

DAMPED Ly α SYSTEMS AS SPIRAL GALAXIES

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Received 1996 December 10; accepted 1997 July 11

ABSTRACT

It is shown that the distribution of element abundances with redshift in damped Ly α (DLA) systems can be adequately reproduced by the same evolutionary models reproducing the halo and disk components of the Milky Way Galaxy at different Galactocentric distances. In this sense, the DLA systems are well represented by normal spiral galaxies in their early evolutionary stages.

Subject heading: early universe — galaxies: abundances — galaxies: evolution — quasars: absorption lines

1. INTRODUCTION

The evolutionary history of galaxies is a subject that has deserved great attention since the early development of theoretical astrophysics. A variety of cosmic phenomena take part in it: large-scale dynamics, star formation and evolution, interactions between stars and interstellar medium (ISM), and so on. In this context, the history of element abundances is of particular importance, since it relates to the history of star formation, the mass distribution in stars, the element nucleosynthesis in stellar interiors, and their ejection and mixing with the ISM.

The solar neighborhood constitutes our vicinity both in space and time, and its observational study can be carried out with a great deal of accuracy. The building of consistent models of its chemical evolution has set the foundations of our present ideas about Galactic evolution. The tracing of the whole Galaxy structure via globular clusters and other Galaxy populations (bulge, halo, and thin and thick disks) has made it possible to study its evolution up to a Galactocentric distance of ~ 15 – 25 kpc and in the past ~ 11 – 16 Gyr. Although data on external galaxies are fewer and much less detailed, they have still allowed their study with the use of similar methods.

However, the number of parameters involved in any chemical evolution model is large, and a unique solution to the problem does not exist. Even the evolutionary picture for the Milky Way Galaxy (MWG), which provides the most complete set of observational data to constrain models, is not yet well established.

In many cases, models that give similar results for the present time diverge significantly at different epochs. New data on high-redshift objects—i.e., objects far away in space and time—can now be used to test model-predicted past Galaxy properties that can then constitute very important constraints for evolution models.

The recent paper by Lu et al. (1996; hereafter LSBCV) presenting a large set of new observations on element abundances of damped Ly α (DLA) systems, together with a compilation of similar measurements from the literature, gives an excellent opportunity to verify the consistence of models and contribute to the understanding of early structures of the universe.

In recent years we have computed self-consistent chemical

evolution models for spiral galaxies (Mollá, Ferrini, & Díaz 1996), which are a natural extension of previously developed ones for the solar neighborhood (Ferrini et al. 1992) and the MWG (Ferrini et al. 1994). In the present Letter we have taken the numerical outputs calculated for the MWG and used them in conjunction with the LSBCV data in order to test damped Ly α systems having abundances consistent with those expected for high-redshift spiral galaxies. Arguments in favor of this hypothesis include the suggestion from Wolfe (1995) that the low-ionization metal absorption lines in damped Ly α systems constitute direct evidence for disks and the direct image identification made in several cases (see LSBCV for references).

To compare directly with data by LSBCV, we have assumed values of q_0 and H_0 of 0.1 and $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, respectively. The redshift z corresponds to the redshift of damped Ly α systems.

2. OBSERVATIONS AND MODEL

LSBCV derived element abundances for 14 Ly α systems from observations with the 10 m Keck telescope. Data for nine other galaxies were compiled from the literature. The objects have redshifts between 0.7 and 4.4, and hydrogen column densities have been derived for 20 of them.

The abundances of three of the elements analyzed by LSBCV are predicted by our models: Fe, Si, and S. A total of 17 objects have Fe abundances derived directly from iron line measurements, and the distribution of [Fe/H] as a function of redshift can be represented by two bands roughly centered at [Fe/H] ~ -1 and [Fe/H] ~ -2 (Fig. 1). The more metallic systems seem to be limited to $z < 3$, while the less metallic ones extend over the whole redshift range. A similar situation is found for Si (also for Cr and Ni). Observational errors in the abundance determinations are of the order of 0.1 dex, according to LSBCV, and therefore do not modify our qualitative interpretation.

The observed distribution suggests the possibility that the observed gas belongs to early Galactic systems with essentially two levels of enrichment, with the highest being limited to $z < 3$. This could be explained by assuming the existence of two different episodes of star formation: an initial one leading to a certain level of enrichment of the ambient gas and corresponding to the lower metallicity level and a second episode, starting from an already enriched gas and corresponding to the higher

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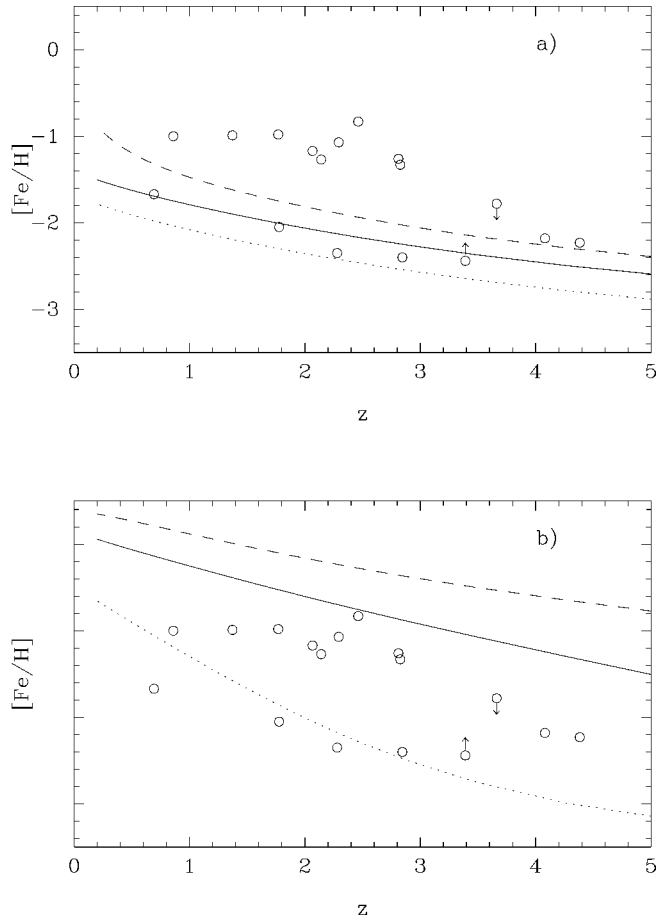


FIG. 1.— $[\text{Fe}/\text{H}]$ vs. redshift according to the Milky Way evolutionary model, for the solar neighborhood (*solid curve*), an inner radius (*dashed curve*), an outer radius (*dotted curve*), for (a) the halo and (b) the disk. The circles are the Lu et al. 1996 data.

metallicity level observed in some systems. This naturally explains the observed distribution with redshift as a time delay.

The simplest structure that we may imagine being able to follow the outlined evolution is a spiral galaxy. Indeed, as already suggested by Larson & Tinsley (1978) and evaluated by Ferrini & Galli (1988), in the initial spheroidal structure of a spiral galaxy, star formation may begin in the halo region. Then, after some delay, a disk is formed, and when the critical conditions for an efficient star formation there are met, a second, and probably more important episode of star formation, will take place. The observed two-level distribution could then be interpreted as the signature of the middle of the early phase and the beginning of the second one. These arguments will be verified a posteriori by the comparison of model results with present observations.

In what follows we describe some of the model features relevant to the present problem. We assume that the primordial gas of the spheroidal protogalaxy collapses to form the halo and that the gas recycled by star formation then collapses onto the Galactic plane to form the disk at a rate inversely proportional to the collapse time, which is an input parameter of the model. The early Galactic sphere is divided into concentric annular cylindrical regions 1 kpc wide, perpendicular to the disk. The numerical code calculates the time

evolution of the halo and disk components of every cylindrical region, considering that the diffuse gas forms molecular clouds and stars are formed either by cloud-cloud collisions or by the interaction of massive stars with clouds (induced star formation). The rates for the occurrence of these processes are functions of the Galactocentric radius (see Ferrini et al. 1994) and are proportional to the corresponding efficiencies representative of the probabilities of cloud formation, cloud-cloud collisions, and the interaction of massive stars, and clouds are assumed to vary with galaxy morphological type (see Ferrini & Galli 1988) since the spiral density wave changes the conditions for star formation in each galactic region: a stronger spiral density wave will compress the diffuse gas, favoring the formation of clouds, and will increase the frequency of cloud-cloud collisions. On the other hand, the induced star formation, because of the interaction of molecular clouds with nearby massive stars, seems to be a local process, and therefore its corresponding efficiency can be taken as constant for every zone and galaxy.

We have assumed the effects of dust to be negligible. The situation regarding the possible presence of dust in DLA systems is not clear. LSBCV do not find any strong evidence for element depletion by dust grains. The recent work by Pettini et al. 1997 claims that dust may be present in some high-redshift galaxies, but always in lower concentrations than in the Milky Way ISM. Galaxies at the highest redshifts (low metallicity) are, most probably, dust free. Therefore, it seems that the presence of dust would affect only the abundances derived for high-metallicity systems, which would have been underestimated.

3. MODEL RESULTS AND DAMPED $\text{Ly}\alpha$ COMPARISON

The simplest piece of comparison we may start with is the evolutionary history of the Milky Way, which is assumed to be a typical spiral galaxy. Therefore, we have taken the model results from Ferrini et al. 1994, where we computed the element distributions in the halo and in the disk of our Galaxy by varying the radial Galactocentric distance of every considered region. As a first attempt we have extracted the outputs for the solar region (1 kpc wide centered on 8 kpc) and two regions centered on 5 kpc and 14 kpc from the Galactic center (hereafter called inner and outer zones). These may be considered representative of three distinct and coherent zones of the Galaxy. We have extracted the abundances of elements in the gas phase in both the halo and the disk components, which we plot separately.

The plot of the halo enrichment history for iron (Fig. 1a) in the three regions, solar (*solid curve*), outer (*dotted curve*), and inner (*dashed curve*), immediately reveals a few features: the evolution has been faster near the center; at the same z there is a difference of ~ 0.2 dex in $[\text{Fe}/\text{H}]$ between different regions. The evolutionary tracks of the three considered regions well cover the group of data with the lower $[\text{Fe}/\text{H}]$ values even at the highest redshifts but do not fit the larger $[\text{Fe}/\text{H}]$ data. The corresponding disk evolution (Fig. 1b) obviously follows the same principle of a more rapid evolution in more central regions, but now the efficiency of matter conversion, because of a higher star formation rate (SFR), is higher, and the differences in the evolution of the various regions are more important: at $z = 3$, $\Delta[\text{Fe}/\text{H}] \simeq 0.5$ between the solar and inner regions, and $\Delta[\text{Fe}/\text{H}] \simeq 1.7$ between the solar and outer regions. Two important aspects should be

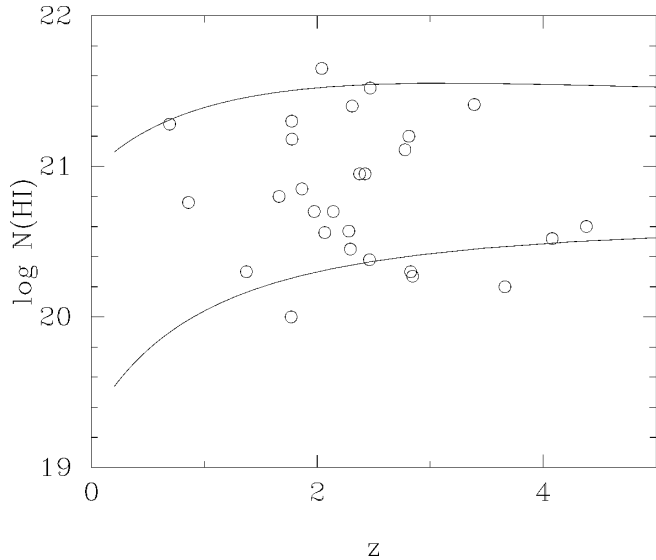


FIG. 2.—Column density for face-on and edge-on Milky Way twins; the circles are Lu et al. 1996 and Pettini et al. 1997 data.

noted: (i) the evolution of disk regions well contain the higher $[\text{Fe}/\text{H}]$ data, with the inner region showing abundances even higher than observed, and (ii) the evolutionary history of the different regions can well reproduce the spread in the observations. In considering the other elements for which data and models can be compared, i.e., S and Si, the same qualitative results as for iron are found: the lower $[\text{Si}/\text{H}]$ data fall on the evolutionary tracks for halo regions, while the higher $[\text{Si}/\text{H}]$ values correspond to disk regions. For sulfur the situation is less clear since only four data points are available. Their values are well covered by the disk region evolution.

Assuming that the absorbing gas in the line of sight to the damped Ly α systems may belong to both halo and disk components, we can evaluate its corresponding theoretical abundance by averaging the abundances derived for the two populations with their corresponding weights. In doing so we find that the halo/disk average in the outer region well reproduces the low-abundance data, while the solar region evolution better fits the higher abundance points. We should also take into account that the observations possibly average not only on the two populations at a certain radius but also over a great part of the whole Galactic structure.

The column density of atomic hydrogen, $N(\text{H I})$, is also derived by LSBCV. Data for a few more objects can be found in Pettini et al. (1997). We can estimate $N(\text{H I})$ as due to the contribution of the gas present both in the spheroidal and disk components of the galaxy. The column density is clearly sensitive to the inclination angle of the disk with respect to the line of sight. In Figure 2 the two solid lines represent the evolution of the total $N(\text{H I})$ for a face-on galaxy (*lower curve*) and for an edge-on galaxy (*upper curve*). The distribution of observed values is bound by these simple estimates.

The possibility that DLA systems are indeed normal spiral galaxies has been considered by LSBCV. The main objection to this hypothesis seems to be the low Fe content of DLA systems when compared with that of old Galactic disk stars (Edvardsson et al. 1993). However, this fact results from the implicit identification of the disk with the solar neighborhood. This is evident from our evolutionary tracks, since outer

Galactic regions show an evolution perfectly compatible with observations. Moreover, the comparison with Galactic disk stars may not be appropriate; indeed, damped Ly α observations refer to gas probably belonging to different components, and therefore the observed abundances are averaged over the halo and disk gas, if not over the whole Galactic content. At early times, in the collapse scenario, it is reasonable to expect that there may be enough gas at low metallicity still present, thus reducing the observed integrated $[\text{Fe}/\text{H}]$. This means that the value of $[\text{Fe}/\text{H}]$ for damped Ly α systems can be smaller than the corresponding Galactic disk star values at the same age. This argument also weakens the need for a significant depletion of iron onto dust grains.

The enrichment level $[\text{Fe}/\text{H}] \sim -2.2$ at $z \simeq 4.4$ is indicative of an early nucleosynthesis. On the other hand, the end of the upper level ($[\text{Fe}/\text{H}] \sim -1$) at $z \leq 3$ may imply that there are different regions involved in the enrichment process whose consequences we are observing and that they begin their activity at different times, perhaps with a delay of a few gigayears between the star formation events responsible for the $[\text{Fe}/\text{H}] \sim -2$ and $[\text{Fe}/\text{H}] \sim -1$ enrichment levels. In the collapse model, this can be interpreted as the delay between the onset of star formation in the halo and the disk. In our models this is naturally understood, since the process of star formation in the disk is not immediate as in the case of adopting a Schmidt law: i.e., it is not sufficient to have gas to produce stars; this would force an immediate star formation even with a limited amount of gas ($\sim 10 M_{\odot}$), and therefore no delay between the star formation in the halo and the disk would be observed. In the multiphase model, the system needs to form clouds as a step prior to star formation, and this produces a natural delay. Furthermore, since the process of star formation is nonlinear—quadratic in the cloud mass fraction in the case of cloud-cloud collisions and proportional to the product of massive star fraction times the cloud fraction in the case of the massive star–cloud interactions—it is inefficient until the cloud fraction is large and enough massive stars are formed. This may be interpreted as a threshold condition. In fact, the consequences of the multiphase approach and the threshold condition are indistinguishable. These physical mechanisms may be responsible for the delay of a few gigayears between the halo and disk populations, as we have shown in previous works. The presence of a thick disk would obviously enforce this delay.

As a final comment concerning the SFR present in the DLA systems, according to LSBCV the absence of Ly α emission in the systems they consider implies a low rate of massive star formation ($\leq 20 M_{\odot} \text{ yr}^{-1}$). The SFR from our models in the interval $0.7 < z < 4.4$ ranges between 1 and $14 M_{\odot} \text{ yr}^{-1}$. Roughly speaking, we may say that the halo component is characterized by a star formation burst taking place in the first half gigayear, while the disk evolves with an almost constant star formation, amounting to a few $M_{\odot} \text{ yr}^{-1}$.

The aim of the present Letter was to verify with detailed evolutionary models the hypothesis put forward by Wolfe and LSBCV that the DLA systems are normal spiral galaxies. We are not concerned here with the cosmological implications of this fact, and therefore we do not compare the consequences of our models with the results of other authors concerning cosmic chemical evolution (Lanzetta, Wolfe, & Turnshek 1995; Pei & Fall 1995; Malaney & Chaboyer 1996; Kauffmann 1996). That is deferred to a forthcoming paper. Using the quantitative results from our models, we can confirm the

conjecture of LSBCV that the large metallicity spread observed in DLA systems can be explained by the heterogeneous mixture of Galactic regions and galaxy types present in the sample. The observed values are a consequence not only of the nucleosynthesis and stellar lifetimes but also of the different timescales for the main star formation episodes in the various regions and of their different star formation histories.

This work has been partially supported by Integrated Action with Italy A-28 and Dirección General de Investigación Científica y Técnica project PB-93-052. Contribution from the Ministero dell'Università e della Ricerca Scientifica and Agenzia Spaziale Italiana are acknowledged. F. F. thanks the Universidad Autónoma de Madrid for an invitation for a sabbatical period, during which this Letter has been written.

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