How Fast Are Galaxies Making Stars?

Galaxies are machines for turning gas into stars. One of the most fundamental questions we can ask about galaxies is how efficient are they, or how fast do they create stars? In this assignment, we will figure out how to estimate the star formation rate of galaxies.

Part 1: Making Pancakes

As an analogy, imagine that you are cooking pancakes. After you cook them and take them off the griddle, they are **steaming hot for about one minute** before they cool enough that they don't give off steam any more. Imagine you've steadily been making pancakes for a little while, and someone comes over and sees this:

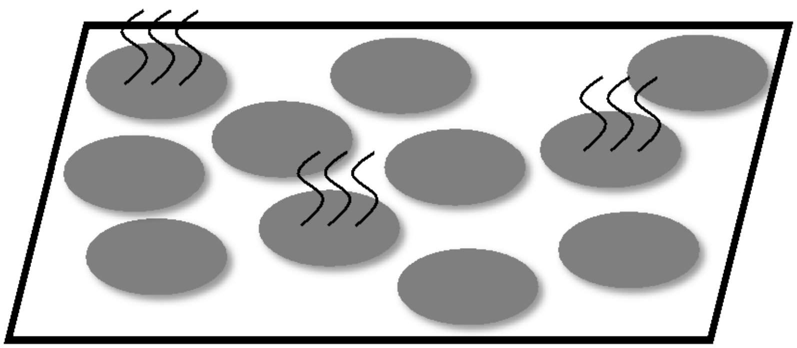


Figure 1: A platter of cooked pancakes, some of which are hot and steamy.

1. How many steaming pancakes are there?

   How many non-steaming pancakes are there?

2. How long ago did you take the steaming pancakes off the griddle? (circle one)

   Within the last minute   More than one minute ago

3. How many pancakes did you cook within the past minute?

4. At what rate are you making pancakes (in units of "pancakes per minute")?

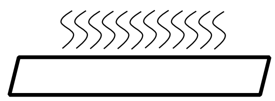
   Explain your reasoning.

5. Which of the following mathematical expressions best expresses your answer from Question 4? (*N* represents the number of steaming pancakes and *T* represents how long pancakes remain steamy)

   a) $T \times N$ b) $T \div N$ c) $N \div T$

6. Why can't you use the *cool* pancakes to figure out the rate that pancakes are being made?

7. Now imagine that you are too far away to see the individual pancakes, but you can see that there are 12 "wiggles" worth of steam (look at Figure 1 to see how steamy each pancake is):



   a. How many hot steaming pancakes are there? Explain.

   b. At what rate are you making pancakes (in units of "pancakes per minute")?

Part 2: Counting Short-Lived Stars

As you discovered in Part 1, we can find the rate that something short-lived is being made by counting how many of these objects exist and dividing by how long they last. We used the hot steamy pancakes as an indicator of pancake production. In a similar way, when thinking about stars, we use the hot bright, short-lived stars as our indicator for star production.

Table 1: Lifetimes of main sequence stars with different spectral types.

Spectral type	O	B	A	F	G	K	M
Typical lifetime	4 million years	100 million years	1 billion years	3 billion years	10 billion years	50 billion years	10 trillion years

8. Using Table 1, which type of star is most like the cool pancakes that might have been around for a long time?

   Which type of star is most like the hot steamy pancakes that must have been formed recently?

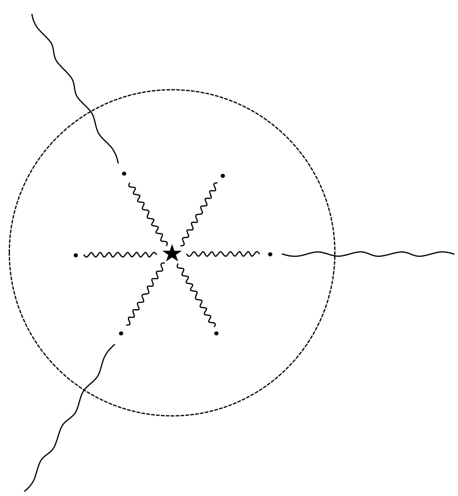
9. As a result, which type of star might you use to estimate the rate that stars are being formed?

Step A: Ionized Bubbles and Hα Photons

Some stars give off very high energy ultraviolet (UV) photons that are energetic enough that they can ionize hydrogen. These stars end up with ionized "bubbles" surrounding them filled with hot gas. Hydrogen atoms in the bubbles absorb UV photons and re-emit the energy at other wavelengths of light; about ½ the time, they emit an optical (visible light) photon called *Hα* with a wavelength of 656.3nm. Therefore, the *ionized bubble that surrounds a star will transform ionizing UV photons into half as many optical Hα photons.*

We can use the *Hα* photons to count stars and measure the star formation rate just like we used the steam to count pancakes and measure the pancake formation rate in Question 7.

Figure 2: Schematic view of a star emitting high-energy UV ionizing photons, and the ionized bubble that is emitting optical Hα photons.

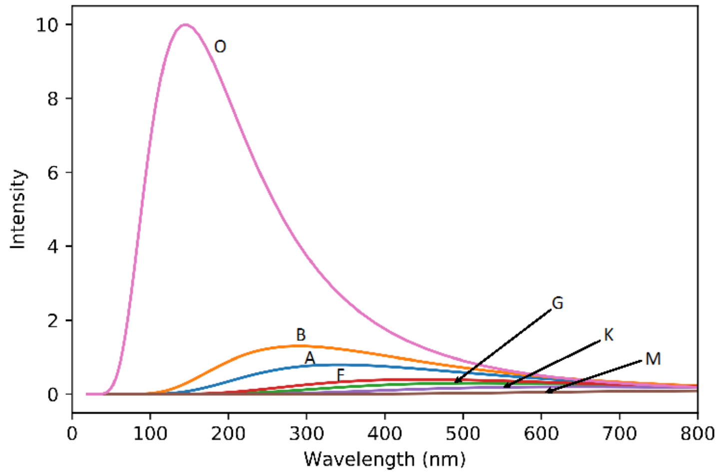


10. In Figure 2, label the following:
    a. Hydrogen atoms
    b. Ionizing UV photons
    c. Hα photons
    d. Ionized bubble of hot gas
    e. Star

    Draw an arrowhead on each of the UV and Hα photons to indicate the direction they are traveling.

11. In Figure 2, for every Hα photon that is emitted by Hydrogen atoms, how many ionizing UV photons did the star emit?

Figure 3: This graph provides blackbody curves for stars of different spectral types. Note that only photons with wavelengths of <u>91nm or shorter</u> have enough energy to ionize a hydrogen atom.



12. Stars of which spectral type emit photons that can ionize hydrogen?

13. Stars of which spectral type should have Hα photons coming from the ionized bubbles surrounding them?

Step B: Measuring Star Formation Rates of Real Galaxies

Now consider the galaxy NGC 6744, shown below. Observations show that it is emitting *Hα* photons at a luminosity of 1.5×10^{41} erg/s.

Figure 4: The galaxy NGC 6744. The reddish glow along the spiral arms comes from *Hα* photons!

14. Given that *Hα* photons have a wavelength 656.3nm, what is the energy of each *Hα* photon?

    Remember that the energy of a photon of wavelength λ is $E = \frac{hc}{\lambda}$ where

    h = 6.63 x 10^{-27} erg s $\quad\quad$ c = 3.00 x 10^{8} m/s

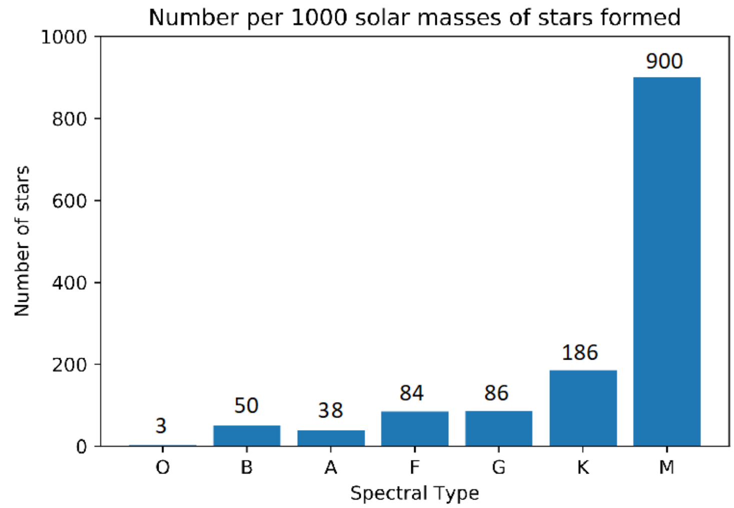
15. What is the rate of *Hα* emission for NGC 6744 (in units of "Hα photons per second")? Show your work.

16. Given the rate of *Hα* production from Question 15, what is the rate of UV ionizing photon production in NGC 6744 (in units of "UV photons per second")? Show your work.

17. The average O-type star emits 1.3 x 10^{49} ionizing UV photons per second. How many O-type stars are there in the galaxy? Explain your reasoning.

18. How fast is the galaxy making O-type stars (in "O-type stars per year")? Explain your reasoning. (Hint: You might want to refer back to Question 5 and Table 1).

19. Consider the following histogram, which shows how many stars of each type are formed every time **1000 solar masses of stars form**.



(a) Every time 2000 solar masses of stars are formed, how many O-type stars are formed?

(b) Given your answers to questions 18 and 19(a), what is the total mass of stars being made each year in NGC 6744 (in "solar masses per year"; this is referred to as the *star formation rate*). Explain your reasoning.

20. What is the rate that this galaxy making new G-type stars like Sun (in "G-type stars per year")? Show your work.

21. Given your answer to Question 20, how many years is it, on average, between when new "Suns" form in this galaxy?

You've just figured out how fast NGC 6744 makes new Suns, just by seeing how much light it's emitting at one particular wavelength!!

Histories of Galaxies

We can learn a lot about the histories of galaxies just by looking at how fast they are forming stars today, which can be measured using Hα light. The figure below can help us understand these histories.

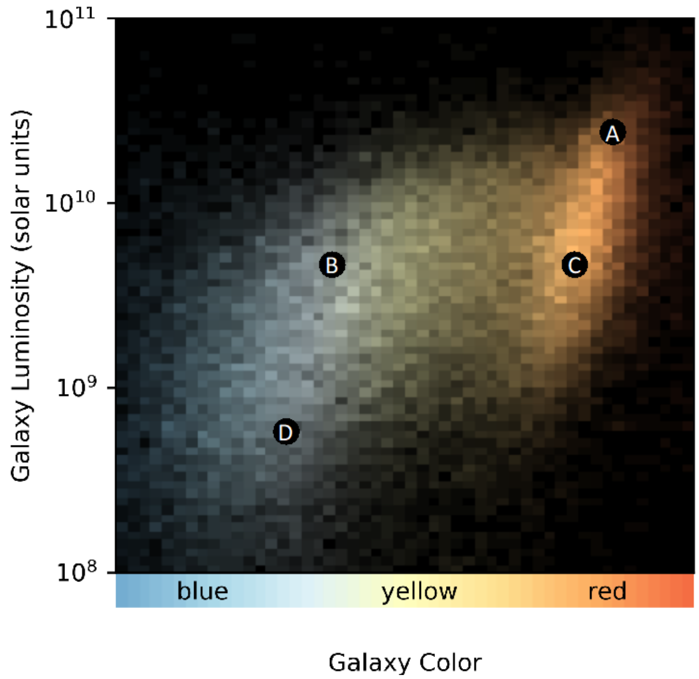


Figure 1: Luminosity of Galaxies versus their Color. The brighter parts of this diagram correspond to combinations that are very common among galaxies, while the dark parts of this diagram correspond to combinations that never or hardly ever occur. The labels A—D correspond to particular galaxies.

1. What can you say about the colors of the *most luminous* galaxies? (circle one)

    a. They are bluer in color.

    b. They are equally likely to be blue as red.

    c. They are redder in color.

2. Give a pair of labels (A, B, C, D) that correspond to galaxies that have *similar luminosity* but *very different color*.

3. Give a pair of labels (A, B, C, D) that correspond to galaxies that have *similar color* but *very different luminosities*.

Now consider the galaxies shown in the table below. These galaxies correspond to the four labels A—D in Figure 1.

	M 74 	IC 767 	Small Magellanic Cloud 	M 105 
Luminosity	Medium	Medium	Low	High
Mass of stars	5×10^9 solar masses	3×10^9 solar masses	2×10^8 solar masses	2×10^{10} solar masses
Current star formation rate	0.5 solar masses per year	0.01 solar masses per year	0.2 solar masses per year	0.0001 solar masses per year
Age	1×10^{10} years	1×10^{10} years	1×10^{10} years	1×10^{10} years
Galaxy type				
Color				
Label from Figure 1				

4. Fill out the missing rows in the table: for each galaxy list what type of galaxy it is (Elliptical / Spiral / Irregular), its color (Red / Blue), and which label A – D from Figure 1 it corresponds to.

5. Do the galaxies with higher star formation rates appear bluer or redder?

6. Do elliptical galaxies have high or low star formation rates?

7. Now focus on M 105.

    a. If M 105 had produced stars at the star formation rate listed in the table over its entire life, would it have produced the mass of stars listed in the table? Explain.

b. What average star formation rate (in "solar masses per year") would M 105 have to have had over its lifetime in order to produce the mass of stars listed in the table?

c. If the average star formation rate you calculated in part (b) was typical of its star formation rate over its lifetime, how old was M 105 when it first had 2 million solar masses of stars in it?

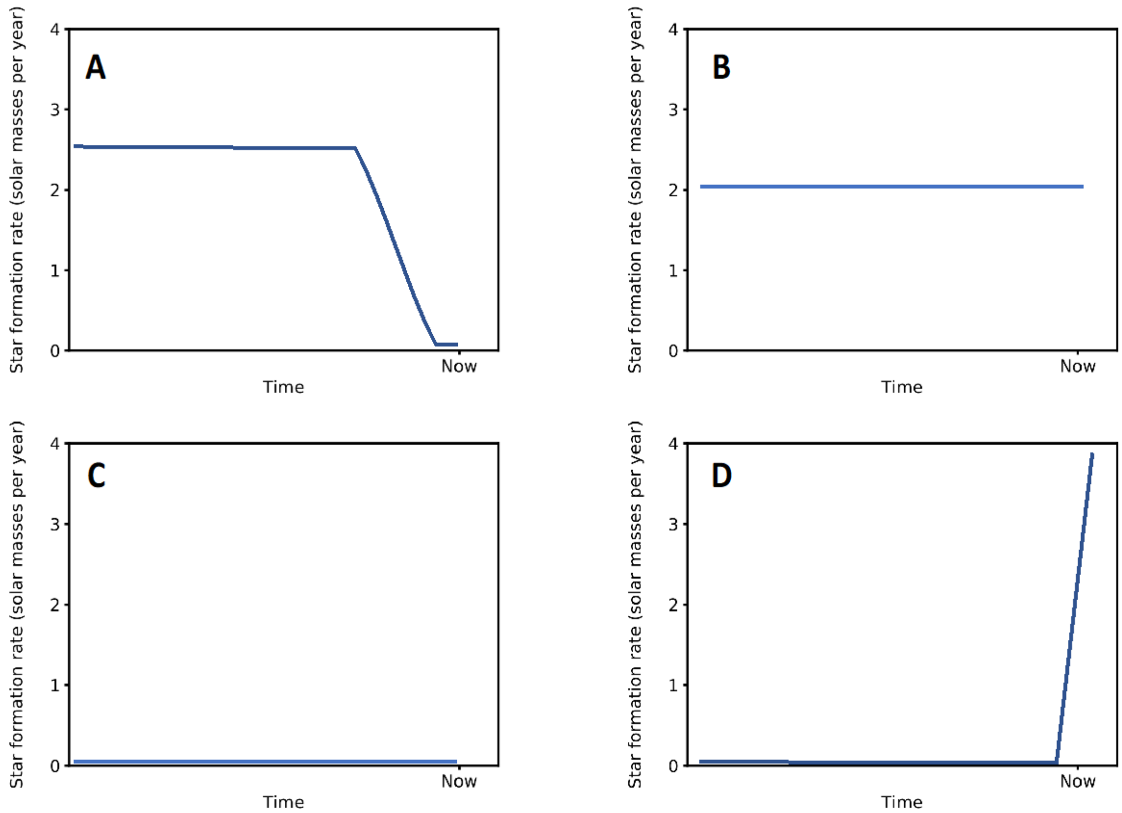
8. How does the current star formation rate of M 105, listed in the table, compare to the average it experienced over its life, which you just calculated? (circle one)

   a. The star formation rate now is much higher than the average I calculated.

   b. The star formation rate now is about the same as the average I calculated.

   c. The star formation rate now is much lower than the average I calculated.

9. Each of these graphs below (A-D) show the star formation rate over the history of a galaxy. Which graph could be the star formation history of M 105?



10. Now calculate the average star formation rate for the Small Magellanic Cloud.

11. How does the average star formation rate of the Small Magellanic Cloud you just calculated compare to the current star formation rate listed in the table?

    a. The star formation rate now is much higher than the average I calculated.

    b. The star formation rate now is about the same as the average I calculated.

    c. The star formation rate now is much lower than the average I calculated.

12. Consider a galaxy whose star formation rate was **high in the past** but is **low now**.

    a. This galaxy is most likely what type?

        Spiral   Elliptical

    b. This galaxy is most likely what color?

        Blue   Red

    c. In the past, when this galaxy's star formation rate was high, it was most likely what color?

        Blue   Red

    d. In the past, when this galaxy's star formation rate was high, it was most likely what type?

        Spiral   Elliptical

13. Which of the following properties of a galaxy can change during a galaxy's life? Circle all that apply.

    Color

    Galaxy type

    Star formation rate