Towards a Direct Detection of Warm Gas in Galactic Haloes at Cosmological Distances

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ABSTRACT

Recent highly sensitive detections of line emission from extended gas in the local universe demonstrate the feasibility of detecting Hα emitting galactic halos out to z ∼ 1. We determine the form of the surface brightness vs. redshift dependence which takes into account UV background evolution. Successful detections will have a major impact on a wide range of fields, in particular, the source of ionization in QSO absorption systems.

Key words: galaxies: ISM—galaxies: haloes—techniques: spectroscopic

1 INTRODUCTION

The optical line emission of extended extragalactic photoionized sources has been recently considered in several both theoretical and observational works (Hogan & Weymann 1987; Maloney 1992; Binette et al. 1993; Bland-Hawthorn et al. 1994; Donahue, Aldering & Stocke 1995; Bland-Hawthorn et al. 1995; Gould & Weinberg 1996; Bechtold et al. 1997; Bland-Hawthorn 1997; Blaine-Hawthorn et al. 1997; Čirković & Samurović 1998). One of the most important possibilities of such observations are direct detections of extended gaseous structures around normal luminous galaxies at various epochs.

Theoretical models of both galactic halo structure (Bregman 1981; Kovalenko, Shechenkov & Suchkov 1989; Norman & Ikeuchi 1989; Wolfe et al. 1995) and QSO absorption line systems (Mo 1994; Mo & Miralda-Escudé 1996; Chiba & Nath 1997) predict vast quantities of photoionized gas at large galactocentric distances (from several kpc to ∼ 102 kpc). Low-redshift observations of Lyα absorbing systems reveal tenuous gas extending to ∼ 300 kpc (Chen et al. 1998, Lanzetta et al. 1995). The empirical evidence for the metal-line absorbers residing in ∼ 50 kpc haloes is very strong as well (Steidel 1993; Steidel, Dickinson & Persson 1994). In view of recent claimed detections of extraplanar gas in recombination Hα emission at large galactocentric distances in the local universe (Donahue et al. 1995), the possibility of such a situation being typical for galaxies at all epochs must be examined.

Hierarchical structure formation models also emphasize such a picture (Mo & Miralda-Escudé 1996). Detailed N-body simulations (e.g. Navarro & White 1994), as well as the gasdynamical approach of Nulsen and Fabian (1997), show that during the process of galaxy formation a halo of hot gas will inevitably form, and subsequently cool until the cooling time becomes similar to the age of the system. A natural consequence of these scenarios is that warm photoionized gas in haloes will be bound to galaxies at all epochs.

More recently, the focus of the discussion of dark matter in galaxy haloes has returned to dark matter in the form of baryons. Big Bang nucleosynthesis requires much more baryons than observed in the stars, interstellar and intracluster medium (Carr 1994; Fukugita, Hogan & Peebles 1998). We investigate the possibility that at least a part of the baryonic dark matter is in the form of gas—presumably the same, or tightly related, gas which produces QSO absorption lines at low redshift. In the best available baryonic census of Fukugita et al. (1998), warm ionized gas around field galaxies is, significantly enough, the largest and simultaneously the most uncertain entry in their low-redshift list.

Deep optical searches, including HDF, severely limit the mass-to-light ratio of the dark matter in halo of our Galaxy and the Local Group (Richstone et al. 1992; Flynn, Gould & Bahcall 1996). The most recent summary of the MACHO project indicates that as much as half of the dark matter in the Galaxy out to the LMC is made up of solar mass objects. The source of the missing mass is controversial, e.g. a halo population of white dwarfs (Adams & Laughlin 1996; Kawaler 1996; Chabrier & Mera 1997), solar mass black holes (Moore 1993), and so on. One approach to ruling out various models is monitoring halo evolution in galaxies from deep broadband images (e.g. Charlot & Silk 1995). For the want of suitable limits or detections, these studies have neglected a possible nebular contribution which may be prominent at cosmological redshifts.
2 EMISSION MEASURE OF THE RECOMBINATION HALO

We assume the evolution of the background ionizing flux at the Lyman limit as \(J_{\text{UV}}(z) = [(1+z)/3.5]^n \times 10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}\), and its frequency dependence at all redshifts as (Chiba & Math 1997; Haardt & Madau 1996)

\[
J_{\text{UV}} = J_{\text{UV}}(z) \left( \frac{\nu}{10^{16} \text{ Hz}} \right)^{-\beta}.
\]

This is the major force driving the redshift evolution of emission measure \(\epsilon_m\) of the ionized gas. We emphasize that this is just a working model, since precise normalization of eq. (1) is still elusive, due to 1σ uncertainties of factors of 6 or more (Bajtlik, Duncan & Ostriker 1988; Kulkarni & Fall 1993; Vogel et al. 1995). Further redshift dependence may come through chemical evolution which influences cooling rate once \(Z/Z_0 > 0.01\) (Böhringer & Hensler 1989). This would imply slow z-evolution of the electron temperature, \(T_e\). The dynamical evolution of the disk–halo connection (through galactic fountain or some similar mechanism) would also change intrinsic properties of the halo clouds. We neglect these rather subtle points in this discussion.

To proceed, we assume the fiducial log \(N_{\text{H}}\) ionized cloud residing in extended galactic halo of a galaxy at redshift \(z\). This (in the first approximation, homogeneous) halo cloud of \(\sim 30 h^{-1}\) kpc in size is what we expect to see according to the metal-line absorption (Steidel 1993; Steidel et al. 1994; Petitjean & Bergeron 1994). Galactic disks are regarded as opaque to the ionizing radiation between 1 and 4 Ryd. Our conclusions are valid as long as the cloud remains optically thin to \(H_\alpha\), which may not be true only at much higher column densities than those discussed here.

Emission measure of the fluorescent Lyα emission under the assumption of isothermal clouds at all epochs is given by

\[
\epsilon_m(\text{Ly}\alpha) = \frac{1.5 \times 10^5}{(2.75 + \beta)(1+z)^4} \left( \frac{N_{\text{H}}}{3 \times 10^{17} \text{ cm}^{-2}} \right) \times \left( \frac{1+z}{3.5} \right)^{\alpha} \left( \frac{T_e}{10^4 \text{ K}} \right)^{0.75} \text{ pc cm}^{-6}.
\]

where \(T_e\) is the electron temperature of the clouds (Osterbrock 1989; Ćirković & Samurović 1998). This equation is valid for one-sided ionization of a hydrogen slab and is only valid for log \(N_{\text{H}}\) \(\lesssim 17.4 \text{ cm}^{-2}\). Once the slab thickness exceeds one optical depth for the ionizing photons, the emission measure depends only on the external ionizing flux. If we denote the \(H_\alpha/\text{Ly}\alpha\) ratio with \(\delta\), we obtain the intensity in the \(H_\alpha\) line (Reynolds 1992):

\[
I_{H_\alpha} = 1.446 \left( \frac{T}{10^4 \text{ K}} \right)^{-0.92} \epsilon_m(\text{Ly}\alpha) R
\]

\[
= 1.46 \left( \frac{N_{\text{H}}}{3 \times 10^{17} \text{ cm}^{-2}} \right) \left( \frac{T}{10^4 \text{ K}} \right)^{-0.17} R,
\]

\((1 R = 10^6/4\pi \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1})\) for a plausible values of \(\delta \approx 0.08\), \(\beta = 1.73\) (Haardt & Madau 1996) and \(\alpha \approx 2\) (Chiba & Math 1997). This formula is valid for the equilibrium case in which electronic and kinetic temperatures of the photoionized phase are equal. Our result thus generalizes a similar one obtained by Bland-Hawthorn et al. (1994). The difference at a fiducial point discussed by Bland-Hawthorn et al. (1994) can be attributed to the different choice of metagalactic background spectral index and other not-well-known parameters. Note that the largest uncertainty in the equation (2) comes from the uncertainty in \(\beta\), since both the models and observational results from the proximity effect exhibit a rather large scatter (Bajtlik et al. 1988; Madau 1992; Kulkarni & Fall 1993; Donahue et al. 1995; Vogel et al. 1995; Haardt & Madau 1996).

Several interesting approximate relationships can be obtained using eqs. (2) and (3). The electron number density in fluorescing clouds is roughly given by

\[
n_e = \sqrt{\frac{\epsilon_m(\text{H}_\alpha)}{f}}
\]

\[
= \frac{0.0048 f}{1+z} \left( \frac{N_{\text{H}}}{3 \times 10^{17} \text{ cm}^{-2}} \right)^2 \left( \frac{l}{10 \text{ kpc}} \right)^{-\frac{1}{2}} \left( \frac{T_e}{10^4 \text{ K}} \right)^{0.375}
\]

where \(n_e\) is given in cm\(^{-3}\) and \(f\) is the filling factor of the ionized gas (Reynolds 1987). For example, for a Lyman-limit system with log \(N_{\text{H}}\) 17.2 cm\(^{-2}\) and size of \(l = 30 h^{-1}\) kpc at low redshift, this formula (with, probably unrealistic, assumption \(f \approx 1\)) gives \(n_e \approx 5.7 \times 10^{-3} \text{ cm}^{-3}\) (using \(h = 0.75\) and \(T_e \equiv T = 3 \times 10^4 \text{ K}\)), both observationally allowed and theoretically attractive value for highly photoionized regions giving rise to metal-line and Lyman-limit absorption systems.

It will be of great interest to compare values obtained through equation (4) with those obtained by some independent procedure, say curve-of-growth measurements of abundance ratios of pairs of coupled metal species, or observations of Faraday screening of background radio-sources by a foreground electron column density (Bland-Hawthorn et al. 1995). Since the cosmological density parameter \(\Omega\) and neutral hydrogen column densities at a given epoch are related (e.g. Ćirković & Samurović 1998), it should be possible to establish what fraction of the cosmological density is contained within the optically thin photoionized gas (eq. 3).

3 SIGNAL-TO-NOISE AS A FUNCTION OF REDSHIFT

We now demonstrate the feasibility of detecting galaxy haloes in optical line emission at cosmological redshift. We know from the Hubble Deep Field that normal galaxies and galaxy haloes were in place by \(z \sim 1\) (Steidel 1998). Suppose that we are observing target subtending solid angle \(\Theta\) with the telescope of diameter \(D\), our detector is of efficiency \(f\), and the total exposure time is \(t\). Then, the total number of photons from the source in the \(H_\alpha\) line is given as \(n_{\text{source}} = \pi D^2 f \Theta \epsilon m_{\text{H}_\alpha}(\zeta)\) (Gould & Weinberg 1996). The fraction of photons penetrating Earth’s atmosphere is denoted by \(\zeta\). The number of photons of the background in the \(H_\alpha\) line profile in this case is approximately equal to \(n_{\text{sky}} = (\pi D)^2 f \Theta \lambda e(4\sqrt{\pi} \sigma) \phi_{\text{sky}}\) where \(\lambda \equiv \lambda_0 (1+z)\) is the wavelength of the line centroid (\(\lambda_0 = 6562.8\) Å for the \(H_\alpha\) line), \((4\sqrt{\pi} \sigma)\) is the width of the line, determined, presumably, by thermal line-broadening, and \(\phi_{\text{sky}}\) is the sky flux.
in photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$ arcsec$^{-2}$. Thus, signal-to-noise ratio is given by

$$S/N = \frac{\pi^4}{4} \zeta D \left( \frac{f l \Theta}{\lambda_0 \sigma (1 + z)} \right) \left( \frac{I_{H\alpha}}{\sigma_{sky}} \right) =$$

$$= 1.7 \times 10^3 \zeta \left( \frac{f}{0.1} \right) \left( \frac{t}{4 \text{ h}} \right)^{\frac{1}{2}} \left( \frac{D}{8 \text{ m}} \right) \times$$

$$\left( \frac{\sigma}{20 \text{ km s}^{-1}} \right)^{-\frac{3}{2}} \left( \frac{\Theta}{1 + z} \right)^{\frac{1}{2}} \left( \frac{I_{H\alpha}}{\sigma_{sky}} \right). \quad (5)$$

We shall take the sky noise as constant and equal to the fiducial value at 8250 Å (Offer & Bland-Hawthorn 1998). The redshift dependence of the actual observing wavelength changes the background flux and it actually does increase as we go at higher and higher redshifts (i.e. deeper in the infrared). We shall take the background flux to be $\sigma_{sky} = 5.44 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$ arcsec$^{-2}$. Our adopted value is sufficiently conservative as there are comparably dark bands between the OH bandheads throughout the $R$, $I$, $z$, $J$ and $H$ bands. In our calculation, we neglect detector read noise: modern day optical and infrared detectors have amplifier noise of only $1 e^-$ and $5 e^-$ pix$^{-1}$ respectively, such that the sky background always dominates.

We note that for a long-slit of width $d$ (in arcsec) and optimal placing, $\Theta \approx d \theta(l, z)$, where $\theta(l, z)$ is the angle spanned by the target of characteristic proper size $l$ at redshift $z$. In general case of FRW-universes with $\Lambda = 0$, this angle is given by (Weinberg 1972):

$$\Theta = \frac{H_0}{2c} \zeta \Omega (1 + z) \left( \frac{1}{2} - 1 \right) \left( \frac{\Omega}{1 + \Omega} - 1 \right) \equiv \frac{H_0}{2c} G(z), \quad (6)$$

where we have denoted the redshift (and cosmological model) dependence by a function $G(z)$. Assuming $\zeta \approx 1$ and using the result obtained for $I_{H\alpha}$ in the equation (2), we may write

$$S/N \approx 19 \left( \frac{f}{0.1} \right)^{\frac{1}{2}} \left( \frac{t}{4 \text{ h}} \right)^{\frac{1}{2}} \left( \frac{D}{8 \text{ m}} \right) \left( \frac{\sigma}{20 \text{ km s}^{-1}} \right)^{-\frac{3}{2}} \times$$

$$\left( \frac{N_{H\text{I}}}{3 \times 10^{17} \text{ cm}^{-2}} \right) \left( \frac{T}{10^4 \text{ K}} \right)^{-0.17} \left( \frac{l}{10 \text{ kpc}} \right)^{\frac{1}{2}} \sqrt{\frac{G(z)}{(1 + z)^{1.5}}}. \quad (7)$$

Note that this equation may be still simplified if we assume that thermal broadening dominates, such that $\sigma = \sqrt{2kT/\mu}$. We consider two plausible cosmologies $\Omega = 1$ and $\Omega = 0.1$ (everywhere $\Lambda = 0$).

There are two basic approaches to obtaining very deep emission line detections at optical and infrared wavelengths: long-slit spectroscopy and Fabry-Perot staring (e.g. Bland-Hawthorn et al. 1995). It is essential to disperse the light over the field of view. The Fabry-Perot interferogram is dispersed radially over the detector and reaches the deepest limits to date (1 mR at 1σ in 6 hours for a source that fills the field.) The power of the method comes, in part, from the ability to disperse a small spectral window ($\sim 20–50$ Å) over a large area detector. The final spectrum is obtained from azimuthal binning over the detector with typically $\sim 10^5$ pixels contributing to each Angstrom bin. In comparison, the long-slit spectrum is dispersed along one axis of the detector. Modern day spectrographs project the same spectral window over orders of magnitude fewer pixels. The deepest diffuse detections to date at the MSO 2.3m telescope with the Double Beam Spectrograph reach emission measures of 10 mR in the same exposure time.*

The shape of the emitting cloud is not important in the first instance, as far as it does not change the optical depth for ionizing radiation significantly. We plot the efficiency and exposure time-normalized $S/N$ as a function of redshift (Figure 1) for an observing run on 8m class telescope for $l = 40$ h$^{-1}$ kpc halo cloud. The differences between cosmological models are negligible. As far as lower redshift objects are concerned, $S/N \approx 10$ for a log $N_{H\text{I}} = 16.5$ cm$^{-2}$ cloud located at $z = 0.5$ would, for instance, be achieved in a total exposure time of $t \approx 3$ h on a 8m telescope with

*At the same resolving power, the Gaussian profile of the slit in signal-to-noise gain compared to the Fabry-Perot Airy profile.
efficiency $f = 0.1$.

In detecting diffuse sources, accurate sky subtraction is critical since variable atmospheric (OH, water, Fraunhofer lines) features can cause spurious positive signals. The best background subtraction is achieved when the sky is observed simultaneously with the data, or almost simultaneously in the case of chopping. In order to match the noise characteristics, there should be an equal number of sky and data pixels. The natural f/8 Cassegrain field for an 8m telescope is approximately 4 arcmin. The redshift at which $\theta(l = 40 h^{-1} \text{ kpc}, z)$ is equal to 4 arcmin is $z \approx 0.01$. At higher redshifts, galaxy haloes occupy only a fraction $x$ of the field of view. Once the object fills more than half the entrance aperture, say, $x$, you are better off rejecting $2(x - 0.5)$ of the data to match the sky solid angle, and there is no need to chop until $x > 0.75$. Thus, the transition between direct and interleaved observation is actually a smooth one. At the Anglo-Australian Telescope, chopping is achieved successfully for any spectrograph with charge shuffling synchronized to the nodding of the telescope.

4 DISCUSSION

Halo gas in galaxy haloes at cosmological distances has traditionally been studied using resonance absorption lines in the spectra of background quasars. However, we find that, in certain instances, H$\alpha$ detections may be possible for metal-line absorbing gas around luminous galaxies out to $z \sim 1$. Our results are contingent upon the assumption that the major force governing the evolution of extended gas around galaxies is the evolving metagalactic ionizing background. Generalized formulae for the emission measure of recombing uniform haloes are given. It is shown that surface brightness of such objects does not conform to a simple $S \propto (1 + z)^{-4}$ relationship. One can, in principle, measure the deviation of H$\alpha$ intensity from eq. (3) and thus trace the intrinsic halo evolution, but only if one can account successfully for transition of baryons from the diffuse gaseous phase to other forms of baryonic matter (stars, molecular clouds, etc.). Since only the integrated neutral column density along the line of sight through a halo comes into play, we agree with Hogan and Weymann (1987) that the feasibility is essentially independent of the exact model of halo clouds.

It is important to add that results for intensity and signal-to-noise ratio of the fluorescing gas at any given redshift should be regarded as the lower limits, for at least two reasons. Apart from the background ionization, there are probably other ionizing sources (Donahue et al. 1995; Fukugita et al. 1998), like leakage of small fraction of Lyman-limit photons from galactic disks, which is small at present (Leitherer et al. 1995; Bland-Hawthorn 1997), but could have been much higher in the past (Giroux & Shull 1997), depending on the timescales for dust formation; other possible influences are ionizing intergalactic shocks, halo (or intergalactic) stars, or even the decaying dark matter (Sciama 1993, 1995). Secondly, the ratio $\delta$ seems to be consistently higher in real systems than in Case B recombination calculations assumed here (see Charlot & Fall 1993; Bechtold et al. 1997 and references therein). A realistic halo model should be able to quantify these effects and determine exact ionization structure of the extended galactic gas. Our results include no correction for reddening (e.g. Tresse & Maddox 1997), since we assume dust-free gaseous haloes and observing far from the Galactic plane.

Such experiments should be able to answer a basic question: to what extent is the recombining gaseous halo a generic phenomena in galaxies? A successful detection of diffuse H$\alpha$ emission from haloes of normal galaxies at low redshifts will have enormous theoretical and practical significance. It will enable direct testing of models for the evolution of the metagalactic ionizing flux. It will also determine what fraction of halo light at intermediate and low redshift is continuum and what fraction is contained in the emission lines (Charlot & Silk 1995). Finally, if halo emission is as luminous as we anticipate, a broad spectral campaign could constrain physical conditions in extended galactic haloes (or disks), e.g. proton density (Reynolds 1987), pressure (Bowyer et al. 1995), clumpiness, and so on.

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