NMSU Astronomy Cume #432 **Moire Prescott**
March 16, 2019

Overview:

This Cume is based on the paper "Galaxy and Quasar Fueling Caught in the Act from the Intragroup to the Interstellar Medium" by Johnson et al. 2018.

The exam contains 6 questions, worth 84 total points. The anticipated passing grade is 63 points or 75%.

Additional Instructions:

- Please start each question on a new page (leaving enough room at the upper left for the staple) and put your name on each page. Staple your packet of pages together in question order at the end.
- If at any point you aren't able to remember or calculate a specific number, just introduce a variable and proceed with the rest of the question.

Useful Information:

- Speed of light $c = 3 \times 10^{10}$ cm s^{-1}
- 1 pc $= 3.08 \times 10^{18}$ cm
- The comoving volume of the survey is approximately 29.8 Mpc^{-3}.
- The authors give the assumed cosmological parameters at the end of the Introduction.

MOTIVATION AND MAIN ARGUMENT

1. Let's think first about the main argument being made in this paper.
   (a) (5 points) In a few sentences, summarize the main question that the paper is asking and at least two (2) specific measurements they are using to go after the answer.
   (b) (5 points) In a few sentences, summarize the main conclusion from the paper, i.e., the main "take-away" result, and at least two (2) specific pieces of supporting evidence.

OBSERVATIONAL TECHNIQUES

2. Now let's look in more detail at the observations and analysis the authors carried out.
   (a) (5 points) Figure 2 presents a subset of the dataset, centered on the quasar. Describe what information the authors are highlighting with the top left panel, the top middle panel, vs. the remaining panels.
   (b) (5 points) In Section 3, paragraph 2, the authors mention using isophotal magnitudes to obtain the "rest-frame $u - g$ colors measured in matched isophotal apertures". In a few sentences, (i) explain what they mean by isophotal magnitudes, (ii) describe another type of magnitude one could use, (iii) and a reason why the authors may have chosen to use isophotal magnitudes in this work instead of an alternative.

TOTAL MASSES AND GALAXY/GAS KINEMATICS

3. Let's think about the total mass and overall kinematics of this system, keeping in mind that the most massive galaxy clusters have total masses of $\sim 10^{15}$ $M_\odot$.
   (a) (2 points) Estimate the typical velocity dispersion of a massive galaxy cluster using the information in Section 3.
   (b) (4 points) Estimate the total mass of the galaxy group using the information given in Section 3, and state what assumption you are implicitly making in doing this.
   (c) (5 points) In Section 3, paragraph 3, the authors describe a Δv and σ for their sample, whereas in Section 4, paragraph 2, the authors discuss a different Δv and σ. How do these two sets of measurements differ, and what do they each tell us?

LUMINOSITY FUNCTIONS

4. The paper tabulates information about the galaxies within the region around the quasar. For reference, the r-band luminosity function for galaxies in SDSS is characterized with parameters of M_r^* - 5 $\log_{10}$(h) = -20.73, $\phi^* = 0.009$ h^3 Mpc^{-3} mag^{-1}, and $\alpha = -1.23$ (Montoro-Dorta et al. 2009).
   (a) (5 points) Use the information in Table 1 to construct a luminosity function (number per comoving volume per magnitude versus absolute r magnitude) for the galaxies in this field. Assume that the comoving volume of the survey is approximately 29.8 Mpc^{-3}. For simplicity, I suggest using absolute magnitude bin widths of 1 mag with the bin centers at 0.5 mag, i.e., with bins going from -18 to -19, -19 to -20, etc.
   (b) (3 points) What type of function would typically be fit to this data, and what do the parameters of this function refer to? Add a sketch of what this would look like to your luminosity function plot.
   (c) (5 points) If you assume that galaxies at this redshift normally follow the *shape* of the SDSS luminosity function, how does the observed galaxy sample compare, particularly at the faint end? Can you give both a observational and an astrophysical explanation for what might be going on here?
   (d) (5 points) Calculate the ratio between the density of galaxies in this sample and the density of SDSS field galaxies at around M_r^*. Does this ratio make sense to you given what else you know about this region?

SURFACE BRIGHTNESS AND A LITTLE COSMOLOGY

5. For this question, you will need measurements for the "S." nebula in Table 2 and Figure 2, and measurements for any galaxy listed in Table 1.
   (a) (3 points) Estimate the total area of the "S." [OIII] nebula on the sky in square arcseconds down to the lowest contour plotted in Figure 2. To simplify the calculation, you may assume that the nebula has an elliptical shape.
   (b) (3 points) Estimate the total [OIII] flux of the "S." [OIII] nebula. You may assume that the nebula is an ellipse of the area you measured above with a constant surface brightness inside that lowest contour.

(c) (5 points) Use the tabulated information on nebulae "S." in Table 2 and your measured [OIII] flux above to estimate the luminosity distance for the assumed redshift and cosmology.

(d) (5 points) Use the tabulated information on any galaxy in Table 1 to estimate the angular diameter distance for the assumed redshift and cosmology.

SPECTRA, EMISSION LINES, AND IONIZATION

6. Let's think about how the authors use spectral information to learn about the ionization of the nebulae.

   (a) (5 points) Using the information provided in the paper, sketch the 1D spectrum you would expect to see from a single pixel within the "S." nebula. Include the key emission lines [OII] (3727+3729), Hβ (4863), and [OIII] (4960+5008) at the correct observed wavelengths and relative flux levels.

   (b) (5 points) The paper focuses on the nebulae detected in a number of emission lines, including Hβ (4863) and [OIII] (4960+5008). How are each of these lines excited? In particular, describe the atom involved, the excitation process, and the meaning of the "[ ]" around OIII.

   (c) (6 points) Emission line diagnostics for high redshift galaxies are often plotted on a so-called Baldwin-Phillips-Terlevich (BPT) diagram. Sketch the most common BPT diagram (including axis labels, but numerical values are not required), indicate where star-forming galaxies vs. shocks/AGN lie in this parameter space, and describe the physical reason for this difference. Use the discussion in Section 4, paragraph 3, to indicate approximately where the nebulae in this paper would likely fall on your BPT diagram.

   (d) (3 points) The authors conclude that photoionization by the quasar is responsible for lighting up the nebulae. Show how they used this and the information in the paper to estimate that the quasar must have been active for at least 3×10^5 years (Section 5, paragraph 1).

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MOTIVATION AND MAIN ARGUMENT

1. Let's think first about the main argument being made in this paper.
   (a) (5 points) In a few sentences, summarize the main question that the paper is asking and at least two (2) specific measurements they are using to go after the answer.
   The authors are interested in the origin of the gas within a galaxy group surrounding a quasar, in particular whether it is relatively cool stripped ISM or cool infalling material or whether it is relatively hot gas from quasar outflows. To answer this question, they are studying the morphology (e.g., presence of tidal features, location near interacting galaxies) and the kinematics (emission line widths) of the gas.
   (b) (5 points) In a few sentences, summarize the main conclusion from the paper, i.e., the main "take-away" result, and at least two (2) specific pieces of supporting evidence.
   The authors find that the nebulae around the quasar is not powered by outflows, but are instead stripped ISM or cool filaments photoionized by the quasar. The nebulae show tidal features and are located near pairs of interacting galaxies, suggestive of being tidally stripped ISM. The linewidths are narrow, so they argue against strong shocks, and the nebulae are highly ionized, consistent with photoionization by the quasar. In one case, the emission line nebula is devoid of galaxies, suggestive of a cool infalling filament.

OBSERVATIONAL TECHNIQUES

2. Now let's look in more detail at the observations and analysis the authors carried out.

   (a) (5 points) Figure 2 presents a subset of the dataset, centered on the quasar. Describe what information the authors are highlighting with the top left panel, the top middle panel, vs. the remaining panels.

   Top left panel: This shows the median flux between 6000-7000Å with [OIII] surface brightness contours overplotted to show the relative locations of the galaxies and the nebulae. Top middle panel: This is the velocity field, measured relative to the quasar systemic velocity, used to show the relatie line-of-sight velocities of both the galaxies and the nebula gas. Remaining panels: These are velocity slices spanning from -1200 km/s to +200 km/s, to individually highlight the nebulae and the interacting pairs of galaxies in velocity space.

   (b) (5 points) In Section 3, paragraph 2, the authors mention using isophotal magnitudes to obtain the "rest-frame $u - g$ colors measured in matched isophotal apertures". In a few sentences, (i) explain what they mean by isophotal magnitudes, (ii) describe another type of magnitude one could use, (iii) and a reason why the authors may have chosen to use isophotal magnitudes in this work instead of an alternative.

   (i) Isophotal magnitudes are computed by summing the flux within a chosen surface brightness contour (isophote). (ii) Other types of magnitudes include apertures magnitudes (using circlar of a fixed radius), Petrosian magnitudes (scaled to the radius at which the surface brightness profile falls to a certain fraction of the peak surface brightness), or model magnitudes (fit surface brightness profile with a parametric function, e.g., Sersic profile, and add up all light under the profile). (iii) The authors may have chosen isophotal magnitudes because they capture all the light within a non-circular region (as opposed to using cicular apertures or Petrosian radii), which is particularly important since they are looking at irregular, interacting galaxies in this study. A downside of isophotal magnitudes is that it will be more difficult to detect down to the same faint outer isophote for galaxies at higher redshifts. However, that is not a problem for this study as they consider only a single redshift population.

TOTAL MASSES AND GALAXY/GAS KINEMATICS

3. Let's think about the total mass and overall kinematics of this system, keeping in mind that the most massive galaxy clusters have total masses of $\sim 10^{15}$ $M_\odot$.

   (a) (2 points) Estimate the typical velocity dispersion of a massive galaxy cluster using the information in Section 3.

   The authors state that they used a velocity window of 2000 km s^{-1}, because that was roughly twice the velocity dispersion of the most massive clusters. Therefore, the massive cluster velocity dispersion is $\sigma \approx 1000$ km s^{-1}.

   (b) (4 points) Estimate the total mass of the galaxy group using the information given in Section 3, and state what assumption you are implicitly making in doing this.

   Assuming that the group is virialized (not necessarily a good assumption), the virial mass is roughly $M_{vir} \approx \sigma^2 \times R/G$. The authors state that they measure a group velocity dispersion of 430 km s^{-1}. If we assume a cluster is 10 times bigger in radius than a group ($R_{group}/R_{cluster} \approx 1/10$), this corresponds to a mass of $\approx (430/1000)^2 \times (1/10) \times 10^{15} M_\odot \approx 1.8 \times 10^{13} M_\odot$.

Alternately, if we remember G and $M_\odot$, we can estimate the radius of a cluster using the assumed velocity dispersion from part (a), $\sigma_{cluster} \sim 1000\ km\ s^{-1}$. $R_{cluster} \approx G \times M_{vir}/\sigma^2_{cluster} \approx (6.67 \times 10^{-8} cm^3 g^{-1} s^{-2})(10^{15} M_\odot \times 2 \times 10^{33} g/M_\odot)/(1000 \times 10^5 cm/s)^2 \approx 1.3 \times 10^{25} cm \approx 4.3 Mpc$. The group radius from this study might be something like the projected distance of G30, 430 kpc, thus the mass of the group would be $\approx (430/1000)^2 \times (1/10) \times 10^{15} M_\odot \approx 1.8 \times 10^{13} M_\odot$.

Alternately, if we estimate the radius of the group from Figure 1 to be $R_{group} \sim 200$ kpc, we can calculate the group mass as $\approx (430 \times 10^5 cm/s)^2 \times (200 \times 10^3 pc \times 3.08 \times 10^{18} cm/pc)/6.67 \times 10^{-8} cm^3 g^{-1} s^{-2} \times M_\odot/2 \times 10^{33} g \approx 8.3 \times 10^{12} M_\odot$.

(c) (5 points) In Section 3, paragraph 3, the authors describe a Δv and σ for their sample, whereas in Section 4, paragraph 2, the authors discuss a different Δv and σ. How do these two sets of measurements differ, and what do they each tell us?

In Section 3, the authors are discussing the velocity of the entire galaxy group relative to the quasar (Δv), and the dispersion of the individual galaxy velocities (σ_{group}), as shown in the histogram in Figure 1 (inset). In a virialized system, this is related to the mass of the gravitational potential well. In Section 4, the authors are describing the velocity offset of the nebulae relative to the quasar (Δv), as measured from the emission lines. The velocity dispersion in this context refers to the internal velocities of the nebula gas, as measured by the width of the emission line profiles (σ), which relates to the source of the gas (outflows would stir up the gas, yielding high dispersion, infall/tidal interactions would lead to lower dispersion).

LUMINOSITY FUNCTIONS

4. The paper tabulates information about the galaxies within the region around the quasar. For reference, the r-band luminosity function for galaxies in SDSS is characterized with parameters of M_r^* - 5 $\log_{10}$(h) = -20.73, $\phi^* = 0.009$ h^3 Mpc^{-3} mag^{-1}, and $\alpha = -1.23$ (Montoro-Dorta et al. 2009).

(a) (5 points) Use the information in Table 1 to construct a luminosity function (number per comoving volume per magnitude versus absolute r magnitude) for the galaxies in this field. Assume that the comoving volume of the survey is approximately 29.8 Mpc^{-3}. For simplicity, I suggest using absolute magnitude bin widths of 1 mag with the bin centers at 0.5 mag, i.e., with bins going from -18 to -19, -19 to -20, etc.

See Figure 1. Using the M_r values for all galaxies in Table 1, we plot up a histogram in bins of 1 mag. The x axis is M_r and the y axis is the number of galaxies per comoving volume per magnitude, where the comoving volume is given to be 29.8 Mpc^{-3}.

(b) (3 points) What type of function would typically be fit to this data, and what do the parameters of this function refer to? Add a sketch of what this would look like to your luminosity function plot.

A Schechter function, defined as $\Phi(L)dL = \Phi^*(\frac{L}{L^*})^\alpha e^{(\frac{-L}{L^*})}\frac{dL}{L^*}$, where the parameters are defined as follows: the characteristic magnitude M^*, the normalization ϕ^*, and the faint end slope α.

(c) (5 points) If you assume that galaxies at this redshift normally follow the *shape* of the SDSS luminosity function, how does the observed galaxy sample compare, particularly at the faint end? Can you give both a observational and an astrophysical explanation for what might be going on here?

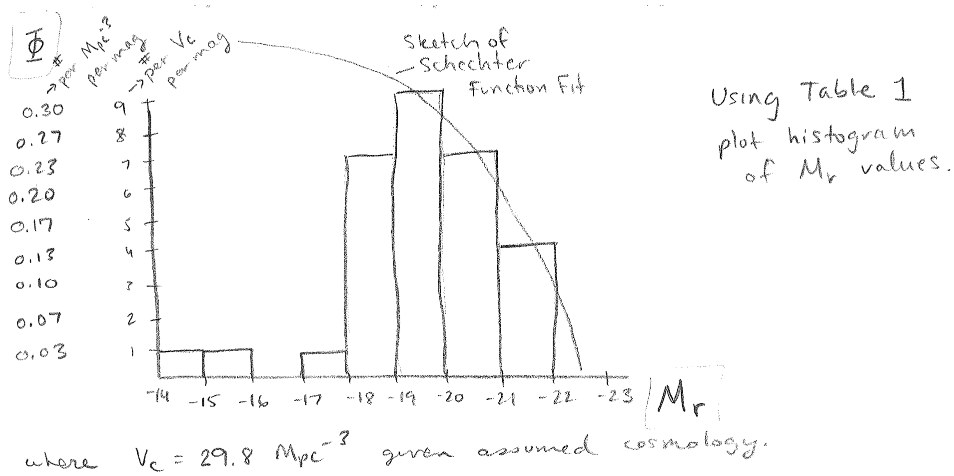

Figure 1: Sketch of galaxy luminosity function using data from Table 1.

There appears to be a drop off at fainter absolute magnitudes ($M_r > -20$). This is likely due primarily to an observational effect – incompleteness of the sample at fainter magnitudes. The authors note that the imaging is complete down to -16, but the table only lists the subset with spectroscopic redshifts, thus this drop-off reflects spectroscopic incompleteness. Given that this a group environment, it is possible that there are also astrophysical effects like interactions triggering star formation (shifting M^*) or merging of smaller galaxies into larger galaxies (changing α).

(d) (5 points) Calculate the ratio between the density of galaxies in this sample and the density of SDSS field galaxies at around M_r^*. Does this ratio make sense to you given what else you know about this region?

The density of SDSS field galaxies at M_r^* is given by $\phi^* = 0.009\ h^3\ Mpc^{-3}$. Given h=0.7, $\phi^* = 0.003\ Mpc^{-3}\ mag^{-1}$ and $M_r^* = -21.5$. In the observed sample, there are 4 galaxies at M_r=-21.5; given the comoving volume of 29.8 Mpc^3, the observed density is ϕ =0.134 $Mpc^{-3}\ mag^{-1}$. Therefore, the observed region is 0.134/0.003∼45 times denser than the field. Given that the authors find this region contains a massive galaxy group, it makes sense that it would be substantially denser than the field.

SURFACE BRIGHTNESS AND A LITTLE COSMOLOGY

5. For this question, you will need measurements for the "S." nebula in Table 2 and Figure 2, and measurements for any galaxy listed in Table 1.

(a) (3 points) Estimate the total area of the "S." [OIII] nebula on the sky in square arcseconds down to the lowest contour plotted in Figure 2. To simplify the calculation, you may assume that the nebula has an elliptical shape.

Using either the contours in Figure 2 (top left) or the tabulated size in Table 2, nebula "S." has major (A) and minor axis (B) lengths of ∼11 arcsec by 7 arcsec. The area of an ellipse is $\pi \frac{A}{2} \frac{B}{2}$, so the estimated area of the nebula is ∼60 arcsec^2.

(b) (3 points) Estimate the total [OIII] flux of the "S." [OIII] nebula. You may assume that the nebula is an ellipse of the area you measured above with a constant surface brightness inside that lowest contour.

The lowest surface brightness contour is at 0.75×10^{-17} *erg* s^{-1} cm^{-2} *arcsec*$^{-2}$*. Assuming the nebula has this constant surface brightness over an area of* ∼*60 arcsec*^{2}*, the total [OIII] flux is* $0.75 \times 10^{-17} \times 60$ *arcsec*^{2} $= 4.5 \times 10^{-16}$ *erg* s^{-1} cm^{-2}.

(c) (5 points) Use the tabulated information on nebulae "S." in Table 2 and your measured [OIII] flux above to estimate the luminosity distance for the assumed redshift and cosmology.

The luminosity distances (d_L) *relates the luminosity and the flux of an object for a given cosmology, as* $F = \frac{L}{4\pi d_L^2}$*. Therefore,* $d_L(cm) = sqrt(\frac{L}{4\pi F})$*. The tabulated [OIII] luminosity for the nebula in Table 2 is* 3.4×10^{42} *erg* s^{-1}*. Given the total [OIII] flux calculated above,* $d_L = sqrt(\frac{3.4\times10^{42}}{4\pi 4.5\times10^{-16}} \approx 2 \times 10^{28}$ *cm)*

(d) (5 points) Use the tabulated information on any galaxy in Table 1 to estimate the angular diameter distance for the assumed redshift and cosmology.

The angular diameter distance (d_A) *relates the physical size of an object* (r) *to its angular size* (θ) *for a given cosmology, as* $r = d_A\theta(radians)$*. Therefore,* $d_A(kpc) = \frac{r(kpc)}{\theta(arcsec)/3600\times\pi/180}$*. Using the measured projected distances in both pkpc and arcsec for G1,* $d_A \approx 1340721.3$ *kpc*$= 4 \times 10^{27}$ *cm.*

SPECTRA, EMISSION LINES, AND IONIZATION

6. Let's think about how the authors use spectral information to learn about the ionization of the nebulae.

(a) (5 points) Using the information provided in the paper, sketch the 1D spectrum you would expect to see from a single pixel within the "S." nebula. Include the key emission lines [OII] (3727+3729), Hβ (4863), and [OIII] (4960+5008) at the correct observed wavelengths and relative flux levels.

See Figure 2. The [OII], Hβ*, and [OIII] doublet lines should be at* $\lambda\times(1.57) = [5853, 7634, 7787, 7863]$*. The relative ratios should be* $[OII]/H\beta \sim 1.3/0.56 \sim 2.3$ *and* $[OIII]/H\beta \sim 3.4/0.56 \sim 6.1$.

(b) (5 points) The paper focuses on the nebulae detected in a number of emission lines, including Hβ (4863) and [OIII] (4960+5008). How are each of these lines excited? In particular, describe the atom involved, the excitation process, and the meaning of the "[ ]" around OIII.

Hβ *is a permitted recombination line of Hydrogen, meaning that H can be photoionized and then recombine, with the transition from n=4 and to n=2 producing the H*β *photon. The [OIII] doublet on the other hand is a forbidden collisionally excited line pair of twice ionized Oxygen. OI is photoionized to OIII, and then collisionally excited into the forbidden OIII doublet levels. At the low densities within these sorts of nebulae, these transitions have time to radiatively recombine emitting [OIII] doublet lines. The brackets refer to this being a forbidden line, meaning that the transition probability is so low that at high densities (i.e., in the lab) the transition is not observed because it would be deexcited collisionally long before it was able to radiatively decay.*

(c) (6 points) Emission line diagnostics for high redshift galaxies are often plotted on a so-called Baldwin-Phillips-Terlevich (BPT) diagram. Sketch the most common BPT diagram (including axis labels, but numerical values are not required), indicate where star-forming galaxies vs. shocks/AGN lie in this parameter space, and describe the physical reason for

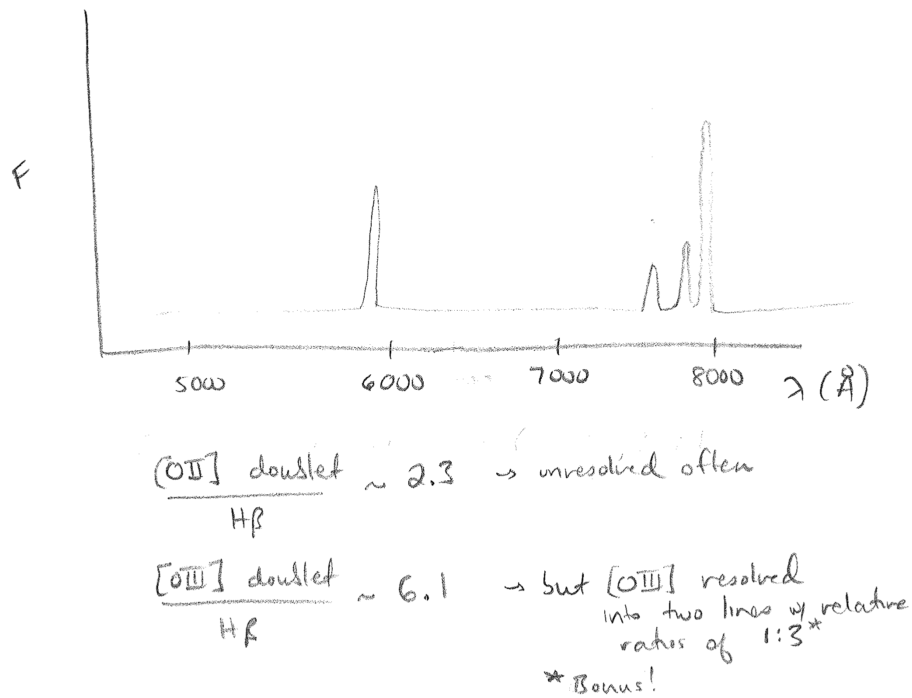

Figure 2: Sketch of the 1D spectrum from a single pixel within the "S." nebula.

this difference. Use the discussion in Section 4, paragraph 3, to indicate approximately where the nebulae in this paper would likely fall on your BPT diagram.

See Figure 3. AGN/shocks are located in the upper right of the diagram, whereas star forming galaxies populate a sequence in the lower left. The basic reason for this difference is that AGN (and shocks) create partially ionized zones, which lead to greater collisional excitation of those collisionally excited lines like [NII]. AGN have harder ionizing continua than stars, which also leads to greater production of OIII via photoionization. Both of these factors lead AGN to populate the upper right. The nebulae are shown to have very high [OIII]/Hβ ratios consistent with AGN photoionization; therefore, while the paper doesn't give [NII]/Hα ratios, we would expect the nebulae to lie up in the AGN portion of the BPT diagram.

(d) (3 points) The authors conclude that photoionization by the quasar is responsible for lighting up the nebulae. Show how they used this and the information in the paper to estimate that the quasar must have been active for at least 3×10^5 years (Section 5, paragraph 1).

They estimated the furthest projected distance from the quasar out to which the nebulae are seen (somewhere between G11, 87.7 pkpc, or G13, 103.4 pkpc) and computed the light-travel time out to that distance.

$100kpc \times 10^3 pc/kpc \times 3.08 \times 10^{18} cm/pc \times \frac{1}{(3\times10^{10} cm/s)} \times \frac{1}{(3.1415\times10^7 seconds/year)} = 3.3 \times 10^5 years$

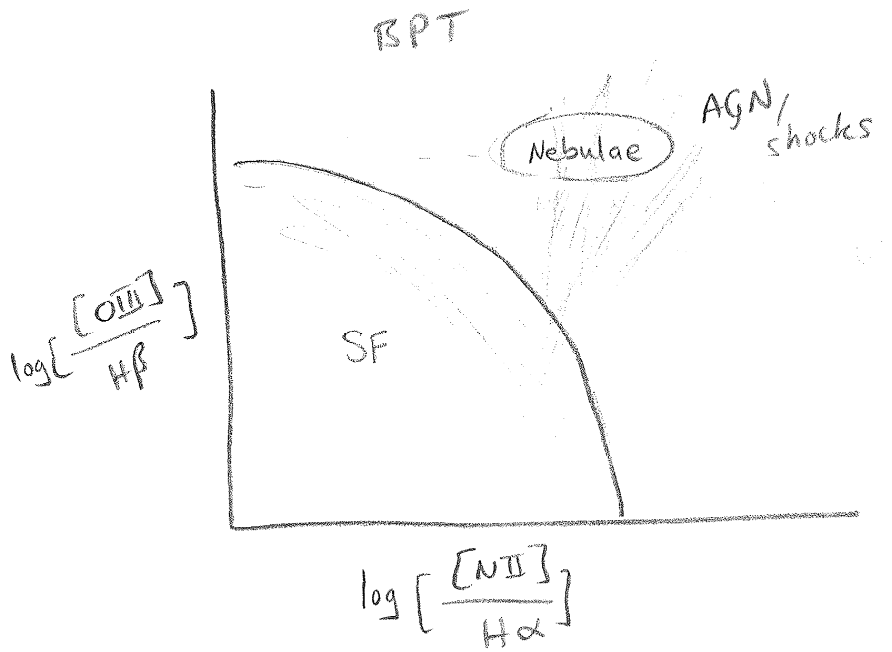

Figure 3: Sketch of the most common BPT diagram, with the star formation (SF) and AGN/shock regions indicated along with the likely location of the nebulae.