Lyman $\alpha$ Systems within Hot Galactic Halos

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ABSTRACT

A hot gas halo is predicted by chemodynamical models during the early evolution of spheroidal galaxies. Cold condensations, arising from thermal instabilities in the hot gas, are expected to be embedded in the hot halo. In the early phases of the galaxy ($t \lesssim 1$ Gyr), a strong X-ray and EUV emission is produced by the extended hot gas distribution, ionizing the cold clouds. This self-irradiating two-phase halo model successfully explains several line ratios observed in QSO absorption-line systems, and reproduces the temperature distribution of Lyman-$\alpha$ clouds.

Key words: cosmology: observations – galaxies: elliptical – galaxies: evolution – galaxies: formation – intergalactic medium – quasars: absorption lines – X-ray: galaxies

1 INTRODUCTION

A hot halo is predicted by chemodynamical models during the early evolution of spheroidal galaxies (Friaça & Terlevich 1998). In the chemodynamical model a hydrodynamical code is coupled to a chemical evolution solver to follow the evolution of a galaxy since the stage of a gaseous protogalaxy. After a settling phase, a partial wind develops, with a cooling flow in the inner regions of the galaxy, and an outflow in the outer parts, giving rise to an extended hot gas distribution with strong soft X-ray and EUV emission in the early phases of the galaxy ($t \lesssim 1$ Gyr). In the self-irradiating two-phase halo model for quasar absorption line systems, the absorbers are identified to colder condensations, embedded in the hot gas halo, which have been formed by thermal instabilities, and which are photoionized by the surrounding soft X-ray and EUV radiation field. This model successfully explained Lyman limit systems (LLSs) in the line of sight of QSO 1700+6416, which show strong C and O high ionization absorption lines as well as a strong He I line (Viegas & Friaça 1995). More recently, the analysis of a number of LLSs has shown that this model can also explain these systems and predicts a subsolar C/O abundance ratio, as found in old Galactic stars and in agreement with the results from chemical evolution models (Viegas, Friaça & Gruenwald 1997). Recent observations have revealed the presence of heavy elements in Ly$\alpha$ systems (Songaila & Cowie 1996). Photoionization models assuming the metagalactic radiation field, a very low density for the absorbers ($\lesssim 10^{-2}$ cm$^{-3}$), and low chemical abundances ($\lesssim 10^{-2}$ Z$_\odot$) can reproduce some of the observed features. However, a few problems remain (Gruenwald & Viegas 1993; Giallongo & Petitjean 1994, hereafter GP): (a) the ionization parameter given by the metagalactic radiation reaching a region with density of the order of $10^{-2}$ cm$^{-3}$ would be too low ($U \approx 3 \times 10^{-3}$) to explain all the C IV systems, (b) if a lower density is assumed, the size of the absorber would be too large to be located within a halo, and (c) the temperature of the Ly$\alpha$ systems would be too high.

In this paper, we analyse the Ly$\alpha$ systems within the scenario of the self-irradiating two-phase halo model, i.e., we assume that the absorbers are the cold and dense clouds, originating from thermal instabilities arising in the hot gas halo, enriched by the strong wind in the early phases of the galaxy evolution, and photoionized by the hot gas radiation, which is the dominant ionizing radiation field. In Section 2 the main characteristics of the absorbers derived from the models are discussed. In Section 3, it is shown that temperatures deduced from the absorption line profiles are reproduced by our models. The conclusions are outlined in Section 4.

2 PHOTOIONIZATION OF THE ABSORBERS

Before discussing the hot halo models, we give a brief account of the results obtained by photoionization models in which the ionization source is the metagalactic radiation.

2.1 Metagalactic ionizing radiation

Photoionization models have been used for many years to analyse the QSO absorption systems assuming the metagalactic radiation as the ionization source (Gruenwald & Aldrovandi 1985, Bergeron & Stasinska 1986). More recently, models considering a power law spectrum for the metagalactic flux and ionization parameter in the range $10^{-2.3} \lesssim U \lesssim 10^{-1.5}$ have been invoked to explain the C II/C IV column density ratio deduced from observed Ly$\alpha$ systems (Songaila & Cowie 1996). The ionization balance
of highly ionized species is sensitive to the shape of the radiation spectrum, which is uncertain because of the \( \text{He}^+ \) absorption in the IGM. Songaila and Cowie have then compared the observed ratios to models with an ionizing radiation spectrum exhibiting a break as invoked by GP to explain the temperature of Ly\( \alpha \) systems. However, in order to reproduce the observed equivalent widths, a high value for the ionization parameter, \( U > 10^{-2} \), is required (Songaila & Cowie 1996). It is generally assumed that absorption systems have densities \( n_H \sim 10^{-2} \text{ cm}^{-3} \). For a metagalactic flux at the Lyman limit of the order of \( 10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1} \), these densities imply \( U \sim 10^{-3} \), which is much smaller than the values quoted above. So, unless \( n_H < 10^{-2} \text{ cm}^{-3} \) (which would imply very large absorbers), the intensity of metagalactic radiation field is too low to explain the observed systems and another energy source has to be invoked. In addition, when deducing chemical abundances for Ly\( \alpha \) and Lyman Limit systems the presence of non-observed ions must be accounted for (Viegas 1995). This is usually done by ionization correction factors which depend on the shape of the ionizing radiation spectrum. Thus, conclusions about chemical abundances deduced from observed absorption lines based on photoionization models should rely on models for which the input parameters concerning the ionizing radiation and the gas density are consistently chosen from the comparison between theoretical and observed column densities.

In the following we discuss a consistent self-irradiating two-phase halo model for the Ly\( \alpha \) systems.

2.2 The self-irradiating two-phase halo

As shown by the chemodynamical model of Friaça & Terlevich (1998), in the early phases of an elliptical galaxy evolution \( (t \lesssim 1 \text{ Gyr}) \), the extremely high rate of star-formation, which is converting the initially entirely gaseous protogalaxy into the galaxy stellar body, leads to the formation of a hot gas halo extending out to \( \sim 100 \text{ kpc} \) (for a present-day \( \sim L^* \) galaxy). This extended hot gas distribution provides a soft X-ray and EUV radiation field, with a 0.5-4 keV luminosity reaching a maximum of about \( 10^{44} \text{ erg s}^{-1} \) at an age of a few \( 10^8 \text{ yr} \), for a galaxy with a total mass of \( 2 \times 10^{11} \text{ M}_\odot \). The hot gas in the halo is subjected to thermal instabilities, giving rise to cold clouds embedded in the hot gas. In this self-irradiating two-phase halo model, the dominant species of C, N, and O in the hot gas are He-like and H-like ions, whereas in the cold clouds less ionized species are present. Since the privileged epoch for formation of large spheroids seems to be at redshift \( 2 < z < 10 \), corresponding to a cosmic age interval 0.36 - 2.5 Gyr (for a \( q_0 = 0.5 \), \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \) cosmology), the \( \sim 1 \text{ Gyr} \) length of the hot halo phase makes it quite probable to find at high redshift (\( z > 2 \)) a young elliptical galaxy in the hot halo stage. At this redshift range, therefore, there is a large supply of cold clouds inside galactic hot gas halos, that would act as QSO absorbers.

Notice that a two-phase halo model has also been proposed by Giroux, Sutherland & Shull (1994) in order to explain the simultaneous presence of HI, HeI, and OIII and the highly ionized species OVI on the line of sight of the QSO HS1700+6416. In their model, the OVI line originates in a hot gas in collisional ionization, while the low ionization species are produced in cold clouds. In this case, the observed column density of OVI requires a temperature for the hot gas of about \( 2 \times 10^5 \text{ K} \). However, in Friaça & Terlevich (1998) chemodynamical models for elliptical galaxies, with masses spanning from \( 5 \times 10^{10} \) to \( 5 \times 10^{12} \text{ M}_\odot \), the halo is considerably more ionized (O VII and O VIII are the dominant ionization stages) and hotter (\( T > 10^6 \text{ K} \)). The evolutionary models show that when the hot gas in the halo begins to cool down, the temperature rapidly falls to a few times \( 10^4 \text{ K} \), the phase assumed by Giroux et al. being highly unstable. In our model (Viegas & Friaça 1995) for the LLSs at \( z = 2.1678 \) and \( z = 2.433 \) towards the QSO HS1700+6416, the OVI absorption line originates in the outer layers of the cold clouds ionized by the hot halo radiation.

Another important result from the chemodynamical model of galactic evolution is the chemical enrichment history of the galaxy stellar population as well as of the hot gas halo. The fiducial model indicates that at an evolution time of the order of 0.3 Gyr, the C/H and O/H abundance ratios in the halo, relative to the solar value, are of the order of 0.1 and 0.2, respectively. These values are higher than generally assumed for the absorbers and are important because C and O are the main coolants of the gas, and also because both C/H and the ionizing radiation will set the observed C IV/H I column.

In this paper, numerical simulations of absorbers are obtained with the photoionization code AANGABA, which has been properly checked against similar codes (Ferland et al. 1995). The metagalactic QSO radiation field (Madau 1991) is added to the hot halo radiation field. However, for a galaxy age \( t \lesssim 1 \text{ Gyr} \), the effect of the metagalactic radiation is usually negligible. Following the results of the chemodynamical model, we assume for the halo gas a chemical abundance of 0.1 solar.

The spectrum shape of the hot gas radiation field evolves with time and depends on the distance from the galactic centre (Viegas & Friaça 1995). The impact parameters associated with the QSO absorption-line systems are a few Holmberg radii (Steidel 1993). Thus, in order to analyse the Ly\( \alpha \) cloud observations we assume that the clouds, giving rise the absorption lines, are at \( r = 30 \) or 100 kpc, for evolution times of \( t = 0.21 \) and 0.36 Gyr, characteristic of the hot halo phase for the \( M_G = 2 \times 10^{11} \text{ M}_\odot \) fiducial model of Friaça & Terlevich (1998). The evolution of the model determines the temperature and density of the hot gas, giving gas pressures at the cloud edge in the range \( 200 < n_H T < 4000 \text{ cm}^{-3} \text{ K} \). Assuming pressure equilibrium in the cloud, the densities inferred from the photoionization calculations are generally larger than the value \( 10^{-2} \text{ cm}^{-3} \) usually assumed for absorbers ionized by the integrated QSO radiation field.

In order for our model to be consistent, the first step is to obtain the range of the ionization parameter. The value of \( U \) can be inferred from the ratio \( N(\text{C IV})/N(\text{C IV}) \), which depends only on the ionizing radiation spectrum. The theoretical results are compared to the observations (Songaila & Cowie 1996) in the N(\text{C IV})/N(\text{C IV}) versus N(\text{C IV}) diagram (Figure 1). For the observed sample, 0.002 \( \leq U \leq 0.03 \), with \( 3 \times 10^{11} < N(\text{C IV}) < 4 \times 10^{14} \text{ cm}^{-2} \).

The C/H abundance can be obtained from the N(\text{C IV})/N(H I) versus N(H I) diagram, since a change
in the abundance used in the model would lead to a vertical shift of the theoretical results. Most of the observed results (Figure 2) are explained by the models with C/H = 0.1 solar, including some Lyman limit systems (N(H I) > 10^{17} cm^{-2}). However, some absorption systems in Figure 2 require U between 0.002 and 0.001, for C/H = 0.1 solar. Since a minimum value $U \approx 0.002$ is given by the N(H I)/N(C IV) ratio of the Lyman α systems (Figure 1), the low N(C IV)/N(H I) objects may have 0.02 < C/H < 0.1 solar.

On the other hand, the Si/C abundance ratio can be obtained from the N(Si IV)/N(C IV) versus N(C II)/N(C IV) diagram (Figure 3). The theoretical results were obtained with solar Si/C, and fit 50% of the systems. The remaining systems with a larger N(Si IV)/N(C IV), which could be explained by a supersolar Si/C abundance ratio, as indicated by the long-dashed curve in Figure 3, corresponding to Si/C twice solar, for the same N(H I)/N(C IV) value. This fact has already been pointed out by Songaila & Cowie (1996). Notice, however, that in order to reproduce all the N(Si IV)/N(C IV) ratios, in addition to a Si/C overabundance, these authors also need to assume an ionizing radiation spectrum largely absorbed at the He$^+$ threshold, as invoked by GP to explain the temperature of the Lyman α clouds.

3 THE TEMPERATURE PUZZLE

As pointed out by GP, previous observations of Lyman α systems with resolution of 20 to 30 km s$^{-1}$ indicated an average value of the Doppler width of about 30 km s$^{-1}$. The inferred temperature of the gas is then less than $5 \times 10^4$ K. This temperature could be explained by photoionization of a low density gas ($\lesssim 10^{-3}$ cm$^{-3}$) by the integrated QSO radiation field. Higher resolution observations (Pettini et al. 1990, Carswell et al. 1991, Hunstead & Petini 1991, Rauch et al. 1992, 1993, Giallongo et al. 1993) revealed, however, narrower absorption lines indicating lower temperatures ($T \approx 2 \times 10^4$ K), which can not be explained by the above models. In order to obtain low temperatures in a low abundance and dilute gas, GP proposed that the ionizing spectrum should be absorbed at the He$^+$ Lyman limit (at 4 Ryd), thus decreasing the heating energy due to photoionization. However, GP need to vary the amplitude of the spectrum break at 4 Ryd by a factor of $10^3$ to obtain temperatures in the range $2 - 5 \times 10^4$ K, as required by the determinations of both low and high temperatures for Lyman α systems. In addition, in order to have an ionization parameter high enough to assure a highly ionized gas, the density of the clouds must be lower than $10^{-3}$ cm$^{-3}$, leading to a recombination time close to the Hubble time.

In the self-irradiating two-phase halo model, the absorbers are associated with relatively cold and dense clouds embedded in the extended hot gas halo, and the radiation from the hot phase gas maintains the high ionization state of the Lyo clouds as shown in Figures 1 and 2. For these clouds, the values of the ionization parameter indicated by N(C II)/N(C IV) ratio range from 0.002 to 0.03, and the temperature from $10^3$ to $5 \times 10^4$ K (Figure 4, bottom panel). In the figure, the variation of temperature with $U$ is shown for chemical abundances 0.01 and 0.1 solar. The temperature range obtained from the observed absorption line profiles (Giallongo et al. 1993) is indicated by the solid vertical bar, whereas the temperature range obtained from photoionization models with the integrated QSO radiation field without a deep break at 4 Ryd (GP) is indicated by the dashed vertical bar. The results of the self-irradiating two-phase halo are
in very good agreement with the observed temperatures. In addition, the characteristic size of filaments with \(N(\text{H I}) = 10^{14} - 10^{15} \text{ cm}^{-2}\) is 0.1 to 100 pc (Figure 4, top panel), being almost independent of the chemical abundance of the gas. For a given \(N(\text{H I})\), the higher the temperature, the larger the filament. Notice that the inverse correlation is found in GP for models with Compton cooling and a break of the ionization spectrum at 4 Ryd. Observations of the C II lines in GP for models with Compton cooling and a break of the ionization spectrum at 4 Ryd. Observations of the C II absorption line could provide an estimate of the absorber volumetric density. Therefore, the real size of the absorbers is unknown, and the relation between the absorber size and its temperature can not be tested yet. The difference between the two models is illustrated even more dramatically by the absorber size (top pannel) of the Ly \(\alpha\) systems as a function of time and much smaller than the Hubble time. Therefore, the small size of the absorbers and their low mass.

As pointed out previously, the hot gas is highly ionized and contributes only to the column density of the He-like and H-like ions of CNO. Thus, the temperature of the Ly \(\alpha\) systems discussed above refers only to the clouds.

4 CONCLUSIONS

We have shown that a self-irradiating two-phase halo, which is suggested by a chemodynamical model of galactic evolution, can explain the results concerning the presence of heavy element absorption lines in Ly \(\alpha\) systems. In particular, since this model allows densities of the absorption systems higher (\(\gtrsim 0.1 \text{ cm}^{-3}\)) than in the standard model (\(\lesssim 10^{-3} \text{ cm}^{-3}\)), the gas cooling is more efficient, leading to lower temperatures in agreement with the observations. In addition, a higher density implies a smaller and less massive absorber, where the cooling time is of the order of the recombination time and much smaller than the Hubble time. Therefore, photoionization models assuming ionization equilibrium are adequate to describe the Ly \(\alpha\) absorbers. Two results of our model for the Ly \(\alpha\) absorbers may be tested in the near future: the small size of the absorbers and their low mass.

Another important point concerns the chemical abundance of the absorbing gas. The chemodynamical model indicates that the halo gas is enriched in heavy elements in a short time scale, reaching solar abundances by \(t < 3 \text{ Gyr}\), even at 100 kpc from the galactic center. It is also in this evolutionary phase that the hot halo develops, so the absorbers may be more enriched than it is usually assumed. Our results indicate that most of the observed Lyman \(\alpha\) absorbers, consistently analysed here using a photoionization model, have \(C/\text{H} \approx 0.1\) solar. For a few others, the carbon abundance should be a factor of 5 smaller. These results are in agreement with the enrichment of the hot gas halo, predicted by the chemodynamical model. Regarding the Si abundances, our analysis of the Si IV absorption line also indicates an abundance ratio \(1 \lesssim \text{Si/C} \lesssim 2\) solar (Figure 3). Although the evolution of the Si abundance is not included in the present version of the chemodynamical code, its behaviour is similar to that of the other \(\alpha\)-elements, and, therefore, can be traced by the evolution of the O. Whereas
the α-elements are produced in massive stars ($M \gtrsim 10 \, M_\odot$) via Type II+Ib supernova events, and the C is partially produced in Type II+Ib supernovae, and most of it in intermediate-mass stars ($0.8 < M < 8 \, M_\odot$). Its behaviour, therefore, is intermediate between that of O (and Si) and that of Fe, mainly produced by Type Ia supernovae. This explains the contrast between the typical overabundance of O, of order of $[O/Fe]=+0.5$, found by Gratton et al. (1998) for low-metallicity inner halo and thick disk stars, and the moderate C enrichment inferred for metal-deficient stars. In fact, $[C/Fe]=+0.2$ at $[Fe/H]=-0.8$ is obtained by Tomkin et al. (1995) in their analysis of 105 dwarf stars, whereas Carbon et al. (1987), for a sample of 83 dwarfs in the range $-2.5 \lesssim [Fe/H] \lesssim -0.6$, found a solar $[C/Fe]$ ratio over most of the metallicity range, with a slight upturn of $[C/Fe]$ at very low metallicities. Therefore, we expect an increase of the α-elements/C ratio from solar to 2-3 solar, as the metallicity varies from solar to 0.1-0.01 solar. This observational trend is reproduced by the chemodynamical model, which predicts $O/C \sim 2$ solar for $C/H \sim 0.1$ solar. Thus, $1 \lesssim Si/C \lesssim 2$ solar may be expected in the absorbers, in agreement with our results.

It should be noted that a fraction of the elements in the Lyman α absorbers is expected to be in the form of grains, thus reducing the gas phase abundances, which are precisely those being measured through the absorption lines. Among the elements observed in QSO absorption-line systems, O, S and Zn are almost unaffected by depletion into grains in the Galactic ISM, whereas C, Si and Fe are typically reduced by 1-2 dex (Savage & Sembach 1996). Therefore, the observational points in Figure 3 could be subject to corrections for depletion into grains.

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