Density measurements at the base of the solar wind

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Why is the coronal hole density useful?

- The fast solar wind is believed to originate in coronal holes
- Models of the fast solar wind require boundary conditions defined in the Sun’s low atmosphere
- Electron density (pressure) is one of the boundary parameters

- Also valuable to spectroscopists for checking diagnostics and atomic data

- Observation requirements:
  - look on the disk to avoid line-of-sight effects
  - density diagnostics formed at log $T = 5.8$-$6.2$

**Standard picture**
Coronal hole density $\approx 1$-$2 \times 10^8$ cm$^{-3}$
Quiet Sun density $\approx 3$-$4 \times 10^8$ cm$^{-3}$
Previous work – on disk

- Skylab
  - Esser et al. (1998, ApJ) derived densities of 7-20 x 10^7 cm^{-3} from Mg VIII

- SOHO/CDS
  - Del Zanna & Bromage (1999, JGR) derived densities of 2-3 x 10^8 cm^{-3} using Si IX
  - Young & Esser (1999a,b conf. proceedings) derived much lower densities (log N_e = 7.0 – 7.5) from Si IX and Mg VIII

Low densities found in darkest regions

Necessary to include photoexcitation in atomic models
Example coronal hole – 11 July 2008

- Large equatorial coronal hole

(Thanks to EIS CO, Yokoyama-san, for excellent observation!)
Example coronal hole – 11 July 2008

- EIS monochromatic raster images
Coronal hole selection

- Six dark coronal hole areas identified in Fe VIII λ185.21 image
- Spatial pixels summed to yield six coronal hole spectra
### EIS coronal hole density diagnostics

<table>
<thead>
<tr>
<th>Ion</th>
<th>Ratio</th>
<th>Log (T/K)</th>
<th>Photoexc.?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg VII</td>
<td>λ280.75 / λ278.39</td>
<td>5.8</td>
<td>No</td>
</tr>
<tr>
<td>Si VII</td>
<td>λ272.64 / λ275.35</td>
<td>5.8</td>
<td>Yes</td>
</tr>
<tr>
<td>Fe VIII</td>
<td>λ186.60 / λ185.21</td>
<td>5.8</td>
<td>Yes</td>
</tr>
<tr>
<td>Fe X</td>
<td>λ257.26 / λ184.54</td>
<td>6.0</td>
<td>No</td>
</tr>
<tr>
<td>Si X</td>
<td>λ258.37 / λ261.04</td>
<td>6.1</td>
<td>Yes</td>
</tr>
<tr>
<td>Fe XII</td>
<td>λ186.88 / λ195.12</td>
<td>6.1</td>
<td>No</td>
</tr>
</tbody>
</table>

Atomic data from v5.2 of CHIANTI, except Mg VII which are from (soon-to-be-released) v6.0
**Mg VII & Si VII diagnostics (log T=5.8)**

- Si VII is sensitive to photoexcitation

### Table

<table>
<thead>
<tr>
<th>Ion</th>
<th>CH Dens</th>
<th>QS Dens</th>
<th>CH Pressure</th>
<th>QS Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si VII</td>
<td>8.26</td>
<td>8.86</td>
<td>14.06</td>
<td>14.66</td>
</tr>
<tr>
<td>Mg VII</td>
<td>(8.58)</td>
<td>8.78</td>
<td>(14.38)</td>
<td>14.58</td>
</tr>
</tbody>
</table>

(Log10 values)
**Si X & Fe XII diagnostics (log $T=6.1$)**

- Si X is sensitive to photoexcitation

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<tr>
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</thead>
<tbody>
<tr>
<td>Si X</td>
<td>8.17</td>
<td>8.39</td>
<td>14.27</td>
<td>14.49</td>
</tr>
<tr>
<td>Fe XII</td>
<td>8.67</td>
<td>8.58</td>
<td>14.77</td>
<td>14.68</td>
</tr>
</tbody>
</table>

*(Log$_{10}$ values)*
Fe X $\lambda$ 184.54 / $\lambda$ 257.26

- In both quiet Sun and coronal holes the measured Fe X ratios are above the low density limit
- The coronal hole values are higher than the quiet Sun values
- Implies ratio is diagnosing density differences...
- ...but, measurements inconsistent with atomic theory
Fe VIII $\lambda\,185.21 / \lambda\,186.60$

- Both lines are strong in coronal hole spectra and comparable in intensity
- Ratio sensitive to photoexcitation
**Fe VIII λ 185.21 / λ 186.60**

- Ratio approximately constant in coronal holes and quiet Sun

![Graph showing Fe VIII λ 185.21 intensity vs. Fe VIII λ 185.21 / λ 186.60 ratio](image)

- Taking average ratio values gives:
  - coronal hole density: \( \log N_e = 7.99 \)
  - quiet Sun density: \( \log N_e = 8.09 \)
Conclusions

- No evidence is found for the very low densities found by Young & Esser (1999a,b)

- Different ions show inconsistent results
  - Si VII, Mg VII, Si X show lower CH densities by 0.2-0.6 dex compared to QS
  - Fe VIII & Fe XII show same density in CH and QS
  - Fe X measurements inconsistent with theory

- Further work
  - need to investigate ‘deep-cleaning’ of CCD warm pixels
  - update atomic data (Si VII, Si X, Fe X)
Note for EIS Chief Observers

- Please run my study PRY_CH_density if you see a nice coronal hole!
- Low data volume study optimised for S-band operations
**Off-limb vs. on disk**

- Off-limb coronal hole spectra are contaminated by non-coronal hole regions

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**Fe X λ184.54, 19-Jan-08, 13:35**
Coronal holes

SOHO/EIT
Fe XII 195

2008/07/11 12:00