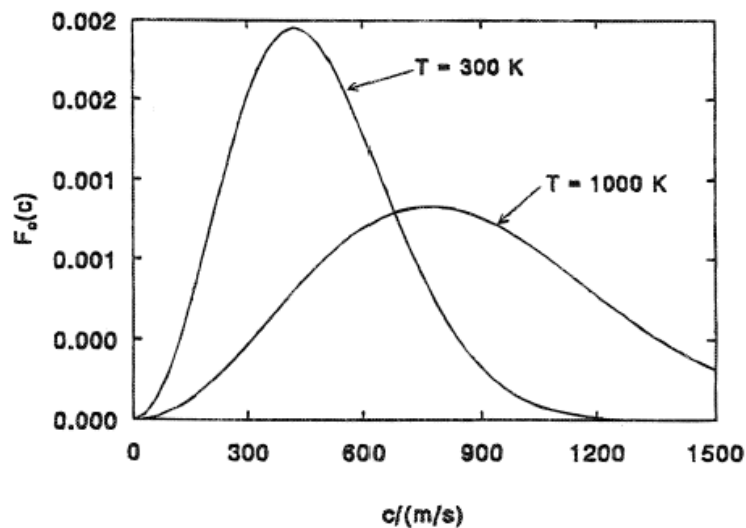


Heating and cooling

- ◆ Free electrons have a kinetic temperature, the only real temperature in the gas
- ◆ Heating is any process that gives energy to the gas, increasing the temperature
- ◆ Cooling is any process that removes energy from the gas, lowering the temperature
- ◆ Thermal equilibrium is when heating and cooling rates match

A Maxwellian velocity distribution



Thermal equilibrium

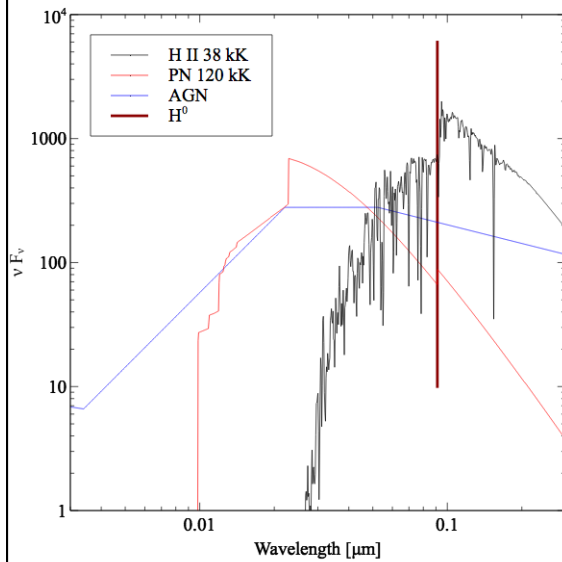
- ◆ Heating by radiation field in photo case
- ◆ In coronal case external process sets temperature
- ◆ Cooling is anything that converts kinetic energy into light that escapes

Photoelectric heating

$$G(H) = n(H^0) \int_{\nu_0}^{\infty} \frac{4\pi J_{\nu}}{h\nu} h(\nu - \nu_0) a_{\nu}(H^0) d\nu \text{ [erg cm}^{-3}\text{s}^{-1}\text{]}. \quad (3.1)$$

- ◆ Depends on SED shape

SED, H⁰ ion limit, photoelectron energy



| SED | $\langle hv - 13.6eV \rangle$ |
|---------|-------------------------------|
| H II | 52.7 kK |
| PN | 266 kK |
| AGN | 321 kK |
| Thermal | 10 – 20 kK |

Let's try different SEDs

- ◆ Density 4, constant temperature, one zone, ionization parameter

Photoelectric heating vs depth

- ◆ **Dependence on depth**
 - Spectrum, heating, across H+ region
 - Hii_paris
 - Save continuum output
- ◆ **Save heating**

Photoelectric heating

- ◆ **Heating proportional to photoionization rate, which is equal to $n_e n_p \alpha$, the recombination rate**
- ◆ **Heating depends on density squared**

$$G(H) = n_e n_p \alpha_A(H^0, T) \frac{\int_{\nu_0}^{\infty} \frac{4\pi J_{\nu}}{h\nu} h(\nu - \nu_0) a_{\nu}(H^0) d\nu}{\int_{\nu_0}^{\infty} \frac{4\pi J_{\nu}}{h\nu} a_{\nu}(H^0) d\nu} \quad (3.2)$$

$$= n_e n_p \alpha_A(H^0, T) \frac{3}{2} kT_i$$

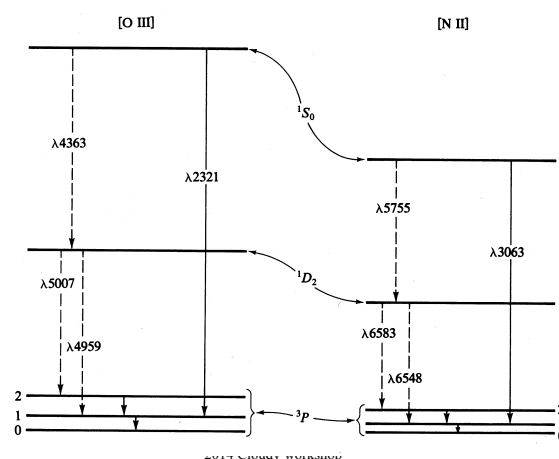
Cooling

- ◆ Anything that converts kinetic energy (heat) into light (which escapes)
- ◆ Collisional excitation of normally most important cooling process

$$L_C = n_e n_1 q_{12} h\nu_{21}. \quad (3.22)$$

[O III]

- ◆ AGN3 Fig 3.1



NIST

◆ <http://www.nist.gov/pml/data/asd.cfm>

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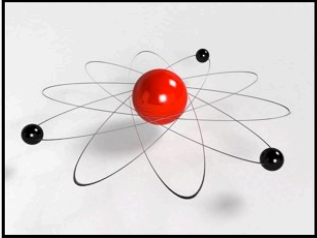
NIST Atomic Spectra Database

Version 4

Welcome to the NIST Atomic Spectra Database, NIST Standard Reference Database #78. The spectroscopic data may be selected and displayed according to wavelengths or energy levels by choosing one of the following options:

LINES Spectral lines and associated energy levels displayed in wavelength order with all selected spectra intermixed or in multiplet order. Transition probabilities for the lines are also displayed where available.

LEVELS Energy levels of a particular atom or ion displayed in order of energy above the ground state.



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NIST ASD Team

Principal Developers (Currently Active):
Yu. Ralchenko, A. Kramida, and J. Reader

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NIST Atomic Spectra Database Levels Form

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

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

Spectrum: c.g., Fe I

Level Units: Extended Search: for all levels search

Format output:

Display output:

Page size:

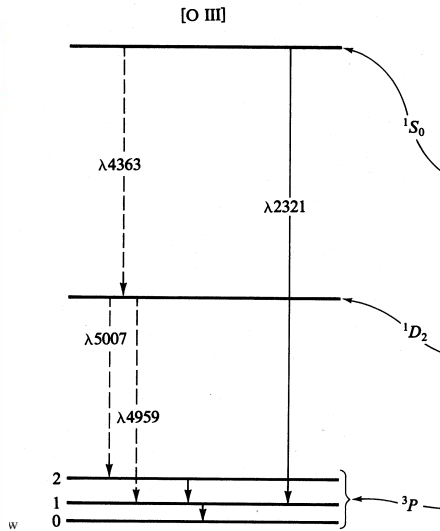
Term ordered term energy

Energy ordered

Level information: Principal configuration Principal term Level J Lande-g

O III

| Configuration | Term | J | Level (cm ⁻¹) |
|---------------------------------|------|---|---------------------------|
| 2s ² 2p ² | 3P | 0 | 0 |
| | | 1 | 113.178 |
| | | 2 | 306.174 |
| 2s ² 2p ² | 1D | 2 | 20 273.27 |
| 2s ² 2p ² | 1S | 0 | 43 185.74 |
| 2s2p ³ | 5S° | 2 | 60 324.79 |
| 2s2p ³ | 3D° | 3 | 120 025.2 |
| | | 2 | 120 053.4 |
| | | 1 | 120 058.2 |



Heating – cooling balance

- ◆ Both heating and cooling depend on square of density
- ◆ So no density dependence
- ◆ Try it! Remove constant temperature command, compare temperatures at two densities

Other cooling processes

- ◆ Save cooling command
- ◆ Look at various output

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Coronal equilibrium

- ◆ Mechanical energy sets kinetic temperature
- ◆ “Coronal” command in Cloudy
- ◆ Try several T,
plot SAVE
CONTINUUM
output

