In [1]:
```
%matplotlib inline
import matplotlib.pyplot as plt
import numpy as np
import mesa_reader as m
```

Lab 3 -- analyzing MESA output for the evolution of a Sun-like star

1. Load the time series data into an object d and list all the possible variables

"star_age" is time

"center_" means calculated for the core

"log*average*" means it is the logarithm of the value averaged over the star

"surf_" means evaluated at the surface

In [2]:
```
# set the path variable to the directory containing the data files
# you can leave this as an empty string if the files are in the sam
e directory as the Jupyter notebook
path = ''
d = m.MesaData(file_name=path+'history.data')
ms = m.MesaData(file_name=path+'profile4.data')
rg = m.MesaData(file_name=path+'profile25.data')
d.read_data()
d.bulk_names;
```

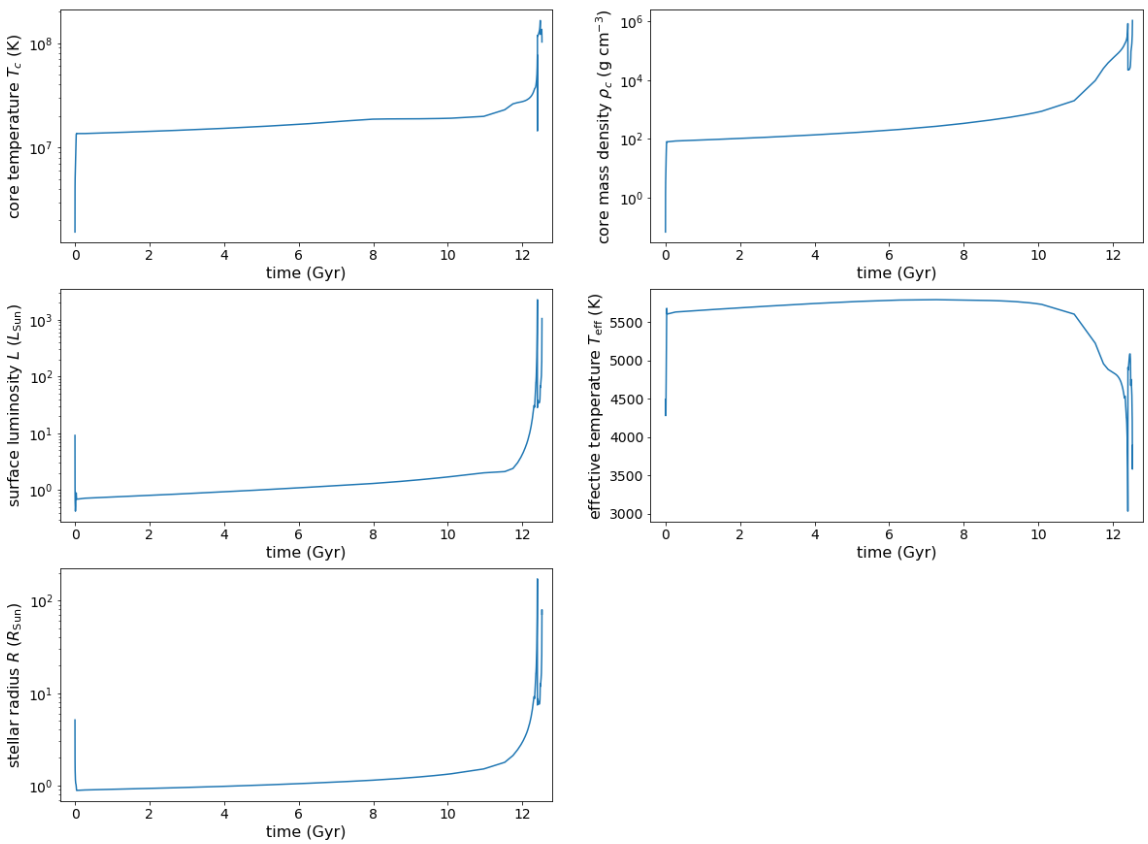
2. identify the main sequence phase of the star

hint: where does H burning in the core start? where does the star leave the "main sequence" strip of the H-R diagram?

you can also "Zoom in" by changing the start and end points of the x-axis tstart and tstop: plt.xlim(tstart,tstop)

In [3]:

```
# change these values if you want to Zoom in to a certain time range
tstart=-0.4; tstop=12.8

fig, axArr = plt.subplots(3,2,figsize=(20,15))
#plt.figure(figsize=(5,4))
axArr[0,0].semilogy(d.data('star_age')/1e9,10**d.data('log_center_T'))
axArr[0,0].xaxis.set_tick_params(labelsize=14)
axArr[0,0].yaxis.set_tick_params(labelsize=14)
axArr[0,0].set_xlabel('time (Gyr)',fontsize=16); axArr[0,0].set_ylabel(r'core temperature $T_c$ (K)',fontsize=16)
axArr[0,0].set_xlim(tstart,tstop)

#plt.figure(figsize=(5,4))
axArr[0,1].semilogy(d.data('star_age')/1e9,10**d.data('log_center_Rho'))
axArr[0,1].xaxis.set_tick_params(labelsize=14)
axArr[0,1].yaxis.set_tick_params(labelsize=14)
axArr[0,1].set_xlabel('time (Gyr)',fontsize=16); axArr[0,1].set_ylabel(r'core mass density $\rho_c$ (g cm$^{-3}$)',fontsize=16)
axArr[0,1].set_xlim(tstart,tstop)

#plt.figure(figsize=(5,4))
axArr[1,0].semilogy(d.data('star_age')/1e9,10**d.data('log_L'))
axArr[1,0].xaxis.set_tick_params(labelsize=14)
axArr[1,0].yaxis.set_tick_params(labelsize=14)
axArr[1,0].set_xlabel('time (Gyr)',fontsize=16); axArr[1,0].set_ylabel(r'surface luminosity $L$ ($L_{\rm Sun}$)',fontsize=16)
axArr[1,0].set_xlim(tstart,tstop)

#plt.figure(figsize=(5,4))
axArr[1,1].plot(d.data('star_age')/1e9,10**d.data('log_Teff'))
#ax = plt.gca()
axArr[1,1].xaxis.set_tick_params(labelsize=14)
axArr[1,1].yaxis.set_tick_params(labelsize=14)
axArr[1,1].set_xlabel('time (Gyr)',fontsize=16); axArr[1,1].set_ylabel(r'effective temperature $T_{\rm eff}$ (K)',fontsize=16)
axArr[1,1].set_xlim(tstart,tstop)

#plt.figure(figsize=(5,4))
axArr[2,0].semilogy(d.data('star_age')/1e9,10**d.data('log_R'))
#ax = plt.gca()
axArr[2,0].xaxis.set_tick_params(labelsize=14)
axArr[2,0].yaxis.set_tick_params(labelsize=14)
axArr[2,0].set_xlabel('time (Gyr)',fontsize=16); axArr[2,0].set_ylabel(r'stellar radius $R$ ($R_{\rm Sun}$)',fontsize=16)
axArr[2,0].set_xlim(tstart,tstop)

fig.delaxes(axArr[2,1])
```



Based of the effective temperature plot, H burning starts at almost t = 0 and stops around 11 gigayears (which is when it leaves the main sequence)

3. let's look at the radial structure of the main sequence star

where in radius do you think is the outer boundary of the "core" and why? how much of the enclosed mass is in the core?

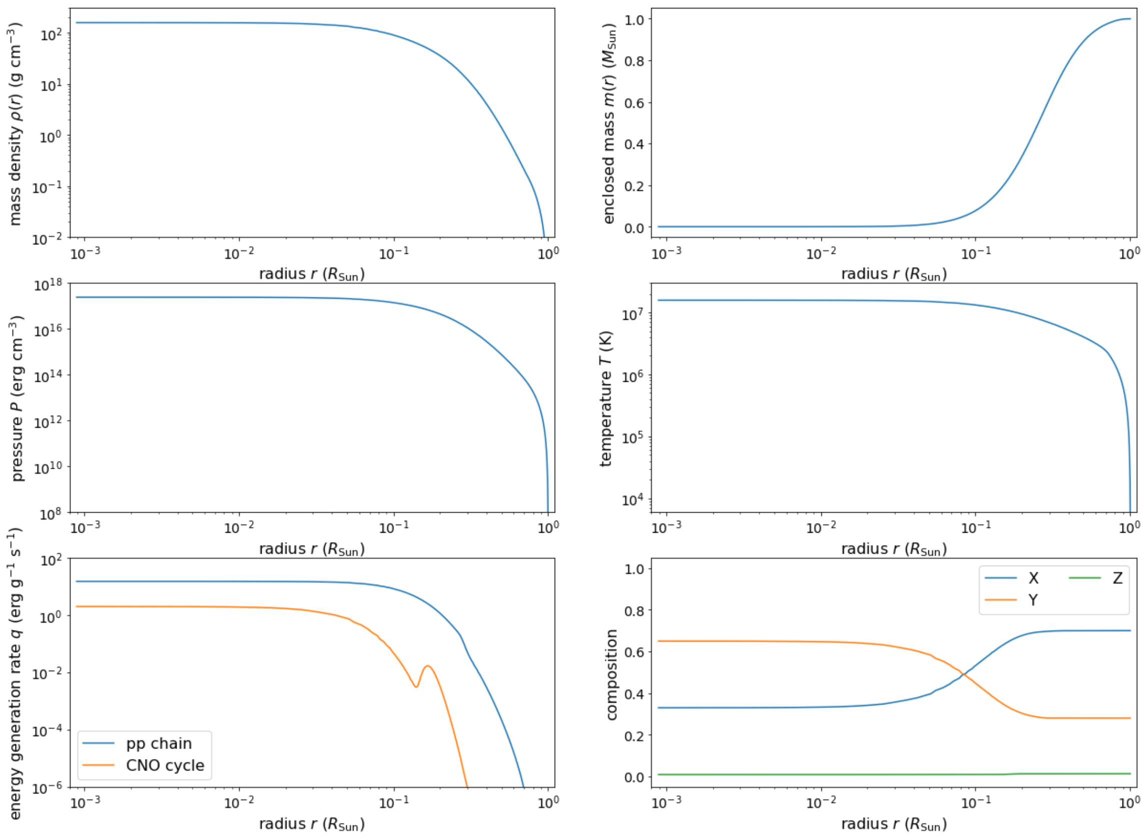
are the conditions what you expect for a main sequence star in terms of core temperature and energy generation?

how does the density profile compare to what we assumed in HW3 problem 1?

In [4]:
```
rstart=8e-4; rstop=1.1

fig, axArr = plt.subplots(3,2,figsize=(20,15))

axArr[0,0].loglog(ms.data('r_equatorial'),10**ms.data('logRho'))
axArr[0,0].xaxis.set_tick_params(labelsize=14)
axArr[0,0].yaxis.set_tick_params(labelsize=14)
axArr[0,0].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[0,0].set_ylabel(r'mass density $\rho(r)$ (g cm$^{-3}$)',fontsi
ze=16)
axArr[0,0].set_xlim(rstart,rstop)
axArr[0,0].set_ylim(1e-2,3e2)

axArr[0,1].semilogx(ms.data('r_equatorial'),ms.data('mass'))
axArr[0,1].xaxis.set_tick_params(labelsize=14)
axArr[0,1].yaxis.set_tick_params(labelsize=14)
axArr[0,1].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[0,1].set_ylabel(r'enclosed mass $m(r)$ ($M_{\rm Sun}$)',fontsi
ze=16)
axArr[0,1].set_xlim(rstart,rstop)
axArr[0,1].set_ylim(-0.05,1.05)

axArr[1,0].loglog(ms.data('r_equatorial'),ms.data('pressure'))
axArr[1,0].xaxis.set_tick_params(labelsize=14)
axArr[1,0].yaxis.set_tick_params(labelsize=14)
axArr[1,0].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[1,0].set_ylabel(r'pressure $P$ (erg cm$^{-3}$)',fontsize=16)
axArr[1,0].set_xlim(rstart,rstop)
axArr[1,0].set_ylim(1e8,1e18)

axArr[1,1].loglog(ms.data('r_equatorial'),10**ms.data('logT'))
axArr[1,1].xaxis.set_tick_params(labelsize=14)
axArr[1,1].yaxis.set_tick_params(labelsize=14)
axArr[1,1].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[1,1].set_ylabel(r'temperature $T$ (K)',fontsize=16)
axArr[1,1].set_xlim(rstart,rstop)
axArr[1,1].set_ylim(6e3,3e7)

axArr[2,0].loglog(ms.data('r_equatorial'),ms.data('pp'),label='pp c
hain')
axArr[2,0].loglog(ms.data('r_equatorial'),ms.data('cno'),label='CNO
cycle')
axArr[2,0].xaxis.set_tick_params(labelsize=14)
axArr[2,0].yaxis.set_tick_params(labelsize=14)
axArr[2,0].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[2,0].set_ylabel(r'energy generation rate $q$ (erg g$^{-1}$ s$^
{-1}$)',fontsize=16)
axArr[2,0].set_xlim(rstart,rstop)
axArr[2,0].set_ylim(1e-6,1e2)
axArr[2,0].legend(fontsize=16)

axArr[2,1].semilogx(ms.data('r_equatorial'),ms.data('h1'),label='X
')
axArr[2,1].semilogx(ms.data('r_equatorial'),ms.data('he4'),label='Y
')
```

```
axArr[2,1].semilogx(ms.data('r_equatorial'),ms.data('c12')+ms.data
('o16'),label='Z')
axArr[2,1].xaxis.set_tick_params(labelsize=14)
axArr[2,1].yaxis.set_tick_params(labelsize=14)
axArr[2,1].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[2,1].set_ylabel(r'composition',fontsize=16)
axArr[2,1].set_xlim(rstart,rstop)
axArr[2,1].legend(fontsize=16,ncol=2)
axArr[2,1].set_ylim(-0.05,1.05)
```

Out[4]: (-0.05, 1.05)



I think the outer boundary of the core is around r = 0.1Rsun because the composition vs. radius plot shows the helium and hydrogen amounts, and we know that most of the helium should be in the core (where its being created). Furthermore, the temp vs. radius plot also starts decreasing around 0.1Rsun, which is where it can no longer fuse hydrogen (ie the boundary of the core). Based off the enclosed mass vs. radius plot, I would say the enclosed mass in the core is around 10% of the total mass. The core temperature (~10^7 K) and the energy generation both match up with what we expect from a main sequence star. The density profile matches what we calculated in porblem 1 of HW3.

4. what happens just after the star leaves the main sequence?

for this part refer to the plots from Q2 as well as the new ones below showing the changes in composition over time

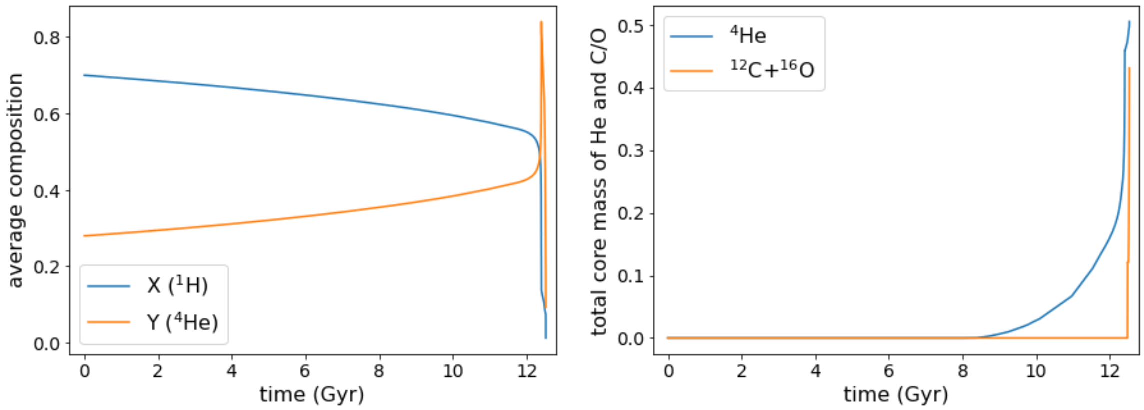
the main sequence is the phase where the star is burning hydrogen in the core. Is most of the hydrogen in the star converted to helium during this phase?

just afterwards, is the core hot enough to burn He? what nuclear fuel is being consumed?

given the star's location on the HR diagram (and/or its radius), what phase do you think this might be?

In [5]:
```
fig, (ax1,ax2) = plt.subplots(1,2,figsize=(15,5))
ax1.plot(d.data('star_age')/1e9,10**d.data('log_average_h1'),label=r'X ($^1$H)')
ax1.plot(d.data('star_age')/1e9,10**d.data('log_average_he4'),label=r'Y ($^4$He)')
ax1.legend(fontsize=16)
ax1.xaxis.set_tick_params(labelsize=14)
ax1.yaxis.set_tick_params(labelsize=14)
ax1.set_xlabel('time (Gyr)',fontsize=16); ax1.set_ylabel(r'average composition',fontsize=16)
ax1.set_xlim(tstart,tstop)

ax2.plot(d.data('star_age')/1e9,d.data('he_core_mass'),label='$^4$He')
ax2.plot(d.data('star_age')/1e9,d.data('c_core_mass'),label='$^{12}$C$+^{16}$O')
ax2.legend(fontsize=16)
ax2.xaxis.set_tick_params(labelsize=14)
ax2.yaxis.set_tick_params(labelsize=14)
ax2.set_xlabel('time (Gyr)',fontsize=16); ax2.set_ylabel(r'total core mass of He and C/O',fontsize=16)
ax2.set_xlim(tstart,tstop)
```

Out[5]: (-0.4, 12.8)



Based on the average composition vs. time plot, most of the hydrogen in the star is converted into helium during this phase. Just afterwards, it's hot enough to burn helium, and is also shell burning hydrogen around the core. Given the star's location on the HR diagram and its radius, I think this star is in the core helium burning phase (horizontal branch).

5. radial structure after leaving the main sequence

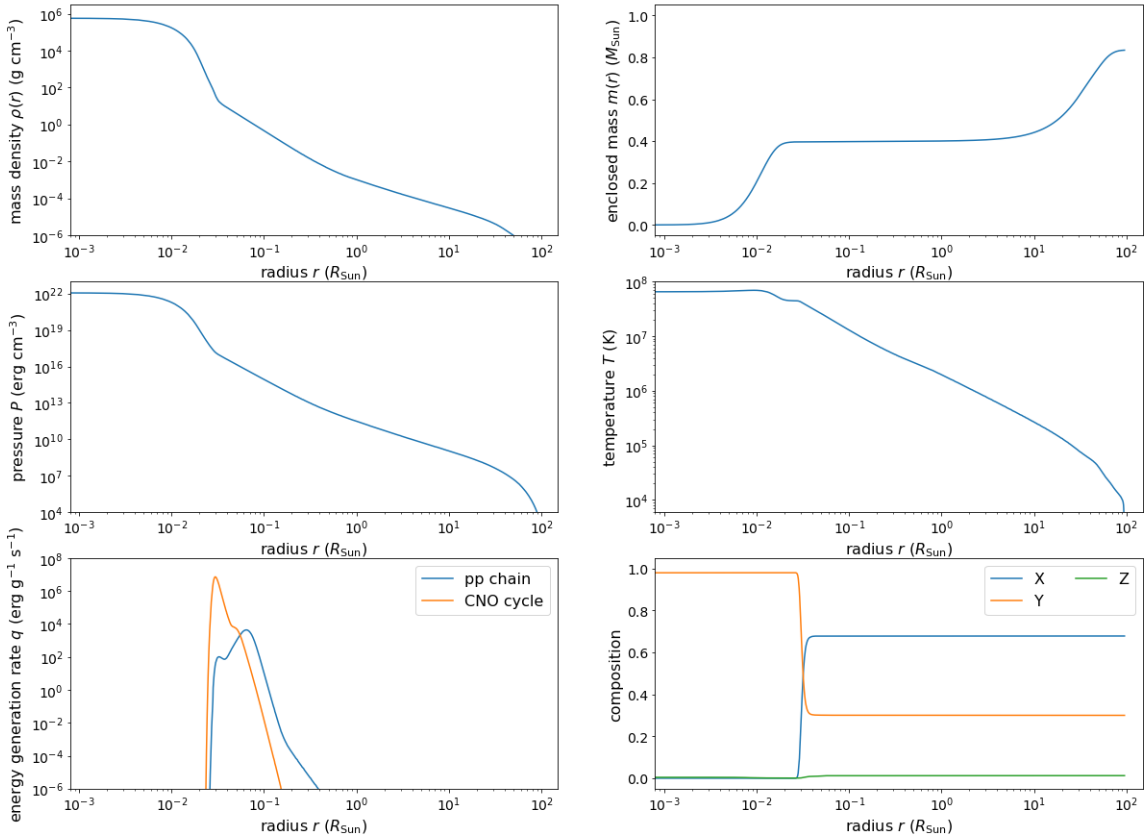
how does the radial structure of the star compare to when it was on the main sequence, e.g. in terms of the central and surface density and total radius and mass? make sure to check the numerical values of the graphs as well as their shapes!

how has the composition of the core of the star changed? where is nuclear fusion occuring in the star during this phase? what is the main nuclear reaction chain taking place? is the peak energy generation rate smaller or larger than it was on the main sequence?

In [6]:
```
rstart=8e-4; rstop=1.5e2

fig, axArr = plt.subplots(3,2,figsize=(20,15))
axArr[0,0].loglog(rg.data('r_equatorial'),10**rg.data('logRho'))
axArr[0,0].xaxis.set_tick_params(labelsize=14)
axArr[0,0].yaxis.set_tick_params(labelsize=14)
axArr[0,0].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[0,0].set_ylabel(r'mass density $\rho(r)$ (g cm$^{-3}$)',fontsi
ze=16)
axArr[0,0].set_xlim(rstart,rstop)
axArr[0,0].set_ylim(1e-6,3e6)

axArr[0,1].semilogx(rg.data('r_equatorial'),rg.data('mass'))
axArr[0,1].xaxis.set_tick_params(labelsize=14)
axArr[0,1].yaxis.set_tick_params(labelsize=14)
axArr[0,1].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[0,1].set_ylabel(r'enclosed mass $m(r)$ ($M_{\rm Sun}$)',fontsi
ze=16)
axArr[0,1].set_xlim(rstart,rstop)
axArr[0,1].set_ylim(-0.05,1.05)

axArr[1,0].loglog(rg.data('r_equatorial'),rg.data('pressure'))
axArr[1,0].xaxis.set_tick_params(labelsize=14)
axArr[1,0].yaxis.set_tick_params(labelsize=14)
axArr[1,0].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[1,0].set_ylabel(r'pressure $P$ (erg cm$^{-3}$)',fontsize=16)
axArr[1,0].set_xlim(rstart,rstop)
axArr[1,0].set_ylim(1e4,1e23)

axArr[1,1].loglog(rg.data('r_equatorial'),10**rg.data('logT'))
axArr[1,1].xaxis.set_tick_params(labelsize=14)
axArr[1,1].yaxis.set_tick_params(labelsize=14)
axArr[1,1].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[1,1].set_ylabel(r'temperature $T$ (K)',fontsize=16)
axArr[1,1].set_xlim(rstart,rstop)
axArr[1,1].set_ylim(6e3,1e8)

axArr[2,0].loglog(rg.data('r_equatorial'),rg.data('pp'),label='pp c
hain')
axArr[2,0].loglog(rg.data('r_equatorial'),rg.data('cno'),label='CNO
cycle')
axArr[2,0].xaxis.set_tick_params(labelsize=14)
axArr[2,0].yaxis.set_tick_params(labelsize=14)
axArr[2,0].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[2,0].set_ylabel(r'energy generation rate $q$ (erg g$^{-1}$ s$^
{-1}$)',fontsize=16)
axArr[2,0].set_xlim(rstart,rstop)
axArr[2,0].set_ylim(1e-6,1e8)
axArr[2,0].legend(fontsize=16)

axArr[2,1].semilogx(rg.data('r_equatorial'),rg.data('h1'),label='X
')
axArr[2,1].semilogx(rg.data('r_equatorial'),rg.data('he4'),label='Y
')
axArr[2,1].semilogx(rg.data('r_equatorial'),rg.data('c12')+rg.data
```

```
('o16'),label='Z')
axArr[2,1].xaxis.set_tick_params(labelsize=14)
axArr[2,1].yaxis.set_tick_params(labelsize=14)
axArr[2,1].set_xlabel(r'radius $r$ ($R_{\rm Sun}$)',fontsize=16); a
xArr[2,1].set_ylabel(r'composition',fontsize=16)
axArr[2,1].set_xlim(rstart,rstop)
axArr[2,1].legend(fontsize=16,ncol=2)
axArr[2,1].set_ylim(-0.05,1.05)
```

Out[6]: (-0.05, 1.05)



Based on the plots, the mass density is much higher in this phase, and falls off slower than when it was on the main sequence. Also, the radius is much larger, around 100 times larger. It's less massive in this phase, and the mass density gradient is much different compared to when it was on the main sequence. Based off the energy generation vs. radius plot, the main nuclear chain reaction is taking place in the core, and is the CNO cycle. There's also pp chain fusion, but it's occuring in shells around the core. The peak energy generation is MUCH higher in this phase than the main sequence, which is more evidence that it's using the CNO cylce to fuse helium in the core.

6. Summary and further evolution

the next phases get even more extreme. When does ^{4}He start fusing in the core (the "helium flash")? Does that make sense in terms of the core temperature?

Based on the graphs in Q2, why are the phases following the main sequence so much shorter? You might reason in terms of energy balance (fuel consumption) or core temperature (luminosity)

Optional to find on your own using the data object d:

--according to this calculation, what are the "final" mass and radius of the star? How can you explain that result for the mass?

--what is the core made of in the end state?

Note that the later stages starting with the "helium flash" are uncertain, and the details e.g. numbers for real stars have some uncertainty

Based on the plots, the helium flash occurs around 12.5 gigayears. This makes sense in terms of the core temperature, as the temperature vs. time plot shows the core temperature increasing to 10^8 K, which is when the helium flash occurs and the CNO cycle can begin. The phases following the main sequence are so much shorter because there isn't as much helium in the core, and the energy generation is greatly increased (which means the reaction can't go as long).

In [ ]: