The solar boron, stellar lithium and deuterium, interstellar deuterium, and extragalactic deuterium abundances

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D, Li, Be, and B are not by formed by ordinary stellar nucleosynthesis. D is primarily formed in the big bang. Because each generation of stars replenished the ISM with material depleted in D, the D abundance decreases with time and is larger in low-metallicity regions. Because Li, Be and B are primarily formed via cosmic-ray spallation reactions, their abundances will increase with time. Some Li and B is produced in supernovae via $\mu$-capture reactions and some Li is produced via mass loss from Li-rich AGB stars.

To determine if the B abundance has increased during past 4.5 Gyr, an accurate Solar B abundance will be determined from newly observing the Li/B ratio. Initial negative results yield B/H $< 3.5 \times 10^{-7}$. The Balmer D$_2$ line was not detected in the high-metallicity star HD 182983, the low-metallicity Pop II halo star HD 140283 (both with detected \(^3\)Li), or in the slowly rotating B star 1 Her and $\gamma$ Peg with B/H $< 1.0 \times 10^{-8}$.

Observations of Li in super-Li-rich AGB C and S stars with strong Li lines confirms that these stars have the largest Li abundance in the Galaxy (Li/H = $10^{-3}$) and that mass loss from these stars may contribute to the ISM Li abundance. Observations of the DCN/HCN ratio in the Galaxy yield B/H $< 1.4 \times 10^{-6}$ in the Galactic Center molecular clouds (10 pc from the center) and a positive B/H gradient in the Galaxy implying that there are no Galactic sources of D and B is cosmological. Extragalactic B (in DCN) is currently being searched for in two gravitational lenses against quasars at $z = 0.7$ and 8.0 and in the Seyfert Galaxy NGC 1068.

1. SOLAR BORON

Because B is formed from cosmic-ray or supernova spallation reactions, the B/H ratio will increase with time and the present solar B/H should be larger than the meteoric B/H = $6 \times 10^{-7}$. However, the solar B abundance B/H = $5 \times 10^{-8}$ only knows within a factor of 2 from observations of the isototyped $^{27}$B resonance line of BI. In order to more accurately determine the solar B abundance observations to detect the weak 1.6 $\mu$m line of BI were done with the National Solar Observatory 1.5-m telescope and Fourier Transform Spectrometer in 1990, 2001, and 2002 (Collaborators: V. Smith and J. King). Cuhna and Smith [1] remeasured the solar atlas and estimated that the weak 1.6 $\mu$m BI line may have an EW = 2 mÅ corresponding to a B/H = $3.5 \times 10^{-10}$. We did not detect

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The 1.6 μB lines in the center and edge of the Sun and we place to obtain high S/N observations of the cooler sunspots to detect these B lines. Our initial negative results gave an EW < 2 mÅ and B/H < 3.5 x 10^-6.

2. STELLAR LITHIUM

Observations of Li in AGB C and S stars with strong Li lines at 6707 Å (FWHM = 8-10 Å) confirms that these stars have the largest Li abundances in the Galaxy (Li/H = 10^-6). The ISM Li is probably produced by cosmic-ray spallation reactions plus mass loss from Li-rich giant stars (produced via H e 2+ + e⁻ + p Li and p spallation reactions in supernovae. Based on negative results from a search for the Li and B radiofrequency hyperfine lines [2] there is no enhanced Li or B in the Galactic Center. This is consistent with the reduced Galactic Center D deuterium abundance, the current low-level cosmic-ray or γ-ray fluxes (previous weak AGN activity is not excluded). In order to understand the super-lithium-rich (SLR) phase of AGB star evolution, we will measure the Li/H and chemical composition in Galactic SLR C and S stars. High resolution echelle spectra of 3/4 C stars and 6/8 S stars have been taken at CTIO in 1998. The remaining C and S stars will be observed in 2003. Future observations include estimating the age-abundance relationship for Li-rich AGB stars in LMC clusters, determining the mass loss in SLR C and S stars from CO 2:1 and 1:0 observations; and determining if Li exists in planetary nebulae that may have evolved from Li-rich AGB stars. (Collaborators: V. Smith, C. Ateia, K. Kwitter, H. E. Turner, V. Mozlari, R. Galindo, W. Abbi, and R. Sahai)

3. DEUTERIUM

The D/H ratio is an important prediction of standard and non-homogeneous big-bang models [3] because the abundance of D depends critically on the temperature and baryonic density during the epoch of deuterium synthesis (first 100 seconds) and might determine if the density is sufficient to close the universe. Thus any Galactic source of deuterium would undermine its use to estimate the baryonic density of the universe and place constraints on big-bang nucleosynthesis models. Alternatively, in homogeneous inflationary or other flat models, the D/H ratio gives the amount of dark matter and an upper limit to the number of ν families. Deuterium is produced by p(p,α)4He, (p,α)7Li or spallation reactions between p, α, and γ-rays and He, C, N, or O and D is easily destroyed by reactions with p, α, or D. D can survive only if formed in a region of rapid expansion and cooling (big-bang or explosive nucleosynthesis) or in cool ruffled gas (ISM). The D abundance will be larger in the past at larger redshifts representing less evolved low-metallicity gas and will decrease with time. Any non-homological deuterium would be a signature of high-energy astrophysical processes and a probe for analyzing cosmic-ray physics, Galactic chemical evolution, and interstellar chemistry (with deuterated molecules). In stellar interiors D is destroyed at T > 5 x 10^8 K and is converted into 4He and 3He during the p-p cycle. Because of diffusion each generation of stars replenishes the ISM with gas depleted in D. Because stars earlier than B4 should have some D remaining in their atmospheres, a search was made for D in the atmospheres of slowly rotating sharp based B stars in which the surface B was not destroyed at T > 2.5 x 10^8 K by convection to the hotter layers. We did not detect the 6561 Å Balmer D line (82 km/s or -1.78 Å from Hα) in the He (B3IV)
or γ Peq (BdV) with D/H < 1 x 10^{-5}) [4]. Searches for Ds in the high-metallicity star HD 82943 (G3V; [Fe/H] = 0.32) [collaborator: Low Hobbs] and the metal-poor halo star HD 140983 (G2V; [Fe/H] = -2.6) also gave D/H < 1 x 10^{-5} [5]. Since Li has been detected in these stars the gas must have been at 5 x 10^6 < T < 10^7 K to have destroyed the D.

DCN has been detected in the Sgr A 50 km/s molecular cloud (10 pc from the Galactic Center) with an estimated D/H = 1.7 x 10^{-4} from a 5260-chemical reaction model [6]. DCN is the best molecule to use because its efficiently synthesized at higher temperatures and chemical fractionation will enhance the abundances of deuterated molecules by up to 10,000 times over the D/H ratio. The Galactic Center (GC) D/H ratio is 9 x lower than the local ISM value (D/H = 1.5 x 10^{-4}) but 340,000 times larger than predicted from models without an additional source of D (D/H = 4 x 10^{-10}). We have confirmed this result with additional observations of DCN in the Sgr A 50 km/s, Sgr 200 km/s, and Sgr B2 molecular clouds where we obtain an average D/H = 1.4 x 10^{-4}. We conclude that there are no significant Galactic Center sources of D, the GC D comes from recent infall of low-metallicity gas, and that the GC has not had recent AGN activity or large fluxes of cosmic-rays or γ-rays. Ongoing observations of DCN in the circumnuclear ring are in progress (with the PRAM 30-m telescope) to determine if D is produced by the GC black hole via cosmic-ray or γ-ray spallation reactions. We have determined the Galactic D/H distribution from observations of DCN and HCN in 15 sources and used our chemical model and the 14N/15N ratio to determine the D/H ratio. We measured a positive Galactic gradient in D/H confirming that there are no Galactic sources of D, but the analysis is complicated by chemical effects. We also have made the first detection of D^{12}CN which can yield the 14C/12C ratio. We expect to make the first detection of the 92-cm lines of D I line and OD in molecular clouds in which D_2CO, NHD_2, or NHD have already been detected to test models of astrochemistry.

Using the Nobeyama mm array in 2003 we will search for DCN in AGN to determine if D is cosmological. We will determine the D/H ratio in the Seyfert Galaxy NGC 1068 to test models that predict enhanced D from γ-rays or cosmic-ray spallation reactions in jets. Ongoing searches for red shifted DCN and DCO in absorption against gravitational lenses at z = 0.7 and 0.9 (optically thin lines of HCN and HCO^+ have already been detected) are being conducted with the Haystack 35-m and U. Arizona 12-m telescopes. (Collaborators: T. Miller, C. Henkel, H. Roberts, G. Stramler, J. Pasachoff, R. Mannersberger, B. Turner, C. Crawford, C. Brunt, and N. Kuro)

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