FUSE - the FAR ULTRAVIOLET SPECTROGRAPH EXPLORER

1 Science Objectives of the FUSE Mission

Primordial D/H: Measure D/H in several locations where the metal abundance is close to zero. Possible locations are the Galactic halo, high velocity clouds near the Galaxy, Lyman-α forest, halos of other galaxies.

- This objective sold the *FUSE* mission.
- Place constraints on what happened in the first 3 minutes of the Universe and the baryon density of the Universe.
- Very difficult experiment because background targets faint, the Lyman absorption line spectrum is complex, the spectrum can be confused (H blueshifted by 82 km/s will look like D).
- Requires high throughput and low background (OK), 15 km/s resolution (almost), difficult selection of the few best (least confused) targets for heroic observations ($> 2 \times 10^5$ seconds).
- No results published yet, but the first important paper on D/H in a high velocity cloud (Complex C) has been submitted.

Local D/H: Measurements of D/H in the local region of the Galactic disk to establish a benchmark for comparison with measurements of D/H at larger distances.

- Targets are mainly hot white dwarfs located within about 500 pc.
- Program nearly complete with D/H = $(1.5 \pm 0.2) \times 10^{-5}$ inside the Local Bubble (out to about 100 pc) but a wide range in D/H (0.5 to 2.5) $\times 10^{-5}$ beyond the Local Bubble.

Galactic Chemical Evolution: Compare D/H with other elements created in stars (e.g., O/H and N/H) in the Galaxy and beyond. The present results from *FUSE* are very conFUSing.

Ionization and density of the Intergalactic Medium: What is the fractional ionization of helium in the IGM? How much intermediate temperature gas ($\log T = 4$–6) in the IGM?

Hot Gas in the Galactic Disk and Halo: O VI is a good tracer of the hot (300,000 K) gas. How is it ionized? How much hot gas is there in the ISM? What drives the kinematics? Many papers on this.

Cold Gas in the ISM: *FUSE* sees H_2 in almost every line of sight. H_2 an important constituent of dense interstellar clouds out of which stars form. Many papers on this.

Cool stars: Magnetic activity, winds, dynamics, flares.

Many other topics: Active Galactic Nuclei, planets, comets, hot star winds, supernovae (e.g. SN1987A), accretion phenomena (TTS, AM Her, black hole disks), end states of stellar evolution, etc.

2 Instrument Description

Spectral range: 905 to 1187 Å observed simultaneously in 8 channels: LiF1A, LiF1B, LiF2A, LiF2B, SiC1A, SiC1B, SiC2A, and SiC2B.

Spectral resolution: $\lambda/\Delta\lambda \approx 15,000$ or 20 km/s.

Effective area: Peak 55 cm^2 at 1050 Å.

Apertures: LWRS (30 x 30 arcsec), MDRS (4 x 20), HIRS (1.25 x 20)

Background flux: About 1×10^{-14} ergs cm^{-2} s^{-1} A^{-1} at night.

Observing modes: TTAG (Time tag) or HIST (histogram)

Comparison: 10^4 times the throughput of the Copernicus satellite.

3 More Information

The website at http://fuse.pha.jhu.edu/ contains much information on the FUSE mission.

The website at http://fusegi.pha.jhu.edu/ contains information for planning and submitting proposals, data archive, target lists, data analysis tools, the FUSE Observers Guide, etc.

Some important publications on FUSE:

- Moos et al (2000) ApJ 538,1.
- Sahnow et al (2000) ApJ 538, 7.
- Moos et al (2002) ApJS 140,3.

4 Spectroscopic Tools of the the Trade

Low Redshift Targets (solar system, Galaxy, Magellenic Clouds, nearby galaxies)

	FUSE (905–1187 Å)	STIS (1150–1μm)
H_2	Lyman electronic bands($\lambda < 1120$)	fluoresced lines (1258–1562)
	Werner electronic bands ($\lambda < 1008$)	–
HD	($\lambda < 1130$)	–
H I	Lβ (**1025**), Lγ (**972**), Lδ (**950**), ...	Lα (**1216**), Balmer lines
D I	**H I lines** –81 km/s	**H I L**α – 81 km/s
He I	**584** (in second order)	subordinate lines
He II	956, 972, 992, 1025, 1085	1640 and other lines
carbon	C I (**many**), C II (**1036**),	C I (**many**), C II (**1335**), C III (1909),
	C III (**977**, 1176)	C IV (**1548, 1550**)
nitrogen	N I (**953, 964, 1134**),	N I (**1200**), N IV] (1486),
	N II (**916, 1085**), N III (**990**)	N V (**1238, 1242**)
oxygen	O I (**many**),	O I (**1302**, 1304, 1306),
	O VI (**1032, 1038**)	O III] (1661, 1666),
		O IV] (1397–1407), O V] (1218)
argon	A I (**1048, 1066**)	–
P	P II (**1125, 1152**), P III (**913, 998**),	P I (**many**), P II (**1301**)
	P IV (**951**), P V (**1118, 1128**)	P III(**1334**)
sulfur	S II (1024), S III (**1012**),	S I (**many**), S II (**1250**)
	S IV (**1062**), S VI (**933–944**)	S III (**1190**), S V (**1199**)
hottest	300,000 K (O VI, S VI)	150,000 K (N V)
	6,000,000 K (Fe XVIII)	10,000,000 K (Fe XXI)

Higher Redshift Targets

Ion	log(T)	λ_o	z(950Å)	z(1100Å)	z(1300Å)
Ne VIII	5.8	770.4	0.23	0.43	0.69
O V	5.4	629.7	0.51	0.75	1.06
Mg X	6.1	625.3	0.52	0.76	1.08
Mg X	6.1	609.8	0.56	0.80	1.13
He I		584.3	0.63	0.88	1.22
He I		537.0	0.77	1.05	1.42
Si XII	6.3	521.1	0.82	1.11	1.49
Si XII	6.3	499.3	0.90	1.20	1.60
Ne VII	5.7	465.2	1.04	1.36	1.79
Fe XVI	6.4	360.8	1.63	2.05	2.60
Fe XVI	6.4	335.4	1.83	2.28	2.88
He II		303.8	2.13	2.62	3.28
Fe XV	6.4	284.2	2.34	2.87	3.57

5 AN IMPLAUSIBLE BUT TRUE TIMELINE

Conception: The first science rationale and rough plan for FUSE presented at a meeting in San Francisco January 4, 1980.

Endorsements: The National Academy of Sciences Astronomy Survey Committees recommended FUSE to NASA as a moderate class mission (1982, 1991).

Early studies: Pre-phase A study (April 1983), Proposal to NASA for a Phase A study (July 1986), Phase A Study Final Report (July 1989).

Joint Mission: Proposal to NASA and ESA for a joint mission called Lyman not accepted (October 1988).

Phase B: Phase B development began January 1990.

Responsibilities: management (Johns Hopkins Univ.; Warren Moos PI), spectrograph (Univ. Colorado; Jim Green), detectors (Berkeley; Ozzy Siegmund), gratings (France), fine guidance sensor and telescope baffles (Canada), science program (The Science Team).

Crisis: Budget for FUSE repriced (cut in half) by NASA (September 1992).

Launch: June 24, 1999 (gestation period 7106 days).

Status: Now all guest observer time. Lost 4 of 6 gyros and can now track with no gyros. Many scientific papers published and being written.

Next due date for observing proposals: September 19, 2003

6 Why are accurate measurements of the D/H ratio important?

A: An accurate measurement of $(\mathrm{D/H})_{prim}$ is probably the best test of theories of the early universe (big bang nucleosynthesis, BBN).

- D was formed only in the very early universe (100–1000 seconds after the beginning). [A few remain unconvinced.] Therefore D is a unique fossil for archaeastronomers to study.
- D is easily destroyed by nuclear reactions in stars (astration). So, $(\mathrm{D/H})_{today} \leq (\mathrm{D/H})_{prim}$. The highest measured value of D/H where there has been no chemical fractionation is the best approximation to $(\mathrm{D/H})_{prim}$.
- $(\mathrm{D/H})_{prim}$ is a very sensitive measure of the density of baryons in the early universe and today
- Metals (e.g., C, N, O) were not formed in the early universe but later by nuclear reactions in stars. Therefore, D/H should be close to $(\mathrm{D/H})_{prim}$ where the metal abundance (Z) is close to zero.

- Is this model basically right?
- Where to find primordial material? Galactic halo? Intergalactic medium? Lyman-α forest clouds towards QSOs? Intergalactic pollution by many very early generation stars ia a potential problem.

B: Measurement of D/H in many regions of the Galaxy is an accurate test of the assumptions underlying Galactic chemical evolution models.

- A major problem in astrophysics is to understand how galaxies form and evolve (cannibalization, structure, chemical evolution).
- Stars form, destroy D, create metals, and return some of this matter to the ISM.
- Hard prediction of theory: D/H will decrease and metal abundances will increase with time. But theoretical models for Galactic chemical evolution rest on many assumptions that measurements of D/H can test. Many of these assumptions are probably wrong.

Deuterium Lyman series line absorption in the warm ISM.
<u>Virtues of this approach:</u>

- In warm clouds ($T \approx 7,000$K) no molecules are present, so no chemical fractionation.
- Percent ionization of H and D the same, therefore D(H I)/N(H I) $\rightarrow$ D/H (they shield each other).
- N(H I) $\sim 10^{18} - 10^{20}$ cm^{-2} and N(H I) $\sim 10^{13} - 10^{15}$ cm^{-2}, so deuterium Lyman-α and higher lines can be studied at –82 km/s from the center of the hydrogen Lyman lines.
- There is a "horizon" for each Lyman line set by the H I column density at which the core of the interstellar H absorption is as wide as 82 km/s: Lyman-α (6×10^{18} cm^{-2}), Lyman-β (4×10^{19} cm^{-2}), etc.

Problems with this approach:

- Confusion: for long lines of sight, too many different velocity components along the line of sight to the target. Can derive $(D/H)_{total}$ but not D/H for each component.
- "Stelth" hydrogen: Low column density clouds of hydrogen that are Doppler shifted with respect to the main interstellar aborption add to the saturated H Lyman line
absoprtion but are not detected in any other spectral lines.

7 What have we learned?

- Within the Local Bubble (out to 100–200 pc from the Sun), D/H probably has a single value (i.e., the local ISM is homogeneous, well mixed).
- Summary of best values of D/H in the Local Bubble,
$(D/H)_{LISM} = \mathbf{15}$ ppm.

D/H Measurements	Published value	Reference
HST (solar-like stars with 100pc)	**15.0±1.0**	Linsky (1998)
FUSE (5 sightlines inside LB)	**15.2±0.8**	Moos et al (2002)
FUSE (D/O and O/H in LISM)	**14.8±1.5**	Moos et al (2002)
FUSE (D/O, solar O/H)	**18.4±2.3**	Moos et al (2002)
FUSE (D/O, solar O/Hx0.80)	**14.7±1.8**	Moos et al (2002)

- D/H measurements beyond the Local Bubble

Star	D(pc)	D/H	Instrument	Reference
BD+28°4211	104	**13.9**±1.0	FUSE	Sonneborn et al (2002)
θ Car	135	**5.0±1.6**	Copernicus	Allen et al (1992)
Feige 110	180	**21.4±4.1**	FUSE	Friedman et al (2002)
γ Cas	188	**11.2±2.5**	Copernicus	Ferlet et al (1980)
λ Sco	216	**7.6±2.5**	Copernicus	York (1983)
γ^2 Vel	258	**21.8±2.0**	IMAPS	Sonneborn et al (2000)
ζ Pup	430	**14.2±1.5**	IMAPS	Sonneborn et al (2000)
δ Ori A	500	**7.4±1.0**	IMAPS	Jenkins et al (1999)
4 QSOs		**30±4**	Keck	O'Meara et al (2001)

- Deuterium astration in the Local Bubble, $(\mathrm{D/H})_{prim}/(\mathrm{D/H})_{LISM} = (30 \pm 0.4)/(15 \pm 1) = 2.0 \pm 0.4$
- Range of D/H in the Galactic disk = **5–22** ppm.
- Range of deuterium astration in the Galactic disk = 1.35–6.0.
- Theoretical estimates of deuterium astration over the lifetime of our Galaxy ≤ 3 (Tosi et al 1998, ApJ, 226). But the models have some questionable assumptions:
  - Initial Galaxy has primordial D/H and no metals.
  - Stars form, destroy D, and create metals.
  - Stars lose D-depleted and metal-enriched gas through winds and supernovae.
  - New stars form from the modified gas.
  - Primordial (or almost) rains down on the galactic disk from the halo.
  - Each ring of the Galaxy (several kpc wide) is well mixed but no mixing with other rings.

- Results in D/H(r,t), Z(r,t) for each ring and time step.

- If the D/H results beyond the Local Bubble are valid, the Galactic chemical evolution models are overly simplified.
- The next generation of Galactic chemical evolution models must include episodic star formation (star bursts) with rapid mass loss and supernovae events and realistic mixing scenarios.
- Since D/H and metal abundance should be anti-correlated, why do the D/H vs O/H results not show this?
- Baryons in the Universe
  - $(\mathrm{D/H})_{prim} \approx (\mathrm{D/H})_{QSO} = \mathbf{30}$ ppm is consistent with the primordial abundance of He and ^{7}Li.
  - $\eta = (5.5 \pm 0.5) \times 10^{-10}$.
  - $\Omega_B = 0.041 \pm 0.009$
  - Big bang nucleosynthesis theory looks basically right.