NMSU Astronomy Cume #419 **Moire Prescott**
October 28, 2017

Overview:

This Cume is based on the paper "ALMA Shows that Gas Reservoirs of Star-forming Disks over the Past 3 Billion Years Are Not Predominantly Molecular" by Cortese et al. 2017. Since this is a short paper, please read through it to get the main ideas from the text and the gist of what the figures are showing. However, make sure you spend no more than about 15 minutes reading before you start answering questions.

The exam contains 15 questions, worth 56 total points. The anticipated passing grade is 42 points or 75%.

Additional Instructions:

- Please start each question on a new page and put your name on each page. Staple your packet of pages together at the end.
- When sketching a plot, make sure to label both axes.
- 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:

- For the assumed cosmology, the luminosity distance at $z \sim 0.2$ is $dL = 980.1$ Mpc and the angular diameter distance is $dA = 680.6$ Mpc.
- Planck's constant $h = 6.626 \times 10^{-27}$ erg s, speed of light $c = 3 \times 10^{10}$ cm s^{-1}
- 1 eV $= 1.602 \times 10^{-12}$ erg

The Main Ideas

Let's think first about the main ideas in this paper.

1. (4 points) In a few sentences, summarize the broader astronomical context for this paper. *In the local universe, the cold gas that is the fuel for star formation is dominated by atomic hydrogen. At higher redshifts, there are predictions that the molecular gas fraction should be higher and the gas disks more turbulent. Some observations support this picture, but directly measuring the ratio of molecular to atomic gas has been difficult at higher redshifts.*

2. (4 points) In a few sentences, summarize three (3) key datasets/surveys (i.e., type of data, sample size, redshifts covered) that are discussed in the paper.

   There are a small sample of galaxies with both molecular (CO) and atomic (HI) gas measurements: the COLD GASS sample at $z \sim 0$, the COOL BUDHIES sample at $z \sim 0.2$, and the CHILES sample at $z \sim 0.4$. This paper expands this number by adding ALMA CO observations and Keck Hα spectroscopy of the HIGHz sample, a sample of galaxies at $z \sim 0.2$ with HI observations from Arecibo. They also compare to a higher redshift sample PHIBSS at $z \sim 1.5$ that has CO but not HI data.

3. (4 points) In a few sentences, summarize the two (2) main hypotheses that the paper is testing and the analysis performed.

   This paper is attempting to test the hypotheses that (1) higher redshift galaxies show a larger fraction of molecular to atomic hydrogen and that (2) these higher gas fractions are accompanied by high gas turbulence. To do this, they obtain ALMA CO observations of a sample of galaxies with pre-existing HI data in order to directly compare the molecular to atomic ratio with what is seen in local galaxies, and they obtain optical spectroscopy to measure the velocity dispersion of the $H\alpha$ emission line to see if these galaxies show any evidence of high gas turbulence.

4. (4 points) In a few sentences, summarize two (2) important conclusions from the paper, i.e., the main "take-away" results.

   The authors find that from the increased sample of galaxies at $z \sim 0.2$ with both molecular and atomic data there is no evidence for strong evolution in the molecular to atomic ratio, at least out to $z \sim 0.2$. In addition, the velocity dispersion profiles are quite low, suggesting that these galaxies are not highly turbulent and that high gas fractions do not necessarily lead to high turbulence.

Observations and Data

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

5. (3 points) Emission from neutral atomic hydrogen gas (HI) is detected at a wavelength of 21 cm. Calculate the energy of this emission line, and describe what causes HI to emit at this particular wavelength.

   A photon with a wavelength of 21 cm has an energy $E = hc/\lambda = (6.626 \times 10^{-27})(3 \times 10^{10}$ cm $s^{-1})/(21$ cm$) \times 1/(1.602 \times 10^{-12}$ erg $eV^{-1}) = 5.9 \times 10^{-6}$ eV. HI can be detected via the 21 cm hyperfine line that results the magnetic interaction between the quantized electron and proton spins. A flip in the relative spins (from parallel to antiparallel) causes a photon to be emitted.

6. (3 points) The authors are interested in the H_2 content of their galaxies, but instead obtain observations of CO and use a conversion factor to estimate H_2. Why do they have to do this?

   H_2 is a symmetric molecule, so it cannot emit via dipole transitions (i.e., no permanent dipole moment). It can emit via quadrupole transitions but that requires much higher temperatures than typical for molecular clouds. Instead, we have to use tracer molecules that we can more easily detect like CO, the second most abundant molecule after H_2, and which does have a dipole moment that is easily excited, in particular via collisions with H_2. The conversion factor between the two is somewhat uncertain, but roughly constant among measurements from GMCs.

7. (2 points) The authors comment in Section 2.1 that they do not think they are missing flux in the ALMA observations. Why do they feel the need to reassure us about this, and what is their argument?

   ALMA is an interferometric array, and the spatial resolution of the observations will depend on the configuration and distances (baselines) between the individual dishes. In particular, the array will be insensitive to scales larger than a certain size, i.e., emission on larger scales will be "resolved out". However, the authors argue that because their ALMA data should be sensitive out to 20" scales, and their objects are much smaller than this scale in the optical, they should not be missing substantial flux due to this effect.

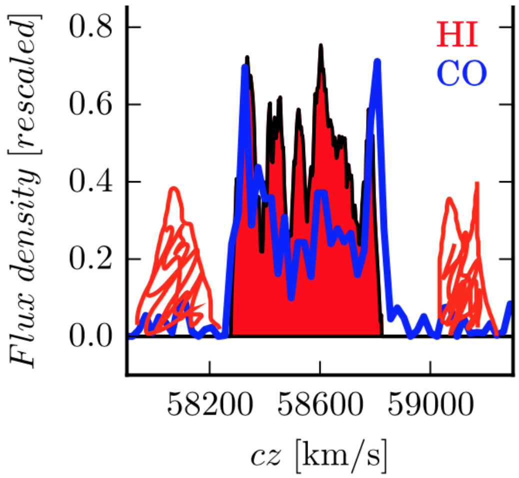

Figure 1: Annotated version of a panel from Figure 1 (third row), showing what it might have looked like if HI emission from satellite galaxies (at higher and lower velocity relative to the target galaxy) had been included in the Arecibo data due to the large beamsize.

8. (4 points) The authors mention the size of the Arecibo primary beam in physical kpc in Section 2.1. Calculate the Arecibo beam size in arcseconds, and describe how it compares to the size of the ALMA beam given earlier in the same section.

   The Arecibo beam is quoted as 800 physical kpc at $z \sim 0.2$. The conversion between arcsec and physical kpc is given by $s = dA \times \Theta$, so an angular size of 1" correspond to $dA \times 1''/3600. \times \pi/180 = 3.3$ kpc. Therefore, the Arecibo beam is 800 kpc = 242.4", while the ALMA beam is 1.7" (from the text in Section 2.2).

9. (4 points) The authors compare the HI and CO spectra in the third row of Figure 1. Describe the issue they are concerned about that led them to make this comparison, and make a sketch to illustrate what they would have seen in the data if there had been a problem.

   Show a sketch similar to Figure 1 and explain that since the beam sizes of the ALMA and Arecibo datasets are so different, the two datasets could in principle be sampling very different emitting regions. In particular, since Arecibo's beam is so huge, it could potentially include emission from neighboring satellites. If this were the case, however, those satellites would be offset in velocity relative to the main galaxy, so we would expect Figure 1 to show HI emission at higher or lower velocities relative to what is seen from the ALMA CO data. Since this is not seen, the authors feel comfortable comparing the two datasets.

10. (4 points) The authors obtain spectroscopic observations of the Hα emission line using the ESI instrument on the Keck Telescope. Given the information in Section 2.2, what is the size of a spectral resolution element (in Å and in km s^{-1}) for these observations? How does your result compare with the quoted final velocity resolution?

    With the rest wavelength of Hα of 6563Å, a redshift of $z \sim 0.2$, and $R \sim 5400$ from the text, the smallest element that can be resolved is $\Delta\lambda = \lambda/R = 1.45$Å. The corresponding velocity resolution is $\Delta\lambda/\lambda \times c = 55.6$ km s^{-1}. This is a FWHM value, so to convert it to a σ width, we use $FWHM/2.35 = \sigma = 23$ km s^{-1}. The authors quote a very similar value of ≈ 20 km s^{-1}.

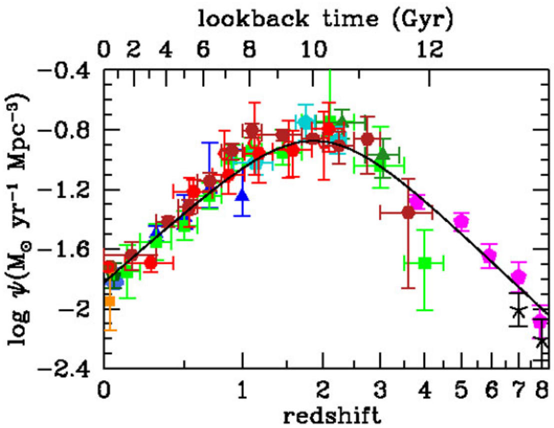

Figure 2: Cosmic SFR as a function of redshift or lookback time, aka the "Madau plot". Example figure pulled from NED (*https://ned.ipac.caltech.edu/level5/March14/Madau/Madau5.html*).

11. (4 points) In Section 2.2, the authors say that they corrected the Hα velocity dispersion measurements for both instrumental resolution and redshift broadening. Using the value reported for AGC242091 at a radius of 15 kpc in Figure 1, work backwards to calculate the Hα velocity dispersion that the authors originally measured (uncorrected).

    Read off the intrinsic velocity dispersion for Halpha for AGC242091 at a radius of 15 kpc – ∼30 km s^{-1}. In the observed frame, this becomes 30 km s^{-1} $\times(1+0.2) = 36$ km s^{-1} due to redshift broadening at $z \sim 0.2$. The instrumental resolution of ∼20 km s^{-1} adds in quadrature to the emission line profile, leading to an observed width of $((36)^2 + (20)^2)^{1/2} = 41.2$ km s^{-1}.

Extragalactic Themes

This paper alludes to a number of key extragalactic themes and observational results.

12. (4 points) The authors mention the concept of "cosmic noon" in the abstract and elsewhere in the paper. Draw a plot showing the observational result that led people to coin the term "cosmic noon", explain why this is a good analogy, and mention what epoch in cosmic history this refers to (i.e., what redshift range corresponds to "cosmic noon").

    Draw the cosmic SFR history (Madau) plot similar to Figure 2, with the cosmic SFR (in $M_\odot$ yr^{-1} Mpc^{-3}) plotted against redshift or lookback time). Explain that "cosmic noon" refers to the fact that there is a peak in the cosmic SFR history at around $z \sim 2$, similar to the peak in the Sun's apparent path through the sky at noon.

13. (4 points) At the end of Section 2.1, the authors say they assume that since the galaxies in their sample are massive, they are also likely metal-rich. Why is this a reasonable assumption to make? Draw a plot and describe the observational result that supports your answer.

    Draw the Mass-Metallicity Relation, e.g., from SDSS, similar to Figure 3, with gas-phase metallicity vs. stellar mass. Explain how more massive galaxies typically have higher metallicities.

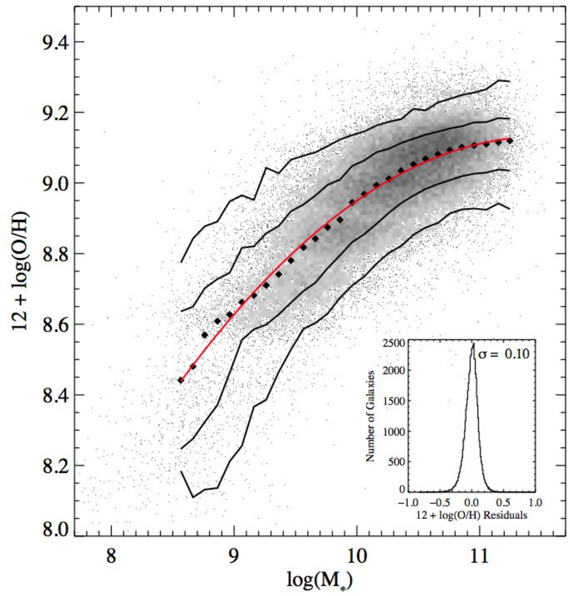

Figure 3: The local Mass-Metallicity Relation from SDSS, showing the gas-phase metallicity of 53,000 galaxies as a function of stellar mass. Example figure pulled from Tremonti et al. 2004 (*http://iopscience.iop.org/article/10.1086/423264/fulltext/*).

14. (4 points) The authors compare their galaxies to the main sequence of galaxies in Section 3 and Figure 3. Draw a plot showing this "main sequence" of galaxies, explain why the authors think it is useful to compare their galaxy samples to it, and describe what it means if a galaxy is slightly higher than this sequence.

    Draw a plot of SFR-M_*, similar to Figure 4, and explain how star-forming galaxies tend to cluster about a relation in this space, such that the more massive galaxies are more highly star-forming. A galaxy's location relative to the main sequence is a rough indication of how typical it is, so lying above the main sequence means the galaxy is more rapidly star forming than average for its stellar mass.

15. (4 points) The authors allude to four different methods for estimating the star-formation rate of a galaxy in Section 3: using Hα, 24 micron, total far-infrared, or a combination of ultraviolet and infrared luminosities. Pick one (1) of these approaches, describe the physics behind why that particular observation can be used to determine a star-formation rate, and list either an advantage or a disadvantage of using that method.

    SFR from Hα luminosities: *Ionization of the surrounding mostly Hydrogen gas by massive, newly formed stars and the subsequent recombination results in strong nebular emission lines, in particular Hα in the optical. An advantage is that this method traces the youngest star formation, as only the most massive stars provide substantial H-ionizing photons. A disadvantage is that it is sensitive to dust, i.e., it does not account for star formation that is heavily obscured.*

    SFR from 24 micron luminosities: *Dust absorbs light from star formation, particularly in the ultraviolet, leading to emission in the infrared. Emission at 24 microns (one of the bands of Spitzer/MIPS) has been shown to correlate well with local star formation. An advantage is that this method reveals star formation that would otherwise be obscured by dust. A disadvantage is that it does not account for star formation that is unobscured by dust.*

Figure 4: SFR (i.e., the number of stars forming) plotted against stellar mass (i.e., number of existing stars), reveals what has been called the "main sequence of star-forming galaxies", or the star-forming main sequence. Example figure pulled from the CANDELS website: *http://candels-collaboration.blogspot.co.uk/2013/02/star-formation-in-mountains.html*.

SFR from total far-infrared luminosities: *Star formation heats local dust in the galaxy, leading to emission in the infrared. An advantage of this method over 24 micron alone is that using the total infrared ensures that all dust-reprocessed emission is counted. A disadvantage is that it does not include star formation that is unobscured by dust, and depending on the galaxy, may also contain a contribution from dust heated by the interstellar radiation field rather than by local star formation.*

SFR from ultraviolet+infrared luminosities: *In any star forming region, some of the light from massive stars will emerge unobscured by dust (in the ultraviolet) and some will be absorbed and reemitted by dust (in the infrared). This method has the disadvantage that it requires multiple datasets (i.e., more data to gather) at different wavelengths (i.e., derived from very different detectors, which may have different spatial resolutions). However, it automatically accounts for both unobscured (ultraviolet) and obscured (infrared) star formation, and so in principle it represents a better estimate of the total star formation rate in the galaxy.*