Temperature measurements using selected Tm and Dy lines in Metal Halide Lamps

Y. Aiura, J. E. Lawler
Univ. of Wisconsin-Madison, Physics Department
The 1 m Fourier transform spectrometer (FTS) at the National Solar Observatory on Kitt Peak was used to record UV to IR emission spectra of Metal Halide-High Intensity Discharge (MH-HID) lamps with doses containing rare earth salts. All intrinsic structure is fully resolved in these spectra. Many additive lines were found to have nearly perfect Lorentzian profiles and to be surprisingly narrow (FWHM < 1 cm⁻¹) [1]. Fitting these profiles to Lorentzian functions provides a sensitive test for radiation trapping and line blending [1]. We have used this fitting approach along with recently measured absolute transition probabilities [2,3] to select sets of lines in Tm I, Tm II, Dy I, and Dy II which are good for temperature determinations in MH-HID lamps. [1] H. Adler, L. Riley, amp; J. E. Lawler in Proceedings of the Ninth International Symposium on the Science and Technology of Light Sources LS:9 ed: R S Bergman (2001, Ithaca: Cornell University Press) p 129. [2] M. E. Wickliffe amp; J. E. Lawler, J. Opt. Soc. Am. B 14, 737 (1997) [3] M. E. Wickliffe, J. E. Lawler, amp; G. Nave, J. Quant. Spectrosc. Radiat. Transfer 66, 363 (2000).
Line fitting  (without self-absorption)

Line center from least square fit (cm⁻¹) = 25127.4633
Line width from fit, FWHM (cm⁻¹) = 0.6767
Line intensity from fit, above baseline = 2920596.7500
Baseline intensity at left edge of plot = 155070.4375
Baseline intensity at right edge of plot = 84564.6016
OK
If we ignore the self-absorption, fitting will be w-shape (bad).

Line center from least square fit (cm\(^{-1}\)) = 25095.3941
Line width from fit, FWHM (cm\(^{-1}\)) = .5102
Line intensity from fit, above baseline = 2100420.0000
Baseline intensity at left edge of plot = 270428.1563
Baseline intensity at right edge of plot = 26081.4766
OK

W-shape (Bad fitting)
We solve the self-absorption problem to divide two fitting area.
Boltzmann plot

- Assume LTE (Local thermodynamic equilibrium)

- Relative population $\propto g_u e^{\frac{-E}{k_B T}}$
  - $g_u$ : Degeneracy
  - $k_B$ : Boltzmann constant
  - $T$ : Temperature
  - $E$ : Energy in upper level

- $\log \frac{I_{ul}}{A_{ul} g_u} = -\frac{1}{k_B T} E_{ul} + \text{const.}$
Boltzmann plot of Tm, Tm+

Upper Level Energy vs Density in Tm
Data: lw49613d.jel

- Slope of graph: $-2.774 \times 10^{-4}$ cm
- Arc Temperature: $5.187 \times 10^3$ K

Upper Level Energy vs Density in Tm
Data: lw49613d.jel

- Slope of graph: $-2.766 \times 10^{-4}$ cm
- Arc Temperature: $5.202 \times 10^3$ K
Boltzmann plot of Dy, Dy+

Upper Level Energy vs Density in Dy
Data: lw49616d.jel

\[ y = 1.027 \times 10^2 e^{-3.037 \times 10^{-4}x} \]

\[ R^2 = 9.263 \times 10^{-1} \]

Upper Level Energy (cm\(^{-1}\))

- Slope of graph: -3.037 \times 10^{-4} cm
- Arc Temperature: 4.737 \times 10^3 K

Intensity/μA

Upper Level Energy vs Density in Dy+
Data: lw49616d.jel

\[ y = 2.456 \times 10^1 e^{-2.630 \times 10^{-4}x} \]

\[ R^2 = 9.314 \times 10^{-1} \]

Upper Level Energy (cm\(^{-1}\))

- Slope of graph: -2.630 \times 10^{-4} cm
- Arc Temperature: 5.471 \times 10^3 K
## Results of temperature cal.

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tm</td>
<td>5187 [K]</td>
</tr>
<tr>
<td>Tm+</td>
<td>5202 [K]</td>
</tr>
<tr>
<td>Dy</td>
<td>4737 [K]</td>
</tr>
<tr>
<td>Dy+</td>
<td>5471 [K]</td>
</tr>
</tbody>
</table>
**Saha Equation**

\[ K_i(T) = \frac{n_e [Tm^+]}{[Tm]} \]

\[ I_{Tm} = gA e^{-E_{ul}/kT} \left[ \frac{Tm}{4\pi} \right] Z_{Tm} \]

\[ I_{Tm^+} = gA e^{-E_{ul}/kT} \left[ \frac{Tm^+}{4\pi} \right] Z_{Tm^+} \]

\[ Z_{Tm} : \text{partition function for } Tm \]

\[ Z_{Tm^+} : \text{partition function for } Tm^+ \]

\[ \left[ \frac{Tm^+}{Tm} \right] = \frac{\left( \frac{I_{Tm^+}}{gA} \right) Z_{Tm^+}}{\left( \frac{I_{Tm}}{gA} \right) Z_{Tm}} \]

---

**Tm lamp**

\[ E_{ul} = 35000 \]

<table>
<thead>
<tr>
<th></th>
<th>Intensity/gA</th>
<th>Temperature [K]</th>
<th>Partition function Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tm</td>
<td>7.045E-03</td>
<td>5187</td>
<td>11.0068</td>
</tr>
<tr>
<td>Tm+</td>
<td>4.995E-03</td>
<td>5202</td>
<td>18.1768</td>
</tr>
</tbody>
</table>

**Average Temperature (Tavg)** | 5194.5 [K]

**Equilibrium const. K(T_{avg})** | 2.874E+15 [cm⁻³]

**electron density (n_e)** | 2.455E+15 [cm⁻³]

---

**Dy lamp**

\[ E_{ul} = 30000 \]

<table>
<thead>
<tr>
<th></th>
<th>Intensity/gA</th>
<th>Temperature [K]</th>
<th>Partition function Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dy</td>
<td>1.134E-02</td>
<td>4737</td>
<td>42.6232</td>
</tr>
<tr>
<td>Dy+</td>
<td>9.197E-03</td>
<td>5471</td>
<td>55.7244</td>
</tr>
</tbody>
</table>

**Average Temperature (Tavg)** | 5104 [K]

**Equilibrium const. K(T_{avg})** | 3.152E+15 [cm⁻³]

**electron density (n_e)** | 2.973E+15 [cm⁻³]
Conclusion

- By fitting of spectral line profiles, the best lines for arc temperature measurements are identified.
- Ion excitation temperature is apparently higher than neutral atom excitation temperature due to the higher concentration of ions on axis.
- Electron density can be determined using the Saha equation.
Future Work

The identification of "good" (strong, unblended, optically thin) lines of Tm, Tm\(^+\), Dy, Dy\(^+\) will enable us to use a small subset of lines in limited wavelength range to determine accurate values for T(r) and n_e(r) from an Abel inversion of emission spectra along chords through the arc.