Star and Planet Formation 2020

Q & A Session 28.04.2020

Example of starburst99 simulations

We use a variety of indirect indicators to measure the star formation rate in galaxies, and one of the most common is to measure the galaxy's infrared luminosity. The underlying assumptions behind this method are that

(1) most of the total radiant output in the galaxy comes from young, recently formed stars, and

(2) that in a sufficiently dusty galaxy most of the starlight will be absorbed by dust grains within the galaxy and then re-radiated in the infrared.

We will explore how well this conversion works using the popular stellar population synthesis package Starburst99 (Leitherer et al., 1999; Vázquez & Leitherer, 2005)

We download the dataset from 1999 here: http://www.stsci.edu/science/starburst99/docs/default-.htm

Fig 1

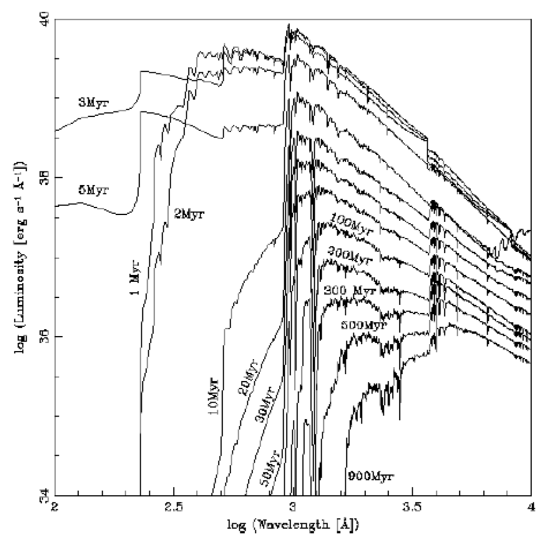


FIG. 1b

FIG. 1.—Spectral energy distributions from 100 Å to 1 μm between 1 Myr and 1 Gyr. Star formation law: instantaneous; IMF: $\alpha = 2.35$, $M_{up} = 100\ M_\odot$; nebular continuum included; (*a*) $Z = 0.040$; (*b*) $Z = 0.020$; (*c*) $Z = 0.008$; (*d*) $Z = 0.004$; (*e*) $Z = 0.001$.

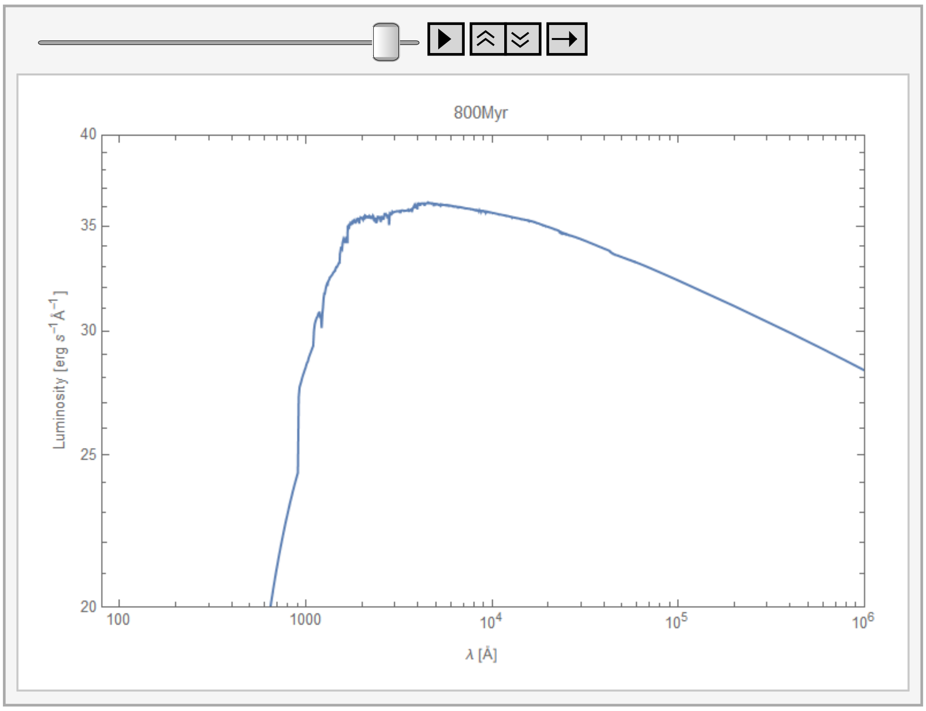
First a simulation with **instantaneous** SF (burst).

```
data1braw = Import[...] // Most;
```

In[∘]:=
```
data1bhead = data1braw[[1 ;; 3]];
data1btimes = data1braw[[3, 3 ;; -1]];
data1bdata = data1braw[[4 ;; -1, 2 ;; -1]];
data1bλ = data1braw[[4 ;; -1, 1]];
data1b = Transpose[{data1bλ, #}] & /@ Transpose[data1bdata];
sel = {1, 5, 10, 20, 23, 28, 32, 36};
```

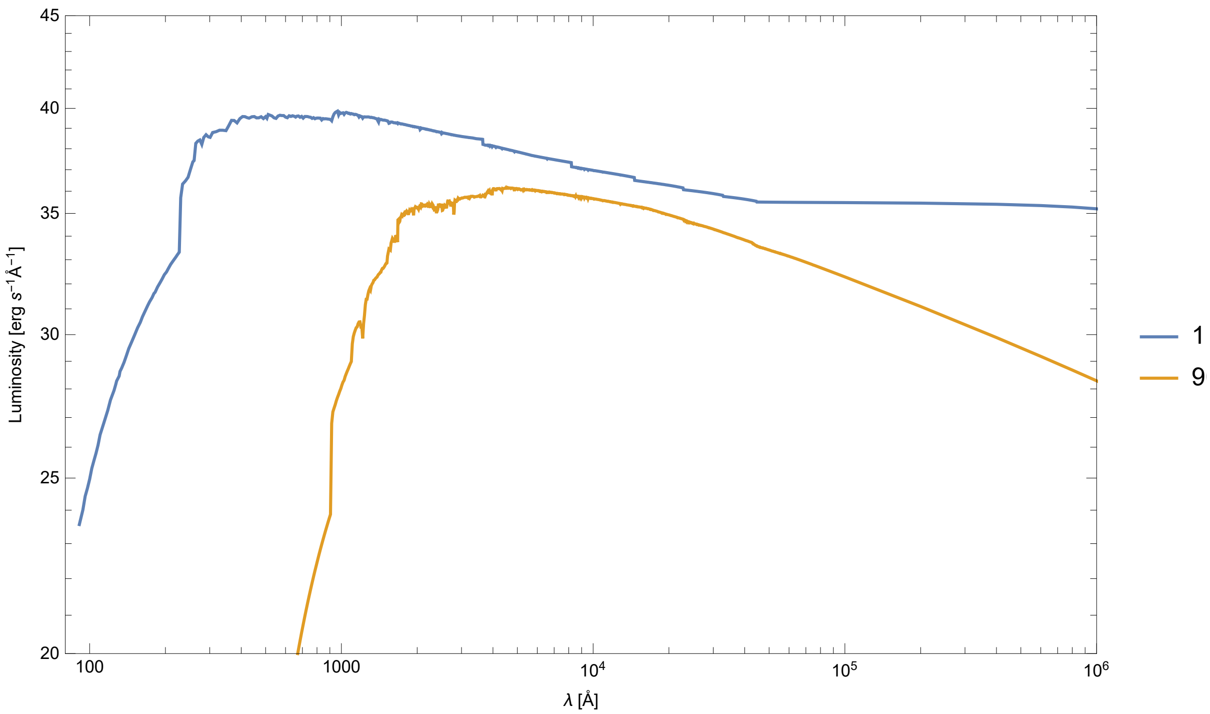
First look at the sequence (in time) of the luminosity. What happens? Why?

Out[∘]=

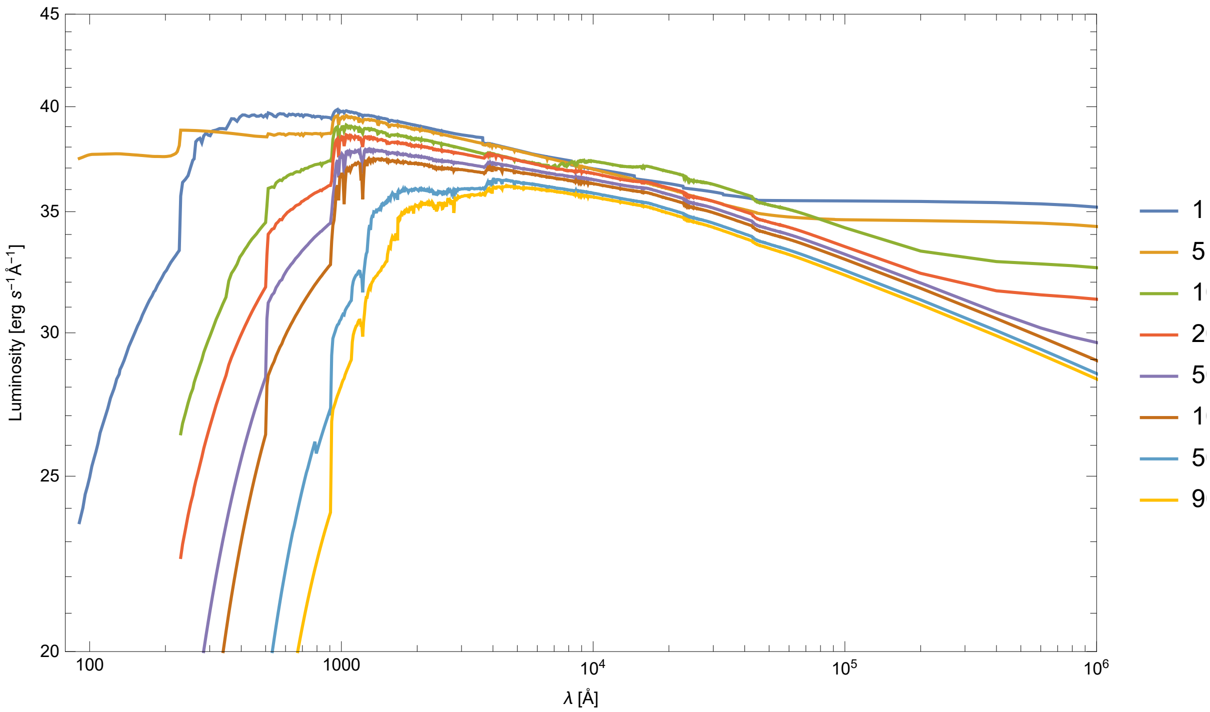


Compare the luminosity after 1 and 900 Myrs.

Out[∘]=



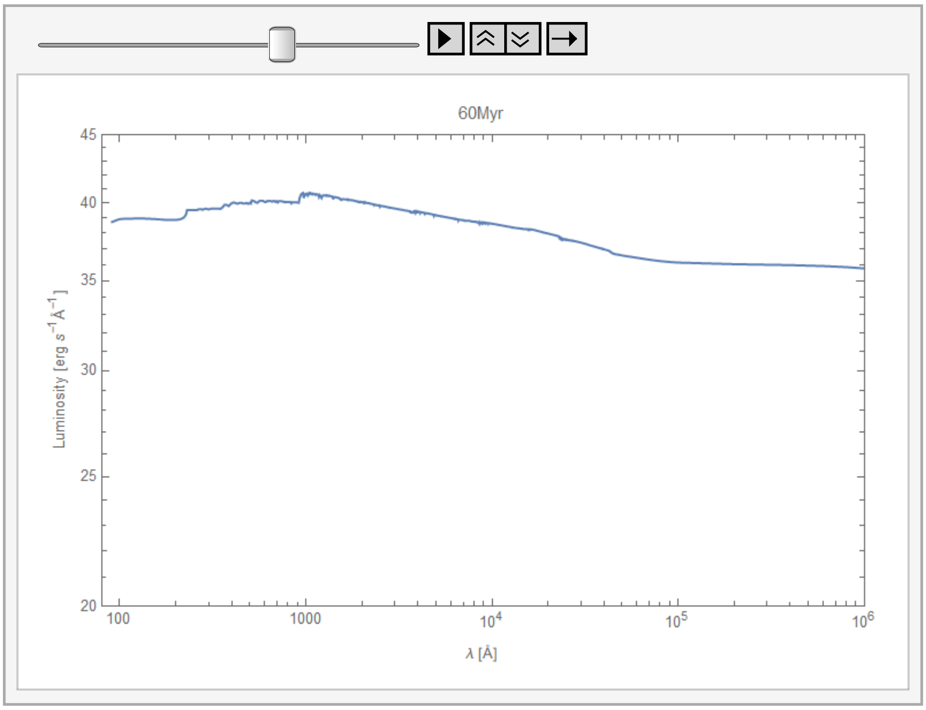
Out[ ]=



Now for a simulation with **continuous** SF.

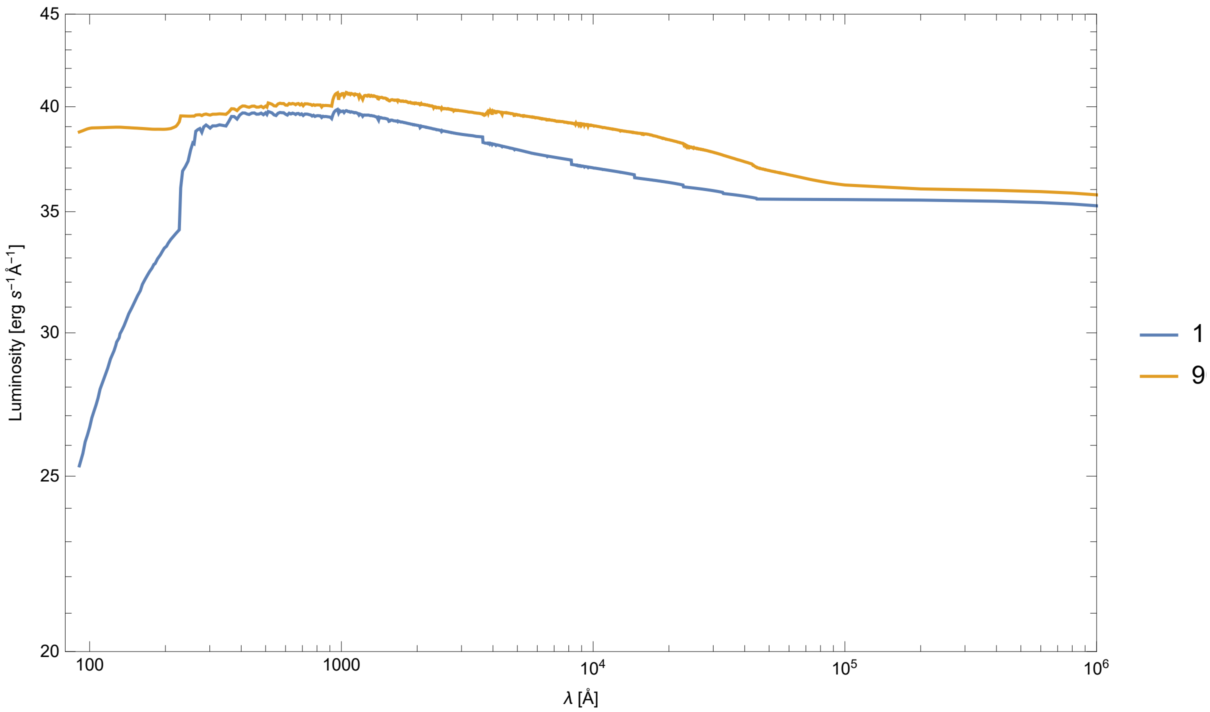
```
data2braw = Import[...] // Most;
data2bhead = data2braw[[1 ;; 3]];
data2btimes = data2braw[[3, 3 ;; -1]];
data2bdata = data2braw[[4 ;; -1, 2 ;; -1]];
data2bλ = data2braw[[4 ;; -1, 1]];
data2b = Transpose[{data2bλ, #}] & /@ Transpose[data2bdata];
sel = {1, 5, 10, 20, 23, 28, 32, 36};
```

Out[ ]=

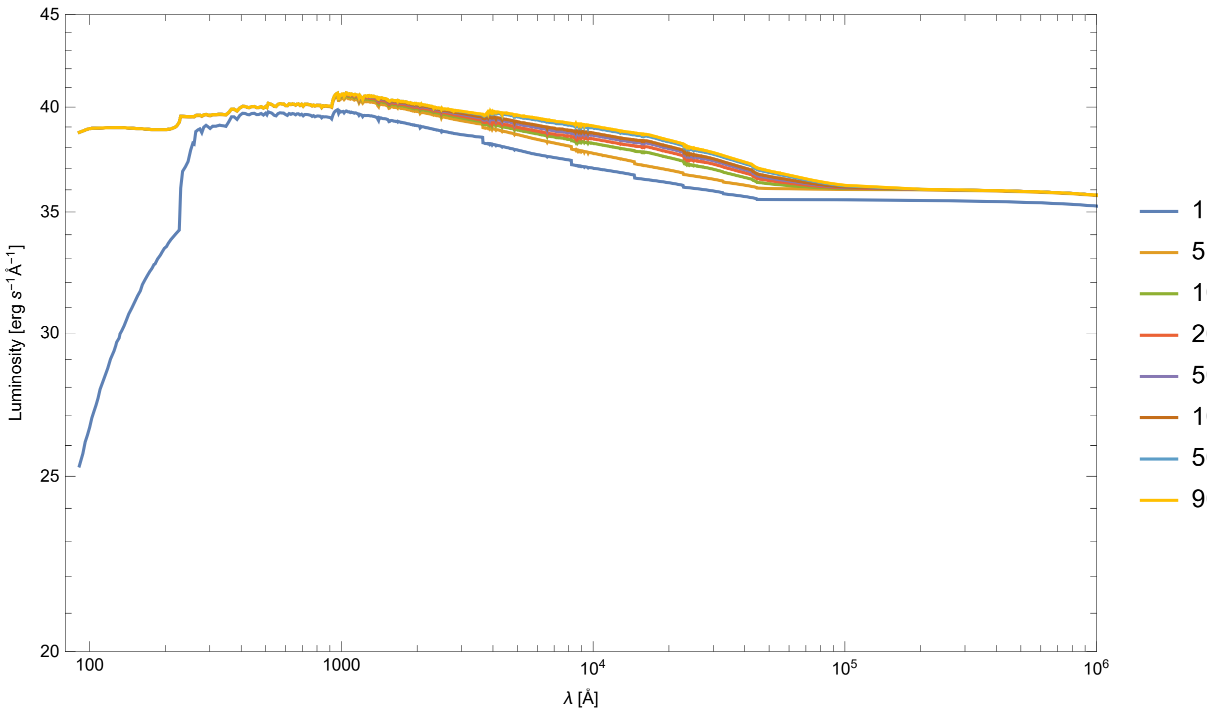


Compare the luminosity after 1 and 900 Myrs.

Out[ ]=



Out[ ]=

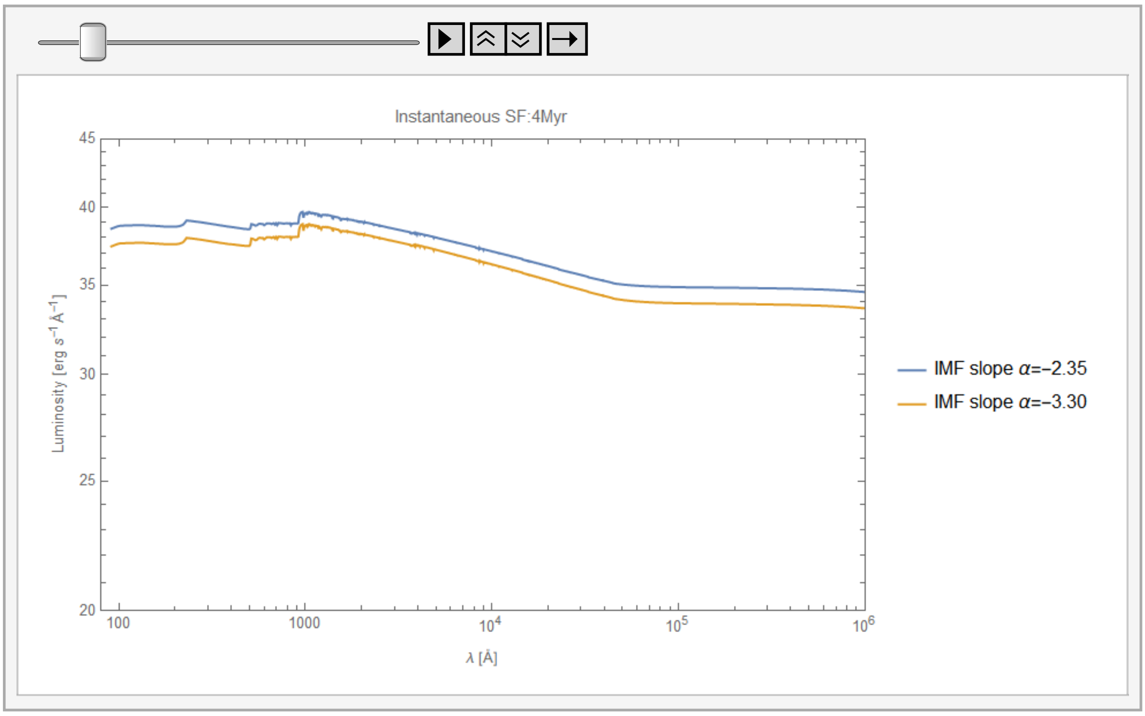


Now change the IMF slope from -2.35 to -3.3 (what does this mean?)

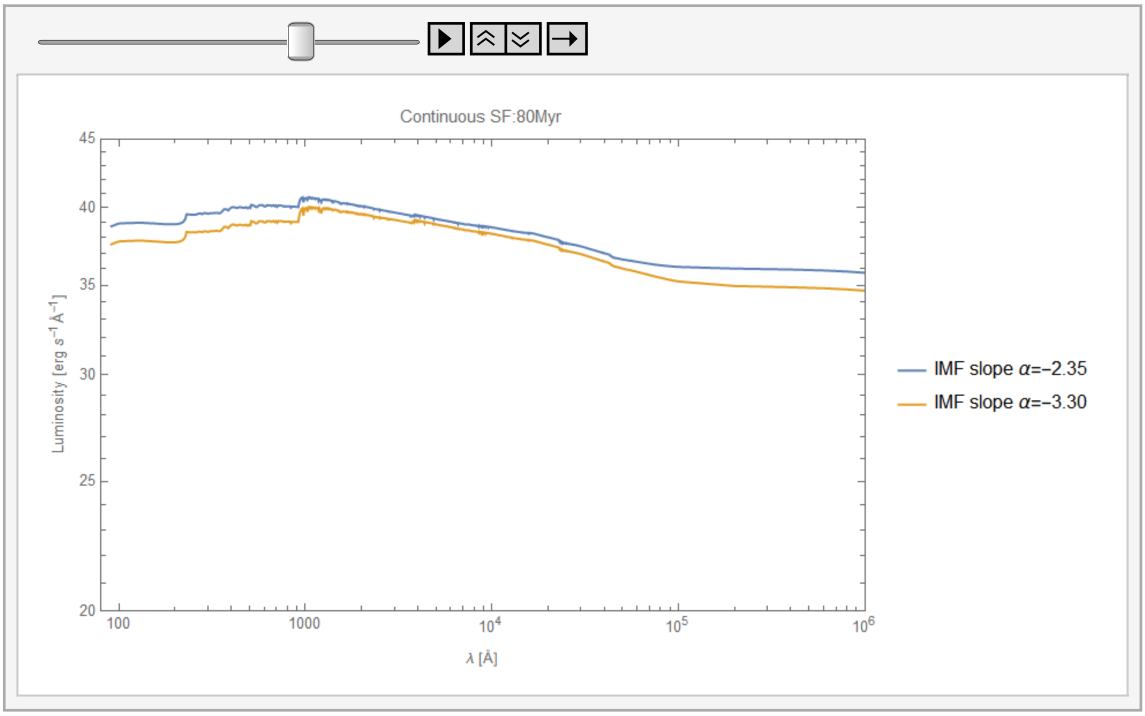
```
data3braw = Import[...] // Most; data3bhead = data3braw[[1 ;; 3]];
data3btimes = data3braw[[3, 3 ;; -1]];
data3bdata = data3braw[[4 ;; -1, 2 ;; -1]];
data3bλ = data3braw[[4 ;; -1, 1]];
data3b = Transpose[{data3bλ, #}] & /@ Transpose[data3bdata];
sel = {1, 5, 10, 20, 23, 28, 32, 36};
data4braw = Import[...] // Most;
data4bhead = data4braw[[1 ;; 3]];
data4btimes = data4braw[[3, 3 ;; -1]];
data4bdata = data4braw[[4 ;; -1, 2 ;; -1]];
data4bλ = data4braw[[4 ;; -1, 1]];
data4b = Transpose[{data4bλ, #}] & /@ Transpose[data4bdata];
sel = {1, 5, 10, 20, 23, 28, 32, 36};
```

Describe the differences. What is the physical reason?

Out[•]=



Out[ ]=

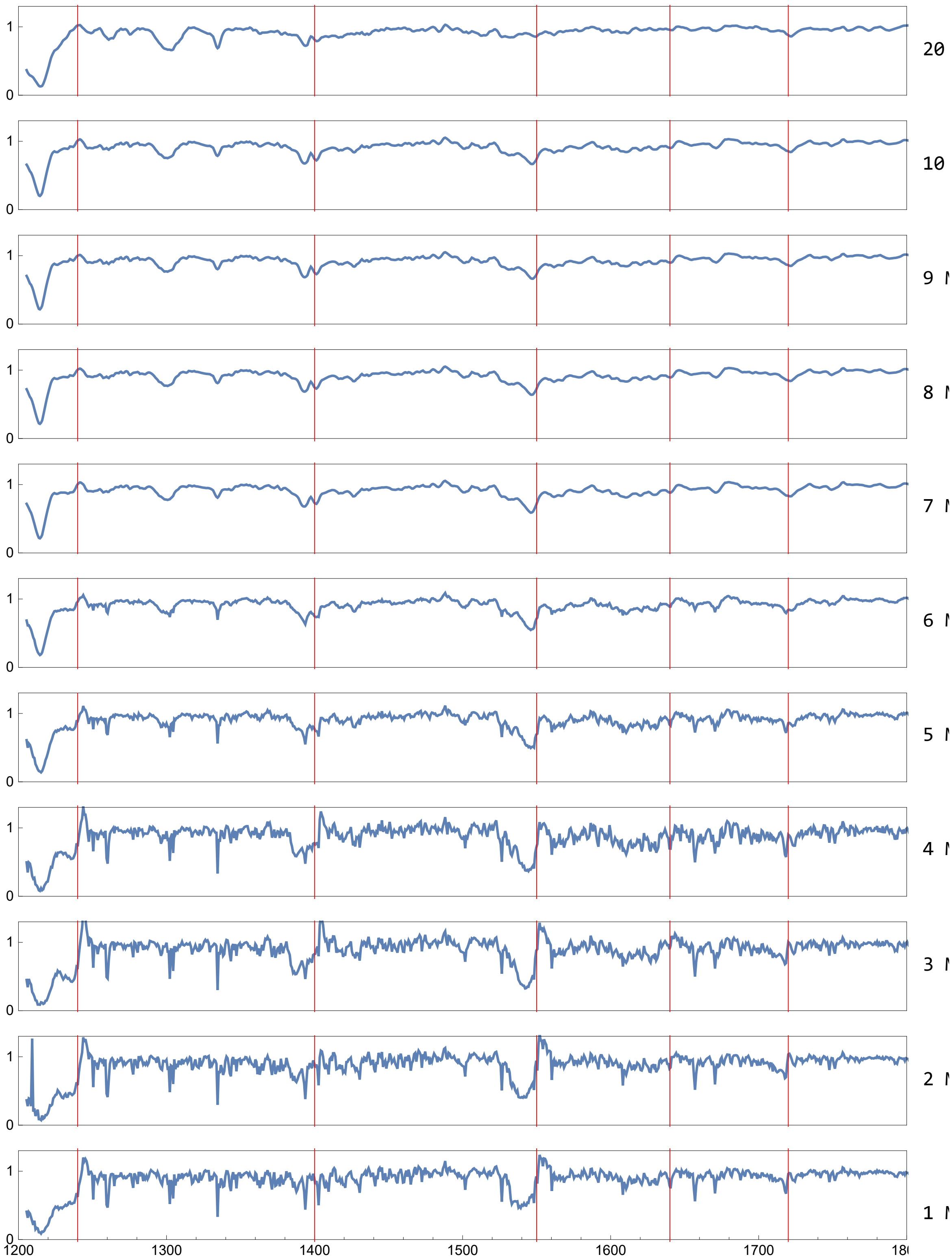


Spectral wind features

```
data13raw = Import[...] // Most;
data13times = data13raw[[3, 3 ;; -1 ;; 2]];
data13data = data13raw[[5 ;; -1, 2 ;; -1]];
data13λ = data13raw[[5 ;; -1, 1]];
data13 = Transpose[{data13λ, #}] & /@ Transpose[data13data];
sel = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20};
data14raw = Import[...] // Most;
data14times = data14raw[[3, 3 ;; -1 ;; 2]];
data14data = data14raw[[5 ;; -1, 2 ;; -1]];
data14λ = data14raw[[5 ;; -1, 1]];
data14 = Transpose[{data14λ, #}] & /@ Transpose[data14data];
sel = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20};
```

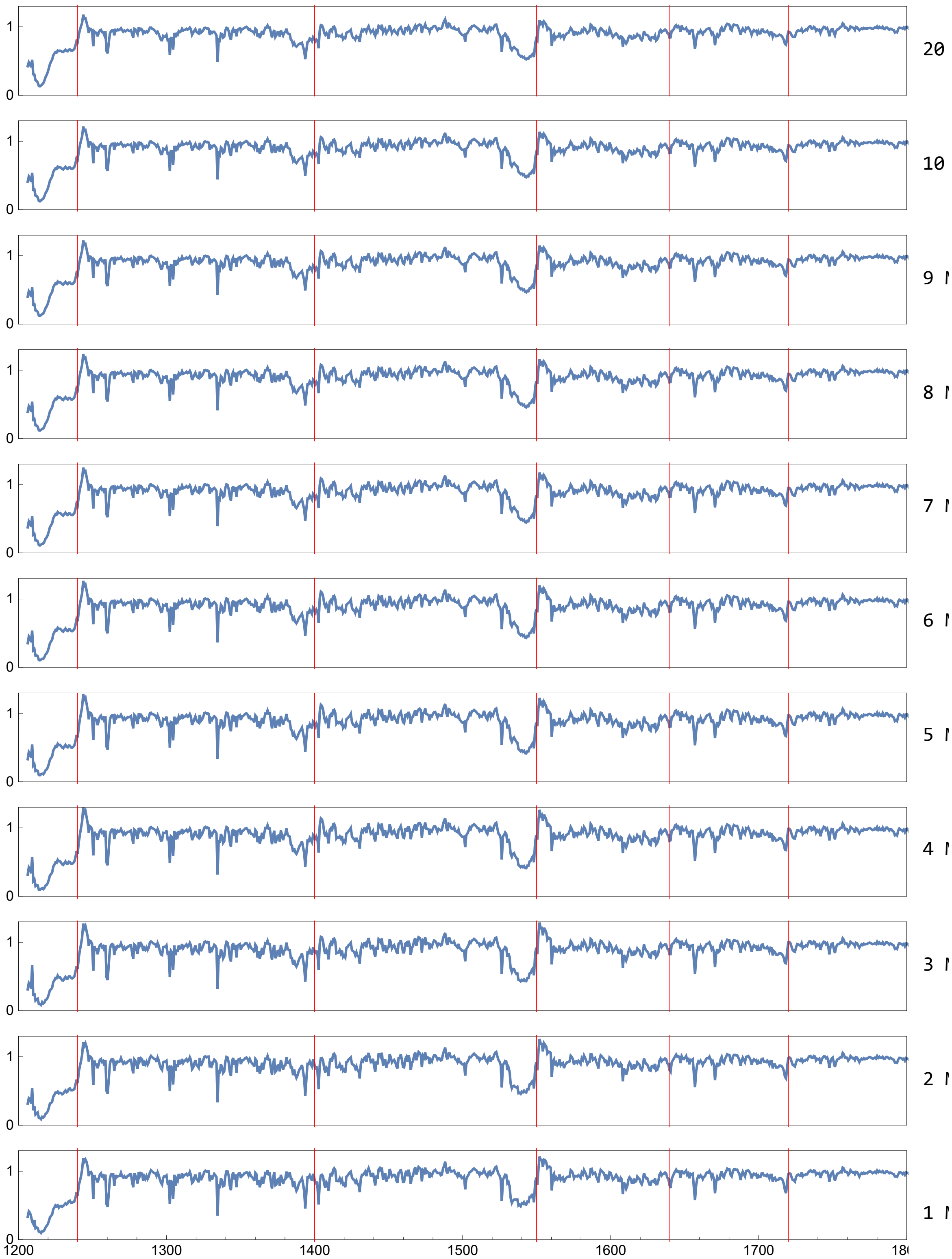
The red lines show indicators of stellar wind: C IV 1550, Si IV 1400, N V 1240, N IV 1720, He II 1640.
After ~7Myr transition from O to B star dominated population.

Out[#]=



for a continuous SF

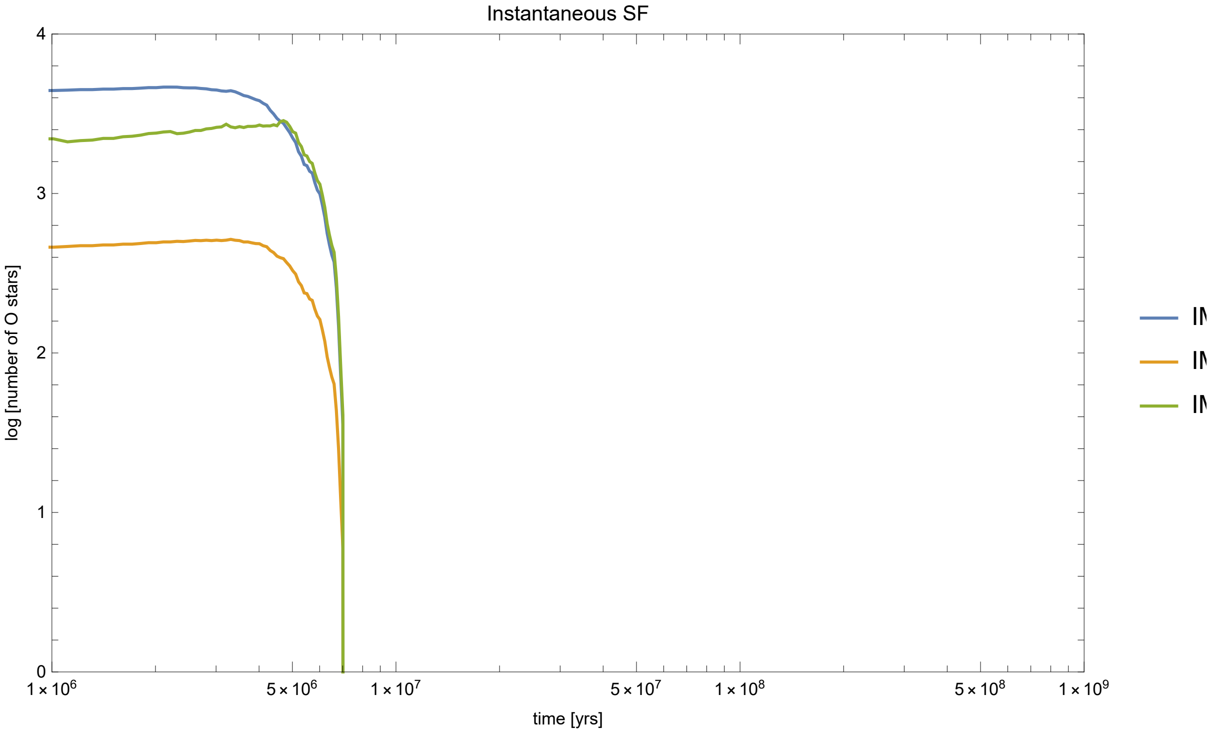
Out[ ]=



Number of O stars

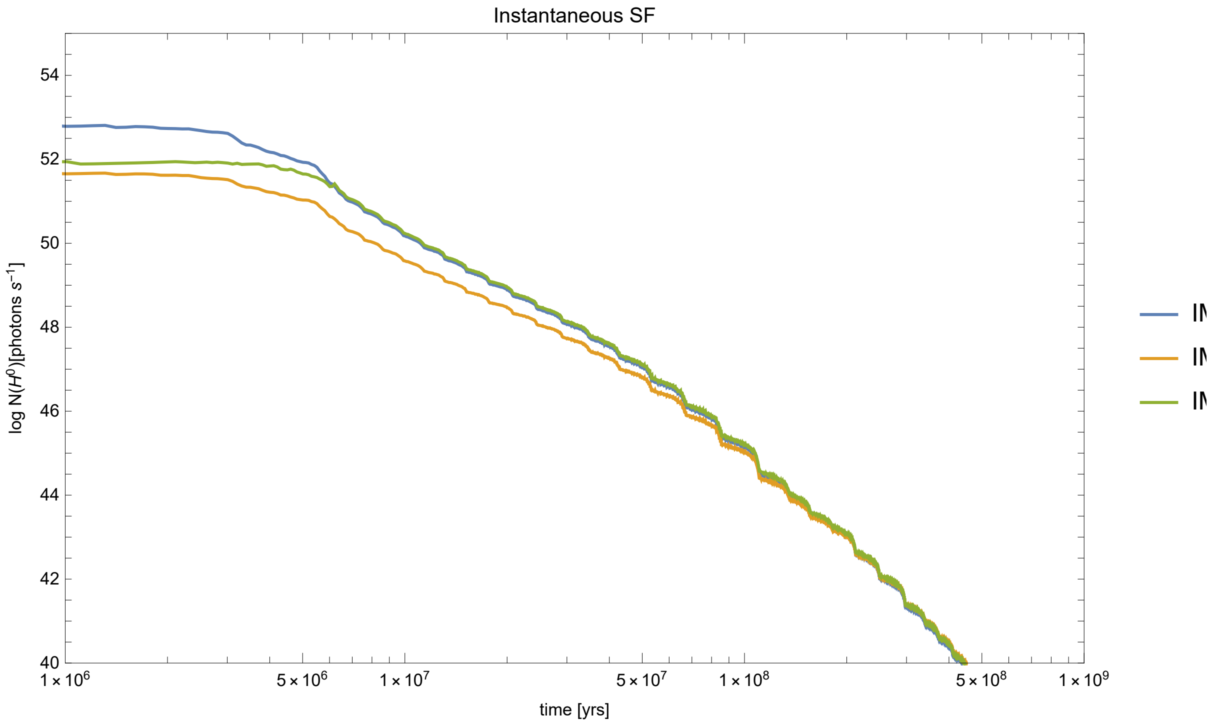
```
data37raw = Import[...] // Most;
data37times = data37raw[[All, 1]];
data37 = Transpose[{data37times, #}] & /@ Transpose[data37raw[[All, 2 ;; -1]]];
data38raw = Import[...] // Most;
data38times = data38raw[[All, 1]];
data38 = Transpose[{data38times, #}] & /@ Transpose[data38raw[[All, 2 ;; -1]]];
```

Out[∘]=



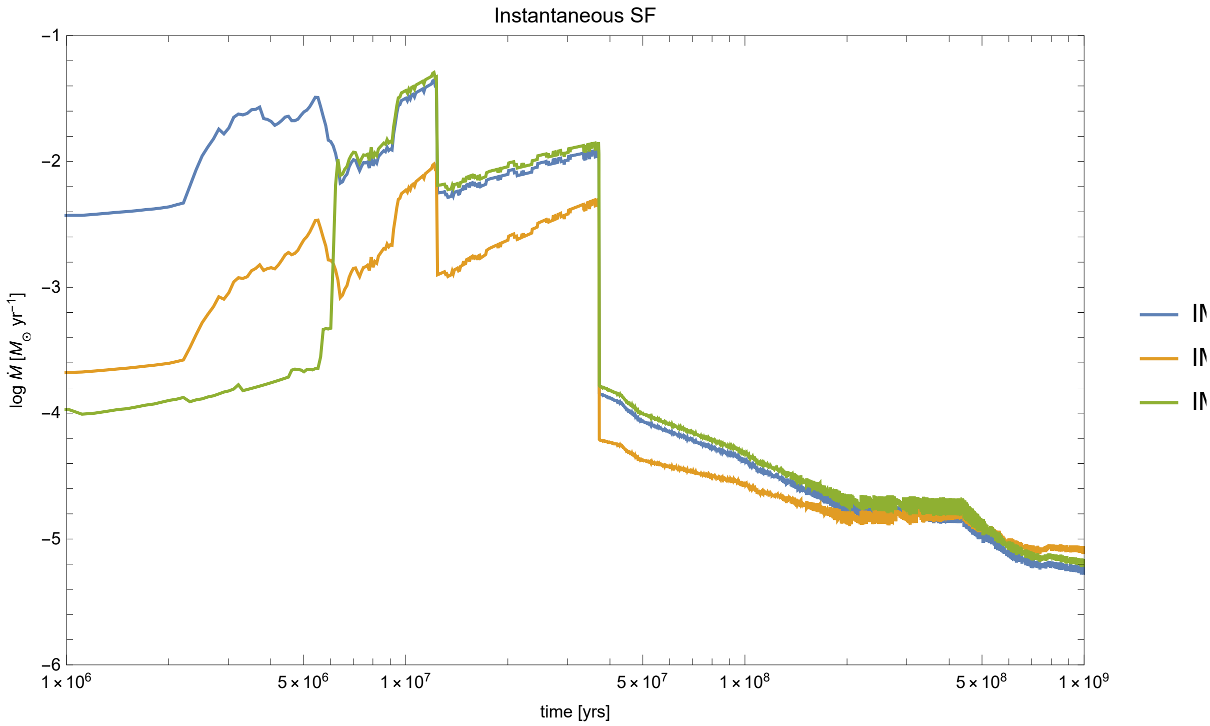
Number of Lyman Photons (λ<912 Å) Fig 77

Out[∘]=



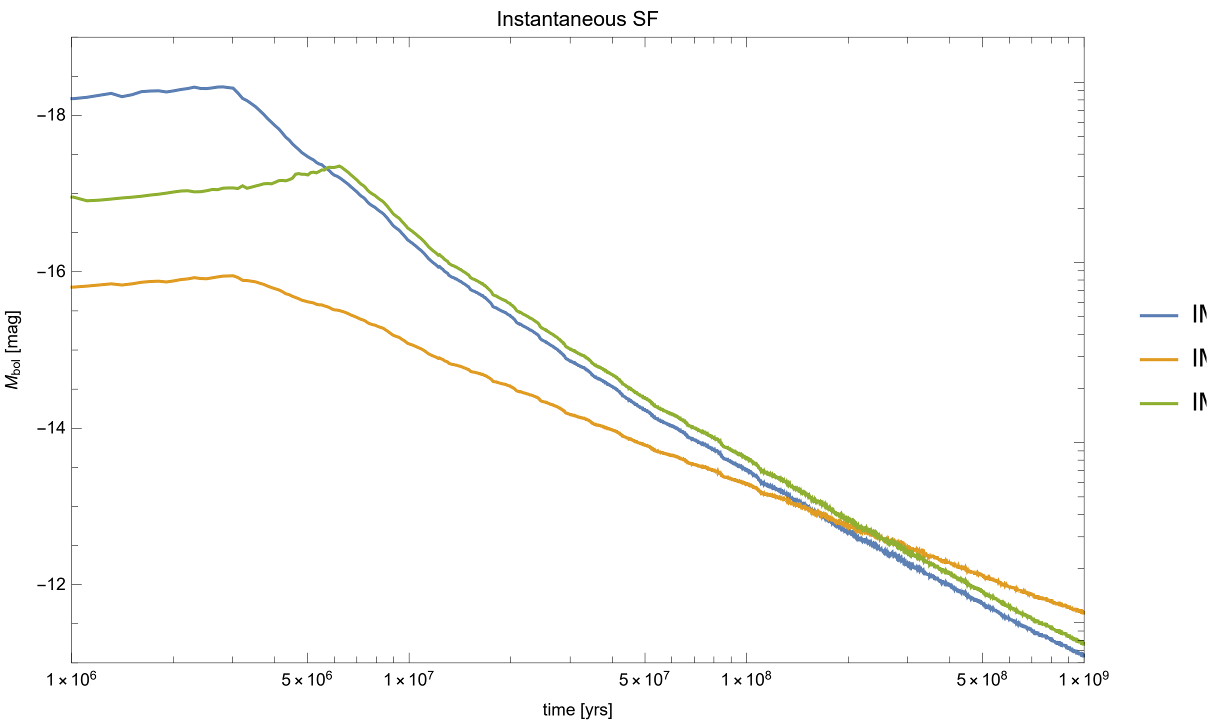
Mass loss rate (stellar winds + SNe)

Out[ ]=



Mbol

Out[ ]=



```
In[∘]:= MbolSun = 4.75;
        LumSol = 3.85 × 10^33
Out[∘]= 3.85 × 10^33
```

With magnitudes M_1 and M_2 and Luminosities/Fluxes S_1 and S_2 we have

$M_1 - M_2 = -2.5\,\mathrm{Log}_{10}\left(\frac{S_1}{S_2}\right)$

```
Luminosity[mbol_] := 10^((mbol-MbolSun)/-2.5) LumSol
```

10 Myr, 100 Myr, 1 Gyr

```
In[∘]:= data46times
In[∘]:= Position[data46times, 1.`*^8]
Out[∘]= {{1001}}
```

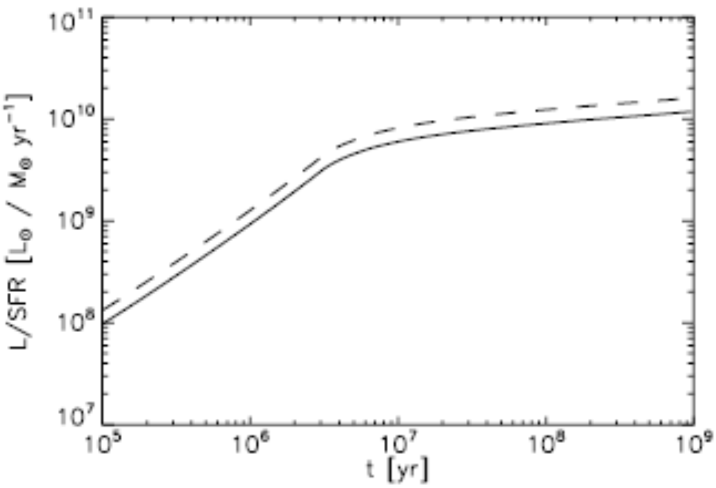
Top heavy IMF

(a) This problem can be done by using the default parameters with starburst99 and writing out the bolometric luminosity on a logarithmic grid from 0.1 Myr to 1 Gyr, for continuous star formation at a rate of 1 $M_\odot$ yr^{-1}. Taking the output luminosities, the results are

$$\mathrm{SFR}[M_\odot\ \mathrm{yr}^{-1}] = 4.3 \times 10^{-44} L_{\mathrm{tot}}[\mathrm{erg\ s}^{-1}] \quad (10\ \mathrm{Myr})$$
$$\mathrm{SFR}[M_\odot\ \mathrm{yr}^{-1}] = 2.9 \times 10^{-44} L_{\mathrm{tot}}[\mathrm{erg\ s}^{-1}] \quad (100\ \mathrm{Myr})$$
$$\mathrm{SFR}[M_\odot\ \mathrm{yr}^{-1}] = 2.2 \times 10^{-44} L_{\mathrm{tot}}[\mathrm{erg\ s}^{-1}] \quad (1\ \mathrm{Gyr}).$$

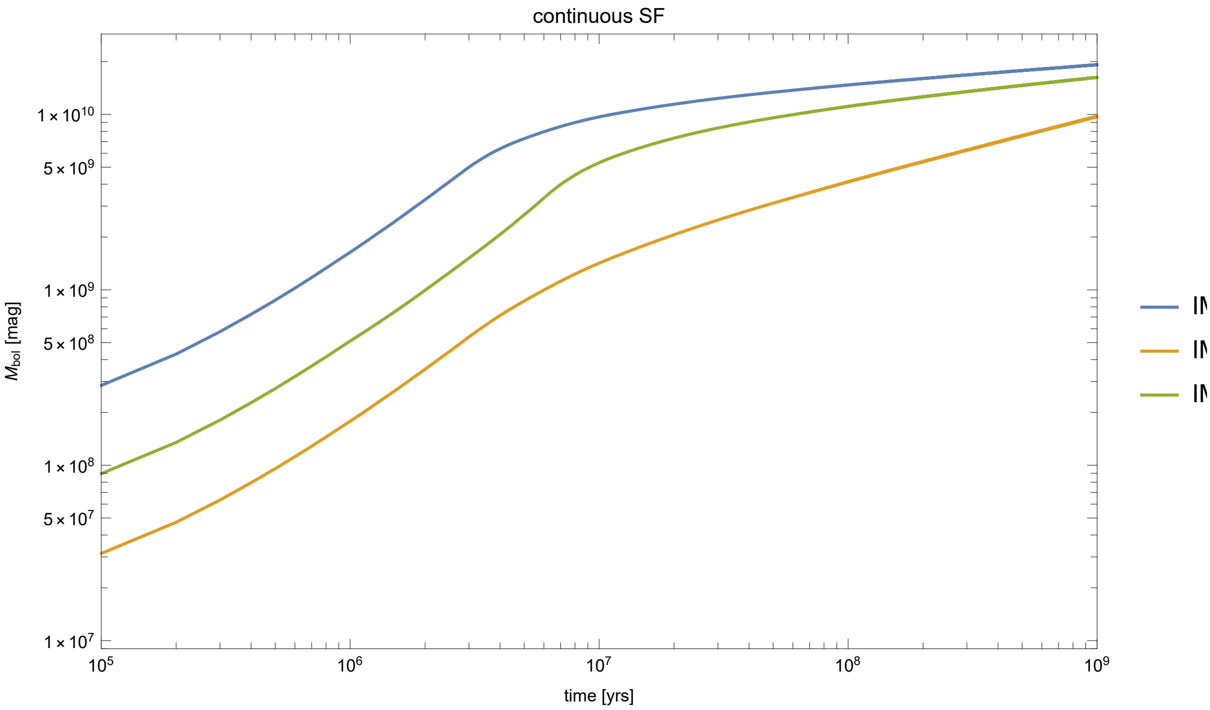
In comparison, the corresponding coefficient given by Kennicutt (1998) is 3.9×10^{-44}, the same to within a factor of 2.

(b) The plot of the starburst99 output is shown in Figure A.1. The solid line is the output with a normal IMF, and the dashed line is the output with a top-heavy IMF, for part (c).




```
In[∘]:= Luminosity[#]^-1 & /@ {data46[[3, 101, 2]],
           data46[[3, 1001, 2]],
           data46[[3, -1, 2]]}
Out[∘]= {4.89936 × 10^-44, 2.33851 × 10^-44, 1.59713 × 10^-44}
```

Out[•]=



Now a normal IMF

In[•]:=
```
Luminosity[#]^-1 & /@ {data46[[1, 101, 2]],
  data46[[1, 1001, 2]],
  data46[[1, -1, 2]]}
```

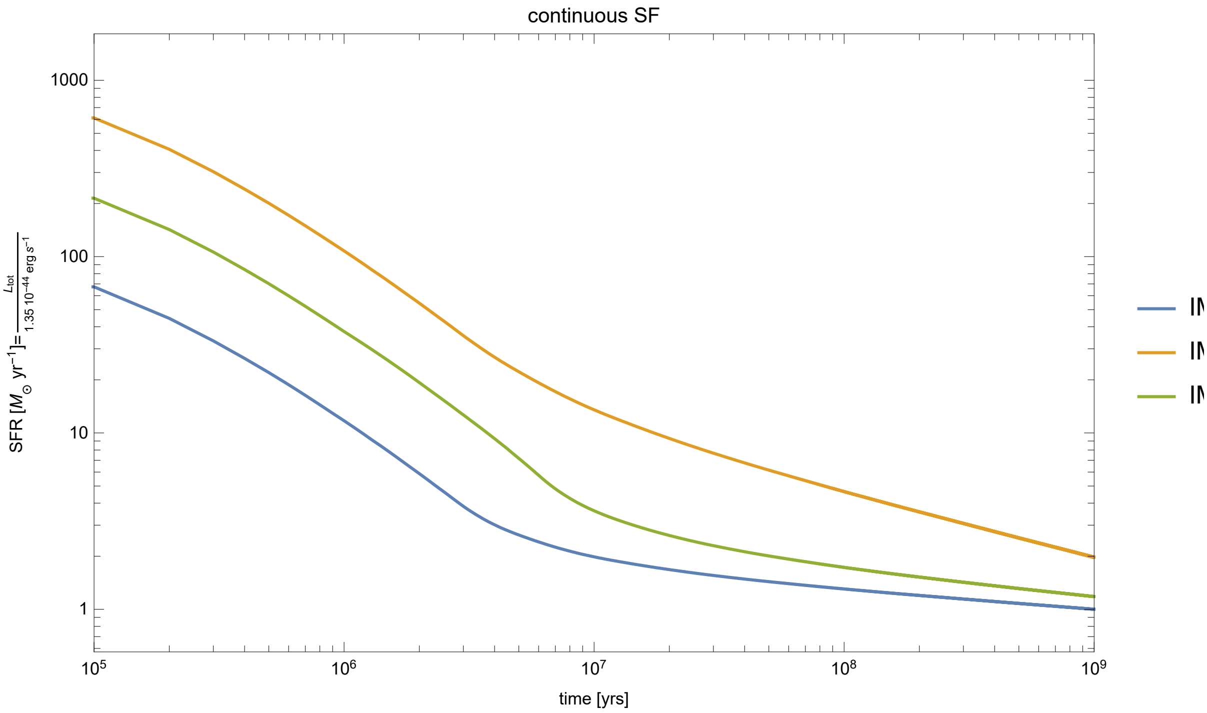
Out[•]= $\{2.68497 \times 10^{-44}, 1.76417 \times 10^{-44}, 1.35313 \times 10^{-44}\}$

(c) To generate this IMF, I told starburst99 to use a 1 section IMF with a slope of -2.3 running from 0.5 to 100 $M_\odot$. At equal ages, the numbers change to

$$\mathrm{SFR}[M_\odot\ \mathrm{yr}^{-1}] = 3.2 \times 10^{-44} L_{\mathrm{tot}}[\mathrm{erg\ s}^{-1}] \quad (10\ \mathrm{Myr})$$
$$\mathrm{SFR}[M_\odot\ \mathrm{yr}^{-1}] = 2.1 \times 10^{-44} L_{\mathrm{tot}}[\mathrm{erg\ s}^{-1}] \quad (100\ \mathrm{Myr})$$
$$\mathrm{SFR}[M_\odot\ \mathrm{yr}^{-1}] = 1.6 \times 10^{-44} L_{\mathrm{tot}}[\mathrm{erg\ s}^{-1}] \quad (1\ \mathrm{Gyr}).$$

These are a few tens of percent lower, because the IMF contains fewer low mass stars that contribute little light. The effect is mild, but that is partly because the change in IMF is mild. These results do suggest that the IR to SFR conversion does depend on the IMF.

Out[ ]=



Flat disk SED

νF_ν is a measure of the flux radiated by an object per logarithmic interval in frequency. Here F_ν is the flux density (units of energy per time per area per frequency), and ν is the frequency of radiation. An infinitesimal flux dF radiated into a logarithmic frequency interval $d(\ln\nu)$ is given by:

$$\text{SED} = \frac{dF}{d(\ln\nu)} = \frac{dF}{\frac{1}{\nu}d\nu} = \nu\frac{d}{d\nu}\left(\int_0^\infty F_\nu\, d\nu\right) = \nu F_\nu \qquad (1)$$

where we have used $d(\ln x) = dx/x$ and $F = \int_0^\infty F_\nu\, d\nu$. If we are interested in the energetics of an radiating object, the SED would be the quantity of interest, because the specific flux F_ν has units erg/Hz/cm^2/s, which, since it is divided by frequency (proportional to energy for photons), gives a number density of photons. To recover the energy within a given frequency band, we need to multiply by frequency (which is proportional to energy).

In other words, $\nu F_\nu = dF/d\ln\nu$ it is a measure of the total amount of energy per time per area (dF) over a logarithmic interval of frequency ($d\ln\nu$). Whatever frequency νF_ν peaks for a broadband emitter, that is the frequency where most of the energy is being emitted. If νF_ν peaks in the infrared, then we say the object is emitting most of its energy at infrared wavelengths.

a) Flux from a star

Assume a star with radius R_* and surface temperature T_* is at a distance D. Calculate the observed flux from the star:

$$F_\nu = \int_{4\pi} B_\nu(T_*)\, d\Omega \qquad (2)$$

The integral $\int d\Omega$ is done over the solid angle of the emitting source (not over full 4π). In case of a star the integration has to be done across the projected area of the star.

Remark to flux through area elements:

The full formula for $d\Omega$ is

$$d\Omega = \frac{\cos\theta}{D^2} d\sigma. \quad (3)$$

This is the solid angle of an area element $d\sigma$ at a distance D. The angle θ is the angle between the normal vector $\vec{n}$ of $d\sigma$ and the distance vector $\vec{D}$.

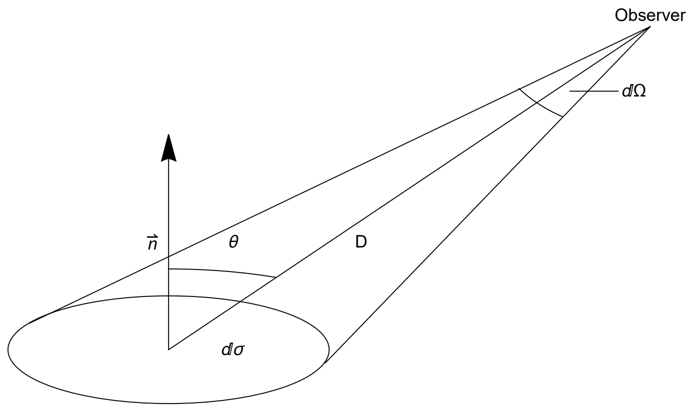


Fig 1: Flux through an area element $d\sigma$ received from an observer.

Solution

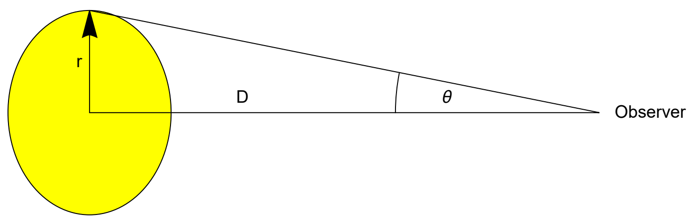
The flux at a distance D coming from a star is

$$F_\nu = \int_{4\pi} B_\nu(T_*)\, d\Omega = \int_{4\pi} B_\nu(T_*) \frac{\cos\theta}{D^2} d\sigma = \int_0^{2\pi}\int_0^{\theta_*} B_\nu(T_*) \frac{\cos\theta}{D^2} \sin\theta\, d\theta\, d\phi \quad (4)$$

$$F_\nu = 2\pi \int_0^{\theta_*} B_\nu(T_*) \frac{\cos\theta}{D^2} \sin\theta\, d\theta \quad (5)$$

This is the geometry of the problem:

Out[ ]=



changing variables: $r \approx D \sin\theta$, $dr \approx D\cos\theta\, d\theta$

$$F_\nu = 2\pi \int_0^{\theta_*} B_\nu(T_*) \frac{\cos\theta}{D^2} \sin\theta\, d\theta = 2\pi \int_0^{R_*} B_\nu(T_*) \frac{r\, dr}{D^2} \quad (6)$$

$$F_\nu = \pi B_\lambda(T_*) \frac{{R_*}^2}{D^2} \quad (7)$$

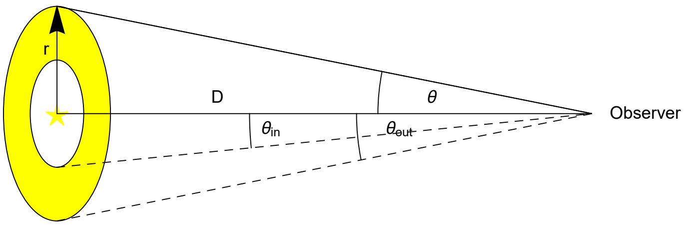
b) Solid angle of a disk

Assume, a black-body disk, with inner radius R_{inner}, outer radius R_{outer}, inclination angel i and distance D. The flux seen by a distant observer (to whom the disk appears to be a point source) will be given by flux ~ specific intensity × solid angle. As seen by the distant observer at distance D, each annulus, which is oriented at an angle i with respect to the observer's line of sight, presents a solid angle of $d\Omega$.

Make a sketch of the geometry of the problem and show that :

$$d\Omega = \frac{2\pi r\, dr \cos i}{D^2} \tag{8}$$

Out[ ]=



c) Flux from a disk

Using equation (8) write down an expression for νF_ν for the black-body disk with temperature law $T(r)$.

Assume the following numerical values:

$T_* = 4000\,K$, $R_* = 2.5\,R_\odot$, $R_{inner} = 6\,R_*$, $R_{outer} = 2.3 \times 10^4\,R_*$, $i = 0\,°$

Plot νF_ν versus ν for different temperature laws:

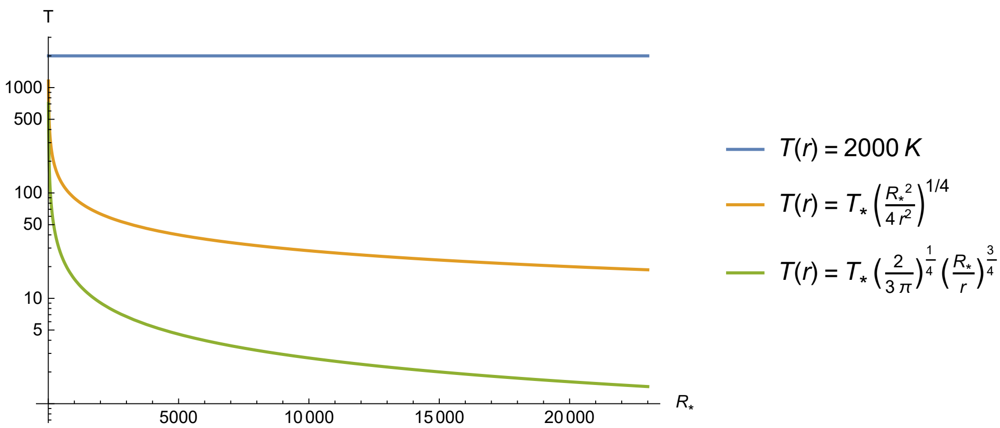
1. isothermal disk of $T(r) = 2000\,K$
2. $T(r) = T_* \left(\frac{R_*^2}{4 r^2}\right)^{1/4}$
3. the Chiang and Goldreich model: $T(r) = T_* \left(\frac{2}{3\pi}\right)^{\frac{1}{4}} \left(\frac{R_*}{r}\right)^{\frac{3}{4}}$

What wavelengths are suitable to study the disk?

Overlay on your sketch the SED of the central stellar black-body. Log-log space is best.

Solution

Out[ ]=



$$\nu F_\nu = \nu \int B_\nu(T(R)) \cos\theta\, d\Omega = \nu \int B_\nu(T(R)) \frac{2\pi r \cos i}{D^2} dr \tag{9}$$

$$\nu F_\nu = \frac{4\pi h \nu^4}{c^2}\frac{\cos i}{D^2}\int_{r_i}^{r_o}\frac{r\,dr}{\mathrm{Exp}\left[\frac{h\nu}{k\,T(r)}\right]-1} \tag{10}$$

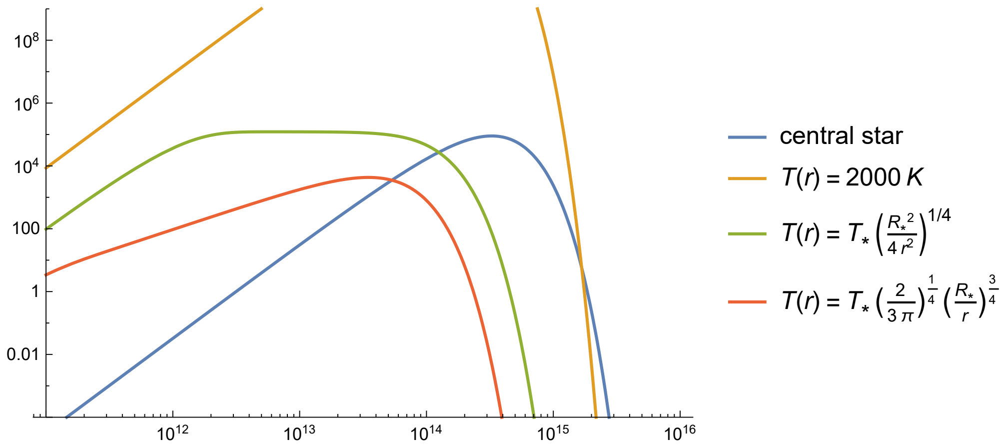
In[◦]:= $\mathrm{B\nu}[\nu\_, T\_] := \frac{2\times 6.6260755\times 10^{-27}\,\nu^3}{2.99792458^{10^2}}\;\frac{1}{\mathrm{Exp}\left[\frac{6.6260755\times 10^{-27}\,\nu}{1.3806504\times 10^{-16}\,T}\right]-1}$

In[◦]:= $\mathrm{\nu F\nu 1}[\nu\_, i\_, D\_, ri\_, ro\_, Tdisk\_] :=$
$\frac{4\pi\, 6.6260755\times 10^{-27}\,\nu^4}{(2.99792458^{10})^2}\;\frac{\mathrm{Cos}[i\,\mathrm{Degree}]}{(D\,3.086\times 10^{18})^2}\;\mathrm{NIntegrate}\left[\frac{r}{\mathrm{Exp}\left[\frac{6.6260755\times 10^{-27}\,\nu}{1.3806504\times 10^{-16}\,Tdisk}\right]-1}, \{r, ri, ro\}\right]$

In[◦]:= $\mathrm{\nu F\nu 2}[\nu\_, i\_, D\_, ri\_, ro\_, Tstar\_, Rstar\_] := \frac{4\pi\, 6.6260755\times 10^{-27}\,\nu^4}{(2.99792458^{10})^2}$
$\frac{\mathrm{Cos}[i\,\mathrm{Degree}]}{(D\,3.086\times 10^{18})^2}\;\mathrm{NIntegrate}\left[\frac{r}{\mathrm{Exp}\left[\frac{6.6260755\times 10^{-27}\,\nu}{1.3806504\times 10^{-16}\,Tstar\left(\frac{Rstar^2}{4\,r^2}\right)^{1/4}}\right]-1}, \{r, ri, ro\}\right]$

In[◦]:= $\mathrm{\nu F\nu 3}[\nu\_, i\_, D\_, ri\_, ro\_, Tstar\_, Rstar\_] :=$
$\frac{4\pi\, 6.6260755\times 10^{-27}\,\nu^4}{(2.99792458^{10})^2}\;\frac{\mathrm{Cos}[i\,\mathrm{Degree}]}{(D\,3.086\times 10^{18})^2}\;\mathrm{NIntegrate}\Big[$
$\frac{r}{\mathrm{Exp}\left[\left(\frac{3\pi}{2}\right)^{1/4}\frac{6.6260755\times 10^{-27}\,\nu}{1.3806504\times 10^{-16}\,Tstar}\,(r/Rstar)^{3/4}\right]-1}, \{r, ri, ro\}, \mathrm{WorkingPrecision}\to 40\Big]$

Out[◦]=

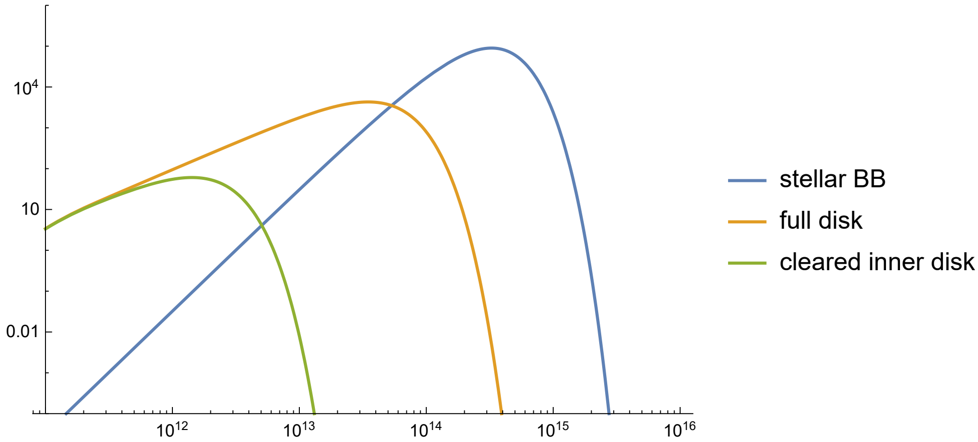


d) SED of the star + evolved disk

As the disk evolves it could form a planet, and this planet will clear out the inner region of the disk. Assuming that the disk was cleared out up to the orbital distance of Jupiter, but then continues normally, plot the observed emission from the system star + disk using your result from problem 2 c). Apply the Chiang and Goldreich model for $T(r)$. What do you notice? What wavelengths are more suitable to study such systems?

Solution

Out[∘]=



In[∘]:= $2.3 \times 10^4 \times 2.5 \times 7 \times 10^{10}$

Out[∘]= 4.025×10^{15}

In[∘]:= $6 \times 2.5 \times 7 \times 10^{10}$

Out[∘]= 1.05×10^{12}

In[∘]:= $5 \times 1.49 \times 10^{13}$

Out[∘]= 7.45×10^{13}