Flare Radiation Hydrodynamics: RADYN lab

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You don't have to complete all of this lab, just as much as possible in 90 minutes. Feel free to take it home over the summer and explore on your own and/or finish the lab. Feel free to e-mail Adam Kowalski (adam.f.kowalski@colorado.edu) with any questions.

Part I. Intro

In this lab, you will analyze two flare simulations with nonthermal electron energy deposition that were calculated with the non-LTE radiative-hydrodynamic code called RADYN (Carlsson & Stein 1997, Allred et al. 2015). This code was originally developed to study the non-equilibrium ionization of hydrogen and the asymmetric line profiles of Ca II that result from convectively-driven shocks passing through the chromosphere in the quiet Sun. A term (Q_{beam}) has been added to the energy equation to simulate flare energy deposition (by solving the time-independent Fokker-Planck equation). Other physics relevant to flares have also been added throughout the decades as discussed in class.

1) List two physical prescriptions (from class) important for modeling flares that are included in the RADYN code:

1)

2)

We will analyze a moderate electron beam energy flux (10^{11} erg/s/cm^2, "F11") and a high electron beam energy flux (3.5 x 10^{11} erg/s/cm^2, "3.5F11").   These are the energy fluxes integrated over a nonthermal electron distribution (aka, "beam") with a power-law index of 4 and a low-energy cutoff of 25 keV. The nonthermal electron beam was injected at the top of the model corona for 10 seconds, and then turned off (the atmosphere was then allowed to relax for an additional 50 seconds as soon as the electron beam heating was turned off). We will use the standard RADYN IDL libraries to analyze the output of these two simulations.

The goals of this lab are the following:
Goal 1) To understand how nonthermal electron beam heating produces a hydrodynamic response in the chromosphere and corona.
Goal 2) To understand the difference between the response from a moderate flux (F11) and a higher flux (3.5F11) electron beam.
Goal 3) To become generally familiar with the model predictions of the emergent radiation that are directly comparable to observations of solar flares.

Part II. Getting Familiar with RADYN: Analysis of the F11 flare model

In this section, you will 1) get familiar with the atmospheric variables calculated with RADYN, 2) you will analyze the time-evolution of several of the variables, and 3) you will analyze the contribution function to the emergent intensity in Hα (656.295 nm) at an interesting timestep (t=6.5s).

Download the package from:
https://www.dropbox.com/s/lhhfknuupeq93p2/radyn_lab.tar.gz?dl=0

```
tar -xzvf radyn_lab.tar.gz
```

This will unpack all routines, RADYN runs, and documents into a folder called radyn_tutorial/

```
cd contents/radyn_tutorial/
```

You will do all your work in this directory.

All IDL commands are already typed up in the file IDL_commands.txt (so you can spend more time analyzing the physics!).

Part IIA: The Radiative-Hydrodynamic Response

```
ls *.cdf
```

The CDF file with the RADYN output from the F11 run is called radyn_out.f11.cdf.

First run this command:

```
cp radyn_out.f11.cdf radyn_out.cdf
```

In this lab, we will only analyze the first 10 seconds in the simulation (when the beam energy deposition is on).

In IDL or SSWIDL, type:

```
IDL>@rinit ;initialize the IDL session for RADYN
IDL>readradyn ; reads RADYN output with the default name
'radyn_out.cdf’
IDL>readradyn, 'radyn_out.F11_d4_Ec25_10s.cdf' ; reads RADYN output
file with specific name
```

```
IDL>readradyn,'radyn_out.cdf', dt_interval=1.0 ; reads that RADYN
output file but only reading every 1 s.
IDL>readradyn  ; re-read in the CDF file with all times steps for
this lab.
```

```
IDL>help ; list all the RADYN variables
```

All variables are have units in **cgs**.

```
IDL>help, z1t, timet, ndep
```

2) Which index of z1t (height variable) is the time index? Which is the depth index?

The 0th index is the top of the corona and ndep-1 is the bottom of the atmosphere (lower photosphere).

3) What is the loop half length modeled here?

4) What do you think taut is?

```
IDL>print,interpol(taut[*,0],z1t[*,0],0.)
```

```
IDL> help,z1t,cmass1t,tg1t,d1t,ne1t,vz1t,n1t,pg1t  ; some of the most
useful hydrodynamic quantities computed by RADYN.
```

What are these:

z1t:
cmass1t:
tg1t:
d1t:
ne1t:
vz1t:
pg1t:
n1t:
nstart:

(see **analysis_tools.pdf** in the distribution for a description of all variables).

```
IDL> help,bheat1t,bmom1t,f20t ; a few flare specific variables.
```

5) What is bheat1t?

```
IDL> plot,timet,f20t ; plots the injected beam flux (erg/s/cm2) as a
function of time.
```

6) Note what time the nonthermal electron beam flux turns off.

```
IDL>plot,timet,tg1t[0,*] ; Plot the temperature at the top of the
corona as a function of time
```

7) Compare the coronal temperature evolution to the beam heating.

8) What is the maximum temperature achieved in this simulation? Compare to your reading Warren et al. 2013 (http://adsabs.harvard.edu/abs/2013ApJ...770..116W) from earlier in the class: how do we already know this simulation (the F11 electron beam heating with these particular parameters: 10s heating, δ=4, etc..) cannot explain the observations of that flare, even without doing a DEM analysis or spectral comparison?

Now, use the routine **mxmovie** to analyze the time-dependent quantities with an IDL widget (note, you will have to run these two commands outside of IDL if you are running XQuartz 2.7.10 and 2.7.11)

```
sudo mv /opt/X11/lib/libXt.6.dylib{,.bak}

sudo cp /opt/X11/lib{/flat_namespace,}/libXt.6.dylib
```

```
IDL>mxmovie, z1t*1e-5, tg1t, /ylog, id = timet ; animated plot of
temperature as a function of height, the time in seconds is shown in
the lower left corner.  Note, we change z1t to km from cm.

IDL>mxmovie, z1t*1e-5, tg1t, yr=[3000,100000], id = timet ; zoom-in
on chromospheric temperatures

IDL>mxmovie, z1t*1e-5,alog10(tg1t),z1t*1e-5,bheat1t/2000 + 3.5,/ps,
id=timet ; plot temperature and beam heating rate as a function
height
```

9) Speculate on why you think the beam heating rate forms two peaks by 6.5s.

10) What happens to the temperature at that height from t=0 to 10 seconds?

11) What happens to the height of the flare transition region from 0.5s to 10s?

12) What has happened to the temperature at z ~ 900 km from t=0 s to t=6.5 s?

First, make sure that index 78 is 6.5s. If not, find the index corresponding to 6.5s.

```
IDL> print,timet[78]
IDL> interpol(tg1t[*,78],z1t[*,78]/1e5, 900.)
IDL> interpol(tg1t[*,0],z1t[*,0]/1e5, 900.)
```

13) Has the photospheric temperature changed?

14) What is the maximum ionization fraction of He II at z~1225 km at t=6.5s?

```
IDL> mxmovie, z1t*1e-5, n1t[*,8,2,*]/totnt[*,2,*], id = timet ; plot
the ionization fraction, He III / (He I + He II + He III)
```

```
IDL> rad2plot ; allows you to plot two atmospheric quantities on the
same plot at a single time step

IDL> rad2plot, z1t*1e-5, alog10(tg1t), bheat1t, 6.5 ; plot
temperature and beam heating rate at 6.5 s on same plot
IDL> rad2plot, z1t*1e-5, alog10(tg1t), bheat1t, 6.5,
/oplot_t0,xr=[-100,2000] ; overplots the t=0s quantities with a dot
added to the line style
```

15a) Now look at the radiative loss rate from the optically **thin** loss function and the beam heating rate together. How do they compare at z=1200 km?

```
IDL> rad2plot, z1t/1e5, trl1t, bheat1t, 6.5,
xr=[-100,1500],yr=[0,1.5e4],y2r=[0,1.5e4]
```

Now add in the cooling from the elements that are calculated in *detail* (remember the level populations of hydrogen, helium, and Ca II are calculated using non-LTE optically thick radiative transfer with the non-equilibrium rate equation).

```
IDL> rad2plot, z1t/1e5, trl1t + coolt1t, bheat1t, 6.5,
xr=[-100,1500],yr=[0,1.5e4],y2r=[0,1.5e4]
```

15b) How does the thin radiative loss rate and the detailed radiative losses compare to the beam energy deposition rate at z~1225 km?

16a) Given the He III ionization fraction that you found at z~1225 km and the radiative loss rate compared to the beam heating rate at 1225 km, do you expect the region at z=1225 km to exceed the temperature where the radiative loss function peaks?   What would happen to the temperature there if helium becomes 100% doubly ionized and the temperature also exceeds this critical temperature?

16b) Which detailed transition provides the most cooling at 1225 km?

```
IDL> for i =0,40 do
print,irad[i],jrad[i],ielrad[i],alamb[i],coolt[114,i,78]
```

; “alamb” is the wavelength of the transition, irad is lower level, jrad is upper level, ielrad is element number (1=H, 2=Ca II, 3=He)

Print the conditions at this height (z~1225 km) and t=6.5.s

```
IDL> print,tg1t[114,78], ne1t[114,78]
```

Now we will analyze the gas velocity evolution, vz1t. Note that negative values mean downflows and positive values mean upflows.

```
IDL> mxmovie, z1t*1e-5, vz1t*1e-5,id=timet
```

17) What happens to the velocities in the corona by t=10s? What is this process called?

18) What causes material to “evaporate” into the corona?

Look at the gas velocity in the lower 1500 km of the atmosphere at t=1, 6.5, 9.9s:

```
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(tg1t),1,xr=[-100,1500],yr=[-20,1
50],y2r=[3,7]
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(tg1t),6.5,xr=[-100,1500],yr=[-20
,150],y2r=[3,7]
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(tg1t),9.9,xr=[-100,1500],yr=[-20
,150],y2r=[3,7]
```

19) You found earlier that the flare transition region goes out then comes back in. Flipping between these three times, why does this happen?

20a) Flip through the 1s, 6.5s, and 9.9s snapshots: What is the maximum downflow speed at T<15,000 K?

20b) The spectral resolution of IRIS is 0.05 Angstroms in the NUV (2800 Angstroms). Would you be able to detect such a redshift of a chromospheric flare line?

21) Compare the gas pressure to the velocity just after beam heating starts (t=0.1s). What drives the upflow velocity?

```
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(pg1t),0.2,xr=[-100,1500],yr=[-5,
120],y2r=[.1,6],/oplot_t0
```

22) Compare the gas temperature to the velocity at heights from 800 to 1500 km:

```
rad2plot,z1t/1e5,vz1t/1e5,alog10(tg1t),0.1,xr=[800,1500],yr=[-5,120],
y2r=[3.5,6],/oplot_t0
```

You can see that the evaporation is actually a transition region evaporation, and not so much a “chromospheric evaporation” (although some chromospheric material does heat to ~60,000 and starts upflowing also).

23a) What feature is obvious in the gas pressure at z~1290 km after the upflow switches to downflow (t=9.9s)? hint: you might have to adjust xr below to see it!

```
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(pg1t),9.9,xr=[-100,1500],yr=[-5,
100],y2r=[1,6],/oplot_t0
```

23b) Note the peak pressure at this feature in 23a. You’ll come back to it when comparing to the high beam flux model (Part III).

24) Where has the density increased in the atmosphere and where has it decreased compared to t=0s (use the /oplot_t0 option)?

```
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(d1t),6.5,xr=[-100,1500],yr=[-5,1
00],y2r=[-15,-7],/oplot_t0
```

25) Finally, why is there a maximum in the beam heating rate at z ~ 1280 km? Is this consistent with your prediction?

```
IDL> rad2plot, z1t*1e-5, alog10(d1t), bheat1t, 6.5,xr=[-100,1500] ;
plot density and beam heating rate at 6.5 s on same plot
```

Part IIB: Spectral Line Profiles

In this part you will analyze the emergent intensity in Hα and in Fe XXI 1354 line.

26) What is the main difference between the modeling approach for Hα and Fe XXI?

We have included atomic data from CHIANTI for several optically thin lines (in the file irislinesgnt.sav).

First, analyze the Fe XXI 1354 line intensity:

```
IDL>rad_thinline_intensity,'Fe_XXI_1354', intensity1354, contrib1354
IDL>plot,timet,intensity1354
```

27) When does the line peak?

Analyze where the line is formed in the atmosphere with respect to the velocity at t= 6.5s and at 25s:

```
IDL>rad2plot,z1t*1e-5,contrib1354,vz1t*1e-5,6.5
```

note: “contrib1354” is the contribution function to the emergent intensity (as discussed in Adam’s lecture), not the contribution function as discussed in Prof. Longcope’s lecture 11.

There are other optically thin lines available too in the routine rad_thinline_intensity. There is also a routine that calculates the column emission measure distribution (rdem.pro), but we have to move on!

```
IDL>radxdetailed
IDL>radxdetailed, user_mu=4, continuum, line1, line2
IDL>help,line1,/str
```

radxdetailed reads in the emergent flux or intensity spectrum calculated in detail in the RADYN code.

Explore the time-evolution of the Hα line compared the t=0 profile:

```
IDL>mxmovie, line1.lam, line1.int, line1.int0, xr= [6560,6566]
```

Plot the contribution function to the emergent intensity of Hα at t=6.5s:

```
IDL>device,decom = 0
IDL>loadct,39
IDL>nlam = n_elements(line1.lam[*,0])
```

```
IDL>time_index = 78 ; t=6.5s
IDL>print,timet[78]

IDL>contour,line1.contribf[*,*,time_index],z1t[*,time_index]*1e-5,lin
e1.lam[*,time_index],/fill,nlev = 256, xr = [0,2000],yr =
[6566,6560],ytitle='Wavelength (A)',xtitle='Height
(km)',xmargin=[10,10], ystyle=1+8
IDL>loadct,0,/silent
IDL>oplot,line1.int[*,time_index]*2000./(max(line1.int[*,time_index])
),line1.lam[*,time_index],color=150,linestyle=2,thick=3
IDL>oplot,[0,2000],6562.95 + [0,0],linestyle=1
```

This is the contribution function to the emergent intensity at mu=0.95. The emergent intensity profile is overplotted (normalized to fit on the plot) as a dashed line. The dotted line is 6562.95, the rest wavelength for Hα.

Now overplot the velocity (thick white line) and the temperature (dashed-dotted line, right axis):

```
IDL>loadct,39,/silent
IDL>oplot,z1t[*,time_index]/1e5,vz1t[*,time_index]/cc * 6562.95 *
(-1.0) + 6562.95,color=255,thick=3,linestyle=0
```

Now, overplot the temperature:

```
IDL>axis,yaxis=1,yr=[3,5],/save,ytitle='log_10 Temperature'
IDL>oplot,z1t[*,time_index]*1e-5,alog10(tg1t[*,time_index]),thick=3,c
olor=255,linestyle=3
```

28a) In the figure, the temperature is the dot-dashed line and the velocity is the thick solid white line. Where is the emergent intensity near the rest wavelength formed?

28b) The wings (wavelengths farther from line center than +/- 1 Angstrom) are formed at about what temperature?

28c) Why doesn't any of the emergent intensity near line center form below about z~1000 km?

29) The enhanced peak to the red of the rest wavelength is at lambda_rest + 0.7 Angstrom, which is +32 km/s. Are there downflowing velocities that are this high in the model?

Part IIC: Balmer continuum optical depth

In this section, you will calculate a Balmer jump ratio (see lecture notes) to determine whether the emergent Balmer and Paschen continua are formed over low or high optical depth.

First, look at the full continuum spectral prediction over time (this is in log wavelength and log intensity):

```
IDL>mxmovie,continuum.lam,continuum.int,/xlog,/ylog,id=timet
```

Now, look between 3200 and 5200 Angstroms (linear x, linear y) at t=6.5s:
We subtract the pre-flare to isolate the flare emission here:

```
IDL>plot,continuum.lam[*,78],continuum.int[*,78]-continuum.int0[*,78]
,xr=[3200,5200],psym=-1,yr=[0,1e6],/ystyle,/xstyle,xtitle='wavelength
(angstroms)', ytitle='intensity (erg/s/cm2/sr/Ang)'
```

30) What is unrealistic about the Balmer discontinuity spectrum here? (hint: see lecture notes).

31) Calculate the Balmer jump ratio at t=6.5s:

```
IDL>time_index=78  ; this should be t=6.5s
IDL>print,interpol(continuum.int[*,time_index]-continuum.int0[*,time_
index],continuum.lam[*,time_index],3600.)/interpol(continuum.int[*,ti
me_index]-continuum.int0[*,time_index],continuum.lam[*,time_index],41
70.)
```

32) Is this Balmer jump ratio indicative of hydrogen recombination formed over low or high optical depth?

Part III. Analysis of the high flux run (3.5F11)

This section will be significantly shorter than Part II!

Exit, then start IDL again.

Download the 3.5F11 CDF file from Dropbox:

If this takes a long time, then download a .dat file with only 0.5s timestep increments:
https://www.dropbox.com/s/71cvuuxevtqnfkz/radyn_out.3.5f11.tar.gz?dl=0

Copy the .tar.gz into the radyn_tutorial folder.

```
tar -xzvf radyn_out.3.5f11.tar.gz
```

For the high energy flux run (3.5 x 10^{11} erg/s/cm^2, “3.5F11”), we used the same power-law index of 4 and a low-energy cutoff of 25 keV as for the F11 run. These parameters including a high beam flux were inferred from the hard X-ray data of the brightest flare kernel in the March 29th, 2014 solar flare (Kleint et al. 2016). The goal of this section is to compare the chromospheric condensation that forms to the downflowing velocities in the F11 model. You will also gain insight into why the chromospheric condensation can be accurately described as a downflowing, heated compression.

33) Is δ=4 a “hard” or “soft” distribution (recall that values in solar flares are found between 3-8)?

Now, load in the 3.5F11 model (higher heating rate):

```
IDL>@rinit
IDL>readradyn,'radyn_out.3.5f11.cdf',dt_int=0.1,/ebal
```

or (if you’ve downloaded the .dat file instead of the .cdf file):

```
IDL>@rinit
IDL>restore,’radyn_out.3.5f11.pt5s.dat’
```

Note, we’ve also included the option “/ebal” with the readradyn command; ebal stands for energy balance. The ebal option reads in individual variables for analysis of the energy equation. For example, it calculates which transitions contribute to the radiative heating (e.g., useful or backwarming analysis of the photosphere) and cooling. These variables are **coolt** and **coolt1t**. Technically speaking, these variables tell you what contributes to the change in *internal energy*, which is the sum of thermal energy density (temperature) and atomic excitation/ionization energy density.

Look at the evolution of the beam heating and temperature in this model:

```
IDL> mxmovie, z1t*1e-5,alog10(tg1t),z1t*1e-5,bheat1t/6000 + 3.5,/ps, id=timet
```

34) What do you notice about the width of the beam energy deposition rate over time?

35) What cools off the atmosphere in response to the beam heating in the lower atmosphere at t=6.5s?

```
IDL>loadct,39 & device,decomp=0
```

`IDL>emovie,id=timet,xr=[-0.1,1.5],yr=[-1e15,1e15]` ; other options are **emovie,/detrad** and **emovie,/edot**

36) What is the maximum downward speed that develops in the lower atmosphere after 0.3s? What about at 6.5s? How does this compare to the F11 run that you found above?

```
IDL>mxmovie,z1t/1e5,vz1t/1e5,id=timet,yr=[-100,100]
```

37) Examine the velocity and density at 1s and 6.5s. Where is the downflowing region at t=1s and and at t=6.5s? Does it increase or decrease in density?

```
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(d1t),1.,xr=[-100,1500],yr=[-100,100],y2r=[-14,-6],/oplot_t0
IDL>rad2plot,z1t/1e5,vz1t/1e5,alog10(d1t),6.5,xr=[-100,1500],yr=[-100,100],y2r=[-14,-6],/oplot_t0
```

38) Note the maximum density at t=6.5s (for later):

39) What do you notice about the heights of the flare transition region (where the temperature jumps up to T > 1 MK) at t=1s and t=6.5s?

```
IDL>rad2plot,z1t/1e5,alog10(tg1t),alog10(d1t),1,xr=[-100,1500],yr=[3,
7],y2r=[-14,-6],/oplot_t0
IDL>rad2plot,z1t/1e5,alog10(tg1t),alog10(d1t),6.5,xr=[-100,1500],yr=[
3,7],y2r=[-14,-6],/oplot_t0
```

40) What's the maximum pressure at the flare transition region at t=6.5s? (you may have to zoom in to see the interesting feature in the pressure at the flare transition region). How does this compare to the pressure in a similar-looking feature in the F11 model in Question 23b?

```
IDL>rad2plot,z1t/1e5,alog10(tg1t),alog10(pg1t),6.5,xr=[-100,1500],yr=
[3,7],y2r=[1,4],/oplot_t0
```

41) At t=1s, notice that the temperature is below 9500 K z < 900 km and jumps up to 60,000 K as you go higher into the atmosphere, then jumps up to millions of degrees at the flare transition region. What is the column mass at T=9500 K at t=1s and t=6.5s? How do they compare? (in the following, must change "10" and "65" indices to "2" and "13", respectively, if you've downloaded the .dat file with 0.5s increments).

```
IDL>plot,z1t[*,10]/1e5,tg1t[*,10],yr=[2500,1e7],/ylog,xr=[-100,1500],
/xstyle,/ystyle
IDL>oplot,z1t[*,65]/1e5,tg1t[*,65],linestyle=2

IDL> print,interpol(alog10(cmass1t[*,10]), tg1t[*,10],9500) ; t=1s

IDL> print,interpol(alog10(cmass1t[*,65]), tg1t[*,65],9500)  ; t=6.5s
```

42) What is the height difference between the flare transition region and the height corresponding to T=9500 K at t=6.5s? at 1s?

```
IDL> print,interpol(z1t[*,65]/1e5, tg1t[*,65],1e5)

IDL> print,interpol(z1t[*,65]/1e5, tg1t[*,65],9500.)
```

```
IDL> print,interpol(z1t[*,10]/1e5, tg1t[*,10],1e5)

IDL> print,interpol(z1t[*,10]/1e5, tg1t[*,10],9500.)
```

43) At t=6.5s, what is the column mass at T=9500 K divided by this height difference? How does it correspond to the density in the chromospheric condensation that you found in Question 39? By 6.5s, what happened to the material at t=1s that was just below the flare transition region? How is this material heated (see Question 36)?

44) Explore **emovie**, which shows the evolution of the terms that are important in the energy equation.

Important note about the 3.5F11 run: The expertise of our group is high flux runs like this one. In Kowalski et al. 2017 (ApJ 837, 125), we found that large ambient electron densities produced in dense chromospheric condensations require a more advanced technique for modeling the broadening of the hydrogen lines than currently employed in RADYN (an update will be implemented circa Summer 2017). Therefore, I caution against using the hydrogen line profiles for detailed comparison to observations; refer to the paper above if you want to analyze a contribution function to the emergent intensity in Hα from the 3.5F11 run. One will have to use the RH code, which has the updated broadening already implemented.

Part IV. How does the beam density in the 3.5F11 model compare to measurements in Above-the-Looptop sources? (extra credit)

Using IDL or Python, calculate the nonthermal electron number flux in the 3.5F11 beam.
Then, using the average electron velocity in the beam, calculate the nonthermal electron number density in the beam (hint: use dimensional analysis). Compare to the density inferred in the above-the-looptop source in Krucker & Battaglia (2014) which was discussed in Prof. Chen's lecture number 22.

Part V. Testing the models against observations of Fe XXI (optional, over the summer)

Using IDL or Python and the lecture 9 and 11 notes (with the data contained in irislinesgnt.sav in this distribution) calculate the spectral evolution of Fe XXI 1354 for all snapshots of both models and compare to observations in the literature.

Note: There is a thorough model grid (but with relatively low beam fluxes, <= F11) available from the F-CHROMA project:
https://star.pst.qub.ac.uk/wiki/doku.php/public/solarmodels/start

Appendix: Some Python commands

```
import scipy.io
ry=scipy.io.readsav('radyn_out.3.5f11.dat’)
print len(ry.timet)
```

Example contribution function (may need some tweaking):

```
x =  ry.vz1t[65,:]/1e5
y = ry.z1t[65,:]/1e5
xx,yy= np.meshgrid(x,y)
z = contribution_function
vel = ry.vz1t[65,:]/1e5
height = ry.z1t[65,:]/1e5
x1=6562.95-20.
x2=6562.95+20.
y1=850
y2=950
fig, ax1 = plt.subplots()
ax1.contourf(xx,yy,Z,cmap='Reds',levels=(0.0001,.01,50,500,1000,2000,3000))
ax1.axis([ (6562.95-x1)/6562.95 * 2.998e5, (6562.95-x2)/6562.95 * 2.998e5, y1, y2])
ax1.set_ylabel('Height (km)')
ax1.set_xlabel('vel (km/s)')
ax2 = ax1.twinx()
ax2.axis([ (6562.95-x1)/6562.95 * 2.998e5, (6562.95-x2)/6562.95 * 2.998e5, y1, y2])
ax3 = ax1.twinx()
ax3.axis([ (6562.95-x1)/6562.95 * 2.998e5, (6562.95-x2)/6562.95 * 2.998e5, y1, y2])
ax3.plot(vel * .77, height, color='red')
ax4 = ax1.twinx()
ax4.axis([ (6562.95-x1)/6562.95 * 2.998e5, (6562.95-x2)/6562.95 * 2.998e5, y1, y2])
ax4.plot(x, ci.spec_cgs * (y2-y1) / max(ci.spec_cgs) + y1,color='black')
plt.savefig('Halpha_Ci.eps',type='eps')
```