CHIANTI

An Astrophysical Database for Emission Line Spectroscopy

CHIANTI TECHNICAL REPORT No. 19

The implementation of photoexcitation and stimulated emission in CHIANTI

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1 Overview

CHIANTI is principally for modeling electron-ionized plasmas and so photon processes are usually not important. However, for coronal plasmas with densities of $\lesssim 10^8$ cm^{-3} photoexcitation can become significant for levels within the ground configuration, and so there are options in CHIANTI to implement both photoexcitation and stimulated emission. By default these processes are not included, however.

The implementation is specific to the case of a plasma located above a spherical irradiating body that has a uniform intensity over its surface.

2 Theory

For a plasma in radiative equilibrium, we have the following relation between the processes of spontaneous radiative decay, stimulated emission and photoexcitation:

$$n_2(A_{21} + B_{21}J_\nu) = n_1 B_{12} J_\nu \tag{1}$$

where $n_{1,2}$ are the number densities of ions in atomic states 1 and 2, J_ν is the mean specific intensity, A_{21} is the radiative decay rate and B_{12} and B_{21} are the Einstein coefficients for stimulated emission and photoexcitation, respectively. J_ν represents the energy arriving at a point in the plasma per unit area per second per solid angle. Now for CHIANTI we work in wavelength units rather than frequency units, so $J_\nu = (\lambda^2/c)J_\lambda$. Note that $B_{12}J_\nu$ is the photoexcitation rate, P_{12}, i.e., the number of 1–2 photoexcitations occurring per second in the plasma.

The three Einstein coefficients are related to each other and, in particular, we have

$$A_{21} = \frac{2hc}{\lambda^3}\frac{g_1}{g_2}B_{12} \tag{2}$$

where h is Planck's constant, c is the speed of light, and $g_{1,2}$ are the statistical weights of levels 1 and 2. We use this to write P_{12} as

$$P_{12} = A_{21}\frac{g_2}{g_1}\frac{\lambda^5}{2hc^2}J_\lambda. \tag{3}$$

At this point we make the assumption that the radiation field is coming from the surface of a star with radius R_*, and that the irradiated plasma is at a distance R from the star's center. In addition the intensity is uniform over the star's surface. Now J_λ is related to the specific intensity, I_λ by

$$J_\lambda = \frac{1}{4\pi}\int I_\lambda \sin\,\theta \mathrm{d}\theta \mathrm{d}\phi \tag{4}$$

and so this evaluates to

$$J_\lambda = \frac{1}{2}I_\lambda(1 - \cos\,\theta_0) \tag{5}$$

where θ_0 is the angle subtended by a tangent to the star's limb. Following some basic geometry we have

$$J_\lambda = W(r)I_\lambda \tag{6}$$

where $W(r)$ is the *dilution factor*, given by

$$W = \frac{1}{2}\left[1 - \left(1 - \frac{1}{r^2}\right)^{1/2}\right] \tag{7}$$

and $r = R/R_*$.

When specifying a radiation field that is not a black body, we request users to specify the *energy density*, U_λ, which is related to I_λ by $U_\lambda = 4\pi I_\lambda/c$. Therefore our final expression for the photoexcitation rate is

$$P_{12} = A_{21}\frac{g_2}{g_1}\frac{\lambda^5}{8\pi hc}W(r)U_\lambda. \tag{8}$$

which is the expression given as Eq. 6 of Landi et al. (2006).

Evaluating the numerical constants gives

$$P_{12} = 2.003 \times 10^{-18} A_{21} W(r)\frac{g_2}{g_1}\left[\frac{\lambda}{\text{Å}}\right]^5\left[\frac{U_\lambda}{\text{erg cm}^{-3}\ \text{Å}}\right] \qquad \text{s}^{-1} \tag{9}$$

2.1 Blackbody source

For the special case of a blackbody, the photoexcitation rate is given by

$$P_{12} = W(r)A_{21}\frac{g_2}{g_1}\frac{1}{\exp(hc/\lambda T) - 1} \tag{10}$$

Comparing Eq. 8 with Eq. 10, and evaluating the constants gives the energy density for a blackbody

$$U_\lambda = 4.991 \times 10^{17}\left[\frac{\text{Å}}{\lambda}\right]^5\left[\exp\left(1.439 \times 10^8\left[\frac{\text{Å}}{\lambda}\right]\left[\frac{\text{K}}{T}\right]\right) - 1\right]^{-1} \tag{11}$$

3 Implementation in CHIANTI

Photoexcitation and stimulated emission were initially implemented in CHIANTI 4 (Young et al., 2003) assuming only a blackbody radiation source. In this case, there are only two input parameters: the radiation temperature, T, and the distance from the star in stellar radii units, r. These parameters are specified with the keywords RADTEMP and RPHOT, respectively. Note that $T = 6000$ K is the default temperature, and the extra processes are only included when RPHOT is specified.

The input RPHOT is converted to a dilution factor by the IDL routine `r2w.pro`.

CHIANTI 5 (Landi et al., 2006) allowed an arbitrary radiation field to be specified, and this is done with the RADFUNC optional input. The user needs to create an IDL function that defines the energy density, U_λ, function and then the name of this function is passed as a string through RADFUNC. The input RPHOT also needs to be supplied.

Appendices A and B give IDL code showing how RADFUNC is defined for an emission line spectrum and a blackbody spectrum. It is a useful exercise for the reader to show that the blackbody implementation gives the same results as using RADTEMP.

3.1 Assessing the contribution of the processes

To check the contribution of photoexcitation and stimulated emission, use the routine `pop_processes.pro`. The example below shows the results for Fe XIII using CHIANTI 8.0.7.

```
IDL> pop_processes,'fe_13',lev=2,dens=1e8,rphot=1.1,data=data
Level:   3s2 3p2 3P1

Log10 Temperature:   6.2
Log10 Density:       8.0

Population leaving level 2
  rad. decay:     2.12e+00     80.05%
  e de-exc:       6.61e-03      0.25%
  e exc:          3.41e-01     12.88%
  p de-exc:       6.94e-04      0.03%
  p exc:          1.64e-02      0.62%
  stim. emiss:    7.43e-02      2.81%
  photoexc:       8.89e-02      3.36%
                  --------
           TOTAL  2.65e+00

Population entering level 2
  rad. decay:     1.36e+00     51.40%
  e de-exc:       9.02e-03      0.34%
  e exc:          1.00e-01      3.78%
  p de-exc:       4.75e-03      0.18%
  p exc:          1.05e-02      0.40%
  stim. emiss:    2.74e-02      1.03%
  photoexc:       1.13e+00     42.86%
                  --------
           TOTAL  2.65e+00
```

The optional output DATA is a structure containing the rates for the various atomic processes that go into the calculation. The photoexcitation and stimulated emission rates are found in the tag AAX. For example AAX[0,1] is the photoexcitation for transition 1 to 2, and AAX[1,0] is the stimulated emission rate for transition 2 to 1.

3.2 Convert from intensity to energy density

If you have an observed spectrum given in specific intensity units of erg cm^{-2} s^{-1} sr^{-1} Å, then the conversion to energy density is simply:

$$U_\lambda = 4.192 \times 10^{-10} I_\lambda \tag{12}$$

4 Additional notes

For most ions found in the transition region and corona of a stellar atmosphere, the resonance lines are found at EUV or X-ray wavelengths. For a cool photosphere such as the Sun's, the photons do not have enough energy to excite the resonance transitions, hence photoexcitation is weak. However, some stars (such as hot white dwarfs) can have temperatures up to 10^5 K, which means the blackbody spectrum peaks at EUV wavelengths. Photoexcitation can then become very strong, and a particular example is the case of nebula around a hot white dwarf.

References

Landi, E., Del Zanna, G., Young, P. R., et al. 2006, ApJS, 162, 261

Young, P. R., Del Zanna, G., Landi, E., et al. 2003, ApJS, 144, 135

A IDL code for emission line example

The IDL code below shows how to define a "radfunc" for the case of a spectrum containing the O IV $\lambda\lambda$1032,1038 doublet. The function is input to the CHIANTI routines by specifying the optional input `radfunc='o6_lines'`.

```
FUNCTION o6_lines, lambda, a

;
; a is the Doppler velocity of the lines.
;
IF n_elements(a) EQ 0 THEN a=0.

siz=size(lambda)
spectrum=dblarr(siz[1],siz[2])

;
; The 1032 line has an integrated intensity of 305.28 erg/cm2/s/sr.
; The FWHM of the lines is 0.2 angstroms.
; The 1038 intensity is a factor two less than 1032.
;
p1=305.28/0.2
p2=p1/2.

c1=1031.914
c1=c1+v2lamb(a,c1)
;
c2=1037.615
c2=c2+v2lamb(a,c2)

w=0.2/2.35

i=where(abs(lambda-c1) LE 6.*w)
IF i[0] NE -1 THEN spectrum[i]=p1*exp(-(lambda[i]-c1)^2/2./w^2)*4.*!pi/2.998d10

i=where(abs(lambda-c2) LE 6.*w)
IF i[0] NE -1 THEN spectrum[i]=spectrum[i]+p2*exp(-(lambda[i]-c2)^2/2./w^2)*4.*!pi/2.998d10

return,spectrum

end
```

B IDL code for blackbody example

The expression for the blackbody energy density (Eq. 11) is implemented in IDL with the following code.

```
function udens_bb, lambda

t=6d3
ee=1.439d8/lambda/t

result=8.*!pi*1.986d-8/lambda^2*(1d8^3)/lambda^3/((exp(ee)-1))
return,result

END
```

C Document history

Version 1.1, 26-Jun-2018: Corrected units for U_λ in Eq. 9 (previously the specific intensity units were given be mistake).