Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

Tetsuya Watanabe (NAO/NINS)
Takako Kato, Izumi Murakami (NIFS/NINS)
Norimasa Yamamoto (Nagoya U.)
Solar-B (NAOJ) & Large Helical Device (NIFS)
Iron M-shell Lines

- Solar-B EIS (NAOJ, JAXA/MSSL/BU/RAL/NRL/UO)
- Atomic Data Evaluation (NIFS)
- Time-dependent Collisional Radiative Model
  Theoretical Calculation (Yamamoto et al.)
- Atomic Data Generation
  EBIS/EBIT experiment (Sakaue et al.)

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Solar and LHD (Large Helical Device)
Plasma Diagnostics in EUV

Solar-B

EUV Imaging Spectrometer (EIS)
Solar Optical Telescope (SOT)
X-Ray Telescope (XRT)

Launch: 23-Sep-2006 (JST)
Booster: JAXA M-V-7
Orbit: H - 630km
Weight: ca 900 kg
Size: 1.6m × 1.6m × 4m
solar panel reach 10m
Launch: 23-Sep-2006 6:36am (JST)

OTA: Optical Telescope Assembly
FPP: Focal Plane Package
XRT: X-ray Telescope
EIS: EUV Imaging Spectrometer

M-V Booster
Uchinoura Space Centre/ J AXA

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**Hinode** (sunrise; “he-know-day”)

- **Epoch:** 2006/10/3 18:00:00UTC
- **semi-major axis:** 7059.706 km
- **eccentricity:** 0.0000
- **inclination:** 98.090 deg
- **altitude of perigee:** 678.452 km
- **altitude of apogee:** 684.682 km
- **period:** 98.387 min
Opening of Telescope Doors (schedule)

- SOT side door; 14-Oct – done!
  top door; 25-Oct
- XRT top door; 27-Oct
- EIS clamshell-front door; 27-Oct
  clamshell-rear door; 28-Oct
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**Filtergraph (FG)**
- High time-resolution
- 2D pictures + 3D magnetic fields
- In 12 wavelengths

**Spectropolarimeter (FPP)**
- Detailed spectro-polarimetry of Fe I absorption line at 630nm for 3-D structures of photospheric magnetic fields

**Focal Plane Package (FPP)**
- SP CCD & heat dumper
- SP electro. box
- SP
- FG CCD & heat dumper
- FG camera
- Tunable narrow band filter
- CT CCD
- CT electro. box
- Aperture to OTA

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X-Ray Telescope (XRT)

Takes X-ray images of dynamically changing solar coronal structures

- grazing-incidence telescope + 2k x 2k - pixel CCD to take X-ray images of solar corona
- angular resolution 1” (x 3 better than Yohkoh)
- Seeing plasma with temperatures 1 - 10 MK.

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Plasma Diagnostics in EUV

EUV Imaging Spectrometer (EIS)

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- FOV: Fine Mirror Scan 360 arcsec
- Slit/Slot: 1", 2", 40", 250" (4-positions)
- Slit length: 512 arcsec (1pixel=13.5µm=1arcsec)
- Min. Exp. Time: < 1 sec (sit&stare/overlappograph), <1.3sec
- Wavelengths: 170 - 210Å & 250 - 290Å
- Temperature Range: $10^5 - 2 \times 10^7$ °K (via HeII ~ FeXXIV)
- Density Diagnostics: $10^8 - 10^{12}$ cm$^{-3}$ (via FeXII)
- Velocity Field: $\Delta v \sim 20$ kms$^{-1}$/pix (250 – 290Å); 1000ph → 1kms$^{-1}$ (line center), 3kms$^{-1}$ (line width)
Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

EIS Field-of-View (FOV)

Shift of FOV center with coarse-mirror motion

Maximum FOV for raster observation

250” slot

EIS slit

40” slot

Raster-scan range

512”

800”

360”

512”
Solar and LHD (Large Helical Device)
Plasma Diagnostics in EUV

EIS Effective Area

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Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

Tetsuya Watanabe (NAOJ) et al.

<table>
<thead>
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<th>T</th>
<th>Incident</th>
<th>Detected</th>
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<th>Detected</th>
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Long Wavelength Band

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<tr>
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Active Region
Active Region

![Graphs showing detected photons/s versus wavelength (Å) for different elements in the Active Region. The graphs depict emissions from Fe XI, Fe XII, Fe XIII, Si X, He II, Fe XIV, and Fe XV.]
Solar and LHD (Large Helical Device)
Plasma Diagnostics in EUV

Tetsuya Watanabe (NAOJ) et al.
Coronal Heating Mechanism

Temperature (K)

Energy Flux

photosphere  chromosphere
transition region  corona
Ionization Equilibrium; Relaxation Time Scales

\[ \text{Ne} \tau_{\text{equil}} \sim 10^{12} \text{ cm}^{-3}\text{sec} \]

Brooks et al. (1999)

<table>
<thead>
<tr>
<th>Region</th>
<th>( N_e (\text{cm}^{-3}) )</th>
<th>( T_e (K) )</th>
<th>( \tau_{\text{transient}} )</th>
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<tr>
<td>upper chromosphere</td>
<td>( 3.7 \times 10^{10} )</td>
<td>( 2 \times 10^4 )</td>
<td>( \sim 5 \rightarrow 6 \text{ minutes} )</td>
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<tr>
<td>transition region</td>
<td>( 1.3 \times 10^{10} \rightarrow 1.3 \times 10^9 )</td>
<td>( 5 \times 10^4 \rightarrow 5 \times 10^5 )</td>
<td>( \sim 3 \rightarrow 20 \text{ minutes} )</td>
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<tr>
<td>corona</td>
<td>( 5.4 \times 10^8 )</td>
<td>( 1 \times 10^6 )</td>
<td>( \sim 1 \text{ hour} )</td>
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</table>
Iron M-shell Line Atomic Data Evaluation

Fe X, Fe XI, Fe XIII

• Survey existing data
• Method of Calculation
• Pick up Recommended data
• Analytical fitting (only) for Fe XIII
Solar and LHD (Large Helical Device)
Plasma Diagnostics in EUV

FeXIII

Fawcett & Mason (1989)
SuperStructure, 48 levels, Distorted Wave

Gupta & Tayal (1998)
26 levels, Semirelativistic R-matrix (Breit-Pauli approximation),
partial waves with $J \leq 22.5$, $E<60$Ryd

Tayal (2000)
26 levels, Breit-Pauli R-matrix, $E<90$Ryd, partial waves with
$J \leq 22.5$, 0.005Ryd mesh

Aggarwal & Keenan (2005)
GRASP, 97 levels, Dirac Atomic R-matrix, $E<120$Ryd, partial
waves with $J \leq 39.5$; 0.001-0.002Ryd mesh
Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

Effective collision strengths:
Fe XIII $3s^23p^2\,^3P_0 - ^3P_1$

Hullac (Rel. DW)
Aggarwal & Keenan (Rel. R-matrix)
Gupta & Tayal (Semirel. R-matrix)
ADAS (DW)


Tetsuya Watanabe (NAOJ) et al.
RESULTS

Electron-Ion Collisions


A fully relativistic approach based on GRASP code for the generation of wavefunctions, and the Dirac Atomic R-matrix Code (DARC) for the computations collision and effective collision strengths. Calculations are in the $jj$ coupling scheme, and Breit and QED corrections have been included.

Advantages of this work:

- Significantly improved the accuracy of energy levels, radiative rates and collision strengths, by including extensive CI and performing the calculations in the $jj$ coupling.
- Improving the accuracy of $\Omega$ values by extending the range of partial waves and by achieving convergence in values of $\Omega$ at all energies and the energy range considered.
- Improving the $\Gamma$ values by resolving resonances in a finer energy mesh and by including additional resonances.
- Extending the range of levels and including many of the desired levels among which the transitions have already been observed.
The results presented in paper Aggarwal & Keenan have obvious advantages in comparison with all earlier results.

In comparison with the work Bhatia & Doschek, these calculations have significantly improved the accuracy of energy levels, radiative rates and collision strengths, by including extensive CI and performing the calculations in the $jj$ coupling.

In comparison to the work Tayal an overall improvement has been made by: (i) including additional CI in the generation of wavefunctions, and thus improving the accuracy of energy levels; (ii) extending the range of levels from 54 to 90, and hence including many of the desired levels among which the transitions have already been observed; (iii) improving the accuracy of $\Omega$ values, by extending the range of partial waves (from 20 to 39) and the energy range (from 90 Ryd to 210 Ryd); (iv) improving the $\Gamma$ values by resolving resonances in a finer energy mesh and by including additional resonances; (v) performing the calculations in the $jj$ coupling instead of the semi-relativistic approach in the $LSJ$ coupling scheme.

Similarly, this work is an improvement over the work of Pelan & Berrington mainly by extending the range of levels (transitions) from 31 (465) to 90 (4005), and by achieving convergence in values of $\Omega$ at all energies.

We recommend to use for Fe X data of Aggarwal & Keenan.

Tetsuya Watanabe (NAOJ) et al.
Proton excitation cross sections for transitions in Si-like Fe XIII: □ - quantum results [Faucher 1977], solid line - semi-classical results [Landman 1975], dotted line – semi-classical results [Masnou-Seeuws & McCarroll 1972]; (1) – transition $^3P_0-^3P_1$, (2) – transition $^3P_1-^3P_2$, (3) – transition $^3P_0-^3P_2$. 
RESULTS

Proton-Ion Collisions

General conclusion:
In low density plasma $N_e \leq 10^{16}$ cm$^{-3}$ proton collisions are important for ions: Fe X, XI, XIII, XIV, XVII, XVIII, XIX, XX, XXI, XXII, XXIII.
In high density plasma $N_e > 10^{16}$ cm$^{-3}$ proton collisions are important for ions: Fe XV, XVII, XXII.

$N_p \sim N_e < A_i/C_i^e$

For Fe XII proton collisions are not important.
For all important transitions we have evaluated available numerical data and recommended data were fitted to analytical formula.

Tetsuya Watanabe (NAOJ) et al.
Collisional-radiative model - Atomic Processes & Energy Levels

Atomic Processes *(rate)*:
- Excitation/de-excitation *(CeNe)* by e- impact,
- Excitation/de-excitation *(CpNe)* by p-impact,
- Ionization *(SNe)* / three-body recombination *(β^t N_e^2)*,
- Radiative transition *(Ar)*, Radiative recombination *(β^r N_e)*

Energy Levels *(configuration)*: \(2 \leq n \leq 5\)

Bare, H-like*(nl)*, He-like*(1snl)*, Li-like*(1s^2nl)*, Be-like*(2l’nl)*, B-like*(2s^2nl, 2s2pnl, 2p^2nl)*, C-like*(2s^22pnl, 2s2p^2nl, 2p^2nl)*, N-like*(2s^22p^2nl, 2s2p^3nl, 2p^4nl)*, O-like*(2s^22p^3nl, 2s2p^4nl, 2p^5nl)*, F-like*(2s^22p^4nl, 2s2p^5nl, 2p^6nl)*, Ne-like *(2s^22p^5nl, 2s2p^6nl)*, Na-like *(2s^22p^6nl)*, Mg-like *(3l'nl)*, Al-like *(3s^2nl, 3s3pnl, 3s3dnl, 3p^2nl, 3p3dnl)*, Si-like *(3s^23l’nl)*, P-like *(3s^23p3l’nl)*, S-like *(3p^23l’nl)*, Cl-like *(3p^33l’nl)*, Ar *(3p^5nl)*, K-like *(3p^6nl, 3p^53dnl)*, Ca-like *(3p^63dnl)*
Collisional-radiative model (Yamamoto et al.)

**Time-dependent Rate Equation:**

\[
dN_i (t, T_e, N_e) \frac{dt}{dt} = -N_i (t, T_e, N_e) \sum_j W_{ij} (T_e (t), N_e (t)) + \sum_j W_{ji} (T_e (t), N_e (t)) N_j (t, T_e, N_e)
\]

**Quasi-steady State Solution:**

\[
N_i (t, T_e, N_e) = \sum_k r_i^{(k)} (T_e, N_e) N_k (t, T_e, N_e)
\]

**Time-independent Rate Equation:**

\[
dr_i^{(k)} (T_e, N_e) \frac{dt}{dt} = -r_i^{(k)} (T_e, N_e) \sum_j W_{ij} (T_e, N_e) + \sum_j W_{ji} (T_e, N_e) r_j^{(k)} (T_e, N_e)
\]
Ion Fraction $N_k$:

$N_k$ is calculated to use total ionization and recombination rate coefficients, $S$ and $\beta$, by Arnaud & Raymond (1992).

Line Intensity $I(\lambda)$: $I(\lambda) = \sum_i N_i A_{ij} \Delta E_{ij} P_i(\lambda)$
Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

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Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

LHD experiment

Te, ne, V

Diagnostics

Tetsuya Watanabe (NAOJ) et al.
Plasma Source: Hydrogen with Fe-pellet injection

Fe-TESPEL:
Polystyrene-shell Fe pellet
Pelet Radius: 780-820μm
Mass of Fe in the shell: 43-66μg
Mass of shell: 250-300μg
Injection Velocity: 300-400m/s
Injection Time: 1.0s

Plasma Heating:
NBI (neutral beam injection)
ECH (electron cyclotron resonance heating)
ICRF (ion cyclotron range-of-frequency)?
Spectrometer:
- Time resolution: 0.1s
- Wavelength resolution: 0.13Å/ch
- Total Frame: 80
- Direction angle: -0.1 degree
- Measurement band: ~165-300Å

Timing of Heating:
- ECH82.7: 0.0-1.0 s, ECH84: 5.5-6.0 s
- NBI#1: 7.0-11.0 s, NBI#2: 1.0-4.5 s, NBI#3: 4.0-7.0 s
- ICRF: ---

Highest Temperature?
Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

Spectra from Low temperature Plasma

Tetsuya Watanabe (NAOJ) et al.
EBIT experiment for Fe M-shell transitions

*CO*(ronal e)*BIT* project

- $N_e: 10^{12} \text{ cm}^{-3}$
- $N_i: 10^{8-9} \text{ cm}^{-3}$
- $E_e$: mono-energetic 1-100 keV

Electron energy $\Leftrightarrow$ ionization stage

*: kobito = dwarf
Solar and LHD (Large Helical Device) Plasma Diagnostics in EUV

Tokyo-EBIT at The Univ. of Electro-Communications

Max. Ee: 200 keV (achieved)
Max. Ie: 330 mA (achieved)

ANY ion can be produced!!! (any charge state, any element)

Tetsuya Watanabe (NAOJ) et al.
CoBIT (Coronal eBIT)

Ee: 0.1-1 keV
Ie: >10mA
B~0.1T
No cooling or LN$_2$ cooled