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Implications of Early Cooling Flows and Galactic Winds for the Evolution of Deuterium

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Abstract. The deuterium abundances in high-redshift QSO absorption-line systems could be an important constraint in models of galaxy formation. Here we investigate the role of galactic winds and massive cooling flows present during the formation of galaxies on the evolution of deuterium abundance. Destruction factors are calculated and the time and spatial scales for the dispersal through galactic winds of the processed deuterium-depleted gas are presented and related to the D/H determinations for QSO absorption-line systems. The calculations are derived from a chemodynamical model within a scenario in which the absorbers are located inside the hot halo of a young galaxy.

1. Introduction

In order to derive the primordial D abundance from that observed in nearby astronomical objects, it is needed to account for the chemical evolution undergone by gas and stars since the big bang nucleosynthesis until now. The chemical evolution of deuterium is very simple: as soon as it is incorporated into stars, it is completely destroyed during star formation, being burned into ^{3}He during the pre-main-sequence evolution. Therefore, the deuterium observed in galaxies, the ISM, the Sun or the solar system is reduced by a destruction factor with respect to the primordial D. In order to recover the primordial D abundance, one needs to know which is the destruction factor for each astrophysical environment. For instance, the abundances observed in the solar system – $(\mathrm{D/H})_\odot = (2.1 \pm 0.5) \times 10^{-5}$ (Geiss & Gloecker 1998) – and in the local interstellar medium – $\mathrm{D/H})_{ISM} = (1.5 \pm 0.2) \times 10^{-5}$ (Linsky 2000) – are lower limits to the primordial deuterium abundance (both $(\mathrm{D/H})_\odot$ and $(\mathrm{D/H})_{ISM} < (\mathrm{D/H})_P$)

One would like to have systems as pristine as possible to get $(D/H)_P$. QSO absorption line systems would be good candidates for such systems, since they are at high redshifts (small cosmic age) and have low metallicities. Therefore, one would expect that the D abundance in these objects should be very nearly the primordial value. However, the so called "high-D, low-D dispute" on the D abundance in QSO absorption line systems has cast doubts on the identification of the D abundances in QSO absorption line systems with the primordial D abundance. The "high-D, low-D dispute" arises from the discrepancy between low deuterium abundances found by Tytler and collaborators – $\mathrm{D/H} = 3.0 - 4.7 \times 10^{-5}$ (Olive, Steigman, & Walker 1999) – and claims of high abundances by other authors $\mathrm{D/H} = (20 \pm 5) \times 10^{-5}$ (Webb et al. 1997). The low-D values are closer to those found in the sun and in the local ISM, and would imply modest destruction factors in the solar neighborhood if they are to be taken as representing the primordial deuterium. As a matter of fact, both model-independent arguments and extensive chemical modeling indicate D destruction factors of of 3 or less, thus favoring the low-D values (Tosi et al. 1998).

On the other hand, even though the QSO absorption line systems have very low metal abundances, their D content must still be considered only a lower limit to the primordial deuterium abundance, and it is possible that some QSO absorbers have already undergone significant chemical evolution, thus reducing the D abundance. Only detailed chemical evolution modeling would allow one to know how much the chemical evolution has affected the D abundances in QSO absorption line systems. Since the QSO absorption line systems were D has been detected have H I column densities typical of Lyman limit systems, we can assume that they are located inside galaxies ($r \approx R_e$), or in their galactic halos (Viegas & Friaça 1995). In this connection, this work addresses the effect on D abundance of massive cooling flows and galactic winds during the early evolution of galaxies. In addition, we can use the D depletion as a probe of the galaxy formation process.

Within the scenario in which the QSO absorption line systems are located inside halos of young elliptical galaxies, we use a chemodynamical model for evolution of galaxies (Friaça & Terlevich 1998) to obtain the D abundance evolution inside and around young galaxies. In particular, we calculate the destruction factors and the time and spatial scales for the dispersal of the processed deuterium-depleted gas.

2. The Chemodynamical Model

The chemodynamical model combines a multi-zone chemical evolution solver with 1-D hydrodynamics to follow the evolution of a galaxy since the stage of gaseous protogalaxy. The galaxy, assumed to be spherical, is subdivided into several spherical zones and the hydrodynamical evolution of its ISM is calculated. Then, taking into account the gas flow, the chemical evolution equations are solved for each zone, giving the evolution of the abundances of six chemical species (He, C, N, O, Mg, Fe). The model galaxy is the sum of three components: gas, stars and a dark halo (with masses M_g, M_*, M_h, respectively). The gas and the stars exchange mass through star formation and stellar mass losses (supernovae, planetary nebulae, and stellar winds). The stars formed are allowed to relax after one free-fall time to a King distribution $\rho_*(r) = \rho_{*0}[1+(r/r_c)^2]^{-3/2}$, where ρ_{*0} and r_* are the central stellar density and the stellar core radius, respectively. ρ_{*0} and r_c are related to the central stellar velocity dispersion σ_* by the virial condition $4\pi G\rho_{*0}r_c = 9\sigma_*^2$. The dark halo has no interplay with the gas and the stars, and it is given by a static mass density distribution $\rho_h(r) = \rho_{h0}[1 + (r/r_h)^2]^{-1}$, where ρ_{h0} is the halo central density and r_h is the halo core radius. Both the stellar distribution and the dark halo are truncated at a common tidal radius r_t. Details of the hydrodynamics and restoring of gas by evolved stars (stellar lifetimes, remnants, SN Ia and SN II rates, nucleosynthesis prescriptions) can be found in Friaça & Terlevich (1998). The models considered here are run until a present-day time $t_G = 13$ Gyr.

3. Results

Table 1. Galactic wind and deuterium destruction results

					10 kpc		100 kpc	
M_G	r_h (kpc)	M_* (10^{11} $M_\odot$)	t_w (Gyr)	M_w (10^{11} $M_\odot$)	t_3	t_{100} (Gyr)	t_3	t_{100}
0.1	2.5	0.0615	0.305	0.0437	1.16	1.20	1.31	1.32
1	2.5	1.32	1.09	0.72	1.23	1.24	1.54	1.56
2	3.5	2.38	1.17	1.42	1.04	1.08	1.70	1.73
5	5	5.90	1.25	4.22	1.34	1.39	2.02	2.04
10	7	11.6	1.51	6.45	1.74	1.89	2.71	2.82

In order to investigate the evolution of deuterium during the early evolution of elliptical galaxies, we have built a sequence of galaxy models parameterized according to the total (initial) luminous mass inside the tidal radius, $M_G = M_g + M_*$ and r_h. The galaxy is initially purely gaseous ($M_g(t=0) \equiv M_G$). For all the models $M_h/M_G = 3$, and $r_t = 28r_h$. In addition, the model galaxies follow a Faber-Jackson relation, $\sigma_* = 200(L_B/L_B^*)^{1/4}$ km s^{-1}. The star formation law is $\nu = \nu_0(\rho/\rho_0)^{x_{SF}}$, with $x_{SF} = 1/2$, where $\nu_0 = 10$ Gyr^{-1} and ρ_0 is the initial gas density averaged inside r_h. For this star formation law, the time scale for star formation is proportional to the local dynamical time. The normalization $\nu_0 = 10$ Gyr^{-1} implies a $\sim 10^8$ yr timescale for star formation required by chemical evolution models in order to reproduce the suprasolar [Mg/Fe] ratio in giant ellipticals. We also assume a Salpeter IMF between 0.1 and 100 $M_\odot$ and a SN I binary parameter $A_{SN\,I} = 0.1$ (see Friaça & Terlevich 1998 for details).

Table 1 shows the results of the models. The first column identifies the model. The models are named by M_G in units of 10^{11} M$_\odot$. Column (2) gives r_h. Column (3) shows the present-day (at $t_G = 13$ Gyr) stellar mass of the galaxy. Columns (4) and (5) exhibit properties of the galactic wind which appears in all models: t_w, the time of the onset of the galactic wind; and M_w, total gas mass ejected by the wind until t_G. The following columns give the depletion times i.e., the times when D is depleted by a factor of 3 (t_3) at $r = 10$ kpc and $r = 100$ kpc, and by a factor of 10 (t_{10}) at the same radii. As in Friaça & Terlevich (1998) we consider as fiducial model the model with $M_G = 2 \times 10^{11}$ M$_\odot$, The fiducial model has $L_B = 2.4 \times 10^{10}$ L$_\odot$, i.e., somewhat fainter than the break luminosity of the Schechter luminosity function ($L_B^* = 3.7 \times 10^{10}$ L$_\odot$), and, therefore, is representative of the population of elliptical galaxies.

Figure 1 shows the chemical abundances of the deuterium and iron as a function of radius for the fiducial model at several epochs. Note that a little earlier ($t = 1$ Gyr) than the onset of the galactic wind ($t_w = 1.17$ Gyr), there is a significant D depletion inside the galaxy ($r \lesssim 10$ kpc) and at the same time the Fe abundance has become suprasolar in this region.

In Figure 2, we can see the evolution of D destruction factor ($X_D/X_{D,P}$) for the fiducial model at several radii, illustrating that the D-depletion time scale

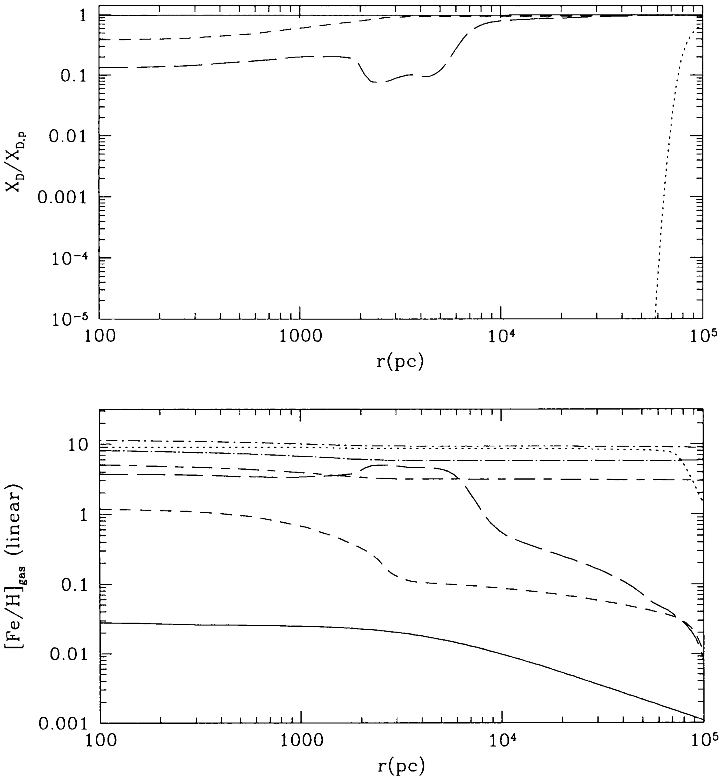

Figure 1. Gas abundance profiles for the fiducial model at several epochs: 0.03 Gyr (solid line), 0.35 Gyr (short-dashed), 1 Gyr (long-dashed), 1.6 Gyr (dotted), 1.9 Gyr (dot-short-dashed), 4.4 Gyr (dot-long-dashed), 13 Gyr (short-dashed-long-dashed).

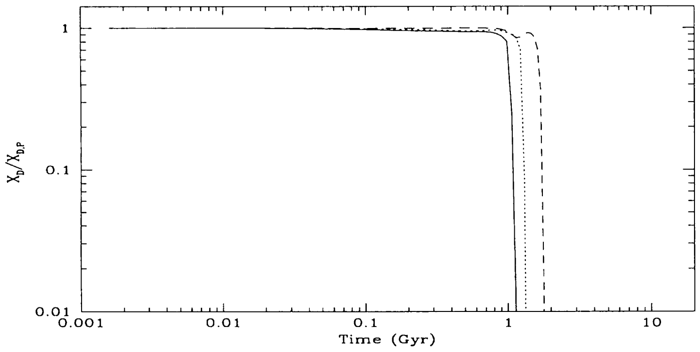

Figure 2. The evolution of D destruction factor for the fiducial model at several radii: 10 kpc (solid line), 30 kpc (dotted line), 100 kpc(dashed line).

for a given radius is very short. Also Table 1 allows one to assess how fast is the D-depletion process. For the fiducial model the time scale for a depletion by a factor 10 is ≈ 1 % larger than that by a factor 3. We have also calculated how much material in the galactic wind has been processed by stellar evolution. 1.55×10^{11} $M_{\odot}$ of gas has been expelled from the wind, of which 8.87×10^{10} $M_{\odot}$ is primordial gas. The deuterium in the total mass removed by the wind is depleted with respect to the primordial value by an amount $X_D = 0.57 X_{D,P}$.

4. Conclusions

During the pre-galactic wind stage, there is only a modest destruction of D. For the fiducial model, $X_D = 0.73 X_{D,P}$ at $r = 10$ kpc and $t = 1$ Gyr. Note that time scale for metal enrichment is very short (for the fiducial model, [Fe/H]=-0.29 at $r = 10$ kpc and $t = 1$ Gyr), and, therefore, high values of D-depletion are forbidden by the typical subsolar metallicities derived for the QSO absorption line systems in which deuterium has been detected.

Significant D destruction occurs only after the the galactic wind has been established, typically 0.5-1 Gyr later. In addition, the total amount of gas ejected by the galactic wind has a $\sim {}^1/_2 - {}^1/_2$ primordial-star processed mixture.

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