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 H\textsubscript{α} emitting galactic halos out to \(z \sim 1\). 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; Bland-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, Shchekinov & Suchkov 1989; Norman & Ikeuchi 1989; Wolfire 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 \(\sim 10^2\) kpc). Low-redshift observations of Ly\textsubscript{α} absorbing systems reveal tenuous gas extending to \(\sim 300\) kpc (Chen et al. 1998, Lanzetta et al. 1995). The empirical evidence for the metal-line absorbers residing in \(\sim 50\) kpc haloes is very strong as well (Steidel 1993; Steidel, Dickinson & Persson 1994). In view of recent claimed detections of extraplanar gas in recombination H \textsubscript{α} 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 intracuster 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 \( J_{\text{UV}}(z) = [(1+z)^{-0.5}] \times 10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1} \), and its frequency dependence at all redshifts as (Chiba & Nath 1997; Haaradt & Madan 1996)

\[
J_{\text{UV}} = J_{\text{UV}}(z) \left( \frac{1+z}{0} \right)^{-\beta};
\]

(1)

This is the major force driving the redshift evolution of emission measure \( m \) of the ionized gas. We emphasize that this is just a working model, since precise normalization of eq. (1) is still elusive, due to uncertainties of factors of 6 or more (Bajtlik et al. 1988; Kulkarni & Fall 1993; Vogel et al. 1995). Further redshift dependence may come through chemical evolution which influences cooling rate once \( Z=Z_\odot \) (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 \( N_{\text{H I}} = 17.4 \) cm\(^{-2} \) photoionized cloud residing in extended galactic halo of a galaxy at redshift \( z \). This (in the first approximation, homogeneous) halo cloud of \( \sim 30 \text{ h}^{-1} \text{ kpc} \) in size is what we expect to see according to the metal-line absorption (Steidel 1993; Steidel et al. 1994; Petietjen & 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 \( H \) , which may not be true only at much higher column densities than those discussed here.

Emission measure of the fluorescent Ly \( \alpha \) emission under the assumption of isothermal clouds at all epochs is given by

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

(2)

where \( T_e \) is the electron temperature of the clouds (Osterbrock 1989; Cirković & Samurović 1998). This equation is valid for one-sided ionization of a hydrogen slab and is only valid for log \( N_{\text{H I}} \leq 17.4 \) 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 \( H \) \( / \text{Ly} \alpha \) ratio with \( f \), we obtain the intensity in the \( H \) line (Reynolds 1992):

\[
I_{\text{H} \alpha} = 1.44 \times \left( \frac{T}{10^4 \text{ K}} \right)^{-0.92} \text{em}(\text{Ly} \alpha) \times \frac{1+z}{1+z^2} \frac{N_{\text{H I}}}{3 \times 10^{17} \text{ cm}^{-2}} \times \left( \frac{T_e}{10^4 \text{ K}} \right)^{-0.17} \text{ R};
\]

(3)

\( (1 \text{ R} = 10^6 \text{ Ly} \alpha \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}) \) for a plausible value of \( f = 0.08 \), \( f = 1.73 \) (Haaradt & Madan 1996) and \( z \approx 2 \) (Chiba & Nath 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 galactic 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; Haaradt & Madan 1996).

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

\[
N_e = \sqrt{\frac{m(\text{H} \alpha)}{f}} = \frac{0.0043 f}{1+z} \left( \frac{N_{\text{H I}}}{3 \times 10^{17} \text{ cm}^{-2}} \right)^{\frac{1}{2}} \left( \frac{1}{10^4 \text{ K}} \right)^{-\frac{1}{2}} \left( \frac{T_e}{10^4 \text{ K}} \right)^{0.75}
\]

(4)

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 \( N_{\text{H I}} = 172 \) cm\(^{-2} \) and size of \( l = 30 \text{ h}^{-1} \text{ kpc} \) at low redshift, this formula (with, probably unrealistic, assumption \( f \approx 1 \)) gives \( n_e \approx 5.7 \times 10^{-3} \) cm\(^{-3} \) (using \( h = 0.75 \) and \( T_e = T = 3 \times 10^4 \) 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. Cirković & 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 \( z \approx 1 \) (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 \( H \) line is given as \( n_{\text{source}} = \frac{\Theta}{D^2} f T n_{\text{H} \alpha} \) (Gould & Weinberg 1996).

The fraction of photons penetrating Earth's atmosphere is denoted by \( \xi \). The number of photons of the background in the \( H \) line profile in this case is approximately equal to \( n_{\text{sky}} = \frac{\Theta}{D^2} f T \xi (4\pi r^2) \), where \( r = \sqrt{1+z} \) is the wavelength of the line centroid ( \( = 6562.8 \) Å for the \( H \) line), \((4\pi r^2) \) is the width of the line, determined, presumably, by thermal line-broadening, and \( n_{\text{sky}} \) is the sky flux...