**Design Reference Mission**

# The Interstellar Deuterium Abundance

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| Program contact: | Rolf Güsten for the GREAT consortium |
| Scientific category: | Interstellar medium, cosmology |
| Instruments: | GREAT |
| Hours of observation: | 25 |


## Abstract

Deuterium is formed in the Big Bang and, because of its relatively weak nuclear binding, its abundance provides strong constraints on the physical conditions during the first few minutes of the universe's expansion and hence the density of baryons. Subsequently, deuterium is lost due to nucleosynthesis when material is cycled through stars in the course of galactic chemical evolution. Deuterium is thus a key element for probing the origin and evolution of the universe as well as the star formation history of the universe. The 100 µm channel on GREAT is designed to measure the ground state transition of HD – the main reservoir of deuterium in molecular clouds – at sub-km/s resolution, in emission in the warm gas associated with photodissociation regions and interstellar shocks, and in absorption toward bright background sources. Observations of a wide sample of sources will thus probe the cosmologically important D abundance and its "astration" by nuclear burning in stars throughout the galaxy (e.g., as a function of the star formation rate). There is no other observatory with the appropriate wavelength coverage and spectral resolution required for this study. Studies of electronic transitions of HD in the far-ultraviolet (FUV) by the Copernicus and FUSE satellites are limited to the lines of sight toward a few nearby bright stars.

## Scientific Objectives

Since the very first Big Bang nucleosynthesis models the importance of measuring the cosmological deuterium abundance for confining the baryon density of the universe has been identified. Unfortunately, the abundance of deuterium is very difficult to determine observationally, and the primordial value has been discussed controversially ever since. There is general consensus that significant quantities of deuterium can only be produced during primordial nucleosynthesis; due to its low binding energy the deuterium nucleus is otherwise easily "burned" into $^3$He. Therefore, one expects that virtually all D that has been processed through stars ("astrated") since the formation of the universe, has been destroyed. The depletion factor is model dependent (on the Initial Mass Function (IMF), galactic history, etc.), but may be large. This can easily be demonstrated in terms of the so-called closed-system approximation with the assumption of instantaneous recycling. In this model, the present-day deuterium abundance $D(t_0)$ is related to the pre-galactic abundance, $D_p$, by

$$D(t_0)/D_p = \mu^{\,r/(1-r)} ,$$

where r describes the IMF-integrated fraction of matter that is returned into the ISM by a given generation of stars; $\mu(t_0)$ is the fraction of the total mass left in the ISM ($\mu_p$=1). Thus, while the deuterium abundance steadily decreases with progressing astration, the enrichment with primary nucleosynthesis products (like $^{12}$C and $^{16}$O) follows in the same model as

$$Z(t_0) - Z_p = y_i \cdot \ln(\mu^{-1})$$

where $y_i$ is the effective yield of synthesis of a given synthesis product Z. Combining the two equations,

$$D(t_0)/D_p \propto [\exp^{(Z(t_0)-Zp)/yi}]^{\,r/(1-r)},$$

Therefore, studying the spatial variation of the D/H abundance across the Milky Way and toward a sample of (nearby) galaxies with a wide range of metallicities (including less evolved systems like the Small Magellanic Cloud) will constrain the astration process. The gas in the Galactic Center, e.g., is known to be strongly astrated and metal enriched, and therefore should be heavily deuterium depleted.

## Observing Strategy

In the molecular ISM deuterated molecular hydrogen is the dominant reservoir of Deuterium. Unfortunately, the HD molecule is difficult to observe because of its very small dipole moment. With GREAT the ground-state transition of HD (at 112 µm, 2.675 THz) will become uniquely assessable (ISO has detected HD towards Orion). But even for a high-altitude flight, the high spectral resolution of GREAT is essential to discriminate the HD line against contaminations by narrow atmospheric absorption lines (see Fig.1). For a high-altitude flight with 4 µm zenith $H_2O$, a zenith atmospheric transmission of ca. 80% is predicted from Fig.1.

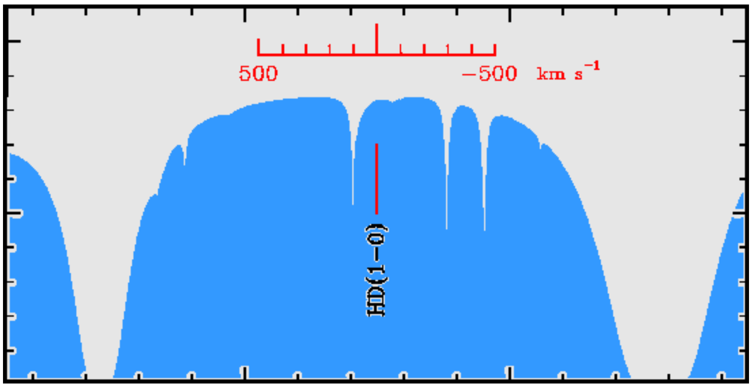


*Fig.1: Atmospheric transmission calculated for 4 µm zenith H2O, using the ATRAN software.*

Assuming a conservative system temperature of 3000 K, HD will be detectable in a large sample of galactic sources and nearby galaxies. For absorption measurements against strong FIR background sources detection limits of equivalent $H_2$-column density less than $10^{21}$ cm$^{-2}$ can be achieved. To quantify the sensitivity: toward SgrB2(N) we expect equivalent background temperatures of 100 K. After 100 min on-source integration a rms noise equivalent of 22 mK will be achieved. The opacity limit as low as $10^{-4}$ corresponds then to $H_2$ column densities well below $10^{-21}$ cm$^{-2}$, which will make all the diffuse line-of-sight absorption features, seen in other tracers towards the Galactic Center, detectable.

We note that unlike in the (F)UV, where studies are limited to the local solar neighborhood, with GREAT we will be able to probe molecular clouds throughout the Milky Way. This will include regions such as PDRs, warm molecular clouds, star-forming regions and hot cores around newly formed stars. The high spectral resolution of a heterodyne instrument like GREAT is essential since – toward, e.g., prominent star-forming cores – the line shape may change rapidly from absorption into emission (or a combination of both).

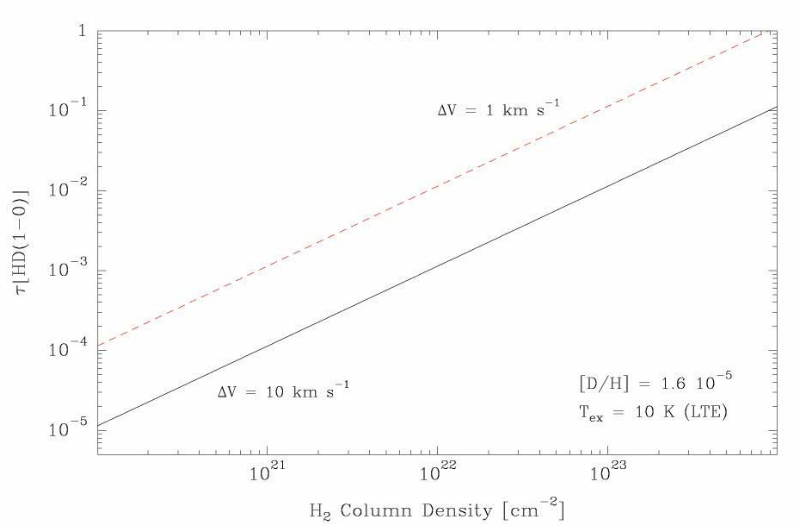


*Fig.2: LTE-modelled opacity of the HD(1-0) transition, assuming an H/D abundance ratio of 1.6 $10^{-5}$, as characteristic for the local ISM, and an excitation temperature of 10 K. Because the HD line is optically thin, derivation of the HD column density is simple and accurate.*

Critically, by supplementary measurements the $H_2$ reference column densities have been or will be derived: indirectly, via the measurements of molecular column density tracers like the CO isotopomers and/or from the thermal emission of the associated dust, or directly, by measurement of the low rotational transitions of warm $H_2$ with the mid-IR spectrometer on board of Spitzer.

Source List

| Source | R.A. (2000) | DEC (2000) | notes |
|---|---|---|---|
| Orion-Bar | 05 35 20.3 | –05 25 20 | HD detected |
| IC443 - B | 06 17 16.0 | +22 25 41 | |
| IC443 - E | 06 18 07.0 | +22 34 47 | |
| IC443 - F | 06 17 07.0 | +22 36 04 | |
| IC443 - G | 06 16 41.8 | +22 31 44 | |
| M+3.06+0.34 | 17 51 26.5 | –26 08 29 | |
| M+2.99-0.06 | 17 52 47.6 | –26 24 25 | |
| M+1.56-0.30 | 17 50 26.5 | –27 45 30 | |
| M+0.94-0.36 | 17 49 13.2 | –28 19 13 | |
| M+0.83-0.10 | 17 47 57.9 | –28 16 49 | |
| M+0.76-0.05 | 17 47 36.8 | –28 18 31 | |
| M+0.58-0.13 | 17 47 29.9 | –28 30 30 | |
| M+0.48+0.03 | 17 46 39.9 | –28 30 29 | |
| M+0.35-0.05 | 17 46 40.0 | –28 40 00 | |
| M+0.24+0.02 | 17 46 07.9 | –28 43 22 | |
| M+0.21-0.12 | 17 46 34.9 | –28 49 00 | |
| M+0.16-0.10 | 17 46 24.9 | –28 51 00 | |
| M-0.15-0.07 | 17 45 32.0 | –29 06 02 | |
| M-0.32-0.19 | 17 45 35.8 | –29 18 30 | |
| M-0.42-0.01 | 17 44 35.2 | –29 17 05 | |
| M-0.50-0.03 | 17 44 32.4 | –29 22 42 | |
| M-0.55-0.05 | 17 44 31.3 | –29 25 45 | |
| M-0.96+0.13 | 17 42 49.3 | –29 41 09 | |
| G+0.68-0.20 | 17 48 00.5 | –28 27 31 | |
| G-0.02-0.07 | 17 45 50.7 | –28 59 39 | |
| Sgr B2 | 17 47 20.3 | –28 23 07 | |
| M17SW | 18 20 23.4 | –16 11 41 | |
| W49N | 19 10 13.3 | +09 06 12 | |
| W51IR2 | 19 23 39.9 | +14 31 06 | |
| W51E | 19 23 43.9 | +14 30 29 | |
| IC1396A | 21 37 07.0 | +57 30 51 | |
| S140 | 22 19 12.0 | +63 18 06 | |

| Source | | R.A. (2000) | DEC (2000) |
|---|---|---|---|
| LMC | 30Dor-10 | 05 38 50.7 | –69 04 15 |
| | N83B | 04 54 22.3 | –69 11 04 |
| | N159A | 05 39 55.0 | –69 45 00 |
| | N160A | 05 39 44.0 | –69 38 48 |
| | N44 | 05 22 01.3 | –67 57 47 |
| | N113 | 05 13 19.8 | –69 22 15 |
| SMC | N81 | 01 09 16.9 | –73 12 02 |
| | N88 | 01 24 08.1 | –73 08 55 |
| | LIRS36 | 00 46 40.2 | –73 06 10 |