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 $\approx 1-2 \times 10^8 \text{ cm}^{-3}$
Quiet Sun density $\approx 3-4 \times 10^8 \text{ cm}^{-3}$
Previous work – on disk

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

- **SOHO/CDS**
  - Del Zanna & Bromage (1999, JGR) derived densities of $2-3 \times 10^8$ 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

![Image of 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>( \frac{\lambda 280.75}{\lambda 278.39} )</td>
<td>5.8</td>
<td>No</td>
</tr>
<tr>
<td>Si VII</td>
<td>( \frac{\lambda 272.64}{\lambda 275.35} )</td>
<td>5.8</td>
<td>Yes</td>
</tr>
<tr>
<td>Fe VIII</td>
<td>( \frac{\lambda 186.60}{\lambda 185.21} )</td>
<td>5.8</td>
<td>Yes</td>
</tr>
<tr>
<td>Fe X</td>
<td>( \frac{\lambda 257.26}{\lambda 184.54} )</td>
<td>6.0</td>
<td>No</td>
</tr>
<tr>
<td>Si X</td>
<td>( \frac{\lambda 258.37}{\lambda 261.04} )</td>
<td>6.1</td>
<td>Yes</td>
</tr>
<tr>
<td>Fe XII</td>
<td>( \frac{\lambda 186.88}{\lambda 195.12} )</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>
<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>

(Log$_{10}$ values)
Si X & Fe XII diagnostics (log T=6.1)

- Si X is sensitive to photoexcitation

<table>
<thead>
<tr>
<th>Ion</th>
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</tr>
</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 $\lambda 185.21 / \lambda 186.60$

- Ratio approximately constant in coronal holes and quiet Sun

- 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

Fe X $\lambda$184.54, 19-Jan-08, 13:35