The Deuterium Abundance and Nucleocosmochronology

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Abstract

We examine galactic chemical evolution models which reproduce the present-day and pre-solar values of deuterium starting with a primordial value which is consistent with a baryon-to-photon ratio of $3 \times 10^{-10}$. We consider various galactic chemical evolution models to determine the viability of significant deuterium destruction and which provide a consistent age of the galaxy at the time of the formation of the solar system and consequently its present day age from nuclear chronometers. These models generally require some amount of infall which we take with rates proportional to the gas mass as well as exponentially decreasing rates and some initial disk enrichment which we limit to the range of 0% to 30%. We present those models which give the observed pre-solar value and present-day value of D/H and which lead to a present-day gas fraction of $\sigma = .05 - .2$. These models result in a broad range for the age of galaxy between 9.8 - 21.6 Gyrs.
1 Introduction

One of the successes of the standard big bang model is its ability to reproduce the observed abundances of the light elements. In two cases, $^4\text{He}$ and $^7\text{Li}$, the primordial value can be directly determined from observation. The primordial value of $^4\text{He}$ is inferred from low metallicity HII regions (see e.g. Pagel et al. 1992; Skillman et al. 1994; Olive & Steigman 1994). The consistent abundance of $^7\text{Li}$ observed in old halo dwarfs is generally assumed to be the primordial value (see e.g. Spite & Spite, 1993). The primordial abundance of $D$, however, is much harder to test observationally since $D$ is destroyed in stars. A pre-solar value determined from meteorites, solar wind studies, and the Jovian atmosphere (see e.g. Geiss 1993) and an interstellar value determined from Space Telescope observations (Linsky et al. 1992) are all that are known. There is a reported detection of $D$ in a high redshift, low metallicity quasar absorption system (Songaila et al. 1994; Carswell et al. 1994) with an abundance which may be the primordial one. Due to the still somewhat preliminary status of this observation and the fact that it can also be interpreted as a $H$ detection in which the absorber is displaced in velocity by 80 km s$^{-1}$ with respect to the quasar (see also Steigman 1994; Linsky 1994), we do not fix the primordial abundance with that value (we will comment further on this possibility below). The primordial value must therefore be explored in the context of chemical evolution models and the observed pre-solar and interstellar values (Audouze and Tinsley 1974).

Several investigations have explored the relationship between chemical evolution and the primordial $D$ abundance. (Vidal-Madjar & Gry, 1984; Clayton 1985; Delbourgo-Salvador et al., 1985; Vangioni-Flam and Audouze, 1988). It is clear that the degree to which $D$ is destroyed will be very sensitive to the chemical evolution model. More recently, Steigman and Tosi (1992) explored the acceptable range for the primordial $D$ abundance without overproduction of $^3\text{He}$ with a given set of chemical evolution models (Tosi, 1988). They found that typically deuterium was destroyed by no more than a factor of $\sim 2$, leading to the conclusion that the baryon-to-photon ratio, $\eta$ was relatively high $\eta \gtrsim 4 \times 10^{-10}$. A different approach was taken by Vangioni-Flam, Olive, & Prantzos (1994), (hereafter VOP). They considered a wider range of chemical evolution models starting with a primordial value
of $D$ of $7.5 \times 10^{-5}$ consistent with a baryon-to-photon ratio of $3 \times 10^{-10}$ a value which is more central with respect to $^4He$ and $^7Li$ consistency. They explored various initial mass functions (IMFs) and star formation rates (SFRs) to find chemical histories which could reproduce a $D$ destruction factor of $\sim 5$ to match the presolar value of $2.6 \times 10^{-5}$ (Geiss 1993) and the present ISM value of $1.65 \times 10^{-5}$ (Linsky et al. 1992). They did not, however, consider infall in their models and argued against infall since the observations indicate that the $D$ abundance has decreased since the pre-solar value. The impact of infall on these types of models has not formally been tested.

A further complication lies in determining the time at which to compare the observed abundances with the results from chemical evolution models. This complication is due to the large uncertainty in the age of the galaxy. The age of the galaxy and pre-solar epochs can be constrained, however, in chemical evolution models which consider, the ratios of long-lived radioactive nuclei such as $^{232}Th$, $^{235}U$, and $^{238}U$ (Cowan et al. 1987). The advantage to including this constraint in with chemical evolution models is two-fold. First, only models which can reproduce the ratios observed for these elements are considered viable. Secondly, these models give times for the formation of the solar system and today at which direct comparisons to observations can be made.

We will consider the evolution of $D$ using the nuclear chronometer constraint; that is, we will only consider models which are capable of producing the correct ratios of $^{232}Th$, $^{235}U$ to $^{238}U$ at the same time. Solar system studies indicate a pre-solar $D$ abundance (Geiss 1993) in the range of $(2.6 \pm 1.0) \times 10^{-5}$. The $D$ abundance has also been determined in the ISM. Lyman absorption spectra in nearby stars indicate a present-day $D$ abundance of $(5.2 \pm 2.0) \times 10^{-5}$ (see e.g. Vidal-Madjar 1991, Ferlet 1992). A more high precision measurement of $D/H$ was determined recently using the HST (Linsky et al. 1992) which indicates a $D$ abundance of $1.65^{+0.07}_{-0.18}$. For this work, we will adopt the HST measurement for the present-day value.

Our goal therefore is to explore chemical evolution models which can account for the deuterium abundances observed at the pre-solar epoch and today from a primordial value of $\sim 7.5 \times 10^{-5}$ constrained by nuclear chronometers. It has been argued previously (Reeves 1991; Reeves 1994) that because of the uranium chronometers, the average galactic nuclear activity today is within a factor of two of its average value over the lifetime of the galaxy and
therefore may limit the degree to which $D$ is strated. To test this hypothesis, we consider various initial mass functions (IMFs), star formation rates (SFRs) and infall rates which in fact can achieve this goal. We also demand that the models reproduce a gas fraction, $\sigma$, in the range of .05 to .2 and require a maximum initial enrichment of 30% with respect to present abundances of heavy elements (for a review see Rana, 1991). Finally, we will consider the oxygen abundances predicted from such models as a gauge for heavy element production.

2 Chemical Evolution Models

2.1 General Equations

In order to examine chemical histories which lead to the observed abundances of $D$, we consider a variety of numerical chemical evolution models. We employ a chemical evolution code which avoids the instantaneous recycling approximation (IRA), that is, the actual stellar lifetimes are considered in the calculation. We consider a variety of IMFs, SFRs, and infall rates. For simplicity, we neglect radial gas flows within the disk for our models, and we do not assume that the galactic disk is homogeneous, but restrict our calculation to the solar neighborhood. We make no assumptions on the age of the disk. The age is constrained in our model by the nuclear chronometers.

Age determinations, which consider the r-process chronometer pairs $^{235}U/^{238}U$ and $^{232}Th/^{238}U$ have been considered by a number of authors (for review see Cowan et al., 1991). These calculations start from the basic equation for gas mass within the galactic disk

$$\frac{dM_G}{dt} = e(t) - \psi(t) + f(t),$$  \hspace{1cm} (1)

where $e(t)$ is the ejection rate,

$$e(t) = \int_{m(t)}^{m_{upp}} (m - m_R) \psi(t - \tau_m) \phi(m) \, dm.$$  \hspace{1cm} (2)

In these equations, $f(t)$ is the infall rate onto the disk, $\phi(m)$ is the IMF, and $\psi(t)$ is the SFR. $m_{upp}$ is the upper mass limit on $\phi(m)$. $\tau_m$ is the lifetime of a star of mass $m$, and $m_R$
is the remnant mass of a star of mass $m$. $m(t)$ is the mass of a star which at time $t$ is returning gas back into the ISM. $m_R$ is taken to be (Iben & Tutukov, 1984),

$$m_R = 0.11m + 0.45M_\odot \quad m \leq 6.8M_\odot$$

$$m_R = 1.5M_\odot \quad m > 6.8M_\odot.$$  (3)

Stellar lifetimes are determined as in Scalo (1986).

Equation (1) can be extended to determine the rate of change in the number of nuclear species $A$,

$$\frac{dN_A}{dt} = P_A\psi(t) - \frac{\psi(t)N_A}{M_G} + \frac{e(t)N_A}{M_G} + \frac{f}{M_G} Z f N_A - \lambda_A N_A.$$  (4)

In this equation, $P_A$ is the number of newly synthesized nuclei of species $A$ per unit mass going into star formation. The relative production ratios, $P_{232}/P_{238}$, and $P_{235}/P_{238}$, are taken to be $P_{232}/P_{238} = 1.60$, and $P_{235}/P_{238} = 1.16$, adopted from Cowan et al. (1987). $\lambda_A$ is the rate of decay of nuclear species $A$. For simplicity, the amount of species “$A$” which decays while locked up in stars has not been considered. This is a good approximation since only the largest mass stars will significantly contribute to the amount of “$A$” produced and returned to the ISM and these stars have lifetimes which are short compared with the decay rate of $^{232}Th$, $^{235}U$, and $^{238}U$. The decay rates used in the calculation are based on the half-lives of the respective parent nuclei. For this work, we have adopted half lives of $\tau_{232} = 1.41 \times 10^{10}$ yrs, $\tau_{235} = 7.04 \times 10^8$ yrs, and $\tau_{238} = 4.46 \times 10^9$ yrs. We have also assumed the metallicity of the infall gas, $Z_f$, to be zero.

Equation (4) can now be solved numerically simultaneously with equation (1). As a boundary condition for equation (4), $N_A(0)$ is allowed to be non-zero to satisfy observational constraints on the metallicity distribution and age-metallicity relation of stars (Pagel and Patchett 1975; Twarog 1980). This is equivalent to assuming an initial burst of star formation. $N_A(0)$ is a free parameter in our calculation and the value of $S_0$, the initial disk enrichment, that results from the choice of $N_A(0)$ is also calculated. Initial disk enrichments of $S_0 \lesssim 0.3$ are considered acceptable. This corresponds to observational constraints necessary to account for the observed metallicities (Lynden-Bell 1975).
The final consideration is the abundance of $D$. We assume no galactic sources of $D$. Furthermore, we consider $D$ to be totally astrated within stars. Under these assumptions, the rate of change of $D$ in the disk can be determined by extending equation (1),

$$\frac{d}{dt}(DM_G) = -\psi(t)D + f(t)D_f,$$

where $D_f$ is the mass fraction of $D$ in the infall gas which we assume to be primordial. By substitution of equation (1) into this equation, it can be rewritten in the form

$$\frac{dD}{dt} = -e(t)D + f(t)(D_f - D).$$

This equation is then solved simultaneously with equations (4) and (1).

2.2 Model Parameters

The models are divided into three groups based on their SFRs and are closely related to the models studied in VOP. In group I, the star formation rate is assumed to be proportional to the gas mass ($\psi(t) = \nu M_G$). Group II considers exponential star formation rates ($\psi(t) = \nu e^{-t/\tau}$). We explore decay constants, $\tau$, with values $\tau = \infty, 10, 8, 5, 3$ $Gyrs^{-1}$. Finally, group III models assume a star formation rate proportional to the gas mass squared ($\psi(t) = \nu M_G^2$). We allow the constant of proportionality in each of these cases to be a free parameter. For most models a simple power-law IMF has been chosen. We do consider the effects of varying the IMF. In what we label group Ib, we consider an IMF as determined by Tinsley (1980). The effect of varying the IMF is also considered for group II models. Group IIb models employ the IMF given by Scalo (1986) and group IId models are based on Tinsley (1980) with an exponential SFR. The IMF is normalized

$$\int_{m_{low}}^{m_{upp}} m \phi(m) dm = 1,$$

where $m_{low}$ and $m_{upp}$ correspond to the lower and upper mass limits on stars. The values of $m_{low} = .4$ and $m_{upp} = 100$ have been chosen for this calculation except in the case of the Tinsley (1980) and Scalo (1986) IMFs where the value $m_{low} = .1$ is used. In VOP, a
power-law IMF with $\phi(m) \sim m^{-2.7}$ was used and was found to be sufficient for obtaining the required $D$ destruction. When we impose the chronometer constraint, we find that in many cases not enough $D$ was destroyed and/or the gas mass fraction tended to be too low. That is, depending on the assumed SFR, solutions which yield consistent ages, did not always destroy enough $D$ and in some cases (e.g. models IIa) very few or no solutions were found that destroyed $D$ by a total factor of 5 with a sufficiently high gas mass fraction. By choosing a flatter IMF, more massive stars which destroy $D$ are produced. Here a power-law IMF with $\phi(m) \sim m^{-2.35}$, has been assumed for most of the models. For model III, an even flatter power law ( $\phi(m) \sim m^{-2.05}$) was required models to destroy enough $D$ to match observations.

Two commonly chosen forms for the infall rate are examined in our calculation. The first of these is an infall rate proportional to the gas mass ($\sim \mu M_G$). Though there is no physical reason for assuming this kind of infall rate, under certain assumptions, an infall rate proportional to $M_G$ can lead to analytic solutions (see e.g. Clayton 1984,1985). We also consider infall rates which are exponential ($\sim \mu e^{-t/\tau}$) in models Ic and IIc. Decay constants of $\tau = \infty, 10, 8, \text{and } 3 \text{ Gyrs}^{-1}$ are examined. This type of model was previously examined by Tosi (1988). A summary of all the models and the various parameters chosen can be found in table (1). We have imposed a cut-off on the total disk mass $M_T$ to be no larger than three times the initial disk mass.

In addition to the constraints outlined above, the abundance of $^{16}O$ will be determined for each of the model types where the yields of Woosley (1993) have been adopted. For models which overproduce oxygen, the value of $m_{\text{upp}}$, the upper mass limit of stars which supernova, is lowered. The impact on the evolution of $D$ by lowering this value to reproduce the $^{16}O$ abundance will be discussed below.

### 2.3 Model Calculation

The calculation is divided into two parts. In the first, we search for matches for the ratios of the nuclear chronometers $^{232}Th/^{238}U$ and $^{235}U/^{238}U$ determined from meteoritic abundances. The abundance ratios used here are $^{232}Th/^{238}U = 2.32$ and $^{235}U/^{238}U = .317$ (Anders and
Ebihara 1982) which have an error of $5 - 10\%$. In our calculation, we have allowed for an error on these values of $\pm 5\%$. We then look for solutions within this range allowing $N_A(0)$, $\nu$ and $\mu$ to vary as free parameters. Chemical histories which produce matches for both ratios at the same time are then considered potential solutions. The model time at which the ratios match is then considered the pre-solar epoch and subsequently 4.6 Gyrs later, today. Next, the $D$ abundance is calculated for models which reproduce these ratios. We test for models which can reproduce the $D$ abundance at the times designated as the formation of the solar system and “today” and which result in a gas mass fraction $\sigma$ within the range of $0.05 - 0.2$. We examine those models in the next section.

3 Results

Most of the model types explored were able to produce chemical evolution scenarios compatible with the observations of the abundance of $D$. We begin by considering the general characteristics that resulted from group I models. Group Ia models which reproduce the observations of $D$ lead to a low of a gas fraction ($\sigma \sim 0.05 - 0.08$) which is only marginally in agreement with observations. A higher gas mass fraction can be obtained by further flattening the IMF. For example, when $\phi(m) \sim m^{-2.7}$, solutions give a value of $\sigma$ no larger than $\sim 0.05$, while for $\phi(m) \sim m^{-2.05}$ we find solution with $\sigma$ as high as 0.2 for model Ia. It is also important to note that our calculational scheme was not designed to maximize the gas mass fraction. Instead our solutions minimize the error in the chronometer abundance ratios. When this condition is relaxed (though still enforcing ratios within 5% of their observed abundances) significantly higher gas mass fractions are found.

In group Ia models, as much as 50% to 70% of the initial disk mass falls onto the disk over the galaxy’s evolution in these models. In general, the higher the star formation rate, the higher the resulting disk mass (see figure 1a). The solutions shown here have been restricted by the requirement that the present $D$ abundance match the ISM measurement to within 3 %. With a higher star formation rate, more $D$ is destroyed. The only source of $D$ is the infall gas. As a result, a larger amount of infall is required to reproduce the observations of $D$ for a higher star formation rate.
Group Ib model solutions closely resemble those of group Ia. They do result in a slightly higher gas fraction than those of Ia (\(\sigma \lesssim 0.09\)) which is in better agreement with observations. The IMF for these models is flatter for the lower mass stars. As a result, less mass is locked up in these stars leading to a larger return to the ISM. This allows for more \(D\) destruction at a higher resulting \(\sigma\). These models require even more infall onto the disk than group Ia; up to 90\% of the initial disk mass is required to fall onto the disk to achieve solutions.

No viable \(D\) evolution was found for group Ica models (those with a constant infall rate). These models result in a very low \(\sigma\) (\(\sigma \sim 0.03\)) before enough \(D\) is destroyed to match observational constraints. Group Icb models can reproduce \(D\) observations with very little infall (only 27–39\% of the initial disk mass), although they do result in a \(\sigma\) on the low side (\(\sigma \sim 0.05–0.07\)). Steeper exponents for the infall rate (groups Icc-Ice) can also produce viable \(D\) evolution scenarios with higher gas fractions at the expense of larger amounts of infall required. In order to achieve a gas fraction of \(\sigma \sim 1\), at least 70–90\% of the initial disk mass is required to fall onto the disk for these model types. Unlike groups Ia and Ib, the total mass that results for these model types decreases as a function of the star formation rate (as seen in figure 1a). Note however, that in models such as Icc, there are solutions in which \(M_T\) is greater than 3. (They are found at \(\nu \sim 0.7\), where our imposed cut-off is visible.)

Group IIa models which can reproduce the observations of \(D\) lead to a gas fractions throughout the range of \(\sigma \sim 0.05–0.20\). Similar to group I types, the higher the resultant SFR, the higher the resultant total mass. Figure 1b clearly demonstrates this trend for group II models. In addition, as can be seen from figure (2) that in general, as the exponent of the star formation rate steepens, we find a lower resulting disk mass and \(\sigma\) which themselves are correlated within each model type.

The amount of initial disk enrichment required changes as a function of the decay constant of the star formation rate. Group IIaa solutions (\(\tau = \infty\)) result in initial disk enrichments of 10–30\%. In general, the steeper the exponent of the SFR, the less initial disk enrichment is required. Group IIae solutions for example all require less than 2\% initial disk enrichment. Figures 3a and 3b show the range of initial enrichments for solutions as a function of star formation rate. Models (except for those with exponential infall rates) with the lowest infall
rates and consequently lowest star formation rates lead to the lowest required initial disk enrichments. This behavior can be credited to the age at which the pre-solar epoch occurs for these solutions. Solutions which have low initial enrichments correspond to later pre-solar epochs. Star formation and infall occur for a longer period of time before the pre-solar epoch and thus proceed at lower rates but require less of an initial disk enrichment to obtain a solution. Figures 4a and 4b show the relationship between the initial disk enrichment, $S_0$, and the pre-solar epoch. The trend of the lower enrichment-later pre-solar epoch is demonstrated for the group I and IIa models. Other model groups produce similar results (this is true for all models including those with exponential infall rates). From these figures, one sees clearly the range of ages for the galaxy at the pre-solar epoch that we obtain in our solutions.

Figures 5a and 5b show a comparison of the evolution of $D/H$ for model groups Ia, Ib, Icb and IIab and their resulting gas fraction. The types are chosen which result in a realistic evolution for $D/H$ and satisfy the gas fraction, disk enrichment and nuclear chronometers constraints. For comparison, solutions were chosen which had equal pre-solar ages. All of these models fall within the errors of both the pre-solar observations and the ISM value. There is apparently very little effect on the $D/H$ evolution due to the IMF’s tested, as these two curves nearly overlap. There is however an effect on the $^{16}O$ abundance based on the choice of IMF which will be discussed below. These solutions are not unique. Other combinations of IMFs, SFRs, infall rates, and resulting pre-solar epochs could produce viable $D/H$ evolutions as well. It should be noted that the shape of a solution for the $D/H$ evolution for a particular model type does not change for differing pre-solar epochs. The general character of each model type remains fixed.

In all of the cases which produce a realistic $D/H$ evolution, the $^{16}O$ abundance is over-produced. Adjusting the upper mass limit of stars which supernova ($m_{\text{upp}}$) for these cases can lower the $^{16}O$ abundance to its observed levels. Such an adjustment is frequently necessary when considering exponentially decreasing SFRs (Larson, 1986; Olive, Thieleman, & Truran 1987; VOP). The effect of lowering $m_{\text{upp}}$ on the $D$ abundance was also considered here. Group I models required lowering the value of $m_{\text{upp}}$ to $\sim 20 M_\odot$ in order to match the solar $^{16}O$ abundance. They suffer virtually no change in their predicted $D/H$ evolution by
changing this value. In contrast, group IIa models are drastically changed. $D$ is virtually all destroyed as a result of lowering $m_{upp}$. This result differs from models which assume the instantaneous recycling approximation (IRA) (see e.g. VOP). Changing $m_{upp}$ to a lower value would result in a lower return fraction. This would mean that less $D$ would be destroyed leading to a higher $D$ abundance. In our models, the infall rate has been set proportional to the gas mass. This means that less infall will occur in a model where less gas is being returned to the ISM due to a lower $m_{upp}$. Without this additional source of $D$, the overall effect is to lower the $D$ abundance. Group IIb models behaved similarly although the $^{16}O$ is not overproduced to as great of an extent due to the IMF being normalized more towards the low end stars. Group Ia and Ib models have this same assumption. However, in addition, the star formation rate is proportional to the gas mass. Thus with less gas returned, the star formation rate is lower, leading to less $D$ destruction. This effect compensates for the depleted source of $D$ due to a lower infall rate leaving the overall $D$ abundance virtually unchanged. Group Ic models, which have exponential infall rates, wind up with an increased abundance of $D$ as a result of lowering $m_{upp}$. In these models, since the infall is independent of the gas mass, less stellar processing occurs due to the shift towards the low mass stars while $D$ is still supplied by the infall gas.

Finally, we have considered the effect of changing the $D$ abundance of the infall gas. All of the models discussed thus far have considered the $D$ abundance of the infall gas to be primordial. In general, it is more difficult to destroy enough $D$ for models which include infall. Lowering the abundance of $D$ in the infall gas should, in fact, make it easier to destroy $D$. As a test case, group Ia models were rerun assuming an infall abundance of $D$ to be 50% primordial and also with no $D$. Figure 6 is a comparison of the $D$ abundance for a group Ia solution. $D$ is destroyed by a factor of $\sim 9$ for a model with 50% of primordial $D$ abundance in the infall gas. With no $D$ in the infall, $D$ is virtually totally destroyed.

4 Conclusion

We have shown that $D$ can be destroyed by a factor of $\sim 5$ under a wide variety of choices of SFRs, IMFs, and infall rates even with the additional constraint of nuclear chronometers.
It does not seem necessary to constrain the initial SFR to within a factor of 2 of the current rate as suggested by Reeves (1991, 1993) in order to reproduce the ratios of the uranium chronometers. Though we did find many solutions, we were in fact strongly constrained by the chronometers. For example, as in Cowen, Thielemann, & Truran (1987), we could not find solutions without infall or without some initial enrichment. The necessity of infall was cause for concern with regard to finding solutions with sufficient D destruction factors (VOP). However, we did in fact find that significant infall rates can still lead to a decrease in the D abundance from the pre-solar value to today.

In our study, we have always chosen a primordial value of $D/H = 7.5 \times 10^{-5}$ corresponding to a baryon-to-photon ratio of $\eta \simeq 3 \times 10^{-10}$. We then selected solutions which yield a present deuterium abundance of $\approx 1.6 \times 10^{-5}$ in order to match the ISM measurement (Linsky et al., 1992). In point of fact, we had solutions with both more and less deuterium destruction. Thus, our solutions should not be viewed as being tied to our choice of $\eta$ or to our assumed primordial abundance of $D/H$. Had we chosen the much higher value of $D/H \approx 2 \times 10^{-4}$ (Songaila et al. 1994; Carswell et al. 1994) we would have still found solutions albeit many fewer of them.

We have also found that adjusting the value of $m_{\text{upp}}$ to match the solar $^{16}O$ abundance can have a dramatic effect on the evolution of $D$. In the case of the group IIa models, $D$ is destroyed almost entirely by lowering $m_{\text{upp}}$. It is clear that such solutions exist as they require nominally less $D$ destruction than those we have already found. Those models which have exponential infall rates (groups Ic, IId) result in the opposite problem. Not enough $D$ is destroyed for these model types when lowering $m_{\text{upp}}$.

Any number of our models could be considered good candidates for the evolution of $D/H$. Usually, those models which match observations and result in a gas fraction of $\sigma \sim .1 - .2$ require too much infall onto the disk. Those models with a lower infall rate result in a $\sigma < .1$. (Bear in mind however, our earlier remarks concerning the relationship between the IMF and $\sigma$ as well as the effect of our calculational scheme on $\sigma$.) These models all assumed infall gas with a primordial $D$ abundance. Lowering the abundance of $D$ in the infall gas could result in models which can better fit $\sigma$ without excess infall.

Our models resulted in the age of the galaxy in the range of 9.8 – 21.6 Gyrs. While
nuclear chronometers may not constrain the age of the galaxy very tightly, they have proven to be a useful tool in determining viable chemical histories for the reproduction of $D$ observations. They give epochs with which to compare with the observations within the models and eliminate those combinations of parameters which can not reproduce the observed ratios of nuclear chronometers.

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Model  | SFR  | IMF  | $M_{low}$  | $M_{upp}$  | Infall Rate  |
---     | ---  | ---  | ---       | ---        | ---          |
Ia      | $\nu M_G$ | $M^{-2.35}$ | $0.4 M_\odot$ | $100 M_\odot$ | $\lambda M_G$  |
Ib      | "     | "     | $0.1 M_\odot$ | $100 M_\odot$ | "           |
Ica     | "     | "     | $0.4 M_\odot$ | $100 M_\odot$ | $\lambda e^{-t/\infty}$  |
Icb     | "     | "     | "           | "           | $\lambda e^{-t/10}$  |
Icc     | "     | "     | "           | "           | $\lambda e^{-t/8}$  |
Icd     | "     | "     | "           | "           | $\lambda e^{-t/5}$  |
Ice     | "     | "     | "           | "           | $\lambda e^{-t/3}$  |
IIa     | $\nu e^{-t/\infty}$ | "     | "           | "           | $\lambda M_G$  |
IIb     | $\nu e^{-t/10}$ | "     | "           | "           | "           |
IIc     | $\nu e^{-t/8}$ | "     | "           | "           | "           |
IId     | $\nu e^{-t/5}$ | "     | "           | "           | "           |
IIe     | $\nu e^{-t/3}$ | "     | "           | "           | "           |
IIba    | $\nu e^{-t/\infty}$ | Scalo | $0.1 M_\odot$ | $100 M_\odot$ | "           |
IIbb    | $\nu e^{-t/10}$ | "     | "           | "           | "           |
IIbc    | $\nu e^{-t/8}$ | "     | "           | "           | "           |
IIbd    | $\nu e^{-t/5}$ | "     | "           | "           | "           |
IIc     | $\nu e^{-t/3}$ | "     | "           | "           | "           |
IIId    | $\nu e^{-t/10}$ | $M^{-2.35}$ | $0.4 M_\odot$ | $100 M_\odot$ | $\lambda e^{-t/10}$  |
III     | $\nu M_G^2$ | $M^{-2.05}$ | $0.4 M_\odot$ | $100 M_\odot$ | "           |

Table 1: Summary of Model Parameters
Figure Captions

**Figure 1a:** Relationship between the Total Mass of the galaxy in units of initial disk mass and the initial star formation rate for group Ia (filled circles), Icb (filled boxes), and Icc (Filled triangles) model solutions.

**Figure 1b:** Same as figure (1a) for models IIaa (x’s), IIac (open triangles), IIad (open boxes), and IIae (open circles).

**Figure 2:** Relationship between the Gas Mass Fraction ($\sigma$) and the Total Mass of the galaxy in units of initial disk mass for groups IIaa (x’s), IIac (open triangles), IIad (open boxes), and IIae (open circles) model solutions.

**Figure 3a:** Relationship between the Initial Enrichment ($S_0$) and the initial star formation rate for models Ia (filled circles), Icb (filled boxes), and Icc (Filled triangles). The cutoff at $\nu = 1$ only represents the range of parameters tested.

**Figure 3b:** Same as figure (3a) for models IIaa (x’s), IIac (open triangles), IIad (open boxes), and IIae (open circles).

**Figure 4a:** Relationship between the Initial Enrichment ($S_0$) and the resulting age of the galaxy at the pre-solar epoch for models Ia (filled circles), Icb (filled boxes), and Icc (Filled triangles).

**Figure 4b:** Same as figure (4a) for models IIaa (x’s), IIac (open triangles), IIad (open boxes), and IIae (open circles).

**Figure 5a:** Corresponding $D$ evolution for the models in figure (5a) including the observations at the pre-solar epoch (Geiss 1993) and today (Linsky et al. 1992).

**Figure 5b:** Evolution of the gas fraction for models Ia (solid line), Ib (dotted line), Icb (short dashed line), and IIab (long dashed line) which resulted in a pre-solar epoch of 9.6 Gyrs.

**Figure 6:** $D$ evolution for group Ia model assuming infall $D$ abundances of primordial (solid line), 50% primordial (dotted line), and no $D$ (dashed line).