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IS DEUTERIUM OF COSMOLOGICAL OR OF GALACTIC ORIGIN?

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ABSTRACT

If deuterium is made primarily in stars, then according to current models of galactic evolution it should have a higher abundance in the metal-rich parts of the Galaxy. If it is produced only in the initial big bang, then astration causes a decrease in D abundance with increasing metal abundance z. Since the sign of the galactic metal abundance gradient is known ($dz/dr < 0$), we propose that a determination of the sign of the deuterium abundance gradient would indicate the probable origin of this isotope. In particular it appears possible that the ratio of the radio recombination line strengths (D/H) from dense H II regions might be measurable with realizable equipment and determine, relatively unambiguously, the ratio of abundances in various parts of the Galaxy.

Subject headings: abundances — cosmology — deuterium

I. INTRODUCTION

We do not yet know whether deuterium is primarily of cosmological or galactic origin. Theoretical investigations have not provided an unambiguous answer, and the question is of some moment. If D is primordial, then recent satellite observations (Rogerson and York 1973; York and Rogerson 1975) and the simplest big bang nucleogenetic scenarios (cf. Gott *et al.* 1974 for review) put strong constraints on the cosmological parameters (q_0, H_0).

Could D have a galactic origin? Cosmic-ray production of sufficient efficiency is now thought unlikely (cf. Reeves 1974), and production in supernova envelopes (Colgate 1974; Hoyle and Fowler 1973) may or may not be consistent with detailed shock structure studies or the abundance of other light elements (Weaver and Chapline 1974; Epstein *et al.* 1974; Colgate 1975).

Although the cosmological implications of the observed deuterium abundance can be confused somewhat by subsequent effects of galactic evolution, the primary ones—astration (burning of deuterium to ^{3}He in stars with subsequent ejection of depleted gas) and infall of gas (either primordial or from an extended stellar halo)—can only reduce the fractional abundance of D below the primordial level and strengthen the cosmological conclusions.

While the important theoretical investigations of this problem continue, we suggest that a possible *empirical* test of the origin of deuterium may be made. The proposed method, which is moderately independent of the specific model of galactic evolution adopted, depends on the fact that primordial D inevitably decreases in relative abundance due to astration as the metal abundance increases, but D produced by stars (directly, or indirectly by star-produced cosmic rays) would increase with increasing z. Since radial gradients in metal abundances exist in our Galaxy (e.g., Janes and McClure 1972; Ryter *et al.* 1975) and in the external spiral (e.g., Shields 1974) and elliptical (Spinrad *et al.* 1972) galaxies, $dz/dr < 0$, we suggest that an effort be made to determine the *sign* of the deuterium abundance (d) gradient, dd/dr. If d increases as z decreases (with r), then D is primarily of cosmological origin; if it decreases with decreasing z, it is of galactic origin.

In § II we present analytical approximations for the relation between d and z predicted by three representative models of galactic evolution, and in § III we describe the observational consequences of the two suggested origins of D and how these depend on the uncertain past course of galactic chemical evolution.

II. MODELS OF CHEMICAL EVOLUTION

We adopt the notation and formalism developed by Tinsley (1974, § III) in her general but approximate discussion of current models of galactic evolution. We assume that the birthrate of stars at a given place is a separable function of stellar mass and time with the constant initial mass function (IMF) labeled $\psi(m)$. We assume further that, at any time, the stars making the primary contribution to evolutionary changes have lifetimes short compared to the time scale for evolution and that the interstellar medium is always well mixed (the instantaneous-recycling, perfect-mixing approximation). The first approximation does not limit the generality of the analysis since it is valid if applied piecewise in time. The second is good for most purposes to an accuracy of several percent (cf. Talbot and Arnett 1971) although quite poor for certain questions like the age distribution of the metals (Thuan *et al.* 1975). The fractional abundance of D can be derived as a function of the fractional gas content μ (which parametrizes in a dimensionless way the age or evolutionary state) and

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the various parameters defining the model. We derive equations for $d(\mu)$ for three representative consistent models, designating by $d_p(\mu)$ the D abundance under the hypothesis of primordial production and $d_*(\mu)$ the abundance which would have resulted from small original abundance with subsequent production proportional to the number of massive stars dying at any time. The equations can be solved to give d_p/d_{p1} and d_*/d_{*1}, where the subscript 1 designates a fiducial locale, say the present solar neighborhood, in terms of the gas density μ and its value at the fiducial point, μ_1. Then we find that we can eliminate poorly known production factors—big bang abundance and stellar deuterium yield—for the two hypotheses, to find the relative deuterium abundance as a function of the relative metal abundance.

a) The "Simple" Model

Assume no infall of gas, with initial values of (z, d_*, d_p) taken to be (0, 0, d_b), where d_b is the big-bang primordially produced deuterium abundance. The initial value of z must in fact be nonzero in this model to fit stellar abundance statistics, but allowing for this needlessly complicates the equations without changing the results significantly. One can show then that

$$\frac{d_*}{d_{*1}} = \frac{1-\mu^r}{1-\mu_1{}^r}, \quad \frac{d_p}{d_{p1}} = \left(\frac{\mu}{\mu_1}\right)^r, \quad \frac{z}{z_1} = \frac{\ln \mu}{\ln \mu_1};$$

or (1)

$$\frac{d_*}{d_{*1}} = \frac{1-\mu_1{}^{r(z/z_1)}}{1-\mu_1{}^r}, \quad \frac{d_p}{d_{p1}} = \mu_1{}^{r(z-z_1)/z_1},$$

where R is the mass fraction of a stellar generation that is returned to the interstellar medium and $r \equiv R/(1 - R)$. We will take $R = 0.2$ throughout. Figure 1*a* shows the relations (1) between metal and deuterium abundance expected under the two hypotheses of origin for two values of μ_1 (0.05, 0.15), which probably bracket its true local present value. As expected, d_p/d_{p1} increases with increasing z/z_1 while d_*/d_{*1} decreases. The effect is not small. If closer to the center of our Galaxy the metal abundance is twice the local value, then, according to the galactic hypothesis, the deuterium abundance would be ~1.5 times the local value, but on the primordial hypothesis, only 0.5 times the local value.

b) The Collapse Model

This is a schematic representation of the models of galaxy formation discussed by Searle (1972) and developed by Larson (1974, 1975) and others, in which stars form and continually recycle matter within a collapsing gas cloud. The abundance gradient is established because stars nearer the center have a larger fraction of their material enriched by ejecta from previous stellar generations farther out in the galaxy. Each radial shell (a "model" here) receives a net inflow of gas which is less astrated and poorer in metals than the ambient gas. Star formation consumes the added gas, keeping the local mass in gas constant. We assume the same initial abundances as before and, for the net inflowing gas (inflow minus outflow), the abundance $z_f = (1 - \beta r)z$, $d_{*f} = (1 - \beta r)d_*$, and $(d_p - d_{pf}) = (1 - \beta r)(d_b - d_p)$ where β is a constant parameter dependent on the infall rate and abundance gradient. The normalized results can be written:

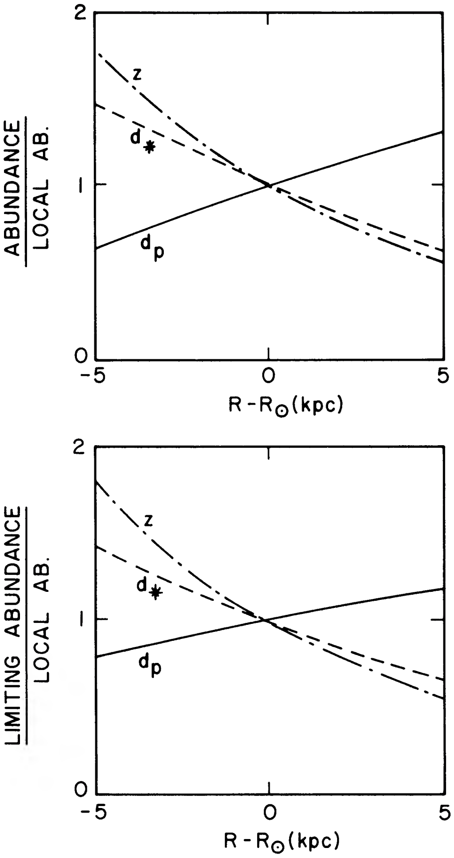

FIG. 1.—Predicted correlations between deuterium and metal abundances, scaled to present local values, in (*a*) the simple model, (*b*) the collapse model, and (*c*) the halo model. In (*a*) and (*c*), curves are labeled with the value of the present local gas fraction μ_1; in (*b*), the label is $1 - \beta r$, the relative enrichment of infalling gas. Solid lines are for primordial D; dashed lines, for galactic D.

$$\frac{d_p}{d_{p1}} = \frac{\beta + \exp(-l)}{\beta + \exp(-l_1)}, \quad \frac{d_*}{d_{*1}} = \frac{1 - \exp(-l)}{1 - \exp(-l_1)}, \quad (2)$$

where l is related to μ and (z/z_1) via $l = r(\beta + 1)(\mu^{-1} - 1)$ and $l\beta/(\beta + 1) = -\ln [1 - (z/z_1)\{1 - \exp[-l_1\beta/(\beta + 1)]\}]$.

Figure 1*b* shows the dependence of (d/d_1) on (z/z_1) for two values of β—(4, 2)—which, since the adopted value of r is 1/4, covers the range from unprocessed to half-processed inflowing material. Note that there are limiting values for z and d which depend explicitly on their yields y_z and y_d (defined in the usual way as the mass of newly synthesized metals or D ejected when unit mass of gas is locked into stars: $z \rightarrow y_z/r\beta$, $d_p \rightarrow d_b\beta/(\beta + 1)$, and $d_* = y_d/r(\beta + 1)$. For $\mu_1 \lesssim 0.2$ the results are nearly independent of μ_1, and the local values of (z, d) are near their limiting values.

c) The "Halo" Model

Here we approximately model the scheme of galactic evolution (Ostriker and Thuan 1975) in which part of the present disk is reprocessed gas ejected by halo stars. Much of the deuterium, like much of the metals, is assumedly made in extreme Population II supernovae. We assume that a fraction $(1 - m_D)$ of the present disk is derived from infalling halo gas which induces a disk stellar birthrate proportional to the infall rate; the proportionality constant is determined by μ_1 (cf. Tinsley 1975, Appendix).

For a relatively brief initial era ($t \lesssim 10^8$ yr), when massive halo stars were dying, the infalling gas was rich in newly synthesized elements. We allow for this by taking values $z(0) = z_0$ and $d_*(0) = z_0 y_d / y_z$. Later, infalling gas has a negligible abundance of metals, and stellar-produced D and all primordial D has been burned to ^{3}He.

If we now let

$$k \equiv \frac{1 - m_D}{1 - \mu}, \quad q \equiv \frac{1 - (1 - k)(1 - R)}{(1 - k)(1 - R)}, \tag{3}$$

we find

$$\frac{d_p}{d_b} = \left(\frac{\mu}{m_D}\right)^q;$$

$$\frac{d_*}{y_d} = \frac{1 - [1 - (z_0/y_z)q(1 - k)](\mu/m_D)^q}{q(1 - k)}; \tag{4}$$

and

$$\frac{z}{y_z} = \frac{1 - [1 - (z_0/y_z)k](\mu/m_D)^{k/(1-k)}}{k}.$$

In the above relations z, d_p, and d_* are given in terms of the ambient values of (μ, m_D). Normalized variations over the face of the galactic disk in (z/z_1), (d_p/d_{p1}), (d_*/d_{*1}) are clearly independent of (d_b, y_d, y_z) and depend only on variations in (μ, m_D).

If $m_D \rightarrow 1$, the halo model reduces to the simple model. But if the disk mass is largely secondary ($m_D \lesssim 0.1$), then for $\mu \approx 0.2$, the abundances are close to their limiting values: $z_1 \rightarrow y_z(1 - \mu_1)/(1 - m_{D1})$, $d_{p1} \rightarrow 0$, $d_{*1} \rightarrow y_d(1 - R)(1 - \mu_1)/(1 - m_{D1} - m_{D1}R - \mu_1 R)$. We show in Figure 1*c* the variation in relative abundances for $m_D = 0.75$, $z_0 = 0.172$ (reasons for these choices given in Ostriker and Thuan 1975 and Tinsley 1974, respectively), and for two values of μ_1. In the figure, galactic abundance variations are assumed to be caused by variations in μ with m_D fixed; a similar dependence of d_* and d_p on z would have been obtained with variations in m_D with μ fixed.

III. PREDICTED GALACTIC GRADIENTS

In the simple model the gas fraction μ is the only possible parameter whose variations can cause an abundance gradient, and the increase in z toward the galactic center is interpreted as a decrease in μ. Figure 2 (*upper*) shows what might be observed within 5 pc of the Sun

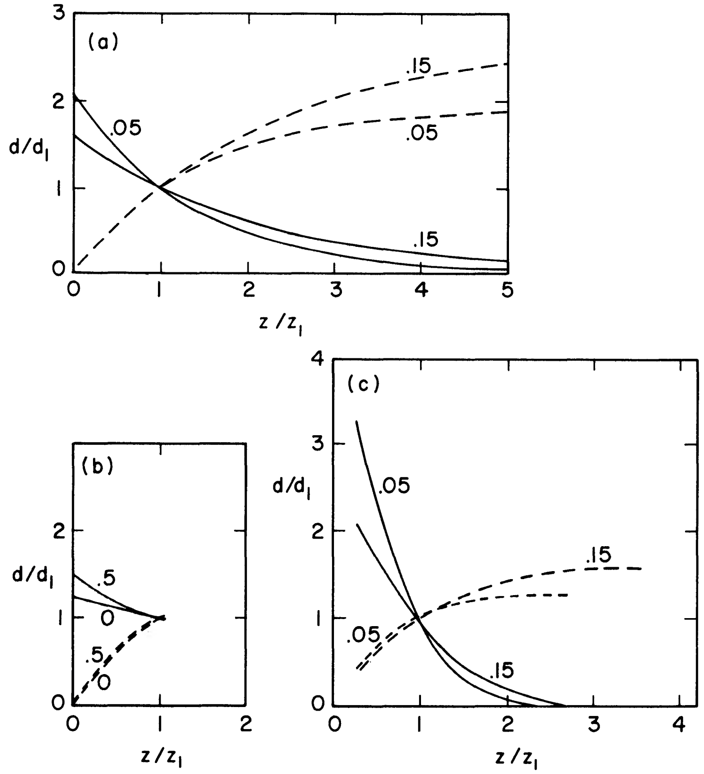

FIG. 2.—Predicted galactic gradients of metal abundance (z), galactic D (d_*), and primordial D (d_p), in the simple model (*upper*) and the collapse model (*lower*).

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assuming a galactic gradient $d \log z/dR \approx -0.5$ per 10 kpc and taking $\mu_1 = 0.10$. As expected, stellar deuterium would increase inward nearly as fast as z; but if deuterium is cosmological, there would be a similar gradient of opposite sign.

Numerical collapse models (Larson 1974, 1975) show that z quickly approaches its equilibrium value, so we do not expect to observe the z change shown in Figure 1 as a function of R. Instead the metallicity gradient is to be interpreted as a decrease in β toward the galactic center. Figure 2 (*lower*) shows the relative equilibrium values with the local value of the reprocessing parameter, $\beta_1 = 2$. In the halo model, if most of the disk is secondary ($m_{\mathrm{D}} \ll 1$), $d_p \rightarrow 0$ in a short time and the very existence of substantial amounts of D points to a galactic origin. For a more realistic value, $m_{\mathrm{D}} \approx 0.75$, it is clear that the gradients will be qualitatively similar to the simple model; but since m_{D}, μ, and even z_0 all will vary with galactic radius, no quantitative prediction can be made without a detailed dynamical model of galaxy formation.

IV. DETECTION

The ideal experiment would be able to detect the atomic abundances of duterium and a "metal" Z (C, N, O) relative to hydrogen in several parts of the galaxy. Then one could plot D/H versus Z/H, and the sign of the slope (positive or negative) would determine whether deuterium were primarily of galactic or extragalactic origin. Carbon would be the preferred "metal" since nitrogen and to some extent oxygen are increased with reprocessing (say via the CNO cycle) in moderate mass stars (cf. Audouze *et al.* 1975 for discussion), which destroys deuterium, whereas the ^{12}C abundance may reflect primarily the massive supernovae which are also the best candidates for shock production of deuterium.

In our Galaxy radio techniques would be required, and three approaches seem possible. Isotope ratios as in the microwave line pair DCN/HCN are measurable with present equipment (Wilson *et al.* 1973; Penzias 1975) from several sites in the Galaxy. Interpretation will be difficult, however, because of the complex effects of chemical fractionation. Radio recombination lines have an opposite set of virtues and defects. It appears from a preliminary assay of the problem that deuterium from a dense H II region could be measured ($\Delta v = 81.6$ km s^{-1} with respect to hydrogen) with a major instrument only if a considerable fraction of a year were dedicated to the experiment. But if lines were detected, the interpretation of their strengths in terms of abundance ratios would be straightforward since non-LTE effects are probably small and the ionization potential is so close to H that the difficulties encountered in interpreting the carbon lines (Palmer 1968) or the helium lines (Mezger and Höglund 1967) would not be present. Finally improved measurements of the deuterium 372-MHz line (cf. Cesarsky *et al.* 1973) would allow the D/H ratio to be determined by a method intermediate with regard to both difficulty of measurement and ambiguity of interpretation when compared with the above two methods.

In conclusion, it seems possible to decide experimentally whether deuterium is primarily of galactic or cosmological origin, by determining the sign of the D/H abundance gradient in the Galaxy. Various models for chemical evolution predict different values of the gradient of D/H relative to the metal abundance gradient, but in all cases a positive correlation between D and metals indicates that D is of galactic origin whereas a negative correlation indicates that it is primordial.

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