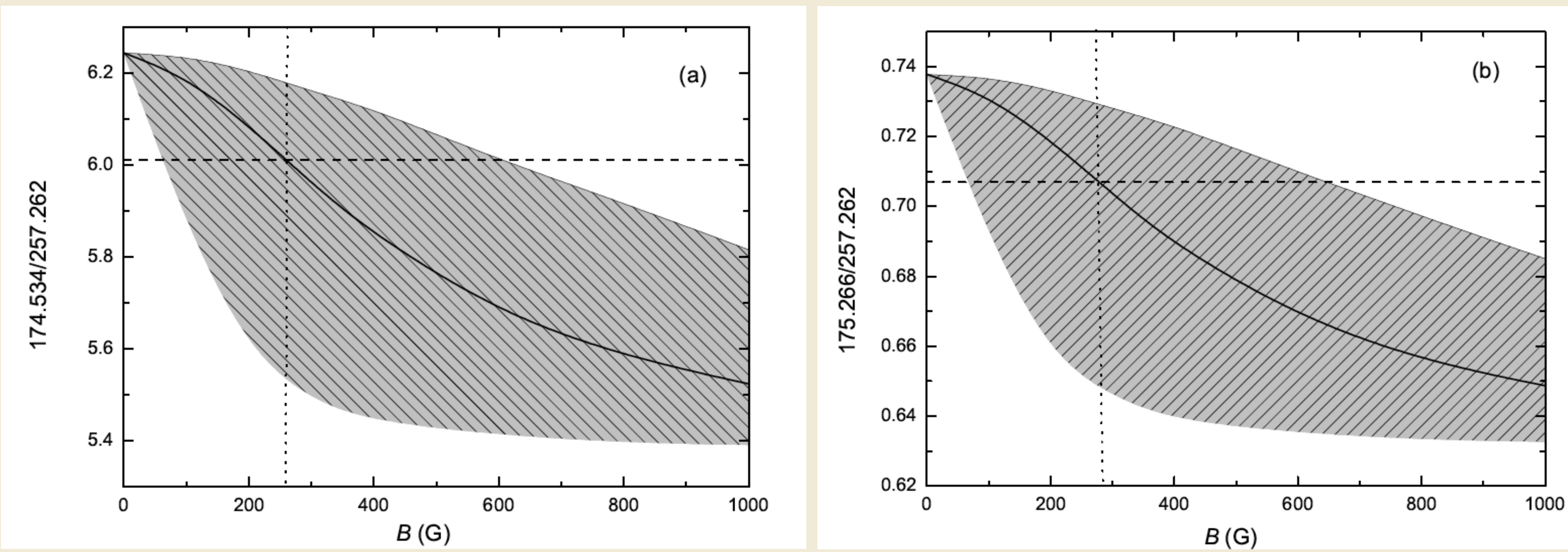
Hinode/EIS Measurements of Solar Coronal Magnetic Fields

Hinode/EIS:
solar corona and upper transition region emission lines in the wavelength ranges
170 – 210 Å (SW) and 250 – 290 Å (LW)



Portion of Fe X spectrum from Hinode/EIS

- 174 and 175 as reference lines (Si et al., ApJL, 2020)
- 174/175 for density determination
- Constant temperature of log T/K = 6.0
- observed intensity ratios from Brown et al. ApJS, 2008, an active region observed on Nov. 4, 2006 on the solar disk from Hinode/EIS



The field strength was determined to be around 270 G.

- reference line: 184 Å (Landi et al. ApJ, 2020, 2021)
- Density measurement: Fe X 174/175
- Constant temperature of log T/K = 6.0

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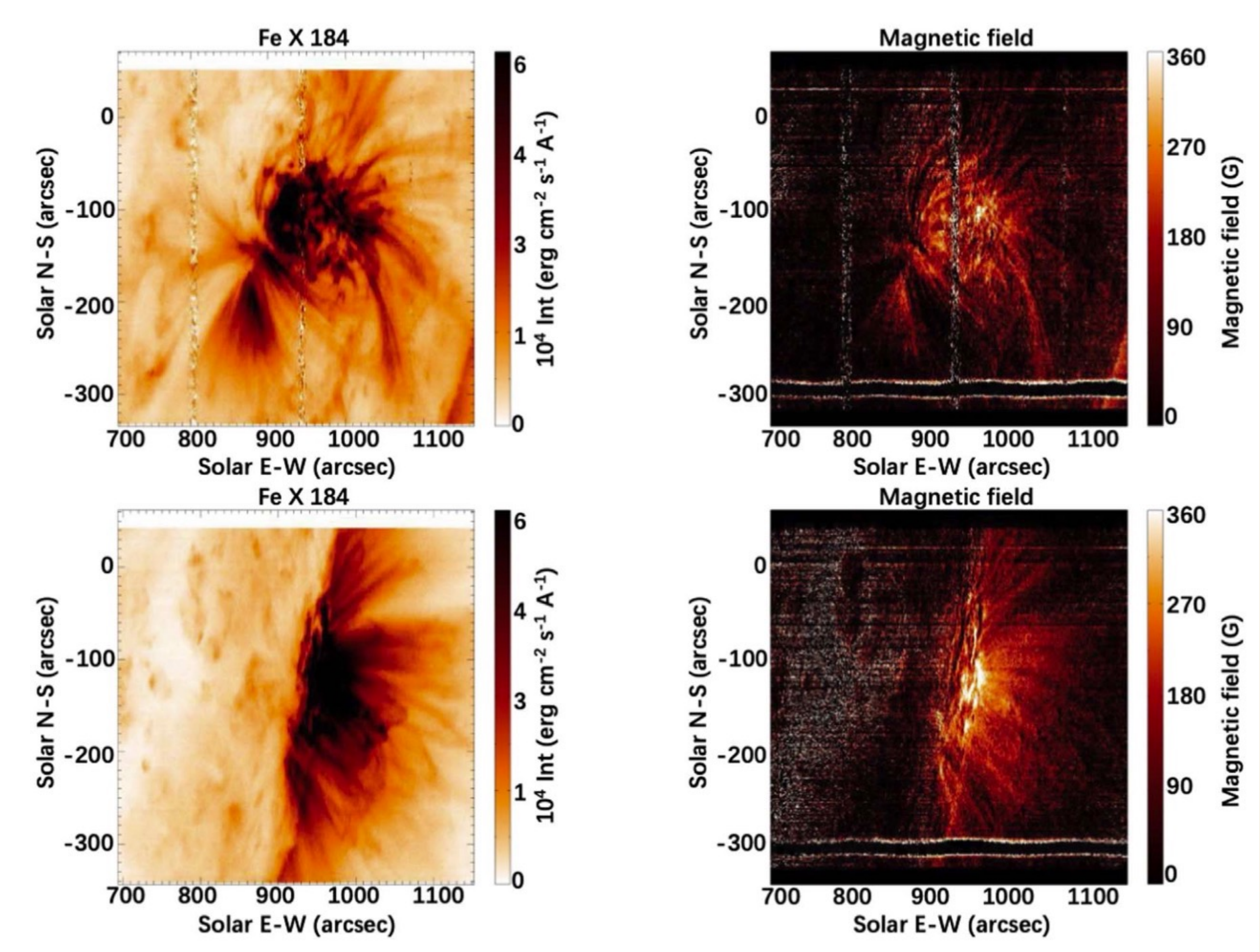

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Limitations and uncertainties

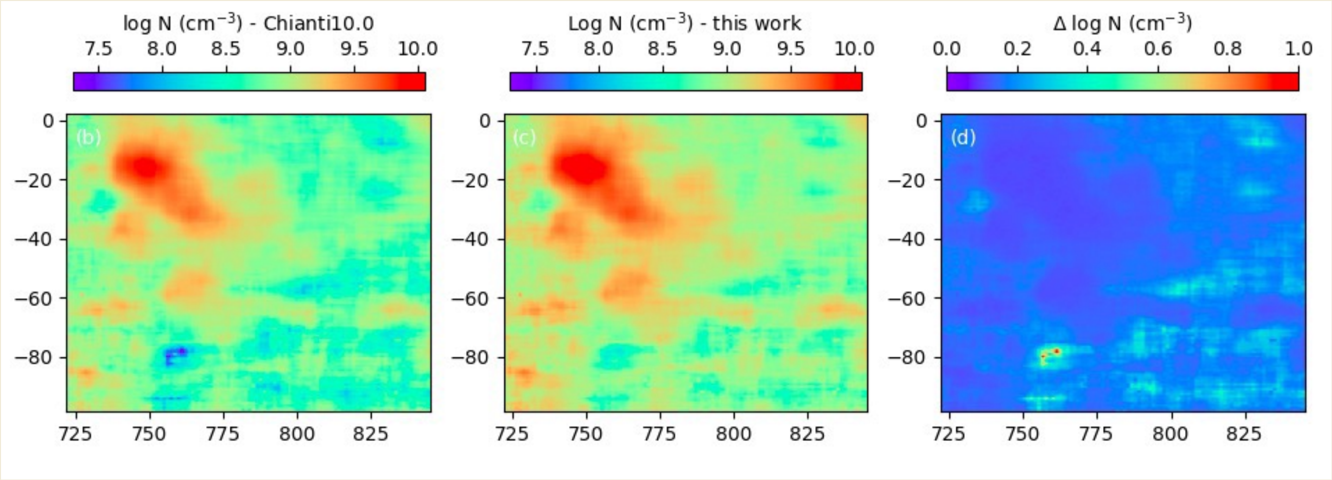
- Only field strength can be measured, but not the direction
- Uncertainty in atomic data:

  ΔE: 20% uncertainty from the SUMER measurements (Landi et al. 2020)

  CHIANTI v10 – transition and collisional data from R-matrix (Del Zanna et al. 2012)

Wang et al. 2020, Li et al. 2021, 2022 :

- large-scale MCDHF calculations for levels and radiative data for states up to n=4
- Dirac Atomic R-matrix calculation for electron-impact collision strengths



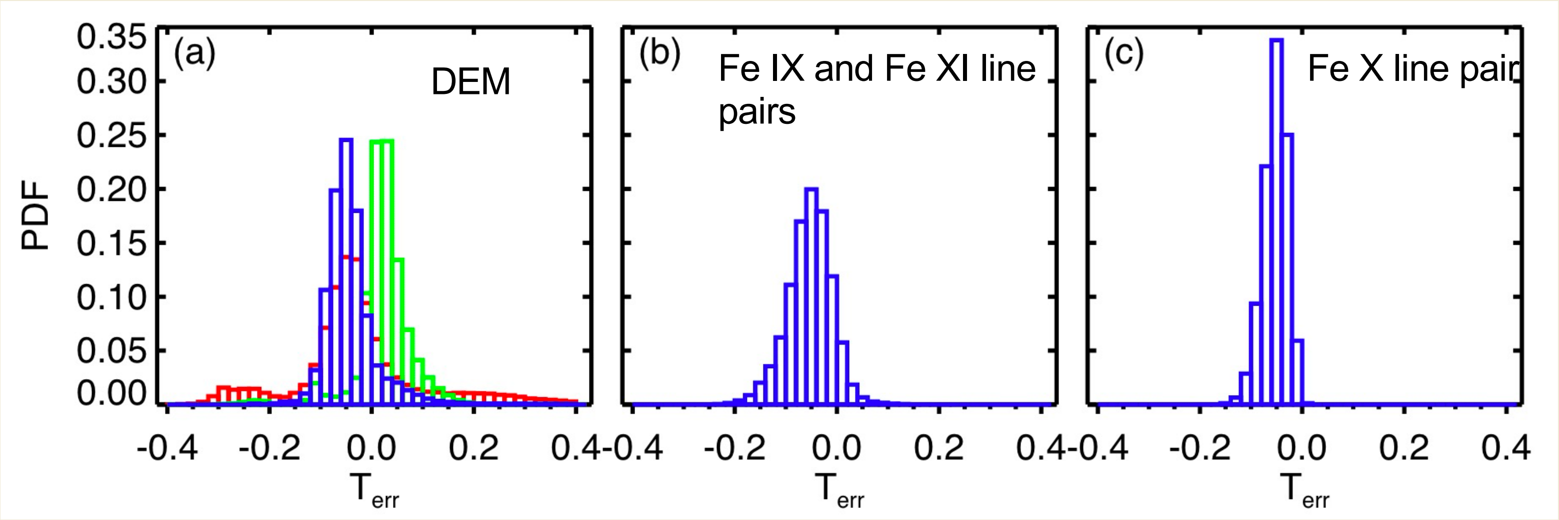
Density map obtained with different atomic data

- the absorption of the Fe X emission from cool plasma significantly affects the accuracy of density and magnetic field diagnostics(Martínez-Sykora et al. 2022)

- Intensity calibration: short-(reference lines) and long-wavelength (257 Å line)

- Temperature measurement

Chen et al. 2023, MNRAS



Summary

- The pseudo-degeneracy of two levels in Fe X causes the magnetic-field-induced transition, MIT@257 Å line to be sensitive to the relatively small magnetic fields expected in the solar corona.

- Forward modeling with 3D MHD models has verified that the MIT technique could provide reasonably accurate solar and stellar coronal magnetic field measurements.

- The MIT method has been applied to HINODE/EIS observations and illustrates the potential of a new diagnostic technique for coronal field strength measurement.

- Further efforts are necessary on both theoretical and observational side to provide a better estimation of magnetic field using the MIT method.

- It is also highly desirable to combine different magnetic field techniques to achieve a better understanding of coronal magnetism.

Thanks for your attention!