

Cume #377

3 Question Categories; 75 Points Possible; 55 Points ($\simeq 73\%$) is Guaranteed Pass
passes below this score are still a possibility

Administered: February 16, 2013

The Star Formation History of Luminous Red Galaxies Hosting Mg II Absorbers

Jean-Rene' Gauthier & Hsiao-Wen Chen (2011), MNRAS, 418, 2730-2735

Please start each question (by number) on a new sheet of paper, write on only one side of the paper, and staple them together in order of question number when finished. Please present your results in the order that the individual questions appear. Also, please do not write anything in the upper left corner so that the staple does not obscure your work. Some possibly useful physical constants are listed in Table 1.

1. [35 pts] The Experiment and Motivation:

(a) [10 pts] Briefly, state what the *scientific* point of this paper is (i.e., what are the authors trying to learn and what have they attempted to demonstrate to the reader?). Provide a brief overview of the observational and analysis methods and main conclusions.

ANSWER: The authors are examining the cool gas content (via MgII absorption) of the circumgalactic medium (CGM) of Luminous Red Galaxies (LRGs) in order to ascertain if there is a connection between the quantity of cool CGM gas (as measured using the covering fraction and physical extent) and the star formation of the LRGs. The reason they select LRGs is because they represent some of the highest mass galaxies and these highest mass galaxies are predicted by theory to *not* harbor a large cool gas reservoir *unless* the cool gas is injected into the CGM via stellar feedback.

They selected 2 samples of LRGs from SDSS. Sample A has known MgII absorption at the redshift of LRGs that resides within a $350h^{-1}$ kpc projected separation of the quasar (impact parameter), and sample B has LRGs that resides within a $350h^{-1}$ kpc projected separation of the quasar but for which there is no *a priori* knowledge about MgII absorption. The latter sample, being unbiased to the gas properties, provides a control group for measuring the gas covering fraction. They also obtain spectra of the LRGs and performed population synthesis analysis to estimate the star formation rates (SFR) and histories (SFH) of the galaxies. They have three main results. (1) the quiescent SFR and old (> 1 Gyr) SFH of LRGs with detected absorption are statistically consistent with those of LRGs with no detectable absorption, implying that the presence of cool gas in the CGM of some LRGs is not connected to stellar feedback; (2) the gas is observed with velocity offsets smaller than the escape velocity of the LRG halos, suggesting that the gas is gravitationally bound (not escaping) the LRGs; and (3) the cool gas must be infalling but the cool gas clouds must not survive long enough to reach and fuel the galaxy itself (or the SFR would be higher and the SFH would be younger in those LRGs with absorbing clouds). They use the latter argument to place limits on the cloud masses.

Additional Points (see Introduction and Discussion sections):

(b) [6 pts] According to this paper, how do the gaseous halos of massive LRGs compare to the gaseous halos of lower mass galaxies (include in your answer the physical extent of the gaseous halos and the covering fraction).

ANSWER: To the equivalent width detection sensitivity of $0.3 \text{ \AA}$, the covering fraction of LRGs is roughly 14%, whereas the covering fraction of the lower mass galaxies is roughly 70%; LRGs have substantially smaller covering fractions. The authors do not have the data necessary to constrain the LRG "gas radius", which is roughly $100 h^{-1}$ kpc for lower mass galaxies.

(c) [4 pts] Why is the result for part (b) "unexpected". Give at least two reasons.

ANSWER: (1) LRGs, being among the highest mass galaxies (i.e., $M = 10^{13} h^{-1} M_{\odot}$), are theoretically predicted to have virtually no MgII absorption (zero covering fraction) because the cool gas cannot survive [reason is not stated in paper, but it is because the cooling time is shorter than the freefall time]. (2) LRGs are believed to have quiescent SFR/SFH ("passive galaxies characterized by old stellar populations"), both which suggest that starburst-driven outflows are unlikely the source of the cool gas.

- in very massive galaxies
 $M_{DM} > 10^{12} M_{\odot}$
due to hot accretion, clouds should not exist

Massive halos should not see MgII

(d) [4 pts] What are the possible mechanisms/origins, as mentioned by the authors, that give rise to the MgII absorbing clouds? Which mechanisms/origins do they say their data favor and why?

ANSWER: (1) starburst driven winds, (2) accretion/infall from the intergalactic medium, (3) tidal disruption and stripping [or association with star forming regions in outskirts of halos], and (4) cloud condensation out of the hot halos due to thermal instability; The authors favor infalling clouds, and rule out (1) and (3) above.

(e) [5 pts] Based upon their analysis, for what reason do the authors state that the cool/warm gas detected in MgII absorption must not be able to fuel star formation in LRGs? How does the sample of non-absorbing galaxies help support this conclusion?

ANSWER: They favor infalling cool clouds. If these cool clouds bring gas into the galaxy ISM, they would elevate star formation. The low SFR and old SHF suggest that the clouds, if infalling, are not surviving all the way down to fuel the galaxy with gas. Since the LRGs with detected absorption and the LRGs without detectable absorption have the similar SFR and SFH, this would indicate that the presence of cool absorbing clouds in some LRGs is not effecting their SFR and SFH.

(f) [6 pts] Outline the argument by which the deduced result for part (e) is used to determine limits on the MgII absorbing cloud masses.

ANSWER: If the clouds are moving through a hot halo (they state $T = 6 \times 10^6$ K) then they are subject to disruption forces. They state that evaporation is the shortest destruction time scale for which they derive $t_{\text{evap}} \simeq 1.1 m_6^{2/3}$ Gyr, where m_6 is the cloud mass in units of $10^6 M_\odot$. They compare this to the time required for the clouds to infall to the center of the halo, which they state is governed by the ram pressure time scale and estimate this as $t_{\text{rp}} \simeq 1.1 m_6^{1/3}$. The condition is that $t_{\text{evap}} \leq t_{\text{rp}}$ if the clouds are to be destroyed before reaching the galaxy ISM. From this condition they estimate $m_6 \simeq 1$.

2. [10 pts] Spectra

(b) [5 pts] The authors state (p 2731) that the "typical [galaxy] redshift uncertainties were $|\Delta v| \simeq 70 \text{ km s}^{-1}$ at $z \simeq 0.5$." From this velocity uncertainty, determine the typical *observed* redshift uncertainty, $|\Delta z|$.

ANSWER: The relationship between the proper velocity interval, Δv , and redshift interval, Δz , is $\Delta v/c = \Delta z/(1+z)$. Thus, $\Delta z = (\Delta v/c)(1+z)$. We have

$$\Delta z = \frac{70 \text{ km s}^{-1}}{3 \times 10^5 \text{ km s}^{-1}} (1 + 0.5) = 0.00035$$

Note: Using the formula $\Delta v = c\Delta z$ works only when $z \simeq 0$. In this case, the comoving velocity and the proper velocity are identical. At higher z , the proper velocity is not equal to the co-moving velocity, so one must include the factor of $1+z$ to recover the proper velocity interval (and thus the corresponding redshift interval). If you incorrectly used $\Delta v = c\Delta z$, your answer would be $\Delta z = 0.00023$.

(c) [5 pts] The authors state [p 2732] that they "adopted a common pixel resolution of $\Delta v = 350 \text{ km s}^{-1}$ " for the stacking of the LRG spectra. If there are three pixels per resolution element, what resolution R does this correspond to?

ANSWER: The resolution is defined as $R = \lambda/\Delta\lambda$, where $\Delta\lambda$ is the wavelength interval of a resolution element (FWHM). The resolution can also be expressed as $R = c/\Delta v$, where Δv is the velocity width of a resolution element. With 3 pixels per resolution element and a per pixel width of $\Delta v = 350 \text{ km s}^{-1}$, we have $\Delta v = 1050 \text{ km s}^{-1}$ per resolution element, yielding $R = 3 \times 10^5 / 1050 = 286$.

3. [30 pts] The Escape Velocity

The authors quote a typical virial mass for LRGs of $M \simeq 10^{13} h^{-1} M_\odot$. The virial radius for a given virial mass is given by $R_{\text{vir}}^3 = (3/4\pi)(M/18\pi^2\rho_c)$.

(a) [10 pts] Show that the escape velocity at the virial radius can be written

$$v_{\text{esc}} \simeq 2.4 \sqrt{\pi G \rho_c^{1/6}} M^{1/3} h^{-1/3}$$



$$\Delta v = 3 \Delta v_{\text{pix}}$$

$$R = \frac{c}{\Delta v}$$

note $h = \frac{H_0}{100 \text{ km/s/Mpc}}$

ANSWER: The escape velocity of a test mass particle at distance r is $v_{\text{esc}} = \sqrt{2GM(r)/r}$, where $M(r)$ is the mass enclosed within r . The virial mass, $M \simeq 10^{13} h^{-1} M_{\odot}$, is the mass enclosed within the virial radius, $r = R_{\text{vir}}$. Note that the authors express mass in units h^{-1} . Substituting Mh^{-1} and R_{vir} , we have

$$v_{\text{esc}}^2 = 2GMh^{-1} \left[\frac{4\pi}{3} \frac{18\pi^2 \rho_c}{Mh^{-1}} \right]^{1/3} = 2GMh^{-1} \left[24\pi^3 \frac{\rho_c}{Mh^{-1}} \right]^{1/3} = 5.76\pi G \rho_c^{1/3} M^{2/3} h^{-2/3}$$

$$v_{\text{esc}} = 2.4\sqrt{\pi G \rho_c^{1/6} M^{1/3} h^{-1/3}}$$

(b) [5 pts] Compute the escape velocity at the virial radius in km s^{-1} for a typical LRG mass galaxy. How does this value compare to the galaxy-absorber line-of-sight velocity separation cut of 350 km s^{-1} applied by the authors?

ANSWER: We need the critical density, which is $\rho_c = 1.88h^2 \times 10^{-29} \text{ g cm}^{-3}$. With $h = 0.7$, we have $\rho_c = 9.21 \times 10^{-30} \text{ g cm}^{-3}$.

$$v_{\text{esc}} = 2.4\sqrt{\pi} (6.7 \times 10^{-8})^{1/2} (9.2 \times 10^{-30})^{1/6} (10^{13} \cdot 2 \times 10^{33})^{1/3} (0.7)^{-1/3}$$

$$v_{\text{esc}} = 2.4 (6.7\pi)^{1/2} (9.2)^{1/6} (2/0.7)^{1/3} \times 10^{-(8/2)-(30/6)+(13+33)/3}$$

$$v_{\text{esc}} = 19.9 \times 10^{6.3} \simeq 4 \times 10^7 \text{ cm s}^{-1} = 400 \text{ km s}^{-1}$$

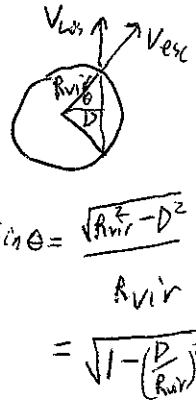
This is a factor of $400/350 = 1.14$ larger than the velocity cut off applied by the authors. [This might suggest that they are limiting their sample so that they must always be seeing gas with velocities below the escape velocity, but see next questions].

(c) [5 pts] Consider a cloud residing at the virial radius, but observed at an impact parameter $\rho < R_{\text{vir}}$. Show that the observed line of sight component of the escape velocity for such a gas cloud is $v_{\text{los}}(\rho) = v_{\text{esc}} \sqrt{1 - \rho^2/R_{\text{vir}}^2}$. [I suggest you present a diagram].

ANSWER: see attached diagram. From the resulting equation for $v_{\text{los}}(\rho)$, we see that $v_{\text{los}}(0) = v_{\text{esc}}$, and that it decreases as ρ increases. The important insight here is that v_{esc} is a velocity that is radially outward with respect to the galaxy center.

(d) [10 pts] For their eight absorbing galaxies (Table 1 of the paper), do you find that they can definitively say the gas is gravitationally bound within the virial radius for their galaxies? [Do not make calculations to test each galaxy, inspection and estimation should provide enough required insight]. What do they claim? Do you agree? Why or why not? Does your conclusion have possible consequences for their conclusions- if so, what?

ANSWER: We have determined that for the "typical mass" of an LRG, $v_{\text{esc}} = 400 \text{ km s}^{-1}$. We have also determined that the line of sight component of v_{esc} decreases as ρ/R_{vir} increases. For instance, if $\rho = R_{\text{vir}}$, then a cloud moving radially outward from the galaxy could be escaping but we would measure a velocity offset from the galaxy of $|\Delta v| = v_{\text{los}} = 0$, and so we can make no statement about whether the cloud might escape the galaxy! This significantly weakens any statements that the observed gas could or could not be escaping the galaxy. As ρ increases, in order for us to claim that the gas cannot be escaping, the observed velocity difference from the galaxy must obey $|\Delta v| < v_{\text{esc}} \sqrt{1 - \rho^2/R_{\text{vir}}^2}$. The authors never apply this very important fact to their data, which null and voids their claim that a single velocity cut off of 350 km s^{-1} ensures that the gas is gravitationally bound to the galaxies. What we are looking for here are galaxy-absorber pairs in Table 1 for which $|\Delta v| = v_{\text{los}}$ is approaching $v_{\text{esc}} \sqrt{1 - \rho^2/R_{\text{vir}}^2}$; these galaxies may be suspect for the gas to be escaping. The larger the value of ρ , the more uncertain we will be whether the gas could be escaping or not. Without knowing the actual masses and therefore virial radii of the galaxies, we can make no definitive conclusions (though they quote $R_{\text{vir}} \simeq 350 h^{-1} \text{ kpc}$); however, the galaxies which may be most suspect for having the observed absorbing gas clouds escape are J114445 ($\rho = 70 h^{-1} \text{ kpc}$, $|\Delta v| = 380 \text{ km s}^{-1}$) and J220703 ($\rho = 171 h^{-1} \text{ kpc}$, $|\Delta v| = 360 \text{ km s}^{-1}$). Recall that the uncertainty in $|\Delta v| = 70 \text{ km s}^{-1}$. The point is that the projection effect of the line of sight renders it very difficult to definitively say that the gas is not escaping the galaxies. Thus, one must be skeptical of the authors simplistic claims that a velocity cut off of 350 km s^{-1} ensures that the



gas is gravitationally bound to the galaxies. The consequences are that this substantially weakens the component of their argument that the gas is *not* leaving the galaxy, since the data cannot tell us whether the gas is infalling or outflowing (we only know the line of sight component to the velocity; the data cannot be used to determine the direction *relative* to the galaxy).

Table 1. Some Possibly Useful Constants [cgs]

quantity	symbol	value
gravitational const	G	$6.67 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$
solar mass	$M_{\odot}$	$2 \times 10^{33} \text{ g}$
Hubble parameter	$h = H_0/100$	0.7
Critical Density	ρ_c	$1.88h^2 \times 10^{-29} \text{ g cm}^{-3}$

Annotations by
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