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ON THE ORIGIN OF SOME QSO ABSORPTION LINES

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ABSTRACT

Some QSO absorption-line systems (QSOALSs) may arise when a QSO sight line intersects a Magellanic-type irregular galaxy (i.e., a gas-rich dwarf). Much of the complexity in the line profiles of metals can be naturally explained in this manner. The frequency of occurrence of QSOALSs then requires that much of the mass of modern galaxies once resided in a halo of gas-rich dwarfs (at the epoch of QSOALS formation).

Subject headings: interstellar: matter — quasars

I. INTRODUCTION

Absorption lines often attributed to intervening material are seen in spectra of quasi-stellar objects. Weymann, Carswell, and Smith (1981) classify the lines into four classes. One type (type C) is a set of narrow (<1000 km s^{-1}) lines at redshifts z much lower than $z_{\rm QSO}$, including lines of hydrogen as well as heavy elements, that would be moving at a large fraction of the speed of light if they represented QSO ejecta. It is common to assume that these systems are not associated with the QSO but represent absorption in intervening material. We address ourselves to this type of QSOALS unless otherwise noted. According to Wolfe *et al.* (1985*a*, *b*), these type C systems may be further subdivided by ionization and hydrogen-line strength.

Suggestions on the origin of these lines are reviewed by York (1982*a*, *b*). A common interpretation is that they arise in halos of galaxies (Bahcall and Spitzer 1969). The association with galaxies is natural because they contain metals, hence, presumably are near sites of star formation, and because they cluster in velocity space like galaxies (Sargent *et al.* 1979; Chaffee *et al.* 1986). The inference that they arise in galaxy halos represents one logical interpretation based on the frequency of occurrence of the QSOALSs: the cross section for metal-line absorption (projected on the sky) must be ~ 10 times the visible extent of modern galaxies (Burbidge *et al.* 1977; Sargent *et al.* 1979). The extent of the halo and the filling factor of the absorbing gas cannot be separately derived from the available data. If A is the halo cross section and ϵ is the probability of detecting C IV absorption on a random line of sight through A,

$$\epsilon A \approx 10\pi R_{\rm H}^2 \tag{1}$$

where $R_{\rm H}$ is the Holmberg radius, as elaborated by Morton, York, and Jenkins (1986).

In this paper we list the properties of QSOALSs and show that high-resolution data suggest a novel interpretation of these systems (§ II). An analogy is drawn between the absorption profiles of gas-rich dwarf irregular galaxies and the QSOALSs (§ III). These ideas are merged with the halo interpretation to show that QSOALSs may represent detection of galaxies actively forming stars (§ IV). Techniques for confirming this conclusion are described (§ V). The broader implications are discussed (§ VI), and a brief summary is given (§ VII).

II. PROPERTIES QSOALSS

a) Velocity Structure

As higher and higher resolution spectrographs have been used for observing QSOs, it has been recognized that the absorption systems are complex. Morton and Morton (1972) pointed out structure on scales of 70 km s^{-1} in profiles of PHL 957. A series of papers by Sargent, Boksenberg, Young, and collaborators show structure on scales of 30 km s^{-1}, (e.g., Young *et al.* 1982 and references therein); Blades *et al.* (1982) found structure at 20 km s^{-1} and later at 10 km s^{-1} (Blades *et al.* 1985). The latter result has now been extended to at least 10 systems (York *et al.* 1984*a*; Bechtold, Green, and York 1986*b*). To our knowledge, no systems searched with adequate resolution have failed to show narrow multiple components.

b) Line Strengths

A wide range in equivalent widths is encountered for C IV, the dominant heavy element absorber in most systems. Selection effects must influence our understanding of these systems, but most reported systems with at least three lines detected contain Lyα and C IV, if the observer had access to these lines (York *et al.* 1986*b*). The strongest C IV lines have $W > 2$ Å in the rest frame. (Unless otherwise noted, W is measured in the rest frame of the system in question and is in units of Å.)

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As noted above, the lines split into many components with widths less than 15 km s^{-1}. Therefore, the values of W for C IV and of other lines often observed (that also split into narrow components) can be thought of as sums of equivalent widths of narrow saturated lines, if each is at a different velocity. Thus, $W(\text{Å}) \approx 0.1na\lambda(\text{Å})/1500$ Å, where n is the number of components and a is a fraction from 0.3–1 representing the range of saturation in lines observed. We use here the assumption that the full width of the lines is ~ 25 km s^{-1} or 0.1 Å at 1500 Å. In fact, cases with FWHM less than 10 km s^{-1} are known. Strong lines, then, represent complex lines. In the complete survey by Young *et al.* (1982), 25% of the C IV lines have $W(1548) > 1.5$ Å, so $n > 15$ for $a < 1$, corresponding to a total width of the systems of greater than 300 km s^{-1}. Eighty-five percent of the systems have $W(1548) > 0.3$ Å or $n > 3$. A histogram of W(C IV) for 150 systems selected by Crotts (1985) from a new absorption-line catalog (York *et al.* 1986*b*) shows that over half of the known QSOALSs have more than three components on this prescription. Systems covering 500–1000 km s^{-1} are common (York *et al.* 1984*a*, Blades *et al.* 1982) and show the many components directly.

Searches for changes in the properties of QSOALSs have been made. Bergeron (1985) concludes from published data that there is roughly one C IV system per unit z with a slight but unconvincing trend for slightly more at higher z. Mg II systems are less frequent, but the number is roughly independent of z. Bechtold *et al.* (1984) concluded that the number of systems per comoving volume element with $z > 1$ in the Lyman limit (virtually always found in conjunction with C IV or Mg II) is unchanging from $z = 0.4$ to 3.5.

c) Ionization Structure

A wide range of ionization conditions can be found among the known systems (Bechtold, Green, and York 1987). Some show only C IV and Lyα. Others show Mg I, Mg II, Si II, Si III, and Si IV in addition. A suggestion by Pettini and West (1982) that W(C IV)/W(Si IV) ≈ 3.5 for integrated strength of QSOALSs is not borne out by high-resolution comparison on a component by component basis. For instance, N(C IV)/N(Si IV) ranges from 30 to 0.5 in the 11 components near $z = 1.79$ in B2 1225+317 (Bechtold, Green, and York 1986). In general, the neutral species show different velocities than the integrated profiles of higher ions, as noted by comparing 21 cm absorption and C II absorption at $z = 2.035$ in PKS 0458−02 (which differ by 100 km s^{-1}) (Wolfe *et al.* 1985*a*).

d) Interpretation

As already noted, the absorption-line systems are often attributed to gaseous halos of galaxies. Ignoring the velocity structure discussed above, and treating each system as a detected halo, $\epsilon = 1$ (eq. [1]) implies $r = 30$ kpc $(100/H_0)$ for C IV and $r = 18$ kpc $(100/H_0)$ for Mg II. The absorbing entities must be numerous in such a halo. Sargent *et al.* (1979) suggested 10^6 clouds would be required for the particular set of parameters they assumed for a typical cloud. ($n_H < 10^{-1}$, $N_H \approx 10^{19}$, $N_H/n_H > 10^{20}$ cm), where H represents all hydrogen $H^0 + H^+$, n_H is volume density, and N is column density. The requirement that $\epsilon > 0.5$ to have more than three clouds and $\epsilon \approx 0.25$ to have more than 15 clouds increases either A, (by up to a factor of 70) if one thinks of single diffuse clouds in a halo as being the individual absorbers, or requires a greater number of absorbing clouds (by a factor of up to 10^3).

There is perhaps no physical reason to deny large values of A, but there is no direct evidence for even the smaller values demanded by the simple picture discussed above (York 1982). Likewise, the density of clouds is completely unknown from physical arguments. There is little evidence for large numbers of absorbers with a high-velocity dispersion in halos of low z galaxies. For instance, our Galaxy has a system of high-velocity 21 cm clouds numbering ~ 150, with a spread of ± 300 km s^{-1}, covering $\sim 10\%$ of the sky, which could be contained within 50 kpc (York, Burke, and Gibney 1986*a*). Producing a complex QSOALS using such clouds would require 10^5 times the number known, assuming all these clouds produce the correct absorption spectrum. Rather extensive searches for extended halos of other galaxies in 21 cm emission and absorption (Briggs *et al.* 1980; Haschick and Burke 1975), in Ca II absorption (Bothun, Margon, and Balick 1984; Morton, York, and Jenkins 1986), in Lyα (York *et al.* 1986*c*), and in our own Galaxy for Si IV and Si II absorption (York *et al.* 1983; York *et al.* 1984*a*, *b*) provide no encouragement that such extensive systems of clouds will be found to be common constituents of low z galaxies. The only direction looking out through our own halo that resembles a complex QSOALS is that of the large Magellanic Cloud, which is discussed in detail in the following section.

Unless future data change this situation dramatically, there seem to be three options for explaining the complex QSOALSs. First, the picture of many single absorbers is correct, but the number of such clouds has changed dramatically from $z > 1$ to the present epoch. Alternatively, "halos" may represent many fewer absorbers, with each absorber producing complex absorption, a possibility we take up in the next section. In the latter case, the entitles with many absorbers are not present in large enough numbers today either, and again evolution from $z > 1$ to the present is implied.

A third possibility is that each galaxy has a simple halo with $\epsilon = 1$ for a single narrow absorber, the complex profiles observed arising because galaxies cluster so that many halos are passed through by a QSO sight line at a given epoch whenever one halo is passed through. This explanation has been recently explored by Pettini *et al.* (1983). Given the clustering properties of galaxies today, only one or two systems are expected to be seen in absorption with total system widths greater than 600 km s^{-1} over the entire sky at any z. In fact, tens of such systems are known, based on the arguments above. It is expected that clustering in the past would be comparable to or weaker than clustering at $z = 0$. We therefore discount this possibility.

III. AN ANALOGY WITH GAS-RICH DWARF GALAXIES

a) Absorption-Line Spectra

The possibility that a halo contains a small number of absorbers, each of which produces complex profiles is now explored. An obvious candidate for the individual source of a QSOALS is a small galaxy, actively forming stars, with each velocity component representing a cloud within the galaxy. To develop this idea further, we argue by analogy with the known properties of gas-rich dwarfs.

It is well known that the complex system of absorption lines seen in high-resolution spectra of stars in the Large Magellanic Cloud (LMC) and to some extent in the SMC (Small Magellanic Cloud) (Savage and de Boer 1981) resemble QSOALSs (Savage and Jeske 1981). At 30 km s^{-1} resolution, complex profiles of C IV appear with integrated equivalents widths

$W(1548) \approx 0.3$–0.5 Å. There are up to six components discernible in the UV resonance lines (see references above), four to five discernible in H I 21 cm emission (McGee, Newton, and Morton 1983). In all these cases, the number of components could double if higher resolution and signal to noise were available. The authors of the above papers interpret part of the absorption as arising in the halo of the Milky Way (the existence of which was postulated by analogy to the halo interpretation of QSOALSs), but according to recent papers (Fitzpatrick and Savage 1983; de Boer and Nash 1982) even some of the lower velocity components may arise in the Clouds. (These would be negative velocity components in the rest frame of, say, the LMC.) York (1982*a*) pointed out that this line of sight is very peculiar in the wide velocity spread of Ca II interstellar components compared to all other halo lines of sight to extragalactic objects. Whereas virtually all lines of sight to LMC stars show 5–7 components of Ca II covering 200–300 km s^{-1}, most directions to extragalactic sources show one to two components over less than 50 km s^{-1} near zero velocity. These statements apply to detection limits of ~ 30 mÅ and exclude those few directions to Oort high-velocity 21 cm clouds, which are far too few to explain the QSOALS phenomenon (York 1982*b*). It is more likely that the absorption is intrinsic to the Magellanic Clouds, a hypothesis supported by an extensive analysis of spectra of 52 LMC and SMC stars (Songaila *et al.* 1986). Meaburn (private communication) has detected high-velocity Hα emission (up to -200 km s^{-1}), again suggesting a Cloud origin for high-velocity gas (Goudis and Meaburn 1984).

Gallagher (private communication) has noted large-velocity full widths (up to ~ 500 km s^{-1}) in Hα emission in a number of gas-rich irregular galaxies. Lower limits to emission-line widths for NGC 604 and II Zw 40 are 350 km s^{-1} and 250 km s^{-1}, respectively, based on Hα velocity maps (Gallagher and Hunter 1983). Since absorption lines observed at sensitivities of 10–20 mÅ are sensitive to total hydrogen column densities $N(H^0) + N(H^+)$ as low as 10^{16} (Cohn and York 1977), while in emission-line studies, $N(H^+) > 10^{19}$, typically (Reynolds 1985), it is possible that even higher velocities could be found when absorption-line studies for gas-rich dwarfs become available.

The systems discussed in the previous paragraph have emission lines of metals, with abundances 0.01–1 times the typical solar values. The ionization in such galaxies varies in emission-line studies. It is clear that a QSO observed through the LMC could show absorption in gas from 100 K up to 10^5 K, i.e., from cool clouds known from C I lines up to C IV discussed by Savage and de Boer (1981). Supernovae remnants are known as well, with hot ($T > 10^6$ K) X-ray emitting gas. Similar statements presumably apply to gas-rich dwarfs in general.

While detailed analyses using 10 km s^{-1} resolution absorption spectra are not yet available for gas-rich dwarfs, the large aggregates of star-forming activity probably lead to a wide range in ratios such as N(C IV)/N(Si IV) because of shielding of various sight lines from the many local sources of ionization (hot massive stars). Unshielded regions will show components with low ratios of N(C IV)/N(Si IV) (Cowie, Taylor, and York 1981) since the UV stellar radiation field dominates. Regions shielded from stellar UV photons will show larger ratios (from evaporative interfaces caused by conductive heating or from clouds at the outside of the galaxy flooded by the QSO background radiation).

We conclude that QSOALSs could be formed when lines of sight to QSOs pass through gas-rich dwarf galaxies. It should be emphasized that the problems naturally solved by this suggestion are the complexity of the QSOALSs in number of components, spread of components, and variable ionization in adjacent velocity components. The actual ratios of ions such as N(C II)/N(C IV), are somewhat higher in the LMC and SMC cases on a component by component basis than in QSOALSs as a group. Saturation makes it difficult to quantify this difference. At any rate, the actual ionization ratios depend sensitively on the actual source of the ionizing photons and amount of shielding from H I and thus do not provide a very useful basis for analogy. This explanation may account for an apparent excess of damped Lyα lines pointed out by Wolfe *et al.* (1985*b*), since lines of sight through star-forming regions may frequently encounter $N_{\rm H\,I} > 10^{20}$ cm^{-2}, a value typical of diffuse clouds even when $E(B-V) < 0.1$, near the Sun.

The spread in components is not well understood physically. Orbital and free-fall components for a dwarf galaxy near a large ($M_B = -20$) galaxy are ~ 300 km s^{-1}, which will be seen as the spread of components only if the large galaxy and the dwarf are both observed in absorption. Rotational components within the dwarf would certainly be less than 50 km s^{-1} because of projection effects along the very narrow column sampled by a QSO image. Tidal effects could be several hundred km s^{-1}, as apparently noted in the LMC (Songaila *et al.* 1986) and in the LMC/SMC system (Lin and Lynden Bell 1982). Bregman (1981) suggested that a "galactic fountain" of material driven by supernovae into the halo, cooling, and returning on ballistic orbits could produce the necessary conditions to produce multiple narrow components covering several km s^{-1} with $\epsilon = 1$ over 50–100 kpc. His models assume supernovae rates of 1/170 to 1/27 yr^{-1}. To quote Bregman, "If supernovae heating is inefficient, as is likely, then these rates underestimate the required supernova rates, and only galaxies with active star formation, and high supernova rates, may be able to heat these coronae." The present (negative) evidence concerning halos in low z galaxies (cited earlier) and the above comments are consistent with the picture presented here. The regions we discuss have high supernova rates and could lead to collective phenomena, but are apparently not common at low redshifts.

The massive stars with winds and the supernova remnants in gas-rich dwarfs have the potential of creating velocities of thousands of kilometers per second. In modeling the active galaxy M82, Chevalier and Clegg (1985) present a wind model, based on supernovae rates of 3–5 yr^{-1}, in a 200 pc volume. Wind velocities of 2800 km s^{-1} are achieved, capable of accelerating typical interstellar clouds (1 kpc away) at up to 430 km s^{-1}. In absorption, in the spectrum of a background quasar, velocity widths (consisting of cloudlike components) of over 800 km s^{-1} would be seen. Hα emission studies of M82 (Williams, Caldwell, and Schommer 1984) indicate an irregular velocity pattern with velocities covering a range of up to 400 km s^{-1} detectable at any one point. While it is not obvious that the particular ionization states observed in QSO absorption lines could reach the velocities noted in these examples of star-forming regions, there do exist regions in our own Galaxy where very high velocity gas is noted in unexpectedly low ionization states. Perhaps the best examples are Ca II at ± 150 km s^{-1} toward stars in the Carina region (Walborn and Hesser 1982) and Ca II and N II toward the Orion Belt stars at -120 km s^{-1} (Cohn and York 1977; Cowie, Songaila, and York 1979).

To the extent that the various sources of velocity (cloud) dispersion are independent, velocity spreads as large as 850 km s^{-1} or more may be expected for absorption lines in star-forming regions near large galaxies. Explaining cases of much higher velocity spread may require other mechanisms or accidental overlap of dwarfs at slightly different epochs. Note that an accidental overlap of two multicomponent absorbers (galaxies) in a few cases may be more plausible than the overlap of the 10–12 single-absorber halos discussed earlier in this paper. A successful mechanism for explaining the QSOALSs requires that high-velocity spreads (>600 km s^{-1}) not be produced all the time, the most common values being 100–400 km s^{-1}.

IV. FURTHER INFERENCES

Dopita (1985) has shown that in virtually all systems with adequate observational material (~ 50 systems), the star formation rate (SFR) appears to decline exponentially in time:

$$\mathrm{SFR} = (M_T/ft_0)e^{-t/t_0}\ M_\odot\ \mathrm{yr}^{-1}\ , \tag{2}$$

where M_T is the total mass of the system, f is the fraction of gas that remains bound up in the stars formed from the gas, and t_0 is the gas depletion time scale, where $t_0 = 3\text{–}5 \times 10^9$ yr. It is thus reasonable that current galaxies, observed at $z > 1$ had much higher star formation rates at earlier epochs. It is likely that massive protogalaxies passed through a phase when they were comprised of a set of Magellanic-like subunits, distributed throughout a more massive halo. From the previous section, it may be seen that if absorption-line statistics existed for the outer regions of galaxies at $z = 1\text{–}3$, the appropriateness of this possibility could be tested. QSOALSs may represent the needed set of statistics. Such statistics could be useful in testing various galaxy formation scenarios at low z (Frenk *et al.* 1985; Gunn 1982).

The largest obvious star-forming regions in dwarf galaxies are 1–2 kpc in size (Hodge 1983; Dopita, Mathewson, and Ford 1985). This may be the size of the entire dwarf or merely a part of the dwarf (30 Dor or Shapley III in the LMC). The value of $\epsilon = 1$ for $r = 30$ kpc $(100/H_0)$ (eq. [1]) then requires ~ 1000 dwarf galaxies at $10^8\ M_\odot$/dwarf galaxy (or star-forming region), $M_T \approx 10^{11}\ M_\odot$ for the mass in the halo, comparable to the total luminous mass of an $M_B = -20$ galaxy. This number of galaxies is an upper limit because in the LMC the regions exhibiting large velocity spreads are not restricted to the 30 Dor region, but encompass the entire angular extent of the galaxy (Songaila *et al.* 1986). On the other hand, the mass per star-forming region is poorly known in such a calculation.

We can roughly estimate a plausible number of subunits around a massive protogalaxy. For the subunits of mass M to retain their individual identities, each would have to be confined to its tidal radius, R_T. If M_g is the total mass of a protogalaxy within the perigalactic radius R_p of the orbit of the subunit,

$$R_T = R_p(M/3M_g)^{1/3}\ .$$

For a set of parameters consistent with LMC–like objects ($M = 2 \times 10^9\ M_\odot$, $R_T = 8$ kpc, $M_g = 10^{12}\ M_\odot$) we find $R_p = 70$ kpc. By mass, there could be $N = 500$ subunits in this example. Units with $M < 2 \times 10^9$, or units with less mass interior to their orbits will give lower values of R_T. Since $N\pi R_T^2 > \pi R_p^2$ in the example, it is possible to have $\epsilon = 1$ for intercepting a multicomponent absorber along a random QSO sightline. According to the statistics cited earlier, this example allows $A \approx 0.3 \times (70\ \mathrm{kpc})^2\pi$.

We conclude that QSO absorption lines may arise in star-forming regions, possibly small portions of massive protogalaxies.

V. OBSERVATIONAL TESTS

Observations of many more QSO absorption-line systems will allow an improvement in the statistics and reveal what percentage of systems might require the explanation we propose. Here, we concentrate on imaging tests in narrow bands that may directly confirm or deny the hypothesis. Star-forming regions are sites of strong emission lines. In particular, the flux in Hα is thought to be directly related to the SFR (Kennicutt 1983; Kennicutt and Kent 1983), so

$$F(\mathrm{H}\alpha) = 1.12 \times 10^{41} \times \mathrm{SFR\ ergs\ s}^{-1}\ , \tag{3}$$

where SFR is in $M_\odot\ \mathrm{yr}^{-1}$. From equation (2), at look back times of 6–8 Gyr, the same mass object may produce up to 10 times the current Hα flux, on average. Stochastic variations may produce much larger fluxes. Thus, even though the surface brightness is lowered by cosmological effects, $[S(\mathrm{ph\ s}^{-1}) \propto (1 + z)^{-3}]$, surface brightnesses in the proposed gas-rich dwarfs need not be much lower than in similar mass objects today. With the *Hubble Space Telescope* the individual large regions should always be resolved (1 kpc > 0″.1 at all z).

Permitted lines as well as forbidden lines may be usefully searched for. For example, the photoionization/shock models run with the A.N.U. Mount Stromlo code, *MAPPINGS*, used for fitting spectra of H II regions in external galaxies, show that I([O II], 3727) > I(Hβ) even with oxygen abundances as low as 1/20 of the solar abundance. Hunter (1984) has shown in a number of irregulars (e.g., NGC 4449) that I[O II]/I(Hα) is 4–6 times stronger in the diffuse medium than in bright H II regions in the same irregulars. While the Hα brightness is lower in the diffuse regions compared to the bright H II regions in irregulars (e.g., NGC 4449), the H II region statistics in irregulars (Hodge 1983) imply that the integrated diffuse Hα emission exceeds the integrated Hα flux from the obvious H II regions. Therefore, the [O II] emission from the diffuse medium exceeds that from the H II regions by at least a factor of 5.

Given the above plausibility arguments for the detectability of star-forming regions at cosmological distances, we now can discuss specific known low z objects and their expected signals extrapolated to high z. H II regions can be classified into five types for our purposes. We equate H II regions to star-forming regions because of the earlier argument that UV photons from hot stars can be counted by Hα photons. The categories are (1) supergiant extragalactic H II regions detached and isolated with little stellar continuum (I Zw 118, II Zw 40, NGC 1705; see Lequeux *et al.* 1981; Lamb *et al.* 1985); (2) blue compact galaxies with a large stellar component and complex structure (II Zw 33, II Zw 185, Mrk 7 and 8, Mrk 325; Coupinot, Hequet, and Heidemann 1982, Casini and Heidemann 1976); (3) interacting galaxies such as M82, near to and often visibly linked by bridges to other galaxies (e.g., M81); (4) giant H II regions in or near galaxies (30 Dor in the LMC, NGC 604 in M33, the bright H II regions in M101; Hodge 1983; Shields and Searle 1978); and (5) normal H II regions with a well-defined number-size relationship in galaxies, with diameters smaller than 100 pc, often associated with normal stars (Hodge 1983). For comparison of total brightness, giant H II regions contain 100–1000 O stars, while blue compact galaxies contain $\sim 10^4$ O stars.

The diffuse Hβ surface brightness in an irregular galaxy such as NGC 4449 is $\sim 10^{-16}$ ergs cm^{-2} s^{-1} Ω_0^{-1}, where Ω_0 is 0.25 arcsec^2 (see Hunter 1982, Fig. 3-2). Giant H II regions are 10–100 times brighter and blue compact galaxies are 10^3–10^4 times brighter. Using energy units, the cosmological dimming in surface brightness varies as $(1 + z)^{-4}$. The detected surface brightnesses are thus reduced from the values by 80, 40, 16, and 5, at $z = 2$, 1.5, 1, and 0.5, respectively. For a reasonable detection limit of 10^{-16} ergs cm^{-2} Ω_0^{-1}, starburst galaxies (classes 1 and 2) are detectable at $z > 1$, and normal H II regions are visible at $z = 0.1$. The diffuse light in NGC 4449 would be visible at lower z, but the integrated power over all of NGC 4449 excluding H II regions could be seen to $z = 1$–2, given a proper instrument.

It is thus evident that images of regions around QSOs made through filters tuned to the known *absorption*-line redshift, should lead to detection of star-forming regions in a number of cases. From the absorption-line statistics, to have a good chance of detecting an irregular implies the existence of many such systems around a given protogalaxy. Returning now to star formation rate predictions, we consider a distant subdwarf at $z = 1.5$. For $q_0 = 0$, luminosity distance $D_L = c(z + z^2/2)/H_0$, angular diameter distance $D_A = D_L/(1 + z)^2$, and $z = 1.5$, we find $D_L = 3 \times 10^{28}$ cm, $D_A = 5 \times 10^{27}$ cm^{-1}. Using the above example that led to 500 subunits in a 10^{12} $M_\odot$ protogalaxy, we find using equations (2) and (3) that $I(\mathrm{H}\alpha) = 5 \times 10^{43}$ ergs s^{-1}, corresponding to a rate of 500 $M_\odot$ yr^{-1}, 50 times the current rate in the galaxy. The subunits in the protogalaxy (70 kpc) will extend over $\sim 8''$, each subunit extends over $\sim 0''.5$, and the total observed flux in Hα is $I(\mathrm{H}\alpha) = 4 \times 10^{-3}$ ph s^{-1} cm^{-2}, corresponding to surface brightness $\sim 10^{-17}$ ergs cm^{-2} s^{-1} Ω_0^{-1} (see above paragraph). Thus, a 4 m diameter telescope gives 500 photon s^{-1} integrated over the entire 8″. It is evident from the previous paragraph that the starbursts (10–100 times the average brightness used here) are just the stochastic fluctuations required to make possible detection straightforward, given the use of filters of 4–5 Å bandwidths.

It is interesting that the 3CR sample of Spinrad and collaborators (private communication) show [O II] luminosities from 10^{42}–10^{44} ergs s^{-1} for $z = 1.2$–1.8. Many of these show extended emission along the slit of 6″ to 8″, that is the [O II] flux has little to do with the radio source in these cases. The extended regions are thus very similar to what we predict here to be the origin of the QSOALSs.

VI. BROADER IMPLICATIONS

An obvious potential problem with our explanation is that the collision time $t_{\mathrm{coll}} \approx 1/nv\sigma \sim 10^8$ yr $(R/50\ \mathrm{kpc})^3$ $(N/1000)^{-1}(r/2\ \mathrm{kpc})^{-2}$ $(v/100\ \mathrm{km\ s^{-1}})^{-1}$ for the subunits, where r is the radius of the subunits, R the radius of the aggregate galactic mass, N the total number of absorbers, and v the velocity of the subunits. This is long enough to allow star formation but is shorter than the free-fall time into the main galaxy. Thus a given subunit may not last very long. On the other hand, since the collision time is shorter than the gas depletion time of 3–5×10^9 yr, these collisions may actually trigger more star formation. The normal free-fall time may be greatly extended because the pressure produced by active star formation can hold off the ultimate gravitational collapse for times comparable to a Hubble time (Silk, private communication).

Silk and Norman (1979) considered a somewhat related situation of slow accretion of gas-rich dwarf galaxies by already existing galaxies, concluding that in typical cases, such dwarfs might be accreted in a Hubble time. For densities of 30 dwarfs per Mpc^3, they suggested that many systems might be in the capture process at $z \approx 0.5$ and that under such conditions the apparent rapid evolution of radio sources might be understood (note above comments on recent work by Spinrad) and the conditions for forming QSO absorption lines might exist. The present considerations suggest that the supposed number density of dwarfs is inadequate to explain the many components seen in the QSOALSs at (statistically) large distances from (statistically) most large galaxies. Rather, the mass of gas-rich dwarfs needed may be so large that an entire galactic mass (10^3 dwarf galaxies) may be needed.

Counts of number of absorbing systems per comoving volume (n_{gal}) would lead to the volume specific star formation rate as a function of time at a typical radius from an L_* galaxy, if our suggestion is correct. No evolution in comoving density of absorbers (a result consistent with current data) would imply a roughly constant rate at $r = 30(100/H_0)$ kpc from $z = 0.5$ to $z = 3.5$, the range over which reasonable, comparable data can be obtained, whereas a decrease in n_{gal} with z would indicate a decreasing rate in time at that distance.

The fate of the star-forming material possibly represented by QSOALSs is of course uncertain. The subunits could eventually be totally stripped by the dominant galaxy, leaving star streams and clusters in unique orbits with abundances appropriate to a common origin (Rodgers and Paltoglou 1984). Gas could be blown out of them, leaving dwarf ellipticals with numerous condensed artifacts of once-active massive star formation, possibly a major contributor to the cold dark matter that could explain the missing mass required on scales smaller than 1 Mpc (Blumenthal *et al.* 1984). Alternatively, the small subunits could end up as part of the present-day luminous matter.

The possibility of high-resolution observations (10 km s^{-1}) of many QSOALSs means, on our hypothesis, that a partially biased inventory of gas can be obtained at all z's out to 3.5. The quasars are randomly distributed with respect to the postulated foreground star-forming regions, so the total amount of material can be estimated independent of any biases introduced by actually depending on luminous galaxies to trace mass. (Of course, any star-forming material that leads to large extinctions could not be completely studied, because any background quasars could not be seen.) To allow this possibility to bear fruit, a classification system would be required to distinguish high-mass regions from low-mass regions. A possibility would be the total line width of a system, which should be related to the amount of star-forming activity, hence, to the total system mass.

Finally, we consider the extinction caused by such systems. There are different extinction curves observed within the Local Group (Prévot *et al.* 1984; Koornneef 1982). The SMC curve shows a ratio $E(1200 - V)/E(B - V)$ of 20/1, with $N_{\mathrm{H}}/E(B - V) = 10^{23}$ atoms cm^{-2} mag^{-1}. This is perhaps the appropriate curve to use because no 2200 Å bump is seen and because the SMC is a region of low metal abundance. Wolfe *et al.* (1985*b*) have published statistics of H I detections in QSOALSs relevant to the range $[N(\mathrm{H\ I}) = 10^{19.3}$–$10^{23}]$. While complete statistical analysis has not been published by them, we can use their raw data for our purposes. They provide a search for Lyα with $W > 5$ Å in 68 QSOs, covering $\Delta z = 56$—typically $\Delta z = 0.85$ per QSO near $z \approx 2.2$—yielding 47 candidate lines, and suggest that follow up studies lead to a 60% confirmation rate. Roughly speaking, $\sim$6% of detected systems have $N(\text{H I}) > 10^{22}$, 28% yield $N(\text{H I}) > 10^{20}$. The weaker lines, and the systems below their detection limit, may not be representative in considerations of dust, because Sargent *et al.* (1979) suggest $N(\text{H}^+) > 10^{20}$ from analysis of ionized metals. Therefore, we assume $N_{\text{H}} = N(\text{H}^0 + \text{H}^+) > 10^{20}$ in typical cases.

For the SMC properties the color excess of an intervening absorber is (for $N_{\text{H}} \approx 10^{21}$ cm^{-2}), $E(B-V) > 10^{21}/10^{23} = 0.01$ for typical systems, reaching more than 0.1 in a few cases. The $E(1200-V)_A$ is 0.2 mag, reaching 2 mag in extreme cases. Typically, up to 5 systems in one QSO including one extreme case, would produce an upper limit of 3 mag for $E(1200-V)$. Note that 1200 Å radiation in the QSO is seen at longer wavelengths, hence giving lower extinction, at each intervening system, and that 10^{21} cm^{-2} is an upper limit to N_{H} for most systems. On the other hand, an LMC extinction curve could give up to 5 times larger $E(1200-V)$ in each system, and a Galactic curve could give up to 10 times larger $E(1200-V)$ in each system. Ostriker and York (1986) discuss the implications of these statistics in greater detail.

Netzer (1985) and Allen *et al.* (1982) have considered the case for intervening extinction in the case of QSOs. Netzer considers the problem of line strength to continuum ratios in QSOs and reviews results of photoionizing models by many authors. He concludes that such models are not viable unless the QSOs have a flatter spectrum than observed, and hence, much more reddening than assumed. Otherwise, there are not enough continuum ionizing photons at the source to explain the total power in the emission lines. As a typical case, he suggests that $E(B-V) \approx 0.5$ might exist, derived using a galactic extinction law (presumably). The QSO would then have a spectrum $F \propto \nu^n$, $n < 2$, and $E(1200-V) < 5$ mag. Bechtold *et al.* (1984) show that QSO spectra in the UV have foreground extinction, possibly attributable to intervening Lyman limit systems or to dust, or both. Of course, the intrinsic spectrum of each QSO is unknown in detail.

Allen *et al.* (1982) consider the ratio Hα/Lyα in two samples of QSOs, a low z sample and a high z(2.1–2.8) sample. They find no significant difference (hence no reddening) in the ratio averaged for the low z set and the high z set, but they do find a correlation of Lyα/Hα with spectral index of the QSO: when the spectrum is steeper, Lyα/Hα is lower, consistent with reddening. The former effect can easily be understood if their small sample (12) at high z had few high N_{H} absorbers ($\sim$1 per unit z is expected) and no extreme case. Their later result is consistent with 1–2 mag of extinction in some objects.

We conclude that appreciable extinction at 1200 Å (rest frame) in QSO spectra is not ruled out by the data or by current models for the emission line regions. From the statistics of QSO absorption lines and expected extinction curves in young star-forming regions, extinction at currently discernable levels might not be expected at all in the picture presented here. On the other hand, careful studies of QSO continua in cases where the intervening absorption systems are well studied may eventually show evidence of intervening dust.

VII. SUMMARY

Many QSO absorption-line systems exhibit complex structure and a wide range of ionization states of common elements. Both these properties could be adequately explained if the absorbers are star-forming regions in the line of sight to the background QSO. The systems that might be explained this way are too numerous to be associated with the few such objects (gas-rich irregulars?) observed today. Following the statistics used to analyze the galaxy halo hypothesis, we suggest the star-forming regions are clustered around galaxy-like potential wells. We then require a large fraction of the baryonic mass of a normal galaxy to be in a halo of star-forming regions (at the epoch of QSO absorption-line formation). The hypothesis can be checked by searches for Lyα, Hα, and [O II] 3727 Å emission at the *absorption*-line redshift, around QSOs. If the hypothesis is correct, QSO absorption-line systems provide a powerful tool for studying galaxy formation over the range $z = 0.5$–3.0.

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