On the Origin of the Clustered QSO Metal Absorption Lines

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Abstract

Observations show that there is significant clustering of QSO metal absorption lines within the range of velocity dispersion between 200 km/sec and 600 km/sec. With a reasonable supernova rate, it is shown that high velocity gases driven by SNe and/or strong stellar winds could explain the clustered absorptions, provided that QSO metal-line absorbers are galactic halos or dwarf galaxies. Rich clusters of galaxies, on the other hand, cannot yield the observed clustering of QSO metal absorption lines.

Subject Headings: Galaxies: Quasars: absorption lines—Stars: supernovae
I. INTRODUCTION

The metal absorption lines in QSO spectra (type C in the classification of Weyman, Carswell & Smith (1981)) have raised great interests because they might reveal properties and evolution of objects associated with galaxies at redshifts \( z > \sim 1 \). The properties of these metal absorption lines were reviewed by Weyman, Carswell & Smith (1981) and recently by York et al. (1991). These absorption lines are commonly associated with halos of galaxies (Bahcall & Spitzer 1969), since halos contain metals, have star formation, and are clustered like galaxies. It is also reasonable if considering that the cross section of the absorbers (if they associate with galaxies) needed to explain these lines is \( \sim 10 \) times the visible extent of modern galaxies (Sargent et al. 1979). Three options for “halos” have been proposed: 1. each absorber corresponds to a single halo (Pettini et al. 1983); 2. a small number of gas-rich dwarf galaxies (like the Magellanic clouds) form each halo (York et al. 1986); 3. many mini-absorbers (with masses much less than those of dwarf galaxies, such as \( 10^3M_\odot \)) in a halo provide the metal-line absorption (Sargent et al. 1979).

A significant portion of these metal-line absorption systems are systems that have multiple absorption lines with velocity splits > 200 km/sec, and lie in the intermediate position between quasars and observers (Pettini et al. 1983; York et al. 1984; Sargent, Boksenberg, & Steidel 1988, hereafter SBS). A two-point correlation calculation of CIV absorption lines in QSO spectra shows that there is significant correlation in the range of 200 km/sec \( < \Delta V < 600 \) km/sec, where \( \Delta V \) is the velocity split between a pair of absorption lines (SBS). In the survey of 55 QSOs by SBS, 111 CIV absorbers are identified with an equivalent width larger than 0.15Å and a relative velocity with respect to the QSO larger than 5000
km/sec; among them 18 pairs of absorbers are found in excess of what would be expected from a random Poisson distribution of absorbers in the range of 200 km/sec < ΔV < 600 km/sec, while no significant correlation is found in the range of 600 km/sec < ΔV < 1000 km/sec. In other words, metal absorption lines are found to cluster in the range of velocity dispersion between 200 km/sec and 600 km/sec.

The clustering of absorption lines in the range of 200 km/sec < ΔV < 600 km/sec cannot, at least mainly, be explained by the differential rotation motion within a galaxy, which typically yields a ΔV of 150 km/sec. Attempts have been made to explain these clustered absorptions by galaxy-galaxy correlation at z ~ 2, the average redshift of these absorbers (SBS). However, it was shown that the amplitude of today’s galaxy-galaxy correlation function extrapolated to z ~ 2, or the galaxy-galaxy correlation calculated from cold dark matter model, fell short to explain the amplitude of the clustering among these absorbers by a factor >3 (SBS; Salmon & Hogan 1986). Although a high biasing factor may improve the fit of the galaxy-galaxy correlation function to the absorber correlation at

*the expected correlation amplitude calculated by SBS from their eq. (24) seems too high. Using all the notations in SBS, it is clear from their eq. (24) that n_c(R) < 2πR^2 \int_0^\infty \Phi(r_c/r)^{1.8} dr. Since \Phi = \Phi_0(1 + z)^3 and r_c = 5h^{-1}(1 + z)^{-5/3}\text{Mpc} (SBS), the number of correlated galaxies per galaxy divided by the mean number of absorbers per unit redshift, n_c/N < 2.5 \cdot 5h^{-1}\text{Mpc} \cdot (5h^{-1}\text{Mpc}/6R_\star)^{0.8}/(d_H\sqrt{1+z}). With R_\star \approx 70h^{-1}\text{kpc}, d_H = 3000h^{-1}\text{Mpc} and z \sim 2, n_c/N < 0.003, a factor of 20 smaller than the 0.062 quoted in SBS. If a gravitationally unbound galaxy-galaxy correlation is assumed, i.e., r_0 = 5(1 + z)^{-1}\text{Mpc}, the resultant n_c/N < 0.01, which still a factor of 6 lower than quoted in SBS.
200km/sec < ΔV < 600km/sec, it may be hard to understand why a significant correlation of absorbers doesn’t extend to ΔV > 600 km/sec, given the high biasing and a not-so-steep power law galaxy-galaxy correlation function (Peebles 1993)

\[ \xi(r) \propto \left( \frac{r_0}{r} \right)^{-1.8}, \]  

(1)

where \( r \) is the distance between a pair of galaxies and \( r_0 \) is a constant.

In this letter, we set aside the galaxy-galaxy correlation explanation to these clustered absorption systems, and investigate two other alternatives: 1) clusters of galaxies which have velocity dispersions as high as 1000 km/sec intercepting quasar lines of sight; 2) high velocity gases inside absorbers driven by supernova shocks and/or stellar winds. We will show that while the first alternative fails to explain the observed clustering of QSO metal absorption lines at 200km/sec < ΔV < 600km/sec, the second alternative may provide a viable explanation.

II. CLUSTERS OF GALAXIES

If a quasar line of sight strikes two or more galaxies in a rich cluster, they can provide clustered absorptions with a velocity spread as high as \( \sim 1000 \text{ km/sec} \), which is the typical velocity dispersion of a cluster (Pettini et al. 1983). However, since rich clusters only have a dense core within a \( 0.2h^{-1}\text{ Mpc} \) radius (Peebles 1993), the chance of a quasar line of sight striking multiple members of a single cluster is small.

Observations show that average rich clusters have a galaxy density distribution of (Lilje & Efstathiou 1988)

\[ n(r) = n_b[1 + (r_0/r)^{-2.2}], \quad \text{for} \ 0.2h^{-1}\text{Mpc} \lesssim r \lesssim 20h^{-1}\text{Mpc}, \]  

(2)
where \( n(r) \) is the number density of galaxies at a distance \( r \) to the cluster center, 
\( n_b \) is the background number density of galaxies, \( r_0 \approx 9h^{-1}(1+z)^{-1.5}\) Mpc, and \( h = H_0/100\) km/sec/Mpc with \( H_0 \) being the Hubble constant. From APM survey \( n_b \approx 0.014h^3(1+z)^3 \) Mpc\(^{-3} \) (Loveday et al. 1992). \( n(r) \) falls off much faster beyond \( 20h^{-1}\) Mpc (Lilje & Efstathiou 1988), and is much smoother inside the cluster core. In our following calculations, it is convenient to assume a uniformly distributed core with
\[
\begin{align*}
\text{at } r < 0.2h^{-1}\text{Mpc,} \\
\end{align*}
\]
\[
n(r) = n_{\text{core}} \lesssim (2R_h)^{-3},
\]
where \( R_h \) is the typical radius of a galactic halo. The detailed functional form of \( n(r) \) in the core, however, does not affect the generality of our calculations in any significant manner. If each galactic halo provides each individual absorber, to explain the number of metal-line absorption systems observed, it was shown that (SBS)
\[
R_h \sim 70h^{-1}\text{kpc.}
\]
Therefore, when a quasar line of sight passes through the cluster with the closest distance \( r_{\perp} \) from the cluster center (as shown in Figure 1), the number of galaxies that the quasar line of sight would intercept is
\[
N(r_{\perp}) = \begin{cases} 
2\pi \int_0^{\sqrt{2^2-r_{\perp}^2}} R_h^2 n(r)dr', & \text{for } r_{\perp} > r_c; \\
2\pi \int_0^{\sqrt{r^2-r_{\perp}^2}} R_h^2 n_{\text{core}}dr' + 2\pi \int_{\sqrt{r^2-r_{\perp}^2}}^{\sqrt{R^2-r_{\perp}^2}} R_h^2 n(r)dr', & \text{for } r_{\perp} < r_c.
\end{cases}
\]
In eq. (3), \( r = \sqrt{r^2 + r_{\perp}^2} \). \( R_c \) is the radius of the cluster. For the moment, we assume \( R_c \) to be \( 20h^{-1} \) Mpc, the fall-off point in eq. (3). According to Poisson statistics, the probability that this line of sight strikes two or more galaxies in the cluster is
\[
P(r_{\perp}) = 1 - [1 + N(r_{\perp})]e^{-N(r_{\perp})}.
\]
Averaging over $r_\perp$, the probability that a quasar line of sight strikes two or more galaxies of a cluster when it passes through the cluster is $\int_0^{R_c} P(r_\perp) \cdot 2r_\perp dr_\perp / R_c^2$. Considering that the number of clusters the quasar line of sight passes through is

$$N_{cl} = \int_{z_{\min}}^{z_{\max}} \pi R_c^2 n_{cl} d_H (1 + z)^{0.5} dz,$$

(7)

where $d_H = 3000h^{-1}\text{Mpc}$ is the Hubble radius, and $n_{cl}$ is the number density of rich clusters today, estimated to be $\approx 10^{-5}h^3\text{Mpc}^{-3}$ (Bahcall 1988). The factor $(1 + z)^{0.5}$ is the product of $(1 + z)^3$ contributed by the number density of rich clusters at $z$, $(1 + z)^{-1.5}$ contributed by the differential proper length, and $(1 + z)^{-1}$ due to the scaling of the proper length at $z$.

A universe with the critical density is assumed. The expected number of events for a quasar line of sight to strike two or more galaxies in the same cluster, therefore, is

$$N_{\text{multi}} = 2\pi \int_{z_{\min}}^{z_{\max}} n_{cl} d_H (1 + z)^{0.5} dz \int_0^{R_c} P(r_\perp) \cdot r_\perp dr_\perp.$$

(8)

With a typical range of $z_{\min} \sim 1$ and $z_{\max} \sim 3$ for CIV absorption lines (SBS), numerical integration of eq. (8) yields an event rate of 0.06 per quasar. $N_{\text{multi}}$ would remain roughly unchanged even if we assume eq. (2) is valid beyond 20 Mpc. It will only increase by 25% if we assume that the halo radii of galaxies in the core of clusters are typically $35h^{-1}\text{kpc}$ instead of eq. (4) (while the halo radius of galaxies outside the core remains unchanged to maintain the required cross section to intercept quasar lines of sight), resulting a $n_{\text{core}}$ eight times higher according to eq. (3). Therefore, the expected number of pairs of absorbers with $200\text{km/sec} < \Delta V \lesssim 1000\text{km/sec}$ due to clusters of galaxies intercepting QSO line of sight is $\lesssim 0.06$ per quasar, or 3 for a survey of 55 quasars, which can not explain the $\sim 20$ pairs observed in this velocity range for 55 QSOs (SBS).
III. HIGH VELOCITY GASES IN GALAXIES

It is well known that supernova (SN) shocks or stellar winds can accelerate the interstellar medium to velocities as high as $\sim 1000\text{km/sec}$. Therefore, the clustered absorption systems in the range $200\text{km/sec} < \Delta V < 600\text{km/sec}$ may originate from the activity of massive stars inside the absorber itself, regardless of whether the absorber is a single galaxy halo (Pettini et al. 1983), a dwarf galaxy (York et al. 1986) or a mini-absorber inside a galaxy (Sargent et al. 1979). A SN typically releases $10^{51}\text{ergs}$ in kinetic energy. A $30M_\odot$ star also deposits $\sim 10^{51}\text{ergs}$ in kinetic energy through mass loss during its main sequence and pulsation life time of $\sim 5 \times 10^6\text{yr}$ (Abbott 1982). Simply on an energetic base, if we assume negligible energy loss, the amount of mass a SN shock or stellar wind can accelerate to a velocity of $v$ for each SN or massive star is

$$M_v = \frac{10^{51}\text{ergs}}{0.5v^2}. \quad (9)$$

In the phase in which SN shocks expand and decelerate to $\gtrsim 10^2\text{km/sec}$, the SN shocks do in fact propagate adiabatically with negligible energy loss according to a power law (as given by the Sedov solution) (Spitzer 1978)

$$v \propto t^{-3/5}, \quad (10)$$

where $t$ is the time of the propagation. In the case of stellar winds, the gases pushed by the strong stellar wind also propagate with negligible energy loss at $v \gtrsim 100\text{ km/sec}$ with a power law (Weaver et al. 1977)

$$v \propto t^{-2/5}. \quad (11)$$

Therefore, for $v \sim 100\text{km/sec}$, $M_v \sim 10^4M_\odot$. 

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We first deal with the case of SN shocks. In our calculations, we assume that gases are uniformly distributed in absorbers, and assume that the absorber and the high velocity region driven by SN shocks are spherical. The geometry of a high velocity cloud due to a SN shock is illustrated in Figure 2. When a quasar line of sight penetrates the cloud, a pair of absorption lines are generated with a velocity dispersion

\[ \Delta V = 2v \cos \theta. \]  

(12)

To yield \( \Delta V > 200\text{km/sec} \), \( v \) has to be larger than 100km/sec. The average cross section of a high velocity cloud driven by a SN shock to generate a \( \Delta V > 200 \text{ km/sec} \) absorption pair before the shock decelerate to 100km/sec is

\[
\langle A \rangle_{\Delta V \geq 200 \text{km/sec}} = \int_0^{t_{100\text{km/sec}}} \pi r^2 \left[ 1 - \left( \frac{100\text{km/sec}}{v} \right)^2 \right] \frac{dt}{t_{100\text{km/sec}}},
\]

where \( r \) and \( v \) are the radius and the velocity of the high velocity gases respectively, \( r_{\text{abs}} \) is the radius of the absorber in which the high velocity gases is embedded (which is either a single galaxy halo, or a dwarf galaxy, or a mini-absorber inside a galaxy), and \( M_{\text{abs}} \) is the mass of the absorber. \( t_{100\text{km/sec}} \) is the life time of the SN shock when its velocity drops to 100km/sec. After combining eq. (9), (10), (12) and eq. (13), we get

\[
\langle A \rangle_{\Delta V \geq 200 \text{km/sec}} = \frac{2}{9} \pi r_{\text{abs}}^2 \left( \frac{M_{100\text{km/sec}}}{M_{\text{abs}}} \right)^{2/3},
\]

(14)

and

\[
t_{100\text{km/sec}} = \frac{2}{5} \frac{r_{\text{abs}}}{100\text{km/sec}} \left( \frac{M_{100\text{km/sec}}}{M_{\text{abs}}} \right)^{1/3},
\]

(15)
where $M_{100\text{km/sec}}$ is $M_v$ at $v = 100\text{km/sec}$.

Since the survey of SBS showed that $\sim 20$ pairs of CIV absorption lines in the range of $200\text{km/sec} < \Delta V < 600 \text{ km/sec}$ were found in the total of $\sim 100$ pairs of CIV absorption lines (within a sample of 111 CIV absorption line systems), it implies that at any time the cross section of these high velocity gases driven by SN shocks to intercept a quasar line of light is $\gtrsim 10\%$ of that of the absorbers. Therefore, it can be estimated that

$$\frac{R_{SN}t_{100\text{km/sec}}(A)\Delta V_{\geq 200\text{km/sec}}}{\pi r_{abs}^2} \gtrsim 0.1,$$

(16)

where $R_{SN}$ is the SN rate in the absorber. The requirement on $R_{SN}$ is then

$$R_{SN} > \left(\frac{100\text{km/sec}}{r_{abs}}\right)\left(\frac{M_{abs}}{M_{100\text{km/sec}}}\right) \approx \left(\frac{100\text{km/sec}}{r_{abs}}\right)\left(\frac{M_{abs}}{10^4 M_\odot}\right).$$

(17)

In the case of high velocity regions being driven by strong stellar winds, the only difference from the SN case is the power law dependence of $v$ on $t$, which only results in a modification of eq. (14) and (15) by a factor close to 1. Since massive stars with strong stellar winds typically have a mass $> 10M_\odot$, they inevitably end as SNe. Therefore, our result, eq. (17), will not be modified significantly. If the cavity created by the stellar wind of a massive star is small, e.g., with a radius $< 50 \text{ pc}$, the supernova blast of the star later on can catch up with the stellar wind and continue to drive the high velocity region according to eq. (9) until radiative losses become important (McCray & Kafatos 1987). This is then an intermediate case between a pure stellar wind and a pure SN shock, and the required $R_{SN}$ will not deviate significantly from eq. (17) either.

For single halo absorber models (Pettini et al. 1983), $r_{abs} \sim 70 h^{-1}\text{kpc}$, $M_{abs} \sim 10^{11} M_\odot$, eq. (17) gives $R_{SN} > 0.015 \text{ per year per } 10^{11} M_\odot$, yielding $1.5 \times 10^7$ SNe in $10^9$ years (which is a reasonable time frame since the detection of these clustered CIV absorption systems
ranges from \( z \approx 1.2 \) to \( z \approx 3 \) (SBS)). Since each type II SN ejects about \( 0.1M_\odot \) iron and type I SN ejects 6 times as much (Truran & Burkert 1994), this rate translates into at least \( 1.5 \times 10^7 M_\odot \) iron in a \( 10^{11} M_\odot \) galaxy, or \([\text{Fe/H}] > -2\), in \( 10^9 \) years. For dwarf galaxy absorber models (York et al. 1986), \( r_{\text{abs}} \approx 8\text{kpc}, M_{\text{abs}} \sim 2 \times 10^9 M_\odot \), eq. (17) gives \( R_{\text{SN}} > 0.0025 \) per year per \( 2 \times 10^9 M_\odot \), or 0.12 per year per \( 10^{11} M_\odot \), which yields at least \( 1.2 \times 10^8 M_\odot \) iron in a \( 10^{11} M_\odot \) galaxy, or \([\text{Fe/H}] > -2\), in \( 10^9 \) years.

In mini-absorber models (Sargent et al. 1979), the above calculation only applies for mini-absorbers with mass \( M_{\text{abs}} > 10^4 M_\odot \), since for absorbers comparable to or less than \( 10^4 M_\odot \), a single SN will disrupt the whole cloud and populations of mini-absorbers will soon be destroyed. For mini-absorbers with a larger mass, such as \( 10^5 M_\odot \) and a radius of 100 pc, eq. (17) yields \( R_{\text{SN}} > 10^{-5} \) per year per absorber, or \( R_{\text{SN}} > 5 \) per year per \( 10^{11} M_\odot \) if we consider that \( 5 \times 10^5 \) such mini-absorbers are needed to match the cross section of a single 70 kpc galactic halo. This SN rate is unacceptably large since the resultant \([\text{Fe/H}]\) after \( 10^9 \) yr will be larger than 0.6.

In other words, if the clustered CIV absorption lines in the range of \( 200 \text{km/sec} < \Delta V < 600 \text{km/sec} \) are solely due to high velocity gases driven by SN shocks (and/or strong stellar winds), the resultant SN rate will be too large for mini-absorber models such as that of Sargent et al. (1979), but remain reasonable in terms of the resultant metal yields in the single halo absorber model and the dwarf galaxy absorber model. The SN rates calculated in the single halo and dwarf galaxy absorber models also lie close to the estimate of the current SN rate, 0.005–0.1 per year per galaxy depending on the morphology of the galaxy (Cappellaro et al. 1993). (The consideration of different type of supernovae will not change our conclusions significantly.)
Conversely, with a reasonable SN rate, high velocity gases driven by SN shocks (and/or strong stellar winds) play little role in the clustering of absorption lines in the mini-absorber models, but may play a significant role in the single halo or dwarf galaxy absorber models. Especially when the absorbers had star-bursts at the redshift the absorptions are detected, which are expected in the early history of galaxies (Yanny 1990), their SN rates would be significantly higher than the SN rate today. The role of SN (and/or stellar wind) driven clouds in producing clustered QSO metal absorption lines could then be even more relevant.

The number of the clustered absorption lines from these SN (and/or stellar wind) driven clouds should scale as \( d(t_{100\text{km/sec}}\langle A \rangle_{\Delta V \geq 200\text{km/sec}})/dv \), or \((\Delta V)^{-4}\), which is much steeper than that expected from a galaxy-galaxy correlation function, eq. (I). According to this dependence law, given the total number of \( \sim 20 \) clustered absorption pairs with \( \Delta V > 200 \) km/sec in SBS (1988), the clustered absorption pairs should fall below 1 at \( \Delta V \gtrsim 500-600 \) km/sec, which coincides with the observation of SBS (1988) that the clustering of absorption lines ends at \( \Delta V \approx 600 \) km/sec. Although the low statistics of available data and the over-simplification of our present calculations do not allow a realistic comparison at the moment, further data with better statistics can potentially test the predicted steep dependence of the number of clustered metal absorption lines on the splitting velocity, and thereby test the role of SN (and/or stellar wind) driven clouds in producing the clustered QSO metal absorption lines.

Our calculations have been based on a spherical symmetry of the absorber and the high velocity region. Although for SNe or stellar winds, a spherical geometry or a nearly spherical geometry is most natural, a geometry severely deviates from a spherical symmetry (e.g., sheet-like) for these high velocity regions may not be impossible. If so, their cross
sections of intercepting a QSO line of sight may increase significantly. However, in such a
group, the velocity is most likely in the direction of stretching of the structures, and the
velocity projected in the direction of large cross section is small.

Another concern is the uniform distribution of gases assumed in our calculation. If
massive stars in absorbers mostly reside in underdensed region, the high velocity regions
their stellar winds or SN shocks generate will have cross sections larger than that calculated
from a uniform absorber. Intuitively, however, massive stars should form more likely in
overdensed regions and gas rich environment.

IV. SUMMARY

We showed that while rich clusters of galaxies cannot explain the clustering of CIV
absorption lines with velocity dispersions in between 200km/sec and \(\sim 600\)km/sec, high
velocity gases driven by SNe and/or strong stellar winds could provide a viable solution to
these clustered absorptions, provided that the QSO metal-line absorbers are single galactic
halos or dwarf galaxies. This provides an alternative to the galaxy-galaxy correlation expla-
nation to these clustered absorbers. Furthermore, the expected number of absorption pairs
due to high velocity gases driven by SNe and/or strong stellar winds decreases much faster
with an increasing velocity split \(\Delta V\) than that expected from the galaxy-galaxy correlation,
which provides a testable feature as the statistics of clustered QSO metal absorption lines
improves. It is also possible that both of these two scenarios, i.e., stellar activities and the
galaxy-galaxy correlation, work at the same time. Then the significance of the SNe (or
strong stellar winds) driven gases in providing the clustered absorptions depends on the SN
rate in absorbers. For single galactic halo models, high velocity gases driven by SN shocks
and/or strong stellar winds become important if the SN rate is \( \gtrsim 0.015 \) per year per \( 10^{11} M_\odot \); for dwarf galaxy absorber models, these gases become important if the SN rate is \( \gtrsim 0.12 \) per year per \( 10^{11} M_\odot \). These rates are in or near the range of the estimated SN rate today. Therefore, if absorbers had star-bursts at the absorption redshift (between \( z \sim 1 \) and \( z \sim 3 \)), their SN rates then would be significantly higher than the SN rate today, and the role of high velocity gases driven by SN shocks and/or strong stellar winds in providing the clustered QSO metal-line absorptions will be important.

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Figure Captions:

Figure 1. The geometry of a quasar line of sight passing through a cluster of galaxies.

Figure 2. The geometry of high velocity gases driven by a supernova shock.