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

Philip Maloney

NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035

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 mÅ. 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 $z \sim 2$ and $z \sim 0$ (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 $n_0 \approx 2.6(N/10)h/(D/100\,\mathrm{kpc})^2\ \mathrm{Mpc}^{-3}$ 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 $N_{\mathrm{H\,I}} \lesssim 10^{16}\,\mathrm{cm}^{-2}$ 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 $\phi_\nu = 4\pi J_\nu/h\nu$ this is $\phi_\nu = \phi_0 I_{\mathrm{Ly}}(\nu/\nu_H)^{-(\alpha+1)}$ where $\phi_0 = 2.3\times10^{-11}$ photons cm^{-2} s^{-1}, I_{Ly} is a scaling factor, and α is the spectral index; $\alpha = 1.45 + 0.490\log(I_{\mathrm{Ly}})$. A value of $I_{\mathrm{Ly}} = 1$ corresponds to a (4π sr) ionizing photon flux $\phi_i = 5.2\times10^4$ photons cm^{-2} s^{-1} and Lyman intensity $J_{\nu_H} = 4\times10^{-23}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}. Solving for the neutral fraction gives

$$x_{H^0} \simeq \frac{1.2\alpha_A n_H}{\xi_H} = \frac{1.2\alpha_A n_H(\alpha+3)}{\phi_0 I_{\mathrm{Ly}} a_0 \nu_H} = n_H(\alpha+3)T_{e,4}^{-0.72} I_{\mathrm{Ly}}^{-1} \tag{1}$$

where n_H is the total hydrogen volume density and ξ_H the hydrogen ionization rate; I have assumed that $n_e = 1.2 n_{H^+}$ and $\alpha_A = 4.18\times10^{-13}T_{e,4}^{-0.72}$.

At the column densities of interest here, $N_H \lesssim 10^{19}\,\mathrm{cm}^{-2}$, 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 σ_{zz})

$$\sigma_h(R) = \frac{(r_c^2 + R^2)^{1/2}\sigma_{zz}}{(4\pi G\rho_c r_c^2)^{1/2}} \simeq R\frac{\sigma_{zz}}{V_A} \tag{2}$$

where the approximation is true for $R^2 \gg r_c^2$; ρ_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 $\sigma_{zz} = 12.9T_{e,4}^{1/2}$ km s^{-1}. Combining equations (1) and (2) and integrating from $Z = 0$ to ∞, the neutral hydrogen column density is then

$$\begin{aligned} N_{\mathrm{H\,I}}(R) &= 2\int_0^\infty x_{H^0} n_H(R,Z)\,dZ \\ &= 1.4\times10^{13}\frac{N_{H,18}^2}{R_{50}}\frac{V_{A,100}}{T_{e,4}^{1.22}}\frac{(\alpha+3)}{I_{\mathrm{Ly}}}\ \mathrm{cm}^{-2} \end{aligned} \tag{3}$$

where R_{50} is $R/50$ kpc, $N_{H,18}$ is the total hydrogen column density $N_H/10^{18}\,\mathrm{cm}^{-2}$, and $V_{A,100}$ is the halo asymptotic velocity $V_A/100\,\mathrm{km\ s}^{-1}$ and I have assumed the gas is isothermal. Assuming that photoionization heating balances recombination and bremsstrahlung cooling, the temperature is

$$T_e = \frac{h\nu_H}{\overline{\beta} k}\left[\frac{(\alpha+3)}{(\alpha+2)} - 1\right]\ \mathrm{K} \tag{4}$$

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

Comparison with Observations. The number of galactic disks expected along a line of sight in a matter-dominated, $q_0 = 0$ universe is

$$N = \left(\frac{c}{H_0}\right)\frac{\sigma_0 n_0}{2}\left[(1+z)^2 - 1\right] . \tag{5}$$

where $\langle\sigma n\rangle_0$ is the luminosity function-averaged product of cross-section and density at the present epoch. Assuming a Schecter luminosity function, a Holmberg relation between cross-section and luminosity, $\sigma_{\mathrm{Ho}}(L) = \sigma_*(L/L_*)^{\delta}$, where σ_* 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 $\sigma_{\mathrm{gas}}/\sigma_{\mathrm{Ho}} = f_{g*}(L/L_*)^{\beta}$, $\langle\sigma n\rangle_0 = \sigma_* f_{g*}\phi_* f_{\mathrm{sp}}\langle\cos i\rangle\Gamma(\delta+\beta-s+1)$ where f_{sp} is the fraction of galaxies which are spirals or irregulars, $\langle\cos i\rangle$ corrects for inclination effects, s is the slope of the luminosity function, and $\Gamma(x)$ is the complete gamma function. Taking $\phi_* = 1.6\times10^{-2}h^3\,\mathrm{Mpc}^{-3}$ (Efstathiou, Ellis & Peterson 1988, MNRAS 232, 431), $R_* = 11.5/h$ kpc (*cf.* Wolfe *et al.* 1986, ApJS 61, 249), $f_{\mathrm{sp}} \approx 0.7$, and $\langle\cos i\rangle = 0.5$ (for thin disks) the number of intercepted disks expected for $z = 0.15$ is $N(z=0.15) \approx 1.1\times10^{-3} f_{g*}\Gamma(\delta+\beta-s+1)$.

If we identify galaxies as the source of the absorption lines seen toward 3C 273, then the observed number of lines constrains f_{g*} and the variation of σ_{gas} with galaxy luminosity. At the $N_{\mathrm{H\,I}} \sim 10^{13}$ cm^{-2} level, galactic halos must satisfy $f_{g*}\Gamma(\delta+\beta-s+1) \sim 8\times10^3$. Thus, either L_* galaxies have huge ($R \sim$ several hundred kpc) halos ($f_{g*} \gg 1$) or low-luminosity (dwarf or low surface brightness) galaxies have large galos 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 σ_{gas} with luminosity.

The nine certain Lyα lines detected by Morris *et al.* (1991) have equivalent widths between 57 and 302 mÅ and derived column densities between $\log N_{\mathrm{H\,I}} = 13.04$ and 14.13 cm^{-2}; the latter is the only line with $\log N_{\mathrm{H\,I}} > 13.6\,\mathrm{cm}^{-2}$. 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 Lyα 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 C IV $\lambda\lambda 1548, 1551$ may be detectable at the tens of mÅ level if the metallicity $Z \sim 0.1 Z_{\odot}$ or greater.

Further studies of the low-redshift Lyα 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.