Low Redshift Lyman Alpha Absorption Lines and the Dark Matter Halos of Disk Galaxies

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Introduction. Recent observations using the Hubble Space Telescope (Morris et al. 1991, ApJ 377, L21; Bahcall et al. 1991, ApJ 377, L5) of the z = 0.156 QSO 3C 273 have discovered a surprisingly large number of Lyα absorption lines. In particular, Morris et al. found 9 certain and 7 possible Lyα lines with equivalent widths above 25 mA. This is much larger (by a factor of 5-10) than the number expected from extrapolation of the high-redshift behavior of the Lyα forest. Within the context of pressure-confined models for the Lyα clouds, this behavior can be understood if the ionizing background declines sharply between z ~ 2 and z ~ 0 (Ikeuchi & Turner 1991, ApJ 381, L1). However, this requires that the ionizing photon flux drop as rapidly as the QSO volume emissivity; moreover, the absorbers must have a space density n_0 ≈ 2.6(N/10)(h/(D/100 kpc))^2 Mpc^{-3} where D is the present-day diameter of the absorbers. It is somewhat surprising that such necessarily fragile objects could have survived in such numbers to the present day.

Here I show that it is plausible that the atomic hydrogen extents of spiral and irregular galaxies are large enough to produce the observed number of Lyα absorption lines toward 3C 273, and that the neutral column densities and doppler b-values expected under these conditions fall in the range found by Morris et al. (1991).

Neutral Hydrogen in Low Column Density Gas Disks. Consider a gas disk in a galactic potential, exposed to an isotropic background radiation field. For neutral hydrogen column densities N_HI ≤ 10^{16} cm^{-2} the attenuation of the incident ionizing flux will be completely negligible. I assume that the radiation field is a power-law matched to the observed background at 1.5 keV; in terms of the photon flux \phi_v = 4\pi J_\nu /h\nu this is \phi_v = \phi_0 I_{Ly} (\nu /\nu_\alpha)^{-\alpha} where \phi_0 = 2.3 \times 10^{-11} photons cm^{-2} s^{-1}, I_{Ly} is a scaling factor, and \alpha is the spectral index; \alpha = 1.45 + 0.490 \log (I_{Ly}). A value of I_{Ly} = 1 corresponds to a (4\pi sr) ionizing photon flux \phi_i = 5.2 \times 10^4 photons cm^{-2} s^{-1} and Lyman intensity J_{\nu H} = 4 \times 10^{-23} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}. Solving for the neutral fraction gives

\[ x_{H^0} \approx \frac{1.2\alpha_A n_H}{\xi_H} = \frac{1.2\alpha_A n_H (\alpha + 3)}{\phi_0 I_{Ly} a_0 \nu_H} = \frac{n_H (\alpha + 3) T e_4^{-0.72} I_{Ly}^{-1}}{\xi_H} \]

where \( n_H \) is the total hydrogen volume density and \( \xi_H \) the hydrogen ionization rate; I have assumed that \( n_e = 1.2 n_{H+} \) and \( \alpha_A = 4.18 \times 10^{-13} T e_4^{-0.72} \).

At the column densities of interest here, \( N_H \lesssim 10^{10} \text{cm}^{-2} \), the gas self-gravity is negligible, and the equilibrium gas vertical density distribution in the potential of a spheroidal halo will be a gaussian with dispersion (for gas vertical velocity dispersion \( \sigma_{zz} \))

\[ \sigma_H(R) = \frac{(r_c^2 + R^2)^{1/2} \sigma_{zz}}{(4\pi G \rho c r_c^2)^{1/2}} \approx \frac{R \sigma_{zz}}{V_A} \]

where the approximation is true for \( R^2 \gg r_c^2 \); \( \rho_c \) and \( r_c \) are the core density and core radius of the halo. If the Z-motions of the gas are purely thermal, then \( \sigma_{zz} = 12.9 T e_4^{1/2} \text{ km s}^{-1} \). Combining equations (1) and (2) and integrating from \( Z = 0 \) to \( \infty \), the neutral hydrogen column density is then

\[ N_{HI}(R) = 2 \int_0^\infty x_{H^0} n_H(R, Z) dZ = 1.4 \times 10^{13} \frac{N_{HI,18} V_A,100 (\alpha + 3)}{R_{50} T_{e_4,22} I_{Ly}} \text{ cm}^{-2} \]
where $R_{50}$ is $R/50$ kpc, $N_{H,18}$ is the total hydrogen column density $N_H/10^{18}$ cm$^{-2}$, and $V_{A,100}$ is the halo asymptotic velocity $V_A/100$ km s$^{-1}$ and I have assumed the gas is isothermal. Assuming that photoionization heating balances recombination and bremsstrahlung cooling, the temperature is

$$T_e = \frac{h \nu}{\beta k} \left[ \frac{(\alpha + 3)}{(\alpha + 2)} - 1 \right] K$$

where $\beta \approx 1.15$. Thus $T_e \approx 46,000$ K for $\alpha = 1$ and $T_e \approx 32,000$ K for $\alpha = 2$; the corresponding doppler parameters would be $b \approx 28$ and 24 km s$^{-1}$.

Comparison with Observations. The number of galactic disks expected along a line of sight in a matter-dominated, $\Omega = 0$ universe is

$$N = \left( \frac{c}{H_0} \right) \frac{\langle \sigma n \rangle_0}{2} \left[ (1 + z)^2 - 1 \right].$$

where $\langle \sigma n \rangle_0$ is the luminosity function-averaged product of cross-section and density at the present epoch. Assuming a Schechter luminosity function, a Holmberg relation between cross-section and luminosity, $\sigma_H(L) = \sigma_*(L/L_*)^\beta$, where $\sigma_*$ is the cross-section of an $L_*$ galaxy, and that the cross-section of the gaseous disk of a galaxy is related to the optical cross-section by $\sigma_{gas}/\sigma_H = f_{gs} (L/L_*)^\beta$, $\langle \sigma n \rangle_0 = \sigma_* f_{gs} \phi_* f_{sp} (\cos i) \Gamma(\delta - \beta - s + 1)$ where $f_{sp}$ is the fraction of galaxies which are spirals or irregulars, $(\cos i)$ corrects for inclination effects, $s$ is the slope of the luminosity function, and $\Gamma(z)$ is the complete gamma function. Taking $\phi_* = 1.6 \times 10^{-3} h^5$ Mpc$^{-3}$ (Efstathiou, Ellis & Peterson 1988, MNRAS 232, 431), $R_\star = 11.5/h$ kpc (cf. Wolfe et al. 1986, ApJS 61, 249), $f_{sp} \approx 0.7$, and $(\cos i) = 0.5$ (for thin disks) the number of intercepted disks expected for $z = 0.15$ is $N(z = 0.15) \approx 1.1 \times 10^3 \Gamma(\delta + \beta - s + 1)$.

If we identify galaxies as the source of the absorption lines seen toward 3C 273, then the observed number of lines constrains $f_{gs}$ and the variation of $\sigma_{gas}$ with galaxy luminosity. At the $N_{HI} \sim 10^{13}$ cm$^{-2}$ level, galactic halos must satisfy $f_{gs} \Gamma(\delta + \beta - s + 1) \sim 8 \times 10^3$. Thus, either $L_*$ galaxies have huge ($R \sim$ several hundred kpc) halos ($f_{gs} \gg 1$) or low-luminosity (dwarf or low surface brightness) galaxies have large halos and are abundant. This second possibility is crucially dependent on whether there is a low-luminosity cutoff in the galaxy luminosity function, and on the faint-end slope relative to the variation of $\sigma_{gas}$ with luminosity.

The nine certain Lya lines detected by Morris et al. (1991) have equivalent widths between 57 and 302 mA and derived column densities between $\log N_{HI} = 13.04$ and 14.13 cm$^{-2}$; the latter is the only line with $\log N_{HI} > 13.6$ cm$^{-2}$. The observed column density distribution will be area-weighted. For a $1/R$ distribution, the neutral column density will fall off as $R^{-3}$, and $N_L(N) \propto N^{-5/3}$. If the total gas distribution is an exponential, then $N_L \propto N^{-a}$, with $a \approx 1.2 - 1.3$. The nine certain Lya lines have $b$-values ranging from 17-111 km s$^{-1}$; the latter is twice the next-highest value. The mean is 38 km s$^{-1}$ (29 km s$^{-1}$ if the 111 km s$^{-1}$ point is discounted). The expected thermal $b$-values are $\sim 20 - 30$ km s$^{-1}$, depending only on the slope of the extragalactic radiation field. For thin disks, the contribution from rotation to the observed velocity dispersion will be small except for nearly edge-on geometries (Wolfe et al. 1986), less than 20 km s$^{-1}$. Thus the expected $b$-values for these thin disks are in reasonable agreement with the minimum observed $b$-values. Metal absorption lines such as CIV $\lambda\lambda 1548,1551$ may be detectable at the tens of mA level if the metallicity $Z \sim 0.1 Z_\odot$ or greater.

Further studies of the low-redshift Lya lines, especially observations of QSOs whose lines of sight intercept the halos of known low redshift galaxies, will constrain both the extragalactic radiation field and the gaseous and dynamical properties of galactic halos.