Change of level

Change of term

Change of configuration
Interstellar medium

From Wikipedia, the free encyclopedia

In astronomy, the interstellar medium (ISM) is the matter that exists in the space between the star systems in a galaxy. This matter includes gas in ionic, atomic, and molecular forms, dust, and cosmic rays. It fills interstellar space and blends smoothly into the surrounding intergalactic space. The energy that occupies the same volume, in the form of electromagnetic radiation, is the interstellar radiation field.

Star forming H II regions

- Hot young stars very close to the molecular cloud that formed it
- Ionizing radiation and stellar winds strike nearby molecular cloud
Idealized structure of an H II region

- Hot H\(^+\) bubble
- Warm H\(^+\) “H II region”
- Warm H\(^+\), H\(_2\) “PDR”
- Cool H\(_2\), “molecular cloud”
Three-phase pressure stability

- tsuite / auto / ism_grid

Heating – cooling balance

- Both heating and cooling depend on square of density
- So no density dependence
- Try it! compare temperatures at two densities
Vary Metals – temperature balance

- Then energy balance
  - varyZ

Thermostat effect AN3 S9.5

- Vary metals with temperature balance
  - varyZ.in
- Look at line ratios, temperature vs Z
- Cooling and heating vs Z
- Thermostat effect – line spectrum does not change dramatically when Z changes
  - Heating and cooling are equal
  - Cooling is mainly O III lines
  - So they are constant when they are the main coolant

Vary blackbody temperature

- Stay or “energy balance” method of determining stellar temperatures
- AGN3 Section 5.10
Three cases

- HI.in – set radiation field, properties of cloud determined self consistently
  - This is how we usually use Cloudy
- coronal.in – no radiation, but gas kinetic temperature set by external physics. Ionization and emission set by gas kinetic temperature
- constant temperature models – may include radiation but kinetic temperature set by external physics. Ionization determined by both radiation field and gas temperature
  - Hazy1 Chap 11

Vary blackbody temperature

- Stoy or “energy balance” method of determining stellar temperatures
- AGN3 Section 5.10

How to make sense of all these lines
Peter’s atomic line list

- [http://www.pa.uky.edu/~peter/atomic/](http://www.pa.uky.edu/~peter/atomic/)
- [http://www.pa.uky.edu/~peter/newpage/](http://www.pa.uky.edu/~peter/newpage/)
  - Beta version with new features
- Search wavelength range to find what lines are present

NIST

- [http://www.nist.gov/pml/data/asd.cfm](http://www.nist.gov/pml/data/asd.cfm)

NIST Atomic Spectra Database

**Version 4**

Welcome to the NIST Atomic Spectra Database, NIST Standard Reference Database #98. The spectral line data may be presented and displayed according to wavelength or energy levels, by choosing one of the following options:

- **Lines**
  - spectral lines and associated energy levels displayed in wavelength order with all selected species included or in a selected range of wavelengths for the lines are displayed,
- **Levels**
  - Energy levels of a particular atom or ion displayed in order of energy above the ground state.

NIST Atomic Spectra Database Levels Form

Best viewed with the latest versions of Web browsers and .jar

This form provides access to NIST critically evaluated data on atomic energy levels.
Two cases

- One and two electron systems
- Levels are closer to the continuum above than the ground state below
Two cases
- Many electron systems
- Levels have range of energies
- Many are close to the ground state below

Two types of lines
- Recombination AGN3 sec 4.2
  - $e + p$ radiative recombination
  - Rate coefficient $q \sim 10^{-13} \text{ cm}^3 \text{ s}^{-1}$
  - Mainly H, He
- Collisionally excited AGN3 3.5
  - Inelastic $e +$ ion collision
  - $q \sim 10^{-9} \text{ cm}^3 \text{ s}^{-1}$
  - Heavy elements

Selection rules for transitions
- AGN3
- Appendix 4 Nebular quantum mechanics
- Appendix 6 Molecular quantum
Species vs spectra

- H\textsuperscript{0}, C\textsuperscript{+}, O\textsuperscript{2+}, H\textsubscript{2}, CO are baryons
- H I, C IV, O III, H\textsubscript{2}, and CO are the spectra they emit / absorb
- O III is a permitted line produced by O\textsuperscript{2+}, while [O III] is a forbidden line
- C III] is a semi-forbidden line, often an intercombination line

Species vs spectra

- H I \textit{Ly}\textalpha\textit{ emission} can be produced by
  - Recombination of H\textsuperscript{+}
  - Impact excitation of H\textsuperscript{0}
- H I absorption can only be produced by H\textsuperscript{0}
- H I is not the same as H\textsuperscript{0}
  - Ambiguous for emission lines
Baryons and spectra

- Hazy 1 Section 2.5
- SpeciesLabels.txt in docs
- Molecules are not ambiguous
  - H2
  - CO
  - O2
  - H2+
  - C2+
  - Their spectra have the same notation as the baryon

Baryons and spectra

- Atomic spectra use number of spectra
  - H 1
  - C 4
- The baryon
  - "H"
  - "He+"
  - "C+2"
  -(C2+ is C2+ in our notation)

Lines in the main output

- Print lines column
- Print lines sort wavelength
- Print lines faint
Finding lines in Cloudy

- A line is identified by a spectral label & wavelength
- docs/LineLabels.txt has label, wavelength, comment about line
  - Generated with command “Save line labels”
- Pick lines from this file

Air vs vacuum wavelengths

- The rule in atomic physics has been to use vacuum wavelengths for $\lambda < 2000\text{Å}$ and air for $\lambda > 2000\text{Å}$
- SDSS has used vacuum for all wavelengths
- Today’s papers use a mix of both
- Vacuum is probably the future
- Print line vacuum
  - But you need to change your wavelengths

Some familiar lines

<table>
<thead>
<tr>
<th>Species</th>
<th>$\lambda$(air)</th>
<th>$\lambda$(vacuum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H 1</td>
<td>1215.67A</td>
<td>1215.67A</td>
</tr>
<tr>
<td>O 2</td>
<td>3726.03A</td>
<td>3727.09A</td>
</tr>
<tr>
<td>O 2</td>
<td>3728.81A</td>
<td>3729.88A</td>
</tr>
<tr>
<td>O 3</td>
<td>4363.21A</td>
<td>4364.44A</td>
</tr>
<tr>
<td>H 1</td>
<td>4861.33A</td>
<td>4862.69A</td>
</tr>
<tr>
<td>O 3</td>
<td>5006.84A</td>
<td>5008.24A</td>
</tr>
<tr>
<td>H. 1</td>
<td>6562.81A</td>
<td>6564.62A</td>
</tr>
</tbody>
</table>
Other database reporting options

- See C17 review article, section 2
- Database print

Line blends

- Blnd 3727
- Blnd 2798
- Blnd 1549

- Two or more lines that appear as a single line in most spectra

Luminosity, relative intensity

- Intensity or luminosity of line – depending on case
- Intensity relative to normalization line, default Hβ – Change with normalize command

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>88.3523m</td>
<td>-5.577</td>
</tr>
<tr>
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<td>3</td>
<td>51.8804m</td>
<td>-5.106</td>
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<tr>
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<td>3</td>
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<td>-8.339</td>
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<tr>
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<td>3</td>
<td>1668.51A</td>
<td>-7.187</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>1666.15A</td>
<td>-6.720</td>
</tr>
</tbody>
</table>
Two level atom AGN3 Sec 3.5

- Excitation, deexcitation rates
- Transition probabilities
- Critical density
- Two limits
  - Low densities, every excitation leads to emission of a photon
  - High densities, levels are n LTE, photon emission proportional to $n\nu A_{ul}$

\[ \Gamma_{ij} = \frac{N_{ui} A_{ui}\nu}{c} \]  

\[
\begin{align*}
ne + Q_{ex} \ne & = \\
\ne + Q_{sex} \ne & = \frac{Q_{ex}}{A_{ui}} \ne \\
\lambda_u & = Q_{ex} \ne \\
\lambda_e & = A_{ui} + Q_{ex} \ne \\
\lambda_u + \lambda_e & = \lambda
\end{align*}
\]

Critical density

\[ A_{ui} = Q_{sex} \ne_{crit} \]  

Low density (LDL)

\[ \ne \ll \ne_{crit} \]

\[ \Gamma_{pij} = A_{ui} \frac{\ne}{\lambda_{ui}} h\nu \]

High density (HDL)

\[ \ne \gg \ne_{crit} \]

\[ \Gamma_{pij} = \frac{\ne}{\lambda_{ui}} A_{ui} h\nu \]
Vary density over extreme range

- Plot emissivity vs density over wide range to see how emissivity changes
- Recombination line, [O III] forbidden lines
- varyn.in

Recombination lines

- H^+ + e \rightarrow H^0 \rightarrow H^0 + photons
- Critical densities of H I, He I, and He II optical lines are very high, n > 1e15 cm^-3, so they are usually in LDL
- Emissivity goes as n^2 for n < 10^{20} cm^-3
- Case B predictions

- H I, He I, He II are the strongest in UV/ Opt/ IR
- Second row (C,N, O, Ne) & Fe in X-ray

<table>
<thead>
<tr>
<th>Ion</th>
<th>Level</th>
<th>n_e (cm^-3)</th>
<th>Ion</th>
<th>Level</th>
<th>n_e (cm^-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II</td>
<td>2P^0_0</td>
<td>5.0 \times 10^3</td>
<td>O III</td>
<td>3P_0</td>
<td>6.8 \times 10^2</td>
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<tr>
<td>C III</td>
<td>3P^0_0</td>
<td>5.1 \times 10^3</td>
<td>O III</td>
<td>3P_0</td>
<td>3.6 \times 10^3</td>
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<tr>
<td>N II</td>
<td>1D_2</td>
<td>6.6 \times 10^4</td>
<td>O III</td>
<td>3P_0</td>
<td>5.1 \times 10^2</td>
</tr>
<tr>
<td>N II</td>
<td>3P_0</td>
<td>3.1 \times 10^5</td>
<td>Ne II</td>
<td>3P_0</td>
<td>7.1 \times 10^5</td>
</tr>
<tr>
<td>N II</td>
<td>0P_2</td>
<td>8.0 \times 10^3</td>
<td>Ne III</td>
<td>3P_0</td>
<td>9.5 \times 10^3</td>
</tr>
<tr>
<td>N III</td>
<td>2P^0_0</td>
<td>1.5 \times 10^4</td>
<td>Ne III</td>
<td>3P_0</td>
<td>3.1 \times 10^4</td>
</tr>
<tr>
<td>N IV</td>
<td>3P^0_0</td>
<td>1.1 \times 10^6</td>
<td>Ne III</td>
<td>3P_0</td>
<td>2.1 \times 10^6</td>
</tr>
<tr>
<td>O II</td>
<td>2P^0_2</td>
<td>1.3 \times 10^4</td>
<td>Ne V</td>
<td>3P_5</td>
<td>1.3 \times 10^7</td>
</tr>
<tr>
<td>S II</td>
<td>2P^0_0</td>
<td>3.4 \times 10^4</td>
<td>Ne V</td>
<td>3P_5</td>
<td>3.5 \times 10^4</td>
</tr>
<tr>
<td>S II</td>
<td>2P^0_0</td>
<td>5.4 \times 10^4</td>
<td>Ne V</td>
<td>3P_5</td>
<td>6.2 \times 10^4</td>
</tr>
</tbody>
</table>

(\text{Note: All values are calculated for } T = 10,000 \text{ K.})
Forbidden lines

- [O III]
- \( O^{++} + e \rightarrow O^{+++} + e \rightarrow O^{++} + e + \text{photons} \)
- \( -n_e n(O^{++}) q_{ud} \)
- Critical densities of many forbidden lines
  \( n \sim 1e3 - 1e5 \text{ cm}^{-3} \), so they can be in LDL or HDL
- Emissivity goes as \( n^2 \) or \( n \)

Compute spectrum of clouds with two very different densities

- \( \text{Hden} = 4 \)
- \( \text{Hden} = 14 \)
  - How will emission from these cloud compare?
  - How can we “trick” the model into having roughly the same emission?

Density indicators

AGN3 Fig 5.7
Temperature indicators

![Diagram showing temperature indicators](image)

Figure 5.8
Calculated variation of [O II] (solid line) and [S II] (dashed line) intensity ratios as functions of \( n_p \) at \( T = 10,000 \) K. At other temperatures the plotted curves are very nearly correct if the horizontal scale is taken to be \( n_p (10^3 T)^{1/2} \).

Temperature indicators

![Diagram showing temperature indicators](image)

Figure 5.1
From temperature-sensitive forbidden line ratios, are chosen as a function of the electron temperature. The [O II] (solid line) and [S II] (dashed line) ratios are nearly uncorrected, partly because of their similar excitation potentials. The lines are chosen to fit the density limit of \( n_p = 1 \text{ cm}^{-3} \).
Radiative recombination edges

- Hrec3, hrec4.in in sims
- Hrec spreadsheet in sims
- Maybe do in x-rays instead? More common application

The ionization parameter

- U, the ratio of ionizing photon to hydrogen densities
- See Davidson & Netzer 1979

2.7 Photoionization of Heavy Elements

\[ n(E) = \sum_{i=1}^{N} \frac{dN_i}{dE} \left( \frac{E}{E_i} \right) \]

where \( dN_i / dE \) is the photoionization cross section of the ionization stage of element \( E \) and \( E_i \) is the ionization potential of \( E \).

U and T(star) determine ionization

- No matter how intense the radiation field, how large the U, ions with ionization potentials higher than the highest energy in the SED cannot be produced