Deuterium in the Galactic Centre as a result of recent infall of low-metallicity gas

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The Galactic Centre is the most active and heavily processed region of the Milky Way, so it can be used as a stringent test for the abundance of deuterium (a sensitive indicator of conditions in the first 1,000 seconds in the life of the Universe). As deuterium is destroyed in stellar interiors, chemical evolution models[1] predict that its Galactic Centre abundance relative to hydrogen is D/H = 5×10^{-12}, unless there is a continuous source of deuterium from relatively primordial (low-metallicity) gas. Here we report the detection of deuterium (in the molecule DCN) in a molecular cloud only 10 parsecs from the Galactic Centre. Our data, when combined with a model of molecular abundances, indicate that D/H = $(1.7 \pm 0.3) \times 10^{-6}$, five orders of magnitude larger than the predictions of evolutionary models with no continuous source of deuterium. The most probable explanation is recent infall of relatively unprocessed metal-poor gas into the Galactic Centre (at the rate inferred by Wakker[2]). Our measured D/H is nine times less than the local interstellar value, and the lowest D/H observed in the Galaxy. We conclude that the observed Galactic Centre deuterium is cosmological, with an abundance reduced by stellar processing and mixing, and that there is no significant Galactic source of deuterium.

The origin of deuterium has been extensively studied because it is not produced via stellar nucleosynthesis and any non-cosmological deuterium would be a signature of high-energy astrophysical processes. 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 nucleosynthesis (the first 1,000 s) and might determine if the density is sufficient to close the Universe. However, D is completely destroyed in stellar interiors via $D(p,\gamma)^3He$ and not returned to the interstellar medium so that the abundance of D will decrease with time unless there are any additional sources of deuterium. Such sources, involving high-energy spallation reactions or large fluxes of protons or neutrons, would undermine the use of deuterium to estimate the baryonic density of the Universe and place constraints on Big Bang nucleosynthesis models.

The Galactic Centre is the most active and heavily processed region of the Galaxy[4], and has a higher abundance of elements heavier than He (metallicity), faster star formation rate, and steeper initial mass function[5]. Thus the astration (recycling) rate in the Galactic Centre should be considerably larger than elsewhere in the Galaxy, resulting in a reduced D abundance. Chemical models at 12 Gyr of the Galactic bulge[6] and the Galactic Centre predict the almost total destruction of deuterium giving D/H = 3.2×10^{-11} and D/H = 5×10^{-12}, respectively. Thus if there were no additional sources of D, the Galactic Centre molecular clouds should be composed primarily of astrated material completely depleted in D, and DCN should not be detectable. Thus the mere detection of D (in DCN) in the Sagittarius A molecular clouds requires a continuous source of deuterium to negate the effects of astration. Alternatively, if D is produced by any stellar or Galactic process, then it should be more abundant in the Galactic Centre and there should be a corresponding gradient in the D abundance[7].

The largest Sgr A molecular clouds are the 50 km s^{-1} cloud (M-0.02-0.07) and the 20 km s^{-1} cloud (M-0.13-0.08), which are 10 pc from the Galactic Centre[8]. These are the appropriate objects in which to search for D because they are clearly related to the Galactic Centre activity. There is one reported marginal 1σ detection of deuterium from the DCN $J = 1$–0 line in the 50 km s^{-1} Sgr A molecular cloud core[9] with corrected antenna temperature $\Delta T_a^* = 0.02 \pm 0.015$ K, but no astrochemistry model was used and the D abundance was not determined. In this initial investigation we observed the 50 km s^{-1} cloud in May and June 1993, and February 2000, with the NRAO 12-m telescope at the position of the peak CS $J = 7$–6 and $J = 5$–4 emission[10] (right ascension 17 h 42 min 42 s, declination −28° 58′ 00″), which ensured that we were observing the densest part of this cloud with an H_2 density $n(H_2) = (7.5 \pm 2.5) \times 10^5$ cm^{-3}. Table 1 gives the results of our observations. We detected both the $J = 1$–0 and $J = 2$–1 lines of DCN, and obtained $T_R^* = 0.061 \pm 0.007$ K (8σ) and $T_R^* = 0.042 \pm 0.02$ K

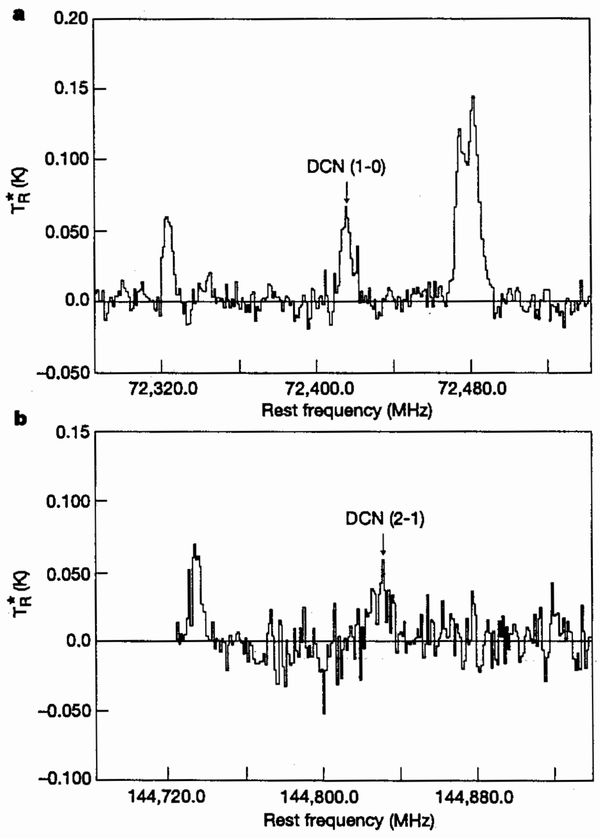

Figure 1 The DCN spectra in the Sgr A 50 km s^{-1} cloud. We used the NRAO 12-m telescope during 16–18 May 1993 and 29 June 1993 to observe the 50 km s^{-1} Sgr A Galactic Centre molecular cloud (M-0.02-0.07). We observed the DCN $J = 1$–0 and $J = 2$–1 lines at 72.4149 GHz and 144.83 GHz in total-power mode using position switching with the 3-mm and 2-mm SIS receivers. We used 1-MHz filters with a 256 MHz bandwidth in parallel, and obtained 4.14 km s^{-1} resolution with an 86-arcsec beam at 72 GHz and 2.07 km s^{-1} resolution with a 43-arcsec beam at 144 GHz. Pointing was checked using Jupiter and Uranus. The double sideband system temperature was 350 K at 72 GHz and 400 K at 144 GHz. **a**, The DCN $J = 1$–0 line. **b**, The DCN $J = 2$–1 line.

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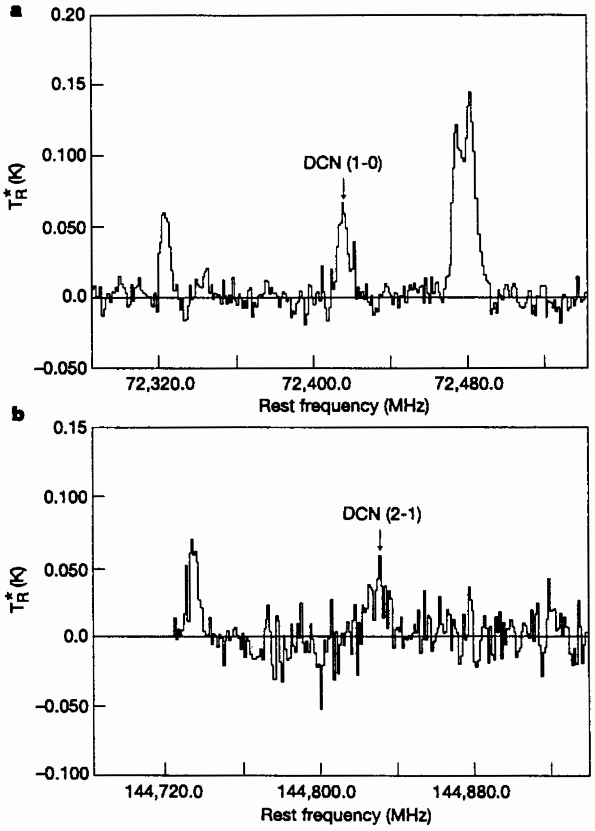

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Our results also constrain models of Galactic Centre activity. By comparing our results to models of activity in active galactic nuclei (AGN) where D is produced from cosmic-ray[21] or γ-ray spallation reactions[22], we conclude that the Galactic Centre has not had a recent AGN or quasar phase. Our results do not exclude weak activity—with a cosmic-ray proton luminosity $L_p = 8.5 \times 10^{41}\,\mathrm{erg\,s^{-1}}$ or γ-ray luminosity $L_\gamma = 1.7 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ for 1 Gyr (which could produce our observed Galactic Centre D/H) coupled with periodic bursts of star formation—if the astration would reduce the Galactic Centre D/H to match the current deuterium abundance. However, these values of L_p and L_γ are respectively 42,500 times and 850 times larger than the current Galactic Centre cosmic-ray proton[23] or γ-ray[24] luminosities of $2 \times 10^{37}\,\mathrm{erg\,s^{-1}}$, but respectively 1,180 and 5,880 times less than quasar L_p or L_γ. Because almost all nucleosynthesis processes that can produce D over-produce Li or B by 10^3–10^5 times, the observed upper limit on the Galactic Centre (GC) Li of $(\mathrm{Li/H})_{\mathrm{GC}} < 3.9 \times 10^{-8}$ or $(\mathrm{Li/H})_{\mathrm{GC}} < 20\ (\mathrm{Li/H})_{\mathrm{disk}}$ further implies there are no significant Galactic Centre sources of deuterium[25]. (Here $(\mathrm{Li/H})_{\mathrm{disk}}$ is the lithium abundance in the Galactic disk.)

If all the deuterium is primordial and the astration models of Prantzos[20] are correct, then the primordial or early Galactic $\mathrm{D/H} = 5 \times 10^{-5}$. For this D/H, standard Big Bang nucleosynthesis models imply that the baryon-to-photon ratio ratio is 3×10^{-10}, that there are fewer than four neutrino families, and that the baryon density of the Universe $\rho_b = 3 \times 10^{-31}\,\mathrm{g\,cm^{-3}}$ is less than the critical density $\rho_c = 3H_0^2/8\pi G = 9.2 \times 10^{-30}\,\mathrm{g\,cm^{-3}}$ (for a Hubble constant $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) necessary to close the Universe assuming a Friedmann–Robertson–Walker cosmological model with $\Omega_b = \rho_b/\rho_c = 0.03$ (ref. 26). Thus the fraction of the critical density contributed by baryons (Ω_b) requires most of the baryons to be in the form of dark matter, and most of this dark matter to be non-baryonic[3]. ☐

Received 22 February; accepted 5 May 2000.

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Acknowledgements

We thank H. Reeves and D. Tytler for comments, and A. Mancuso, S. Diaz, M. Pickard, R. Souza, K. Pagliuca and M. L. Kutner for their help. T.J.B. was a visiting scientist at the National Radio Astronomy Observatory, Tucson. The NRAO is a facility of the NSF operated under cooperative agreement by Associated Universities, Inc. We acknowledge a Research and Development Grant from Hofstra University, a Bronfman Science Center Grant from Williams College, and a PPARC grant at UMIST. J.M.P. and T.J.B. benefited from the Keck Northeast Astronomy Consortium.

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The mean free path for electron conduction in metallic fullerenes

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The electrical resistivity, ρ, of a metal is usually interpreted in terms of the mean free path (the average distance, l, an electron travels before it is scattered). As the temperature is raised, the resistivity increases and the apparent mean free path is correspondingly reduced. In this semi-classical picture, the mean free path cannot be much shorter than the distance, d, between two atoms. This has been confirmed for many systems and was considered to be a universal behaviour[1,2]. Recently, some apparent exceptions were found, including alkali-doped fullerenes[3–7] and high-temperature superconductors. However, there remains the possibility that these systems are in exotic states, with only a small fraction of the conduction electrons contributing to the conductivity; the mean free path would then have to be correspondingly larger to explain the observed resistivity. Here we report a model calculation of electron conduction in alkali-doped fullerenes, in which the electrons are scattered by intramolecular vibrations. The resistivity at large temperatures implies $l \ll d$, demonstrating that there is no fundamental principle requiring $l \gtrsim d$. At high temperatures, the semi-classical picture breaks down, and the electrons cannot be described as quasiparticles.

We have also calculated the resistivity due to electron–electron scattering for a half-filled Hubbard model. In this case the resistivity saturates and l is not very much smaller than d. This difference is traced to the difference between bosons and fermions. The resistivity is often calculated using the Boltzmann equation. Although this equation is usually derived semi-classically, assuming $l \gg d$, in our model for electron-vibration scattering it does not break down qualitatively at large temperature, T, where $l \ll d$. For small T the calculated ρ due to electron-vibration scattering has a linear dependence on T and a strong dependence on the pressure, in agreement with experiment[8].