Title

The role of radiation pressure in the dynamics of HII regions at z>1

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The Role of Radiation-Pressure in the dynamics of HII regions at high redshift

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1 Introduction

Galaxies form most of their stellar mass at $z \sim 2-3$, when irregular clumps of star formation evolve into the Hubble sequence in the local universe. In order to understand the process of galaxy formation, it is of interest to study the physical nature of galaxies at this epoch. Deep UV-IR photometry and spectroscopy surveys are efficient in detecting $z \sim 2-3$ star-forming galaxy populations (Erb et al. 2006, Tacconi et al 2008, Bouché et al. 2007, Liu et al 2008), making such studies possible. From the large samples of available data, it is possible to infer global properties of these galaxies such as stellar mass, dynamical masses, star formation rate, chemical abundances, and population age. These studies have greatly increased the understanding of the physical nature of $z \sim 2-3$ galaxies, indicating the large variety of evolutionary states. One particularly interesting result, which is the focus of our work, is that a considerable fraction of $z \sim 2-3$ galaxies do not follow the excitation sequence described by nearby HII regions and star forming galaxies.

Liu et al. (2008) compared local galaxies from Sloan Digital Sky Survey (SDSS) to $0.1 < z < 1.5$ and UV-selected $z \sim 2$ galaxies. Their work shows that the physical conditions of HII regions change with redshift. In particular they infer that at $z \sim 2$ the ionization parameter U must be significantly higher than the value in the local universe. The observed value of the ionization parameter in the Milky Way is $3 \times 10^{-4} \leq U \leq 3 \times 10^{-3}$ (Kewley & Dopita 2002), while at $z \sim 2$ it is $U \sim 10^{-2}$ (Liu et al. 2008). With this work we want to give a possible explanation of why the ionization parameter increases at higher redshift.

Krumholz & Matzner 2009 studied the role of radiation-pressure in the dynamics of HII regions. When radiation-pressure dominates they expect a ionization parameter $U \sim 10^{-2}$. They study a case of non-hydrostatic equilibrium, but when the timescale for the shell to expand is small compared to the signal speed within the shell, quasi-hydrostatic equilibrium should be established in the shell. In hydrostatic equilibrium Dopita & al. (2002) show that when radiation-pressure becomes significant the ionization parameter never rises above a critical value $U \sim 10^{-2}$, above which dust absorption is more relevant than photoelectric absorption. Radiation pressure piles up gas against the inner wall of the expanding shell, preventing the value of the ionization parameter to go up.

In $z \sim 2$ galaxies the star formation rate is about $10 M_{\odot}/yr$ (Erb et al. 2006), a large fraction of OB stars are likely to be produced. The total amount of ionizing luminosity is then larger than $S \sim 10^{50} s^{-1}$ typical value in the Milky Way. Additionally, the ambient mean density is an order of magnitude higher than the local universe. Under those conditions, the expansion of an HII region can be described by the radiation-pressure dominated regime. The expanding shell is stopped by the ambient density and the HII region will show a higher value of ionization parameter as a signature.

In order to prove this scenario, we use a population synthesis code that generate a family of HII regions and let them evolve according to the analytic formula of Krumholz & Matzner (2009). We suppose that the galaxy is spatially unresolved and that the star formation rate and the ambient density are constant. We also want to compare our results with observations, to do so we generate the expected line luminosity of a family of HII region with CLOUDY code. We implement those luminosities in the population synthesis code and sum over the all galaxy.

2 Population Synthesis Code

To help understand the high ionization parameter observed in $z \sim 2 - 3$ galaxies, we wrote a code that reproduces a synthetic set of data comparable with observations. The code consists of two parts: a population synthesis code and Cloudy prediction of line luminosities.

The population synthesis code creates, evolves and destroys HII regions. It is built under the assumption that the galaxy can be represented as a point source that contains a collection of HII regions. The star formation rate and the ambient density are constant.

2.1 HII regions creation and destruction

HII regions are created according to the star formation rate that regulates the total amount of mass it is allowed to be created in stars. We use the same distribution of association mass M_a as in Krumholz et al. (2006)

$$\frac{dF_{a,M_{cl}}}{d\,ln\,M_a} \propto \frac{H(\epsilon M_{cl} - M_a)}{1 - (\epsilon M_{cl}/M_a)^{\alpha-\beta}} \left(\frac{1}{M_a}\right). \tag{1}$$

$H(x) = (1, 0)$ for $(x > 0, x < 0)$ is the Heaviside step function, $\alpha \approx 0.6$ and $\beta \approx 0.67$. Equation 1 regulates how many massive star and how many small stars populate a star-forming region. We use a random generator to pick the mass of the next association to be formed. When an association is created, we assign an ionizing luminosity

$$S_{49} = \frac{\langle s_{49}(m)\rangle_{IMF}}{\langle m\rangle_{IMF}} M_a,$$

and the main sequence ionizing lifetime

$$\langle t_{ms}\rangle_a = \frac{\langle s_{49}(m) t_{ms}\rangle_{IMF}}{\langle s_{49}(m)\rangle_{IMF}} M_a,$$

where $s_{49}(m)$ and t_{ms} are the ionizing luminosity (in units of 10^{49} photons/sec) and main-sequence lifetime of a star of mass m. Values for $s(m)$ and $t_{ms}(m)$ are taken from Parravano et al. (2003) for, which, together with the Kroupa (2001) IMF, give $\langle s_{49}(m)\rangle_{IMF} = 7.2 \times 10^{-4}$, $S_{49} = 3.4 \times 10^{-3}(M_a/M_\odot)$, and $t_{ms} = 3.8 Myr$.

We do not follow the HII regions evolution when the main-sequence lifetime of the parent star is over. That is when we destroy HII regions.

2.2 HII region evolution

HII regions evolve in time according to the analytical formula derived in Krumholz & Matzner 2009. They study the role of radiation pressure in the dynamics of HII regions. While in classical HII regions the radiation pressure can be ignored, in regions with large ionizing luminosities cannot. In these regions the ambient velocity dispersion and escape velocity exceed the ionization gas sound speed.

Let the density profile be $\rho = \rho_{cl}(r/R_{cl})^{k_\rho}$ as described above. When radiation pressure is negligible, the source ionizes the surrounding material that expands due to its thermal pressure. The neutral gas is then swept up and collected into a thin shell. When radiation pressure is important and after an initial rapid expansion, the momentum eqaution for the thin shell of swept up gas is

$$\frac{d}{dt}\left(\frac{4}{3}\pi r_{II}^3 \bar{\rho}\, \dot{r}_{II}\right) = 4\pi r_{II}^2 \left\{\rho_{II}\left[c_{II}^2 + u_{II}(u_{II} - \dot{r}_{II})\right] + \frac{f_{trap}L}{4\pi r_{II}^2 c}\right\} \tag{2}$$

where r_{II}, u_{II} and ρ_{II} are the radius, the velocity and the density of the gas interior to the shell. The mean density inside the sphere of radius r is $\bar{\rho}(r) = [3/(3-k_{rho})]\rho_0(r/r_{cl})^{-k_\rho}$. The variable f_{trap} accounts for an enhancing factor for the radiation-pressure force by trapping of energy within the expanding shell. When $f_{trap} = 0$, the shell is optically thin and photons pass through it without depositing any momentum. When $f_{trap} = 1$, the shell is optically thick and every photon is absorbed. In our calculations we assume a factor $f_{trap} = 2$ to account for the different factors of trapping of energy, such as stellar winds, dust grains and resonant interaction of photons.

The right hand side of equation 2 consists of two terms: gas pressure and radiation pressure. When radiation-pressure is dominant, Krumholz & Matzner 2009 rewrite the momentum equation in terms of $x = r/r_{ch}$ and $\tau = t/t_{ch}$, where r_{ch} and t_{ch} are:

$$r_{ch} = \frac{\alpha_\beta}{12(2.2)^2\pi\phi}\left(\frac{\epsilon_0}{k_B T_{II}}\right)^2 f_{trap}^2 \frac{\psi^2 S}{c^2} \tag{3}$$

$$t_{ch} = \sqrt{\frac{4\pi}{3-k_\rho}\frac{\rho_0 r_0^{k_\rho} c}{f_{trap}L} r_{ch}^{4-k_\rho}}. \tag{4}$$

Here ψ is the ratio between total luminosity L and ionizing luminosity S; ϕ instead is a dimensionless number that account for absorption of photons by dust grains or by other elements' free electrons. For numerical calculations we used the following values: $T_{II} =$

$7000K$, $\phi = 0.73$, $\psi = 2$, $f_{trap} = 2$ and the recombination rate $\alpha_\beta = 3.46 \times 10^{-13} cm^3 s^{-1}$. With the described change of variables, the momentum equation 2 can be re-written:

$$\frac{d}{dt}\left(x_{II}^{(3-k_\rho)}\frac{d}{dt}x_{II}\right) = 1 - x_{II}^{1/2}. \tag{5}$$

Krumholz & Matzner found an approximate solution for equation 5 by weighting the two contibutions of radiation-pressure regime and gas-pressure regime. The approximate solution of the expansion of the shell of an HII in radiation-pressure dominated regime is:

$$x_{II,approx} = \left(x_{II,rad}^{(7-K_\rho)/2} + x_{II,gas}^{(7-K_\rho)/2}\right)^{2/(7-K_\rho)} \tag{6}$$

where the gas-pressure term is

$$x_{II,gas} = \left(\frac{(7-2k_\rho)^2}{4(9-2k_\rho)}\tau^2\right)^{2/(7-2k_\rho)} \tag{7}$$

and the radiation-pressure term is

$$x_{II,rad} = \left(\frac{4-k_\rho}{2}\tau^2\right)^{1/(4-k_\rho)} . \tag{8}$$

Equation 6 describes the time evolution of the HII region radius and it is implemented in the code.

2.3 Time stepping

Instead of setting a fixed timestep, we adopte a timestep regulated by the star-formation rate. Since the star formation rate $\dot{M}_*$ is fixed, and we know what is the mass of the next association $M_{next,a}$ we are going to create, the timestep dt is set accordingly as

$$dt = \frac{M_{next,a}}{\dot{M}_*}.$$

With this choice we optimize the code and avoid useless calculations when there is no possibility of generating new associations.

As consequence of our time stepping procedure, we notice a periodicity in the outputs. Figure 1 shows the logarithm of the scaled ionizing luminosity $s49 = S/10^{49}s^{-1}$ versus the logarithmic radius after $\sim 6Myr$ (left) and $\sim 24Myr$ (right). The color code indicates the total number of HII regions. It seems that there is a periodicity of creation of HII regions even though we are randomly picking stars out of distribution, one at each time step. We claim that it is only a consequence of the time stepping. Consider that it is more likely to produce a lot of stars with small masses than very massive ones and that small stars are all created at tiny dt. As a consequence a collection of small stars are produces almost at the same time. When a massive star can form, the time step dt increases. During that dt, all the little stars previously created evolve in radius,

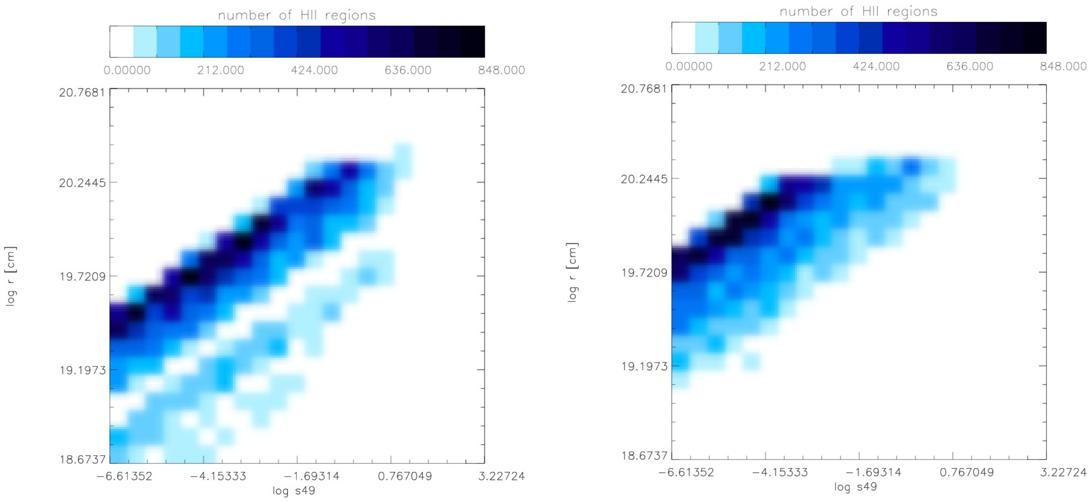

Fig. 1: Logarithm of the scaled ionizing luminosity $s49 = S/10^{49}s^{-1}$ versus the logarithmic radius after $\sim 6Myr$ (left) and $\sim 24Myr$ (right). The color code indicates the total number of HII regions. For this run, the star-formation rate is $1M_{\odot}/yr$ and ambient density is $1cm^{-3}$.

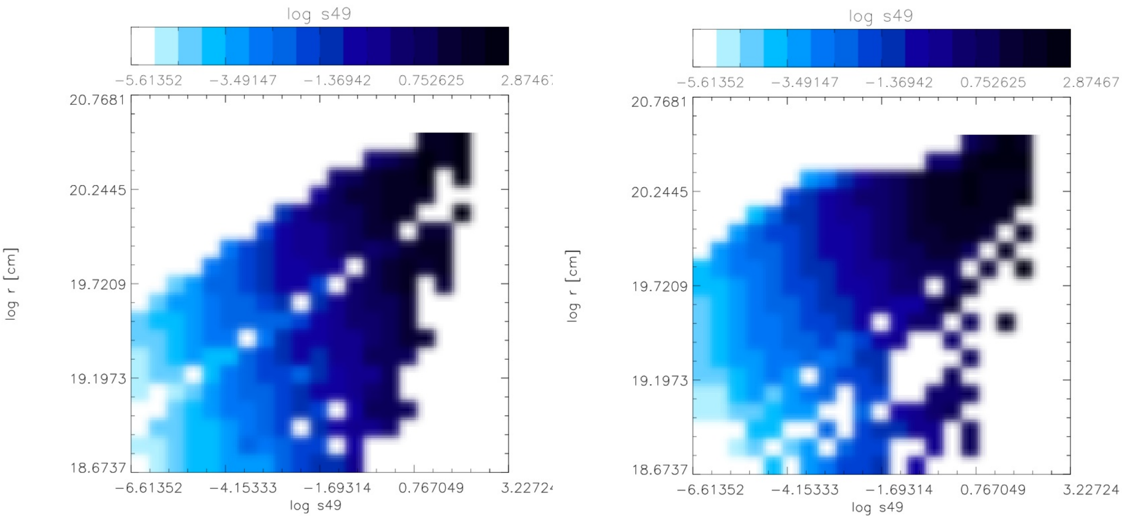

Fig. 2: Same as Figure 1, but with the color in each pixel weighted by the total ionizing luminosity in that pixel rather than the number of HII regions.

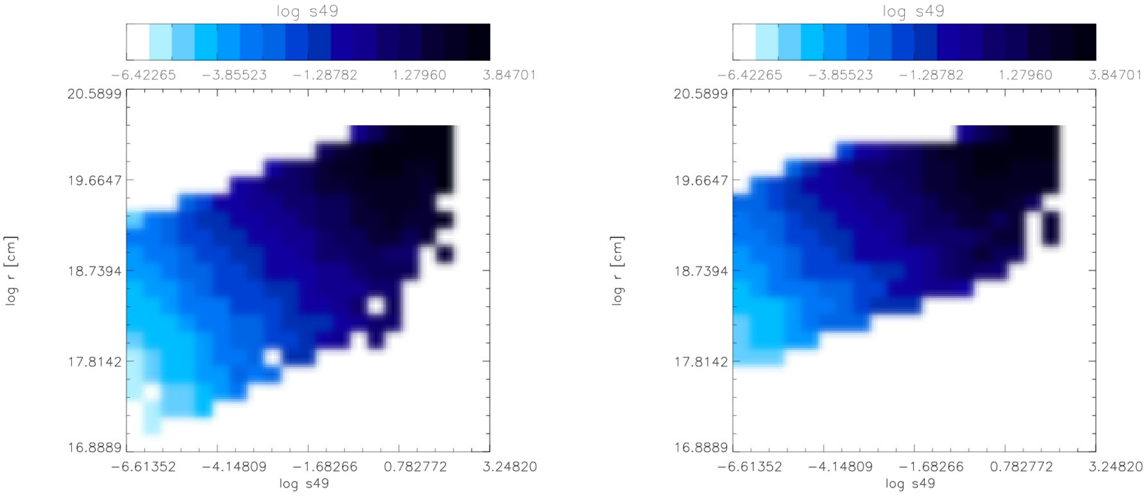

Fig. 3: As Figure 2, but notice the different color coding scale. Lyman-Break conditions: star-formation rate is $10 M_{\odot}/yr$ and number density is $10 cm^{-3}$.

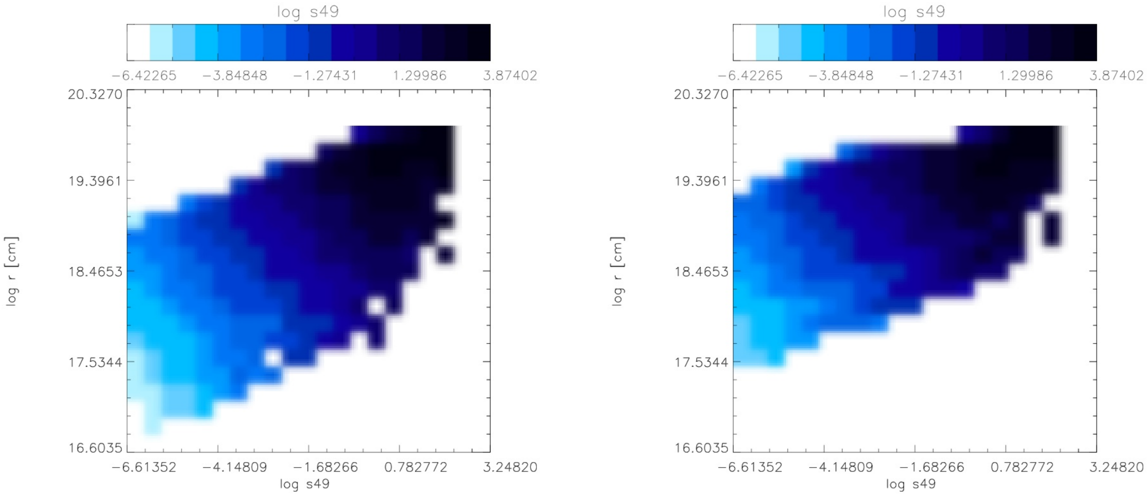

Fig. 4: As Figure 2, but notice the different color coding scale. Lyman-Break conditions: star-formation rate is $10 M_{\odot}/yr$ and number density is $100 cm^{-3}$.

therefore upwards in the plot. Looking at figure 1 the left plot has a bottom strike that mearged with the top strike (because those HII regions evolved) in the plot on the right.

Figure 2 shows the logarithm of the scaled ionizing luminosity $s49 = S/10^{49}s^{-1}$ versus the logarithmic radius after $\sim 6Myr$ (left) and $\sim 24Myr$ (right). The color code indicates the sum of the ionizing luminosity. By comparing Figure 1 and 2, we notice that small HII regions that are high in number (as Figure 1 shows) have very small ionizing luminosity. Therefore the effect we highlighted earlier, that is due to small HII regions, it is irrelevant at the end of this work.

Figure 3 and 4 shows again the same as Figure 2: the logarithm of the scaled ionizing luminosity $s49 = S/10^{49}s^{-1}$ versus the logarithmic radius after $\sim 6Myr$ (left) and $\sim 24Myr$ (right) with color code the sum of the ionizing luminosity. We simulate now a Lyman-Break galaxy. For Figure 3 we set star-formation rate $10M_{\odot}/yr$ and number density $10cm^{-3}$. For Figure 4 we set we keep the star-formation rate at $10M_{\odot}/yr$ and increase the number density to $100cm^{-3}$. We notice how increasingly important is the effect of massive HII regions in terms of ionizing radiation.

3 Ionization parameter

The ionization parameter describe the ratio of photons to baryons. It is a measure of the degree of ionization and the relative thickness of the HII region. In our calculations we define the ionization parameter as $U = S/(4\pi R_{st}^2 n^2 c)$, where R_{st} is the Strömgren radius and n is the number density. The definition we use for U is good for a classical HII regions, as the Spitzer (1978) self-similar solution: after an fast accelerating initial phase, the expanding shell of swept up material evolve self-similarly in an constant ambient medium. However, in the radiation-pressure dominated regime the density does not stay constant. Therefore, our prediction of ionization parameter are not exactly the same as the ionization parameter derived from line ratios as it is done for observations. In fact, when the density is not constant, the ionization parameter is not well defined.

Figure 5 shows the cumulative function of the ratio of the ionizing luminosity over the total ionizing luminosity of all HII regions as a function of the logarithm of the ionization parameter U. The top plot represents a Milky Way kind of galaxy: star-formation rate of $1M_{\odot}/yr$ and number density $1cm^{-3}$. Lower plots show the situation for a Lyman-Break galaxy with star-formation rate of $10M_{\odot}/yr$ and number density $10cm^{-3}$ (left) $100cm^{-3}$ (right). As predicted, the ionization parameter increases for conditions typical of Lyman-Break galaxies.

4 Future work: Cloudy tables

In order to compare our results with observations, we need to know the luminosity of the galaxy. We will generate the expected line luminosity of a family of HII region with CLOUDY (Ferland et al. 1998) code. CLOUDY is a spectral synthesis code that simulate conditions of the interstellar medium under different initial conditions. It computes the non-equilibrium ionization, thermal, and chemical state of a cloud that is exposed to an

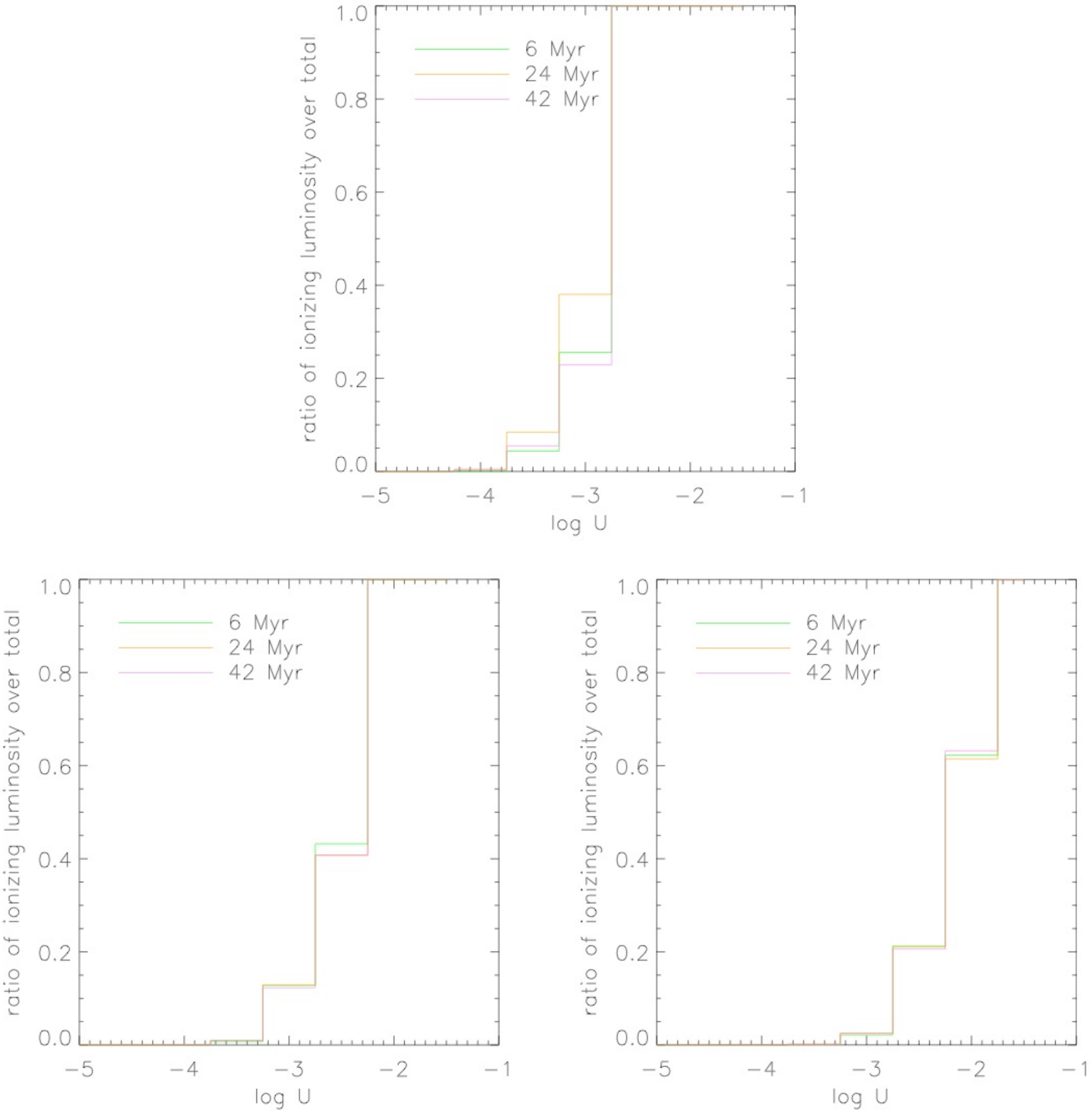

Fig. 5: Cumulative function of the ratio of the ionizing luminosity over the total ionizing luminosity of all HII regions as a function of the logarithm of the ionization parameter U. Top plot represents a Milky Way kind of galaxy: star-formation rate of $1 M_\odot/yr$ and number density $1 cm^{-3}$. Lower plots show the situation for a Lyman-Break galaxy with star-formation rate of $10 M_\odot/yr$ and number density $10 cm^{-3}$ (left) $100 cm^{-3}$ (right).

external source of radiation.

4.1 Input parameters

CLOUDY determines the ionization, temperature, and chemical state of a cloud and then predict its spectrum. Few free parameter must be specified, in particular the shape and brightness of the radiation field, the total hydrogen density, the composition of the gas and whether grains are present, the thickness of the cloud.

When we pick the initial conditions for CLOUDY, we want to make sure we are in the radiation-pressure-dominated regime. Therefore we set the inner radius smaller than the characteristic radius, eq. 3. Then we create a family of HII regions by changing the number density of the cloud. The radiation source is a blackbody with temperature $\log T_{rad}/K = 4.65$ and ionizing luminosities $S = 10^{49.6}$ and $S = 10^{52.6}\, s^{-1}$. The dust grains have sizes appropriate for the ISM in our galaxy and the abundance is the mean of the Orion Nebula abundance.

5 Conclusions

We wrote a population synthesis code to generate a family of HII regions and and let them evolve following a solution that accounts for both radiation pressure- and gas pressure-dominated evolution. We suppose that the galaxy is spatially unresolved and that the star formation rate and the ambient density are constant. We find that the ionization parameter increases for Lyman-Break galaxies thanks to the effect of HII regions evolution under radiation-pressure dominated regime. In order to draw further conclusions, we should compare our results with observations. We will do so by creating a set of synthetic data with CLOUDY code.

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