The Far Ultraviolet Spectroscopic Explorer Legacy

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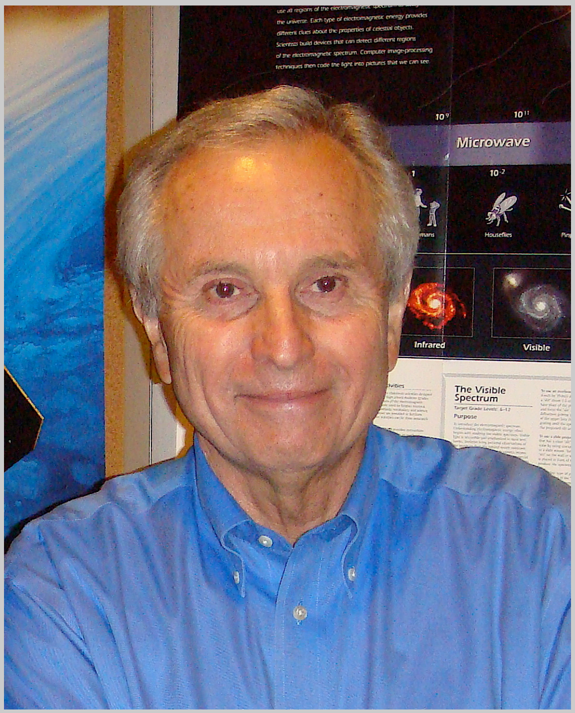
FUSE Mission Summary

- NASA Explorer mission with Canadian (CSA) and French (CNES) participation.
- 905 - 1187 Å spectroscopy ($\lambda/\Delta\lambda$~20,000)
- Launched June 24, 1999
  - 765 km altitude orbit, incl=25^{o}
  - Science operations: Dec 1, 1999 to July 12, 2007
  - Decommissioned Oct 18, 2007 following failure of last reaction wheel
  - 65 Ms of science time obtained
- Since 1995, developed and operated as a PI-Class Mission led by the Johns Hopkins University.
  - FUSE PI: Dr. Warren Moos
  - Flight and science operations, engineering, and project management at JHU
  - Key instrument components from University of Colorado Boulder and University of California Berkeley
- Guest Investigator program awarded >50% of time first 3 years, 100% thereafter

FUSE Mission Summary



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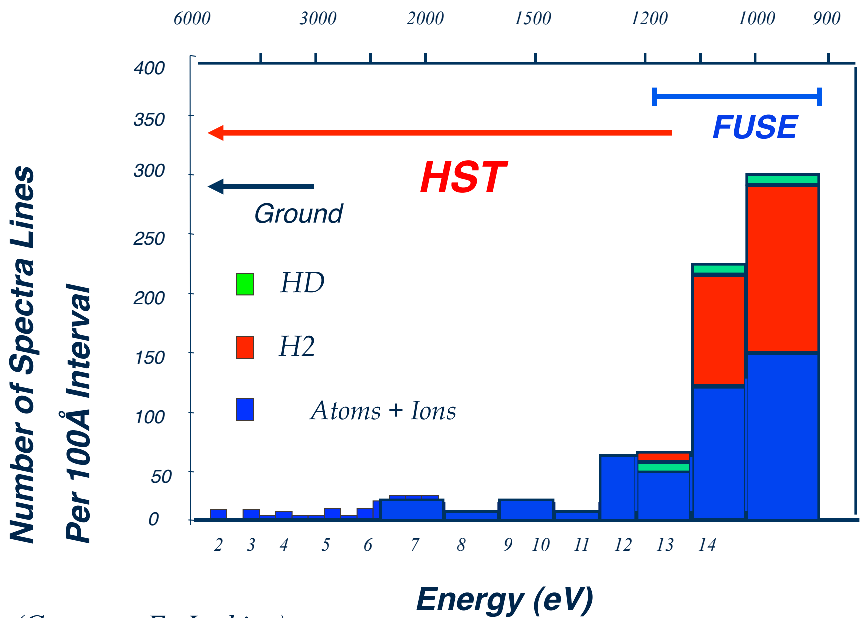
Why This Spectral Region?



(Courtesy E. Jenkins)

Known for decades:

Large number of strong transitions, many unique to FUV

H I & D I Lyman transitions except Ly α

O VI λλ 1032-38 (T ≥ 3x10^5 K)

S VI λλ 933-45, P V 1118-28

Strong electronic transitions of H_2 & HD

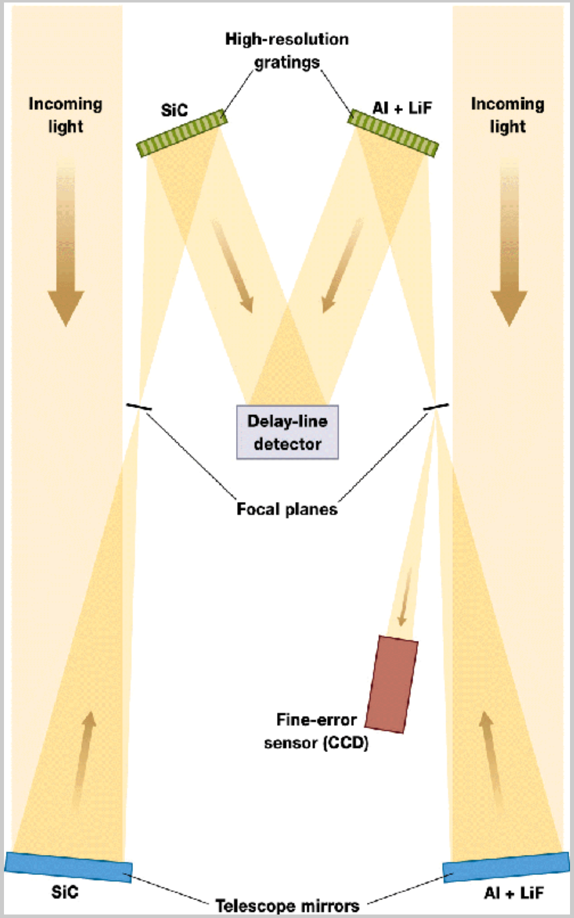
Temperature & ionization diagnostics (C I-III, N I-III, Ar I, Fe II-III,)

New since FUSE launch:

Many high-ionization lines seen in stellar spectra for first time by FUSE

- **powerful diagnostics of T and nucleosynthesis in very hot stars**
- **Ne VII, Ne VIII, Fe VI-X, Ni VI, Ar VII – VIII, Ca X, etc**

FUSE Satellite and Instrument



- FUSE: 1330 kg, 5.4 m tall
- 4-channel Rowland circle spectrograph design
  - **Inspiration for COS**
- 905 – 1187 Å
- $\lambda/\Delta\lambda$ ~ 20,000 (pt source)
- Optical coatings optimized for far-UV
  - 2 channels LiF (>1000 A)
  - 2 channels SiC (<1000 A)
- Double delay line MCP detector, KBr photocathode
- ~ 1 arcsec pointing

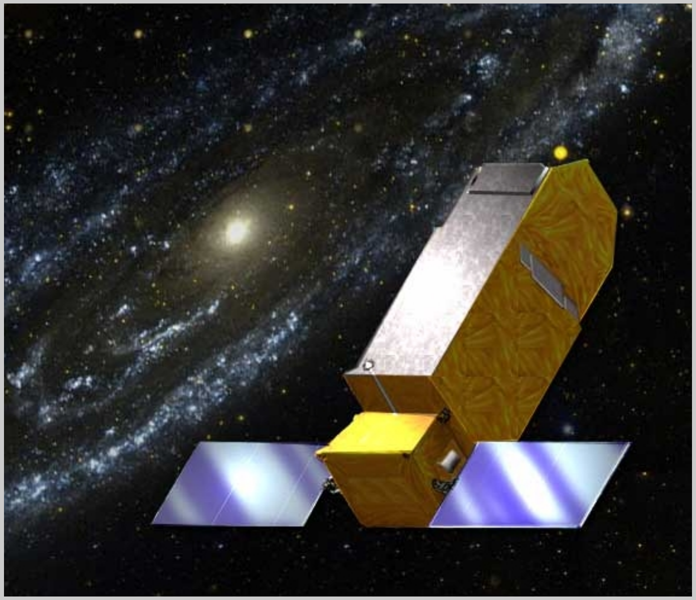
Science and Flight Operations

- Satellite Operations Center at JHU Physics and Astronomy Building
  - Satellite command and control
  - Science operations
  - Co-located science and engineering staff
- Dedicated ground station at Univ. Puerto Rico - Mayaguez. 6 to 7 contacts/day.
- Satellite autonomy important
  - Event-driven onboard script system to execute the observing timeline
- Observed about three targets per day
  - Average observation time ~11 ksec
- Low-earth orbit ➔ Complex timeline, target occultation for ~35 min every 100 min, reacquisition each orbit.
- Observing efficiency 30-40%

FUSE By the Numbers

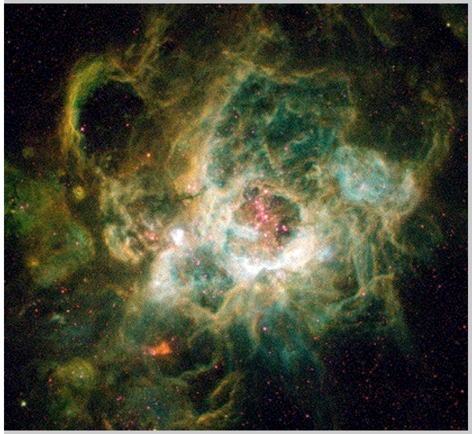
- 694 observing programs covering broad scientific range
  - 557 GI Programs
  - 106 FUSE PI Team programs
  - 31 other
- 263 unique observing program PIs, 750 unique investigators
- 5500 observations on ~2800 unique objects.
  - 41,000 individual exposure data sets (spectra) available through MAST at STScI
- 65 Msec of on-target exposing time
  - 34 Msec GI Program targets
  - 13 Msec PI Team targets
  - 18 Msec other (Discretionary, sky background, etc)

- 575 refereed scientific papers (through May 2012)
- 1544 total publications
- 39 PhD dissertations



From planets to quasars (and everything in between)

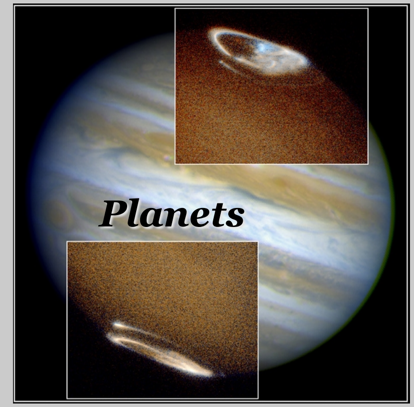
FUSE STUDIED A BROAD RANGE OF ASTROPHYSICS



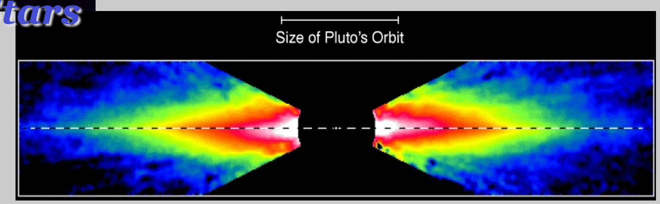
Hot Stars and Nebulae

Active Galaxy Nuclei

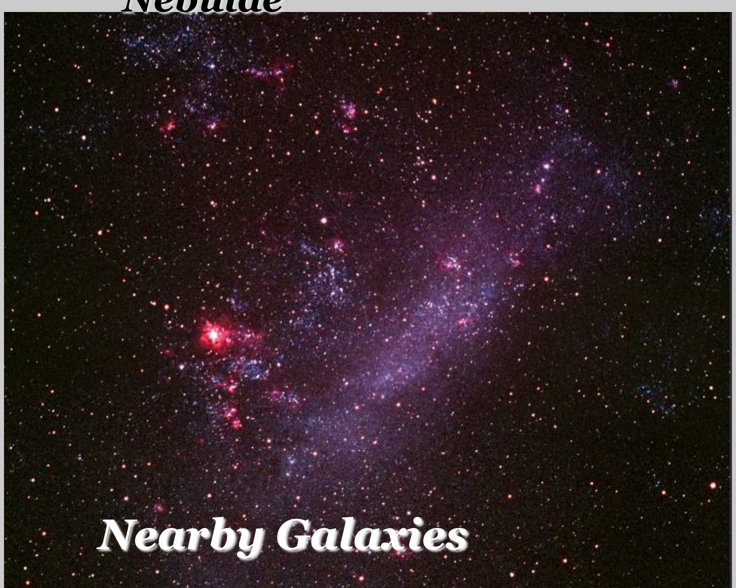
Planetary Nebulae & Central Stars



Planets

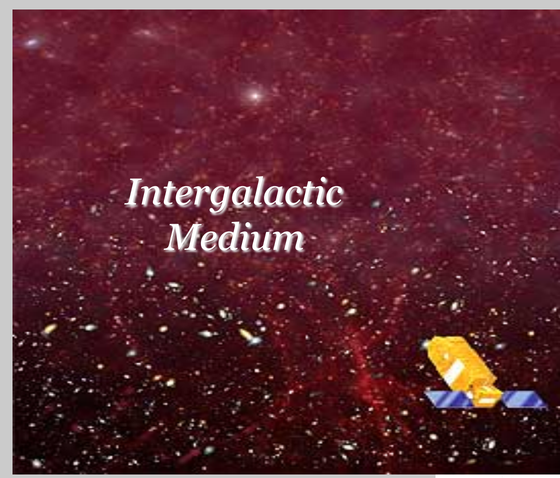


Circumstellar Disks



Nearby Galaxies

Supernova Remnants



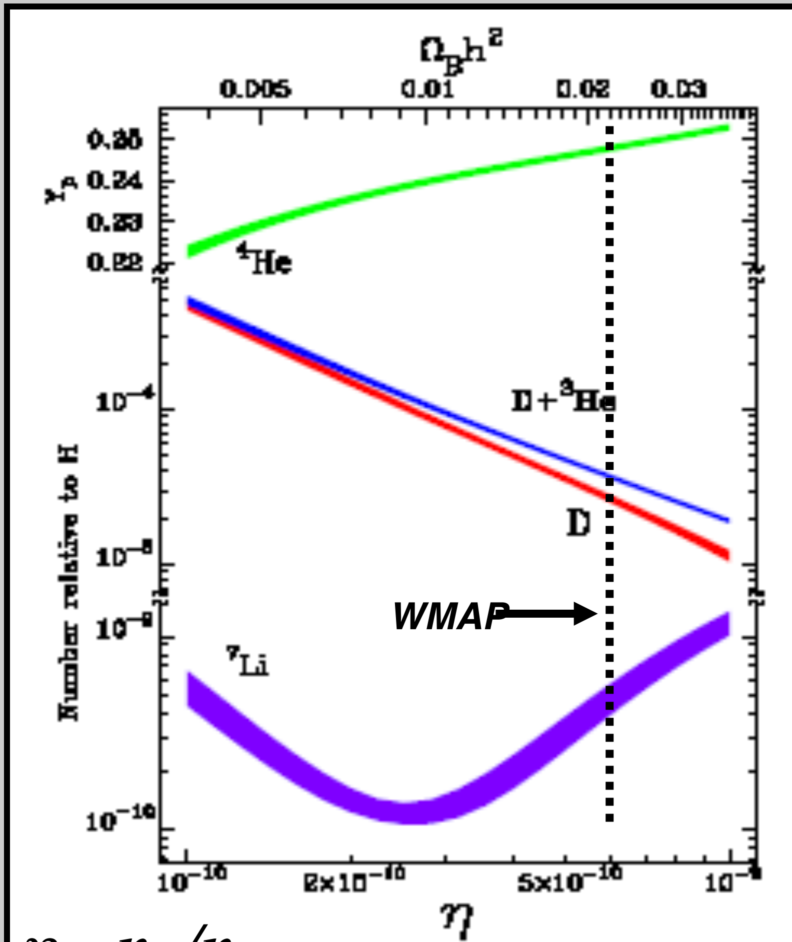
Intergalactic Medium

FUSE enabled major advances in virtually every field of astrophysics

- Properties of interstellar gas across 4 dex in temperature, 8 dex in column density, 6 dex in distance, and 3 dex in metalicity
- Atmospheres and outflows of stars across the HR diagram, in the Milky Way and Magellanic Clouds
- Intergalactic medium
- Galactic nuclei and outflows
- Proto stars and circumstellar disks
- Supernova remnants, planetary nebulae, and other end stages of stellar evolution
- Planets, satellites and comets

Deuterium

- D is the most sensitive indicator of Ω_B among the light elements created in the Big Bang.
- D is destroyed inside stars and there are no known significant sources of D other than the Big Bang. Thus, **D/H in the Milky Way provides a lower limit to the primordial value.**
- York & Rogerson (1976) found D/H varied from 6 to 25 ppm for 5 sight lines. Was this variability real? Controversial for over 20 years.
- **Reliable measurement of D/H in the Galaxy was the scientific problem behind the FUSE mission.**

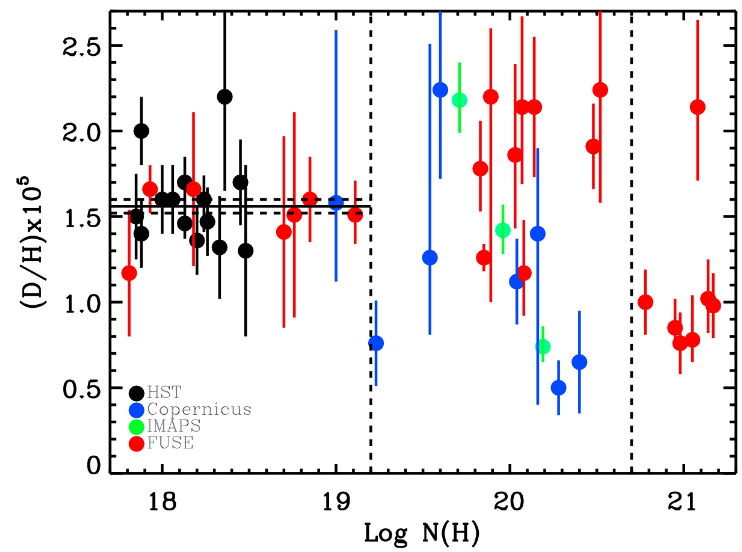


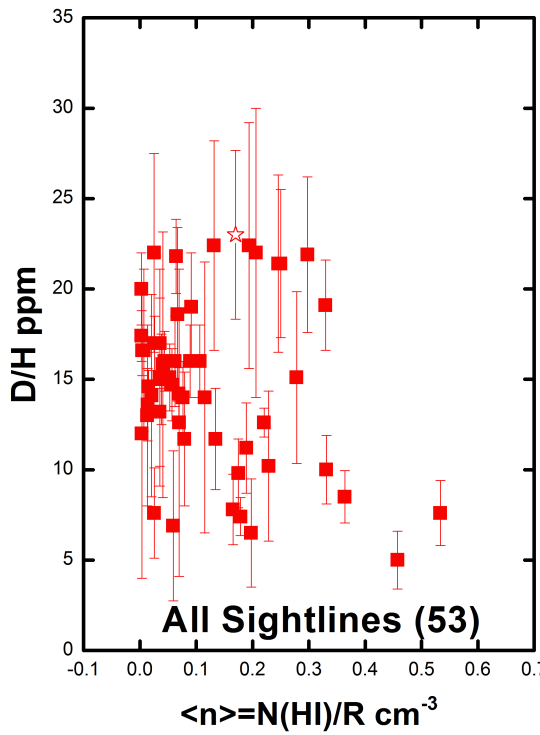
$\eta = n_N / n_\gamma$

Burles, Nollett & Turner 2001

Deuterium

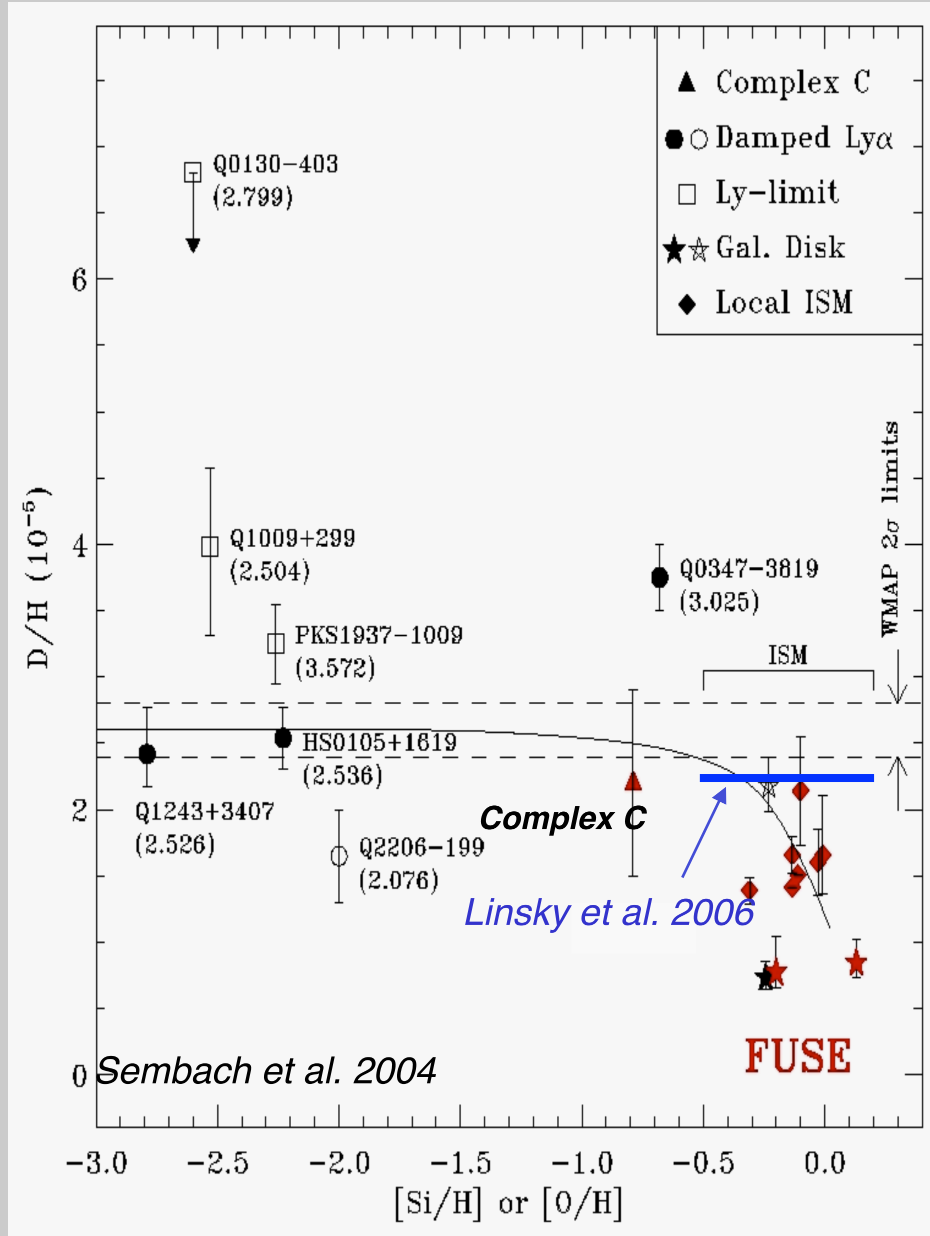
- A large number of measurements by space missions (Copernicus, HST, IMAPS, and especially FUSE and WMAP) shows:
  - D/H in the Local Bubble = 15 ppm.
  - **Beyond 100 pc D/H ranges from 4 to 22 ppm. Highly variable.**
  - **Primordial D/H=26 ppm (WMAP + Big Bang Nucleosynthesis)**
- **The largest values (≥22 ppm) represent the Total D/H in the Milky Way**. (Linsky, Draine Moos et al. 2006)
- Astration of ISM gas is low. New models of chemical evolution agree. (Romano et al. 2006).
- **Further underpinning of WMAP results.**





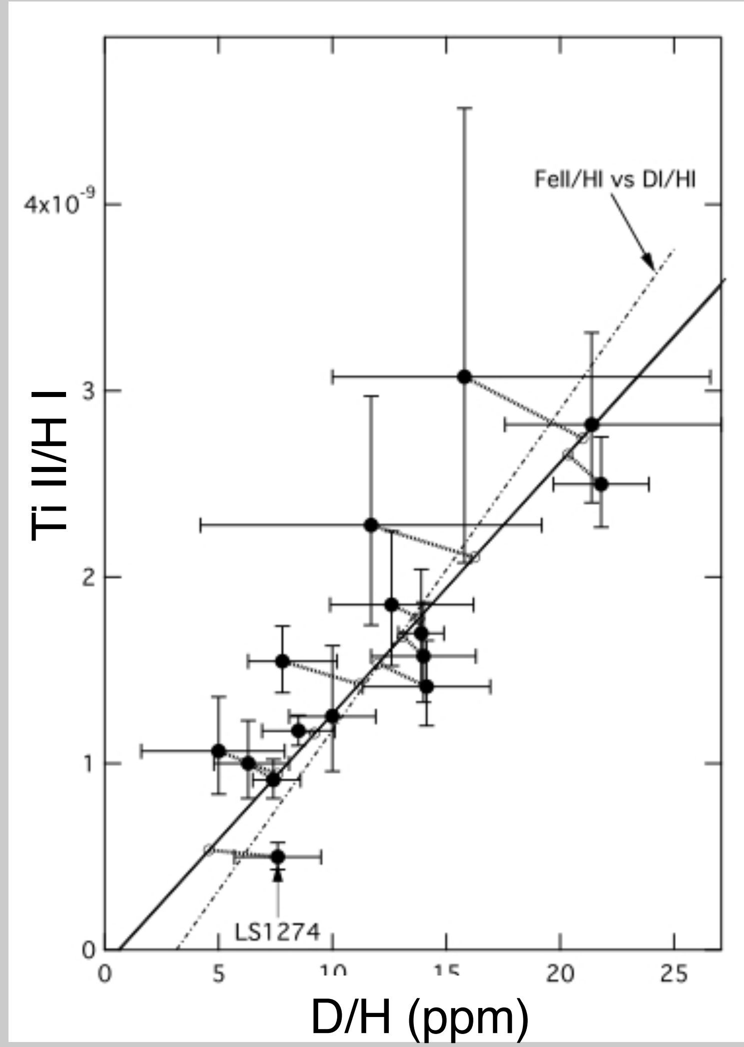
Deuterium

- Highest D/H found in intergalactic medium (IGM), but with very large scatter.
  - Overall, consistent with WMAP
- Complex C is a low metallicity cloud falling onto the Milky Way, with D/H = 22±7 ppm (Sembach et al. 2004)
  - Consistent with processing intermediate between IGM and the Milky Way disk.
- <u>D/H in Milky Way disk's interstellar medium is lower than the IGM, but highly variable.</u>



Why is D/H so variable?

- O/H much less variable than D/H
- Correlation of D/H with metal depletion (SI, Fe, Ti)
- **D is depleted onto dust grains**
- Draine (2005, 2006) ΔE=0.083 eV
  - Carbonaceous interstellar grains, polycyclic aromatic hydrocarbons (PAHs), are a possible repository for D.
- D-rich or D-poor gas is injected to the disk in an inhomogeneous manner
  - Extragalactic infall (D-rich) or processed gas ejected by stars



Lallement et al. 2008

Can D/H understanding be improved?

- FUSE PI Team studied over 600 lines of sight to OB stars and white dwarfs as potential targets for the D/H program.
- Only several dozen were promising. The yield for the more distant sight lines was particularly low.
  - Complex structure and intervening blue shifted H I eliminated most
- Many lightly-reddened OB stars were too bright for FUSE.
  - There are many nearby (100 pc < d < ~1kpc) hot stars that could be observed in the future, filling in the “FUSE hole” (~19.0 < log(N(HI)) < ~19.8).
- FUSE made one measurement of D/H in a high velocity cloud; additional HVCs are needed to determine the range of D/H in infalling gas
- D/H in the LMC and SMC cannot be done because their radial velocity puts D at the same velocity as foreground MW H I
  - D/H in M31 or Local Group dwarf galaxies would be very interesting

O VI

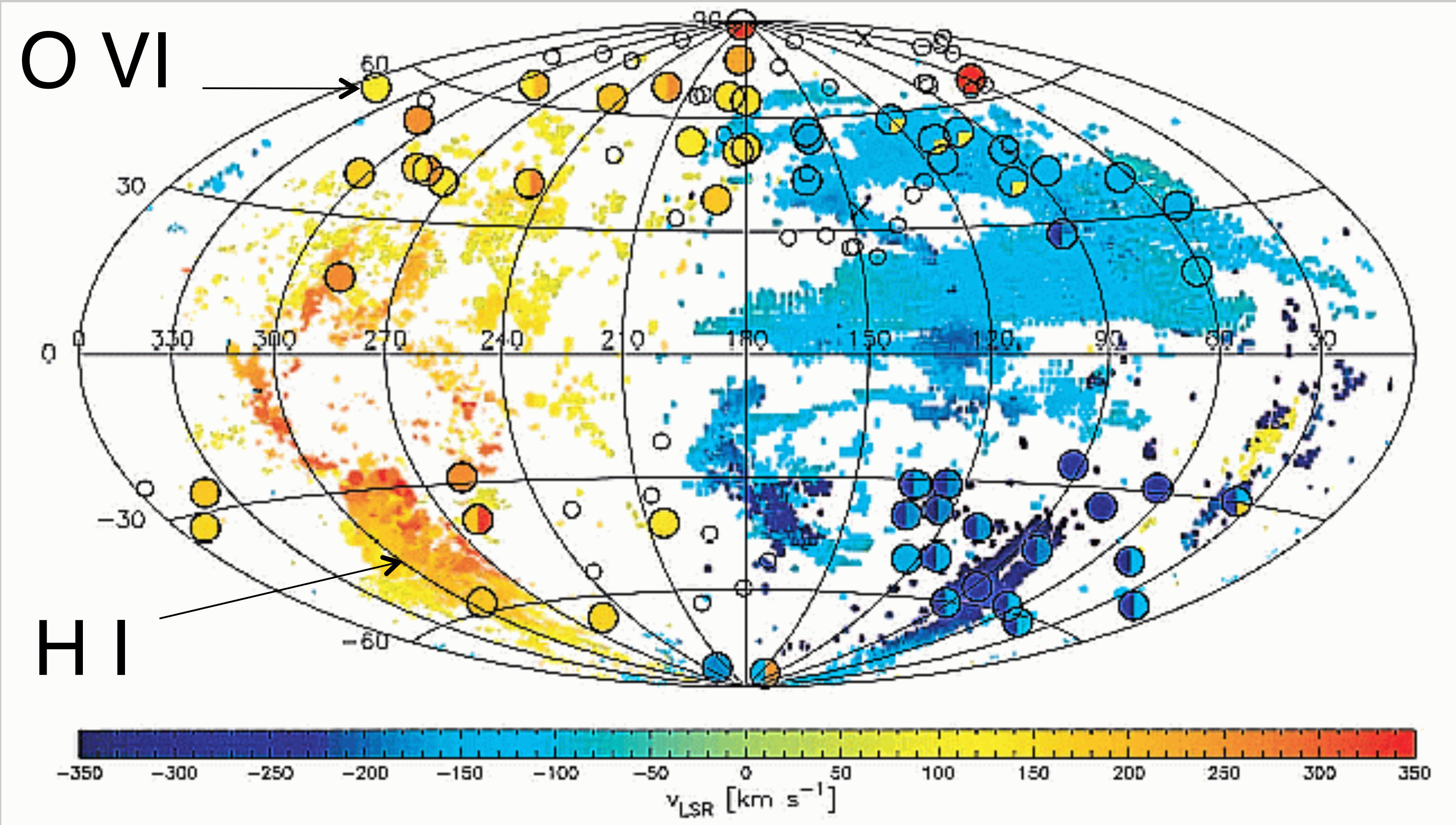
O VI in the Milky Way and Beyond

- O VI resonance lines have become a powerful diagnostic in virtually every branch of astronomy.
  - A powerful tracer of ionized warm-hot gas, ≥300,000 K
  - Diffuse gas, stellar winds, accretion disks, hot stars, shocks
  - ~40% of FUSE refereed papers mention O VI in the abstract
- Systematic study of O VI absorption was a major use of FUSE observing time, e.g.:
  - Local Bubble Oegerle et al. 2005, Barstow et al 2010
  - Hot ISM in Milky Way Disk Bowen et al. 2008
  - Milky Way halo {survey Wakker et al., halo ISM Savage et al., high-velocity gas falling into halo Sembach et al. 2003}
    - Absorption+emission → plasma density measured for a halo sightline Dixon & Sankrit 2008.
  - Intergalactic medium Danforth & Shull 2005, 2007
- **Any future UV mission needs to include wavelength coverage down to 1000 Å.**

Discovery of the Milky Way Corona

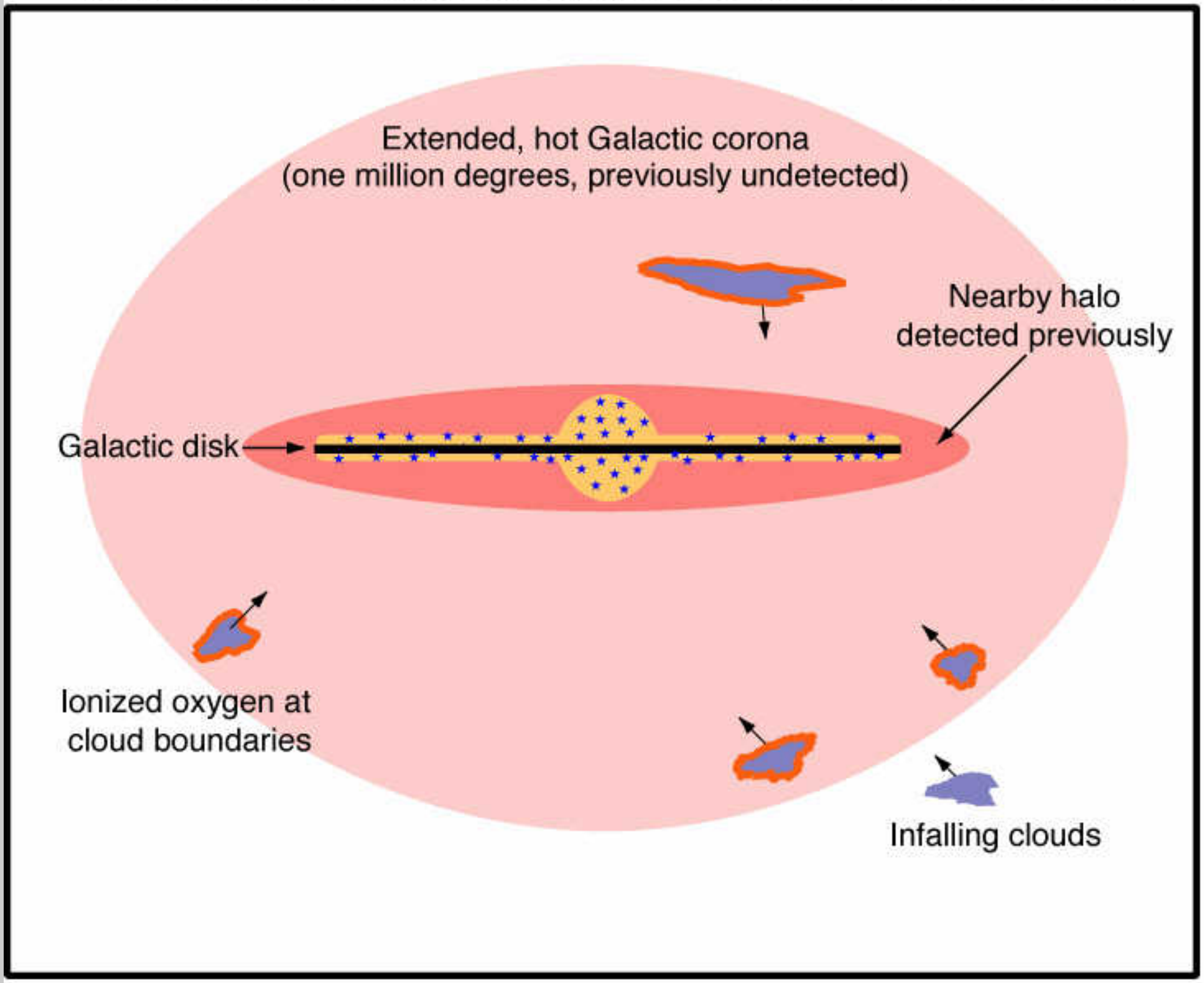
- A spectacular discovery from the FUSE mission – many high-velocity O VI absorbers distributed all over the sky.
- O VI absorbers associated with H I high-velocity clouds implies that O VI is at cloud interface with a hot, very low density medium
- **FUSE discovered a hot corona around galaxy to ~70kpc** **Sembach et al. (2003)**
- Used survey of 100 extragalactic objects + 2 distant halo stars.
  - Dedicated issue of ApJ Supplement
- Observe material ejected from the disk as well as IGM gas from galactic group. Traces tidal interactions with LMC & SMC.
- In high halo, distances > 10 kpc, infalling high-velocity ionized gas clouds, v> 100 km/s, over ~ 70% of the sky.

High-Velocity Clouds Observed in O VI



Sembach et al. (2003)

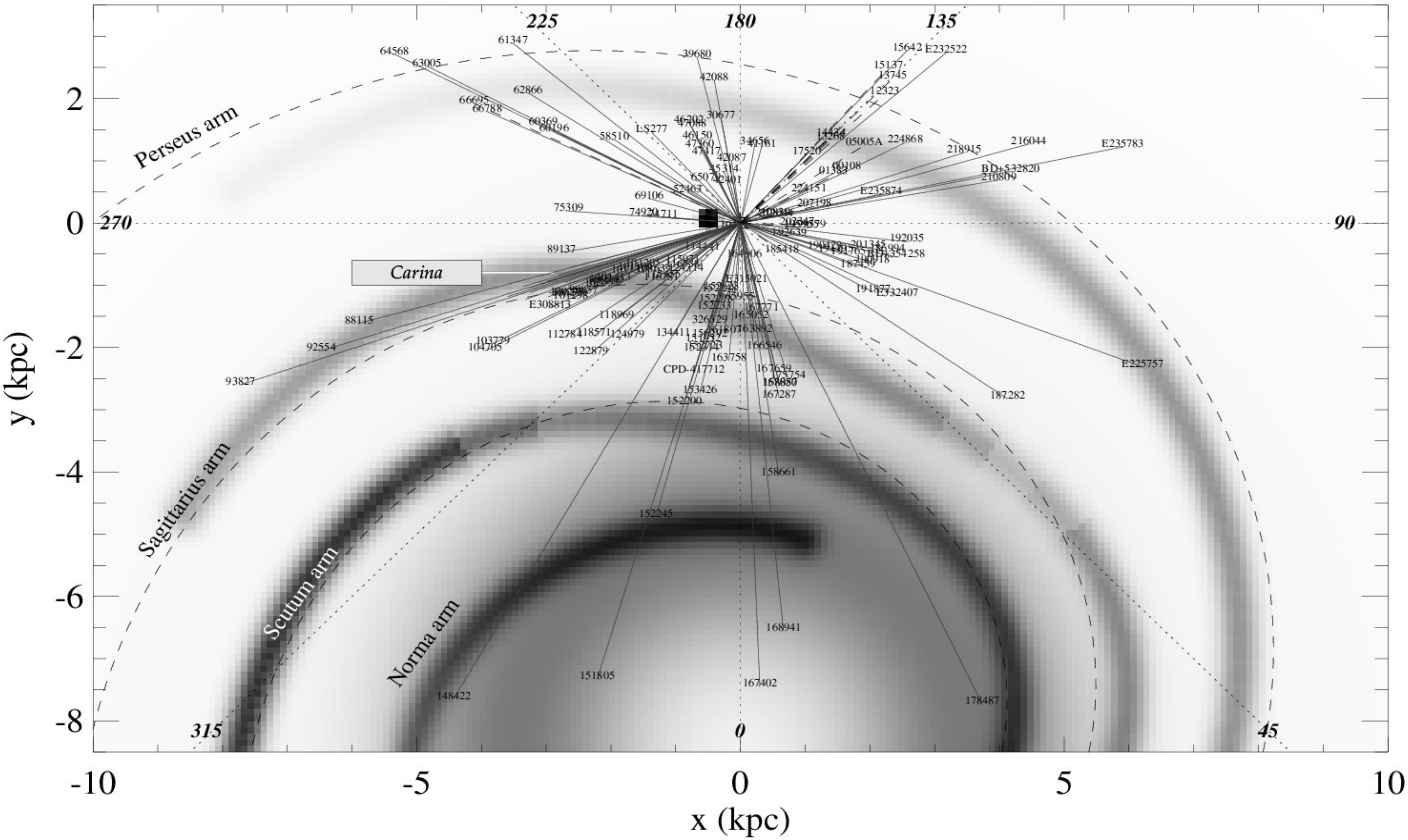
Infalling Clouds Light Up and Reveal Hot Galactic Corona



This illustration shows clouds falling onto our galaxy, the Milky Way. These clouds "light up" in ionized oxygen when they encounter the hot, extended corona of gas that surrounds the Milky Way.

Galactic Disk O VI Survey - 148 sightlines

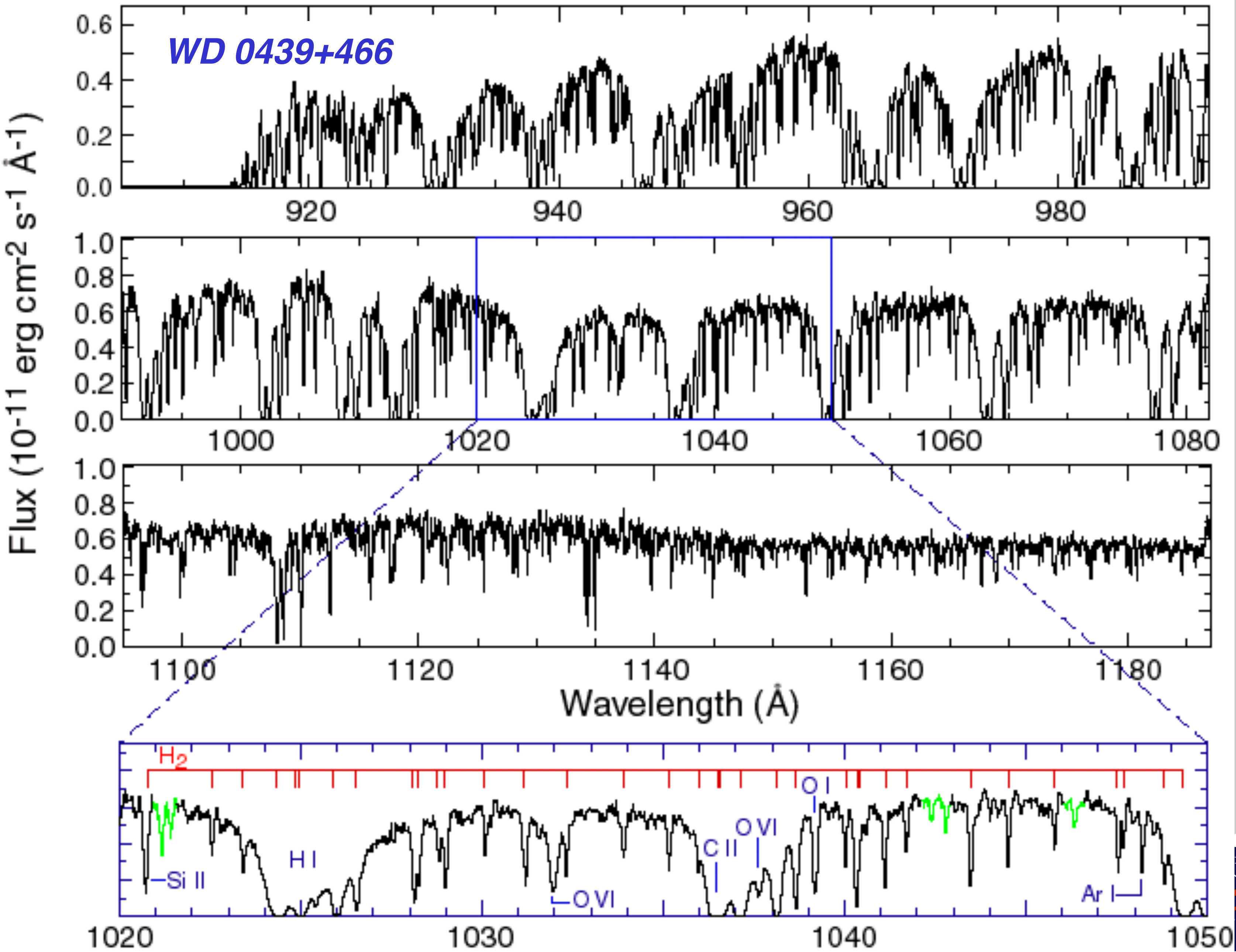
Bowen et al 2008



Conclusions of the O VI Disk Survey

- O VI is ubiquitous throughout the disk of the Galaxy
- O VI density declines with |*z*|, but dispersion of data much larger than expected for a smooth ISM
- Contribution of O VI from (X-ray emitting) hot bubble of a target star is small
- *N*(O VI) correlated with distance, so interstellar, and multi-component origin.
  – but dispersion is large, and doesn't follow what's expected for intercepting identical clouds
- **The O VI gas traces a hot, turbulent multi-phase medium churned by shock-heated gas from multiple supernova explosions.**

TYPICAL FUSE INTERSTELLAR SPECTRUM



H_2: the Ubiquitous Molecule

FUSE found H_2 in diverse places, including:

The Galactic disk and halo *Shull et al. 2004; Gillmon et al. 2004; Wakker 2006; Burgh et al. 2007*

Translucent clouds *Rachford et al. 2009*

Intermediate velocity clouds (IVCs) *Richter et al. 2003*

The Monoceros Loop SNR *Welsh et al. 2002 – re-formed H_2 post-shock?*

Planetary nebulae *McCandliss et al. 2007*

Circumstellar disks *Martin-Zaïdi et al. 2008*

High-velocity clouds *Sembach et al. 2002 – suggests HVCs have dust*

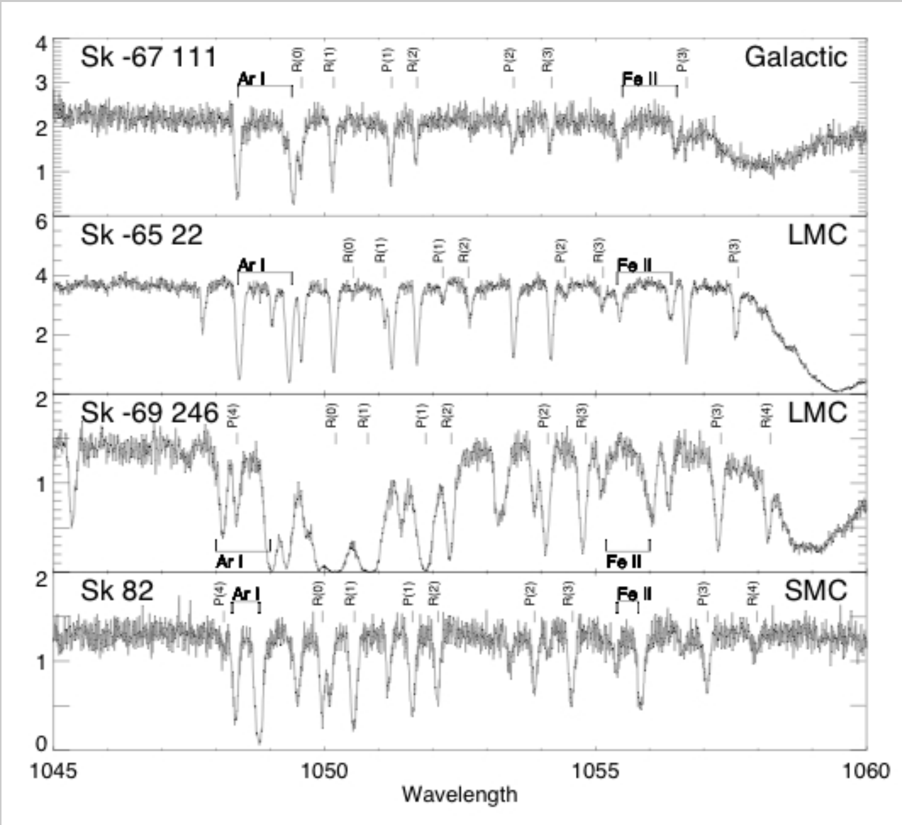
The Small and Large Magellanic Clouds *Tumlinson et al. 2002; Bluhm & de Boer 2001*

The Magellanic Stream and Bridge *Sembach et al. 2001; Lehner 2003*

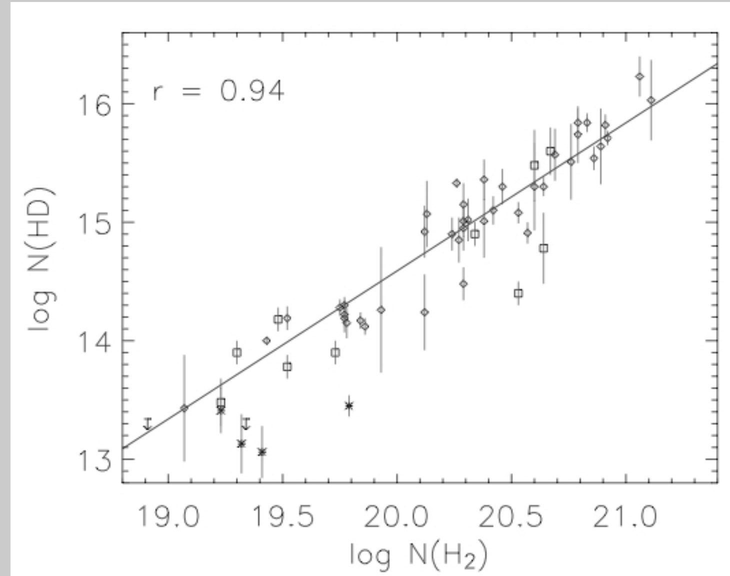
The Local Group spiral galaxy M33 *Bluhm et al. 2003*

These surprising results mean that H_2 can be used as a sensitive indicator of local physical conditions.

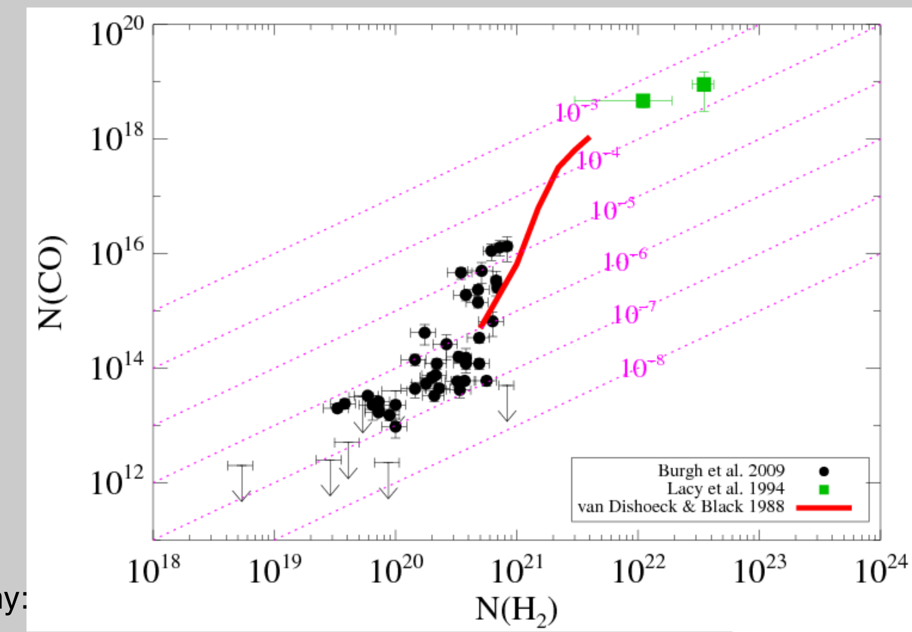
Survey of H2 in LMC
Tumlinson et al 2002



Survey of HD in Milky Way
Snow et al 2008



CO/H2 structure of interstellar clouds
Burgh et al. 2009



First Detection of H_2 on Mars
(Krasnopolsky & Feldman 2001)

- Observed line strength (0.15 Rayleighs) corresponds to a H_2 mixing ratio of 15±4 parts per million in the lower atmosphere.
  - Previous attempts to detect H_2 resulted only in upper limit (1.5 R, Mariner 9, W. Moos)
- H_2 and HD mixing ratios agree with photochemical fractionation of D between H_2O and H_2
- Photochemical model for Martian atmosphere combined FUSE (H_2), HST (D I Ly-α), and MGS/MOLA (polar ice cap volume), and ground IR data (HDO/H_2O)
- Analysis of deuterium fractionation shows Mars has lost a global ocean of water more than 30 meters deep
  - Only 4% of accreted H_2O remained after hydrodynamical escape
  - Mars could have had even more water per unit mass than Earth

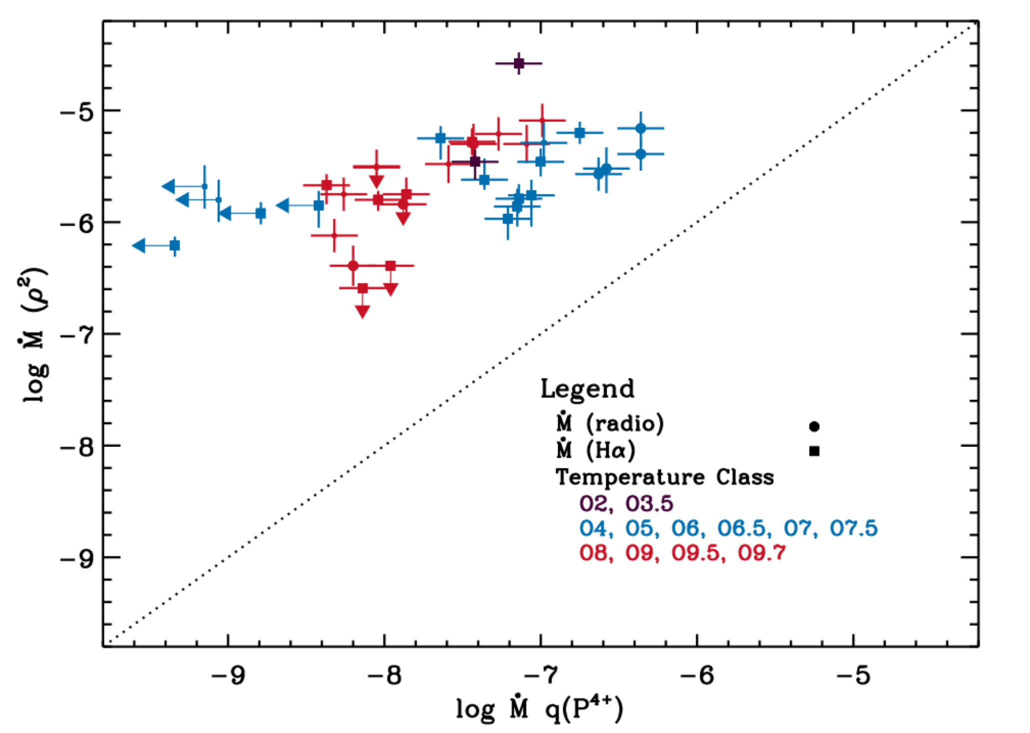
Top 10 Most Cited FUSE Scientific Papers

1.	Sembach et al. 2003	Highly Ionized High-Velocity Gas in the Vicinity of the Galaxy
2.	Fullerton et al. 2006	Discordance of Mass-Loss Estimates for Galactic O-Type Stars
3.	Crowther et al. 2002	Revised Stellar Temperatures for Magellanic Cloud O Supergiants from FUSE and VLT Spectroscopy
4.	Bouret et al. 2005	Lower mass loss rates in O-type stars: Spectral signatures of dense clumps in the wind of two Galactic O4 stars
5.	Savage et al. 2003	Distribution and Kinematics of O VI in the Galactic Halo
6.	Tumlinson et al. 2002	FUSE Survey of Interstellar H2 in the SMC & LMC
7.	Hillier et al. 2003	A Tale of Two Stars: The Extreme O7 Iaf+ Supergiant AV 83 and the OC7.5 III((f)) star AV 69
8.	Moos et al. 2002	Abundances of Deuterium, Nitrogen, and Oxygen in the Local ISM: Overview of First Results from the FUSE Mission
9.	Wakker et al. 2003	FUSE Survey of O VI Absorption in and near the Galaxy
10.	Crowther et al. 2002	Stellar and wind properties of LMC WC4 stars. A metallicity dependence for Wolf-Rayet mass-loss rates

O Star Mass Loss Rate Discrepancy

Fullerton, Massa, & Prinja (2006)

- P V 1118-28 A profiles of O stars require mass loss rates 2-4X <u>lower</u> than previous work
- FUV resonance lines P V, S IV, S VI, N III in addition to O VI, have had a major impact on massive star astrophysics
  - Affects models of stellar evolution
- P V and S IV, in particular
  - Low cosmic abundance
  - Unsaturated P Cygni line profiles
- Stimulated very significant theoretical and observational programs

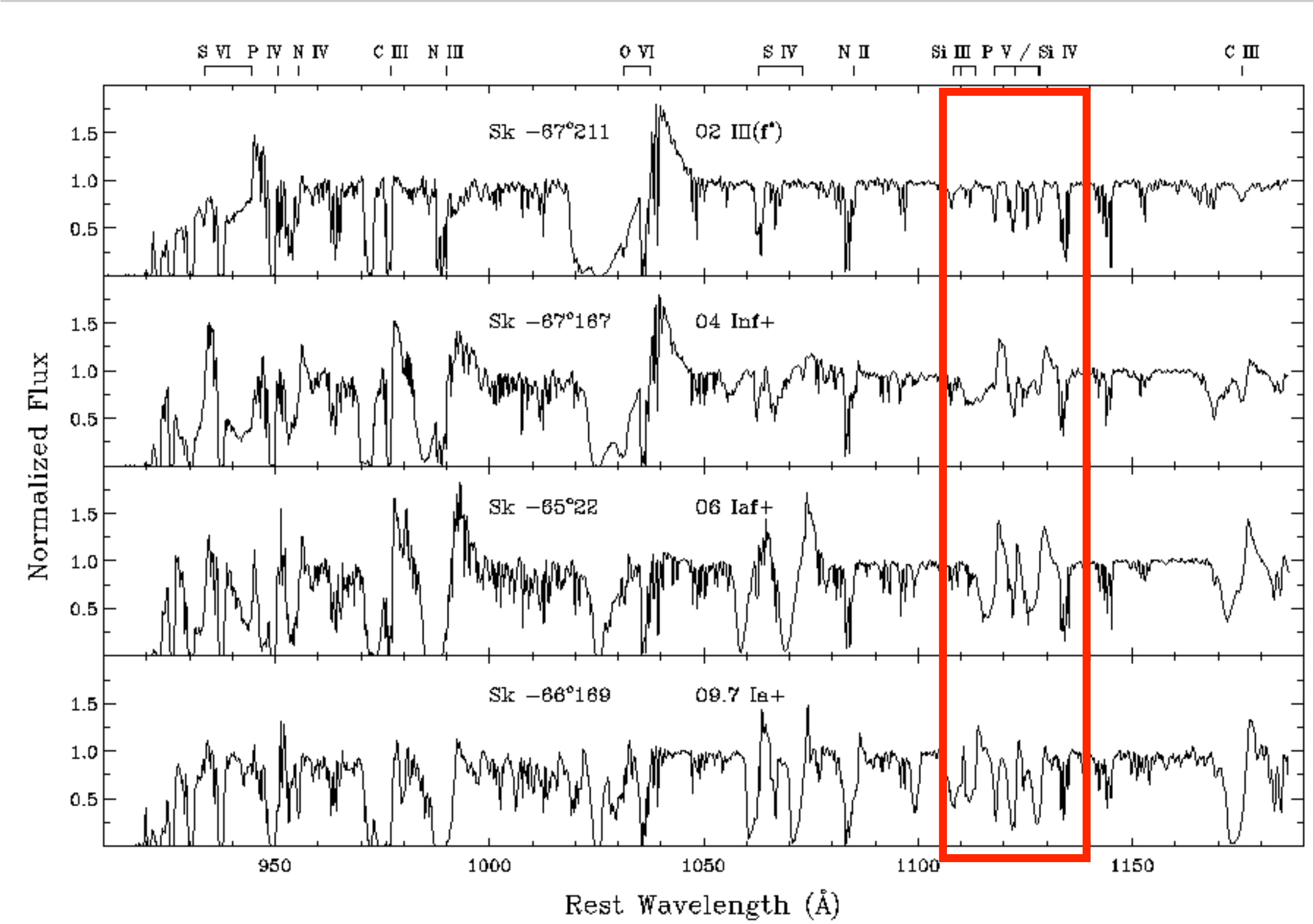


Thermal radio emission: free-free $\propto \rho^2$

Hα emission: recombination $\propto \rho^2$

UV resonance lines: scattering $\propto \rho$

The Power of P V



Walborn et al., 2002 , ApJS, 141, 443

O2

O4

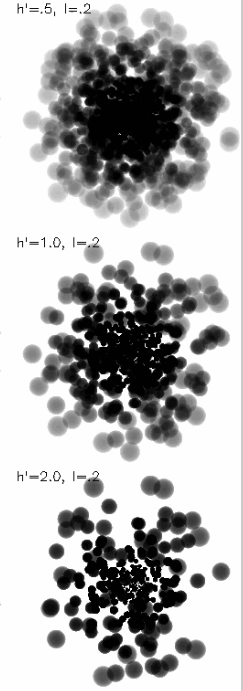
O6

O9.7

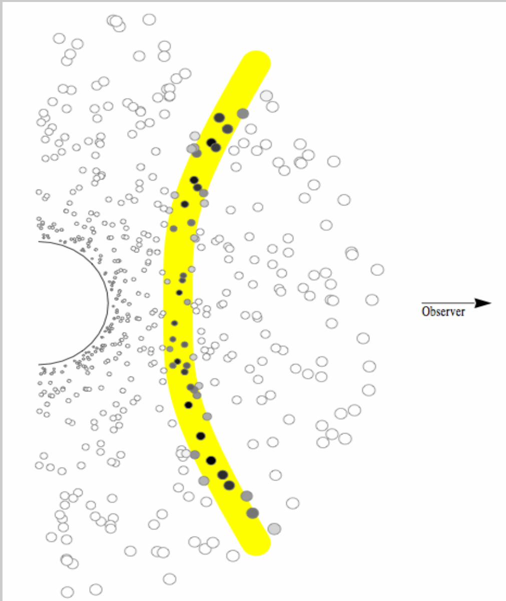
- Low cosmic abundance of P
- Unsaturated P Cygni profiles

- Derive product of mass-loss rate and ion fraction

- Not directly affected by distribution of optically thin clumping



Porosity

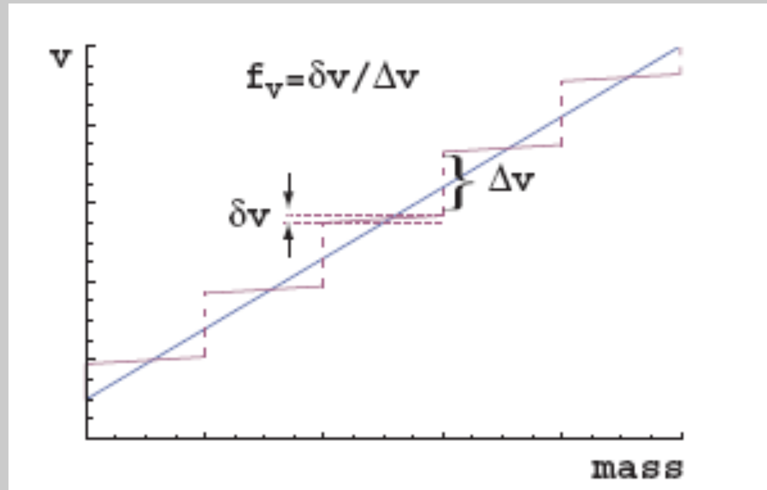


(e.g. Oskinova et al. 2007)

- If clumps are optically thick, their geometrical distribution is important.
- The wind becomes more transparent from 'holes' and the effective line-opacity is reduced.
- → 'true' mass-loss rates from PV lines may be higher than suggested by line-analyses neglecting this effect.

'Vorosity' (velocity porosity)

Owocki (2007) → extend the porosity formalism → account for a 'clumped' velocity field.

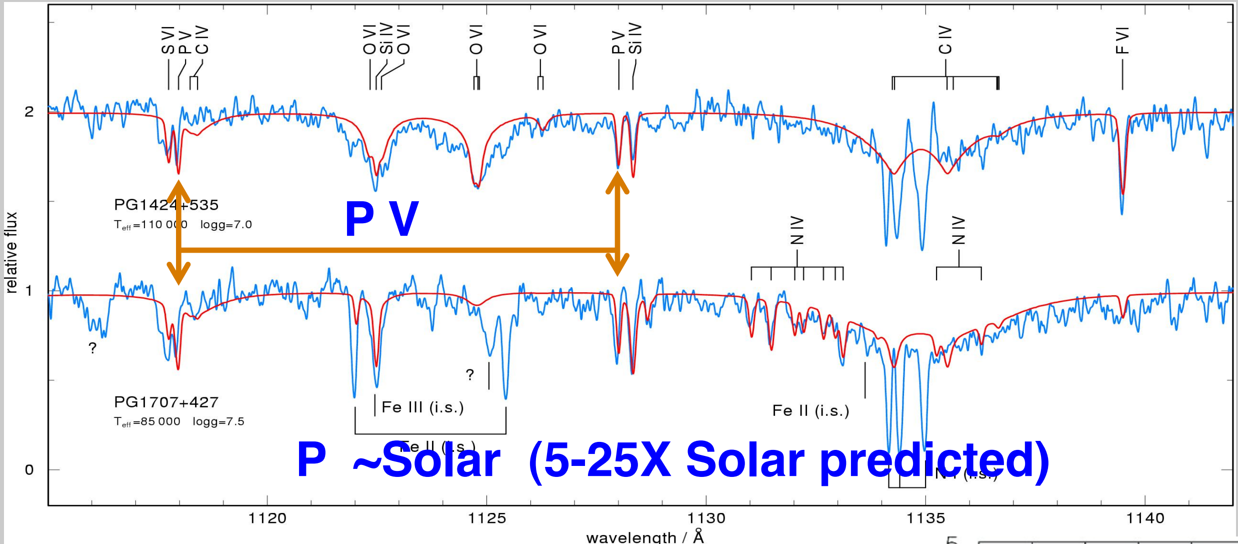


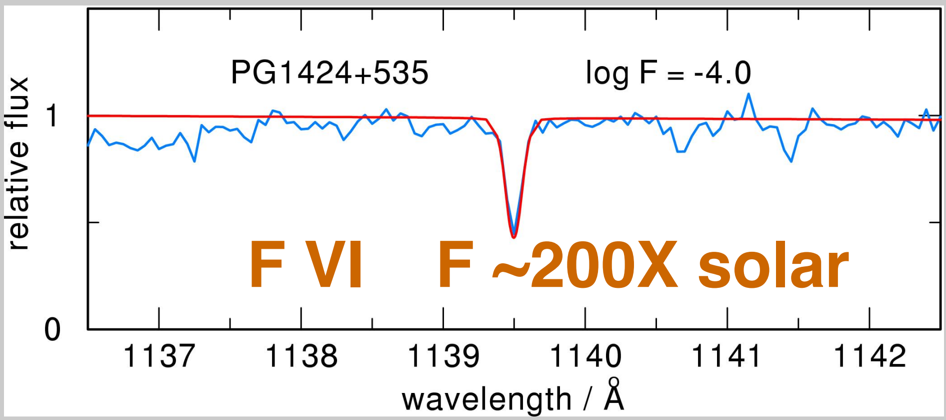
Initial results → reduces the line-absorption, but would not remove the 'PV problem' entirely.

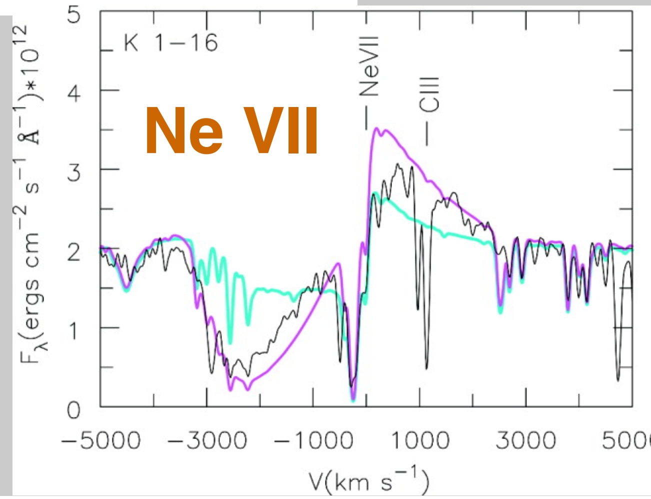
Effects from porosity and vorosity on the derived mass-loss rates still remained to be established

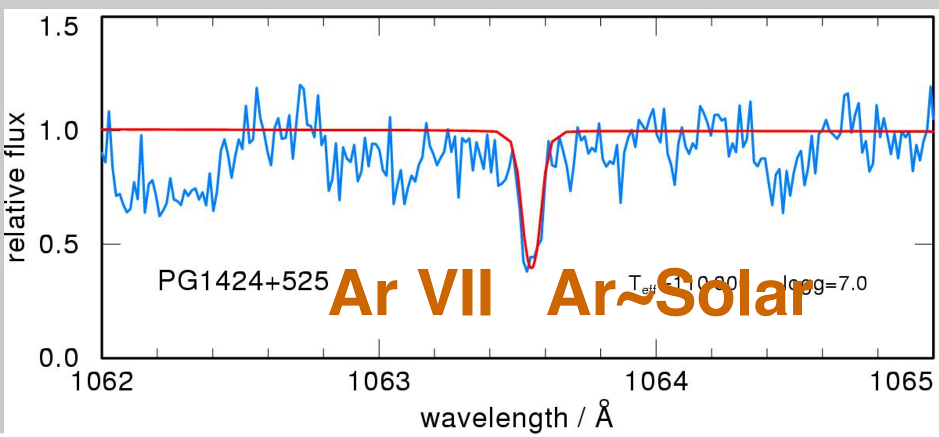
Nucleosynthesis in Post-AGB stars
(T > 100,000 K)

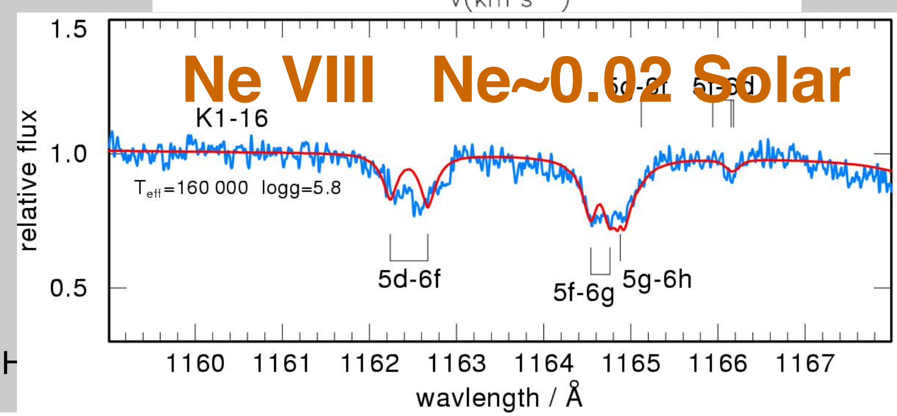
- Atmospheres are composed of former AGB-star intershell material (formed between He and H burning shells) and dredged up to surface
- Byproducts of late-stage nucleosynthesis observed in FUV
- Observed abundances represent a strong test for stellar models and predicted metal yields
- Abundances of many atmospheric constituents (He, C, N, O, F, Ne, Ar, (Fe)) are now in agreement with stellar evolution and nucleosynthesis models
  - Werner, Rauch, Kruk et al (2002, 2007, 2008, 2010)
  - Many of these features identified for first time in stellar spectra by FUSE
- But **some elements point at significant flaws in models:**
- Strong depletion (1% Solar) of S and Si in some objects is a serious problem. Solar abundance of P is another. Perhaps Fe


S VI P V C IV
O VI Si IV O VI
O VI
O VI
P V Si IV
C IV
F VI
PG1424+535
T_eff=110 000 logg=7.0
P V
N IV
N IV
PG1707+427
T_eff=85 000 logg=7.5
Fe III (i.s.)
Fe II (i.s.)
P ~Solar (5-25X Solar predicted)
relative flux
wavelength / Å


PG1424+535
log F = -4.0
F VI F ~200X solar
relative flux
wavelength / Å


K 1−16
NeVII
CIII
Ne VII
V(km s−1)

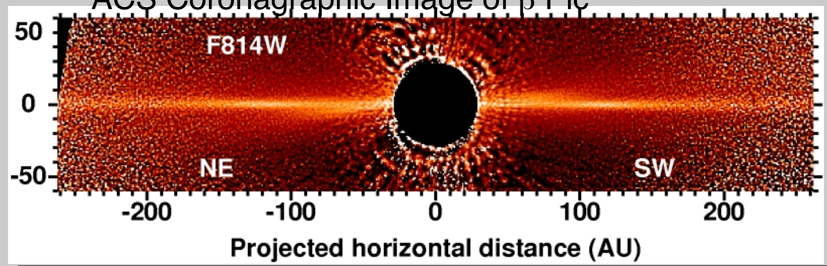

PG1424+525
Ar VII Ar~Solar
logg=7.0
relative flux
wavelength / Å

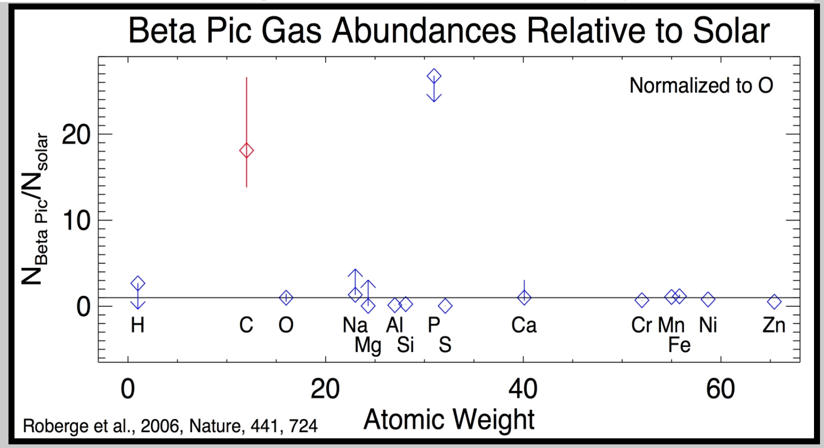

Ne VIII Ne~0.02 Solar
K1-16
T_eff=160 000 logg=5.8
5d-6f
5f-6g
5g-6h
relative flux
wavlength / Å

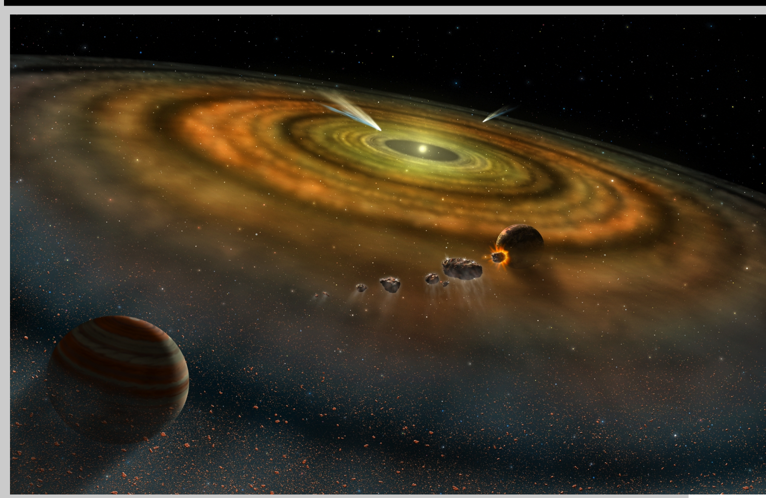
Solar Systems Under Construction

- Beta Pictoris, the prototype young stellar disk system
- Lack of H_2 FUV absorption (FUSE) plus presence of CO (HST) in dusty beta Pic disk is signature of ongoing cometary evaporation.
  Lecavalier des Etangs et al. (2001)
- FUSE discovered huge atomic carbon overabundance (~18X solar) in beta Pic disk, explaining how gaseous disks are stabilized
  Roberge et al. (2006)
- FUSE found strong relationship between O VI emission (disk accretion) and system age
  Grady et al. (2004)

ACS Coronagraphic Image of β Pic







Probing Low Redshift Galaxies and the Magellanic Clouds

- First direct measurement of Lyman continuum radiation escaping from a starburst galaxy. Bergvall et al. (2006)
  - Thought to be related to a significant source of ionizing radiation in the early universe.
- LMC & SMC: Interstellar gas and stellar evolution at different metallicities than Milky Way
  - FUSE established that the LMC and SMC have a hot, multiphase halo
  - LMC has signatures of galactic outflows, possibly a galactic wind
  - Magellanic Stream has metalicity like SMC (or like LMC 1.5 Gyr ago)
  - Magellanic Bridge has metalicity like SMC 2.5 Gyr ago
  - Increased number of UV-detected SNRs by ~3X
  - Legacy archive of ~300 LMC and SMC OB & W-R stars observed at high spectral resolution Special thanks to Bill Blair for leading the creation of this great resource.

Barbara A.
MIKULSKI ARCHIVE FOR SPACE TELESCOPES

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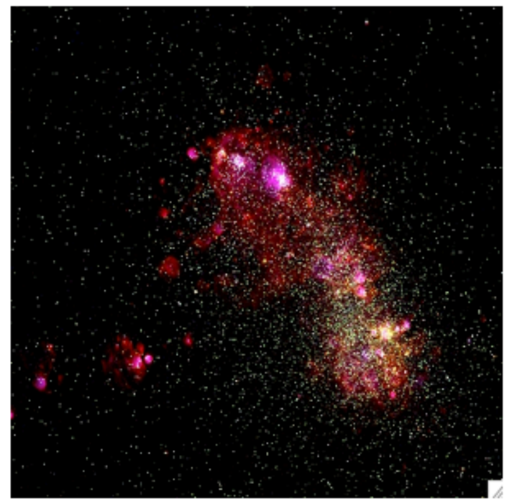
FUSE Magellanic Clouds Legacy Project

The FUSE Magellanic Clouds Legacy Project provides a Quick Look capability for scientists interested in the stellar and interstellar characteristics of the Magellanic Clouds, as discernible from the high resolution far ultraviolet spectral data obtained with the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. FUSE observed the 905 -1187 Ångstrom region with a spectral resolution of ~20,000, corresponding to a velocity resolution of ~15 km/s, depending on exact wavelength.

The Large Magellanic Cloud



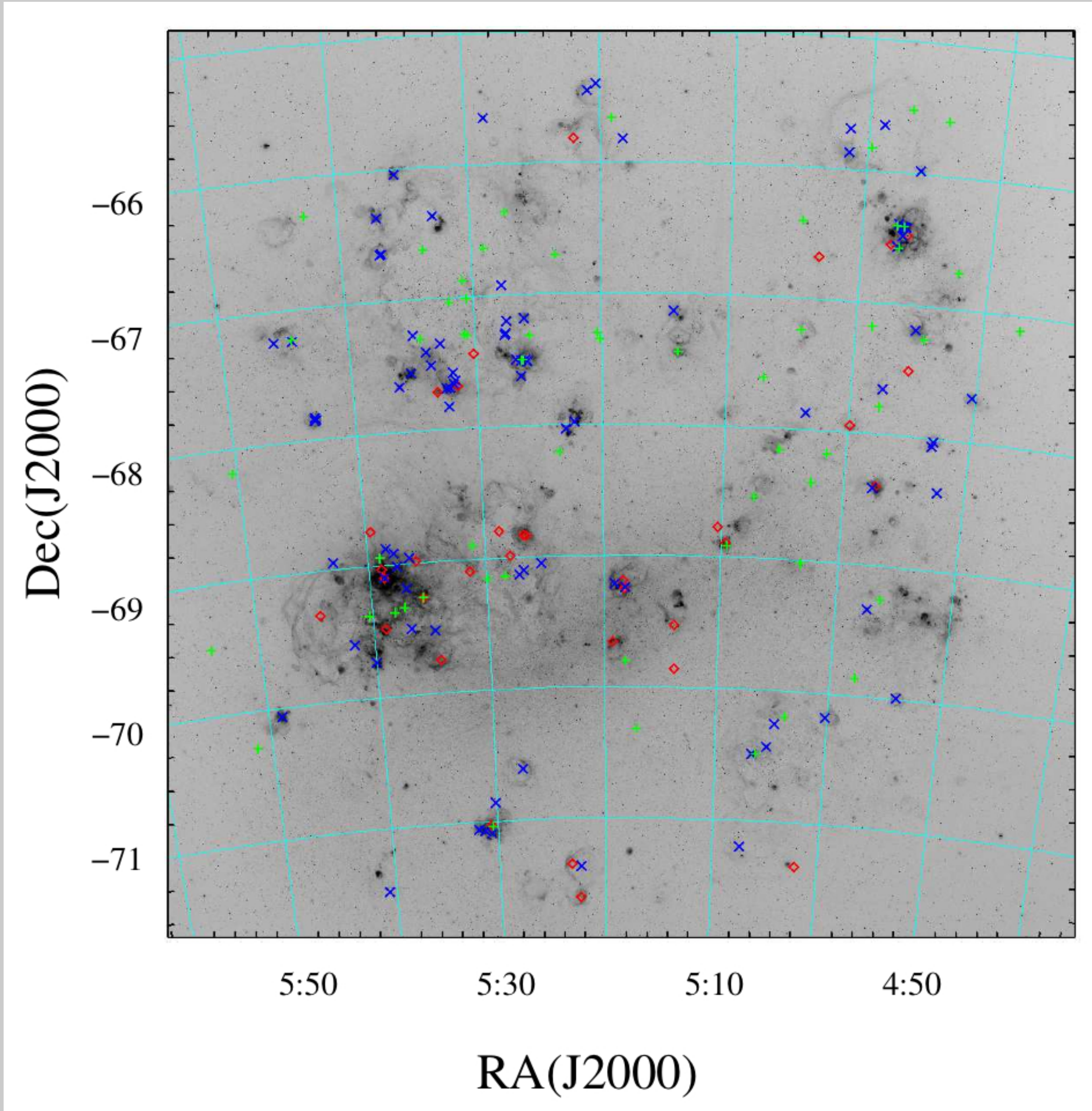
The Small Magellanic Cloud

Click on either image to see overview images showing the distribution of FUSE sight lines across each galaxy.

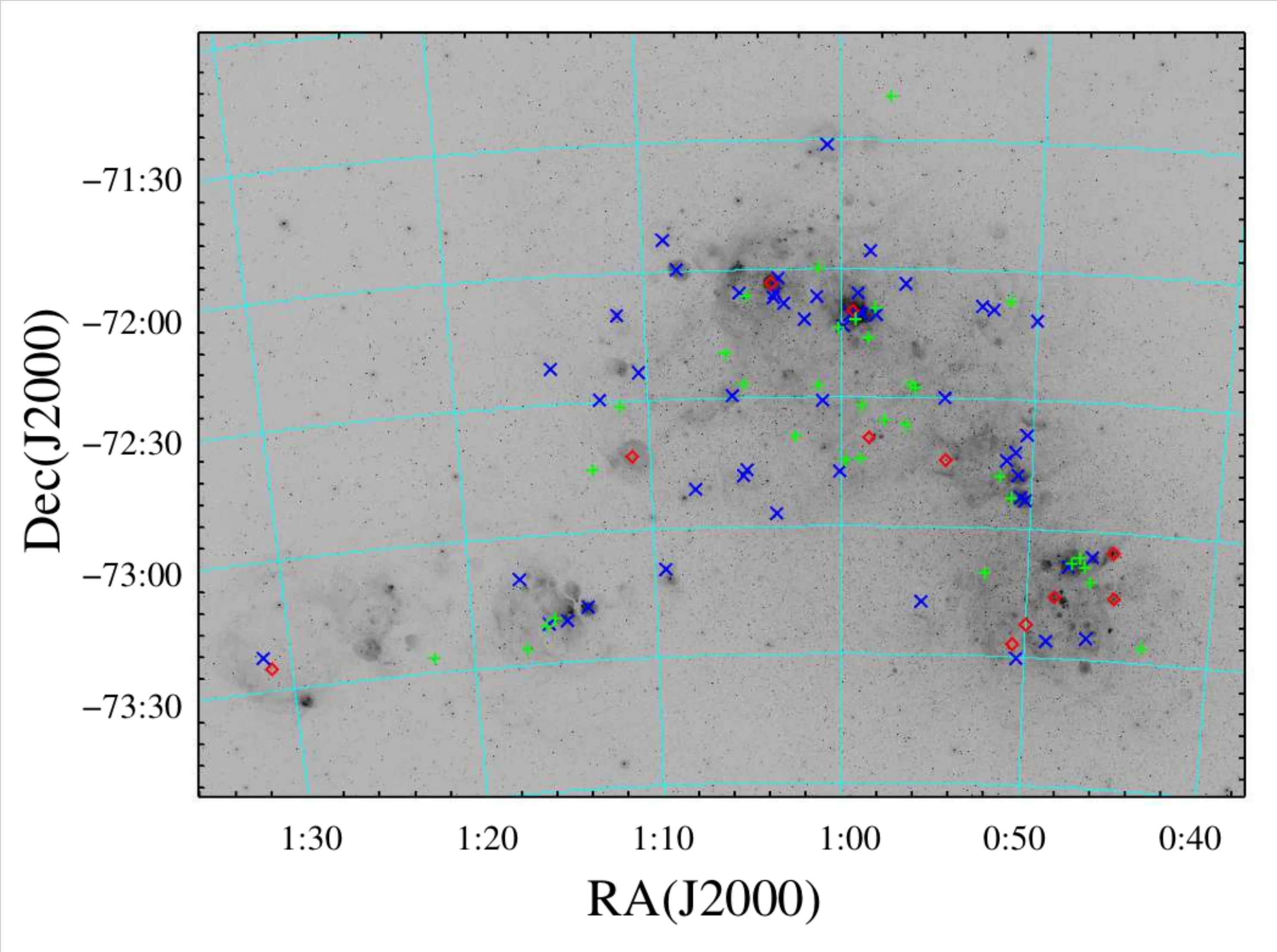
Over its eight years in operations, FUSE was used to observe 187 hot stars in the Large Magellanic Cloud (LMC) and 100 hot stars in the Small Magellanic Cloud (SMC). Each FUSE spectrum contains a wealth of information, from the spectrum of the star itself to a broad range of interstellar absorption lines from both hot and cold gas, often at both rest velocity (from the Milky Way) and at the redshifted velocity of the appropriate Magellanic Cloud. Sifting through this complex mountain of data can be a daunting task for researchers interested in a particular science topic.

In the links below, we provide access to a broad range of summary information for each FUSE target, to support the analysis of these data for a wide range of potential science programs. The FUSE data for all objects have been reprocessed with CalFUSE 3.2, the archival version of the FUSE calibration pipeline software. The pipeline software is described in detail by Dixon et al. (2007,PASP,119,527). For each star, the FUSE data are shown in

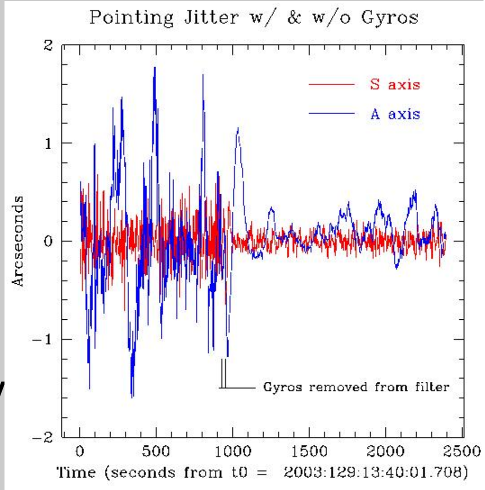
Stars observed in LMC



Stars observed in SMC



In-flight hardware problems



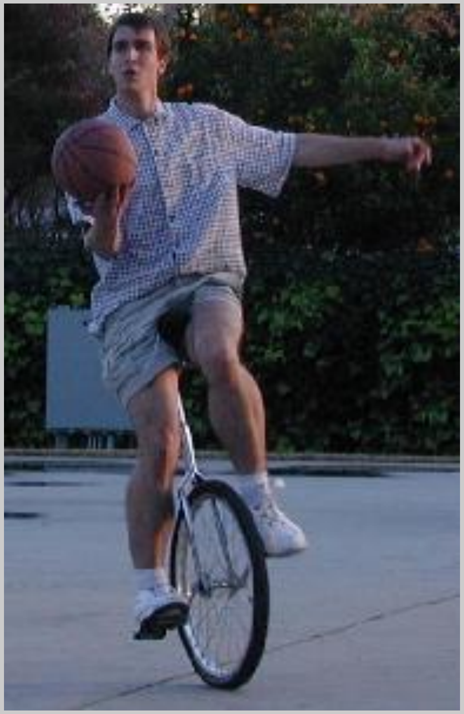
- Gyro lifetime concerns before launch were addressed proactively with new flight s/w. 2 of 6 gyros left at end.
  - Demonstrated ability operate with zero gyros if necessary
- Instrument:
  - Thermal motion of optics. Controlled with new planning scenario and frequent alignments of the telescopes.
  - FES A lost temperature control early 2005; switched to FES B.
- Reaction wheel failures redefined the mission
  - Two failed in late 2001, threatening to terminate the mission
  - JHU and Orbital developed and demonstrated a new control concept in a month (magnetic torquer bars + 2 remaining wheels)
    - Science resumed a month later; no loss of performance or efficiency
  - Recovery from third wheel failure (late 2004) was more difficult, but was successful after 10 months. Efficiency and sky coverage reduced.
- All other subsystems showed minimal degradation

FUSE--A Brief History

FUSE-Dec. 1999

FUSE-Feb. 2002

FUSE-Mar. 2004



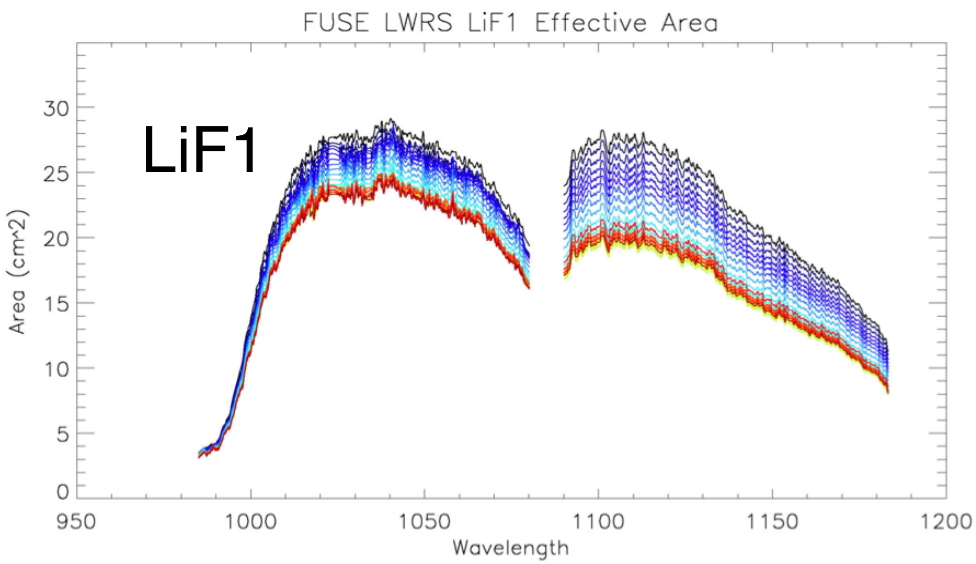
FUSE-Sept 2005

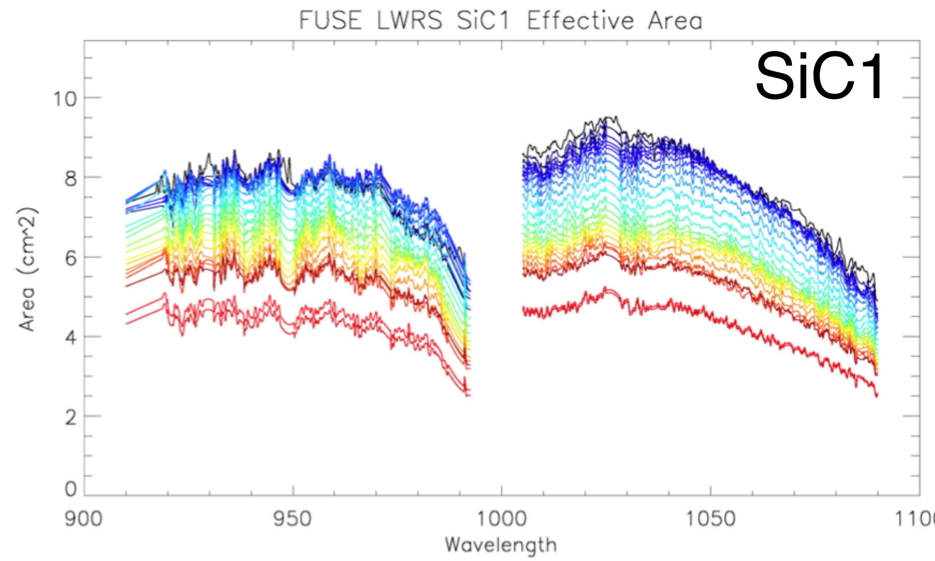
Courtesy Bill Blair

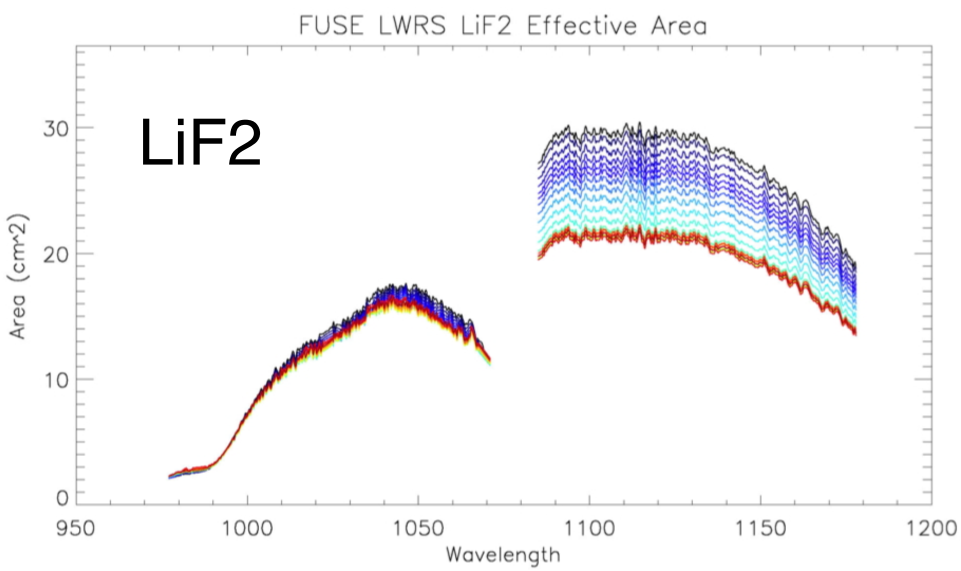
NASA

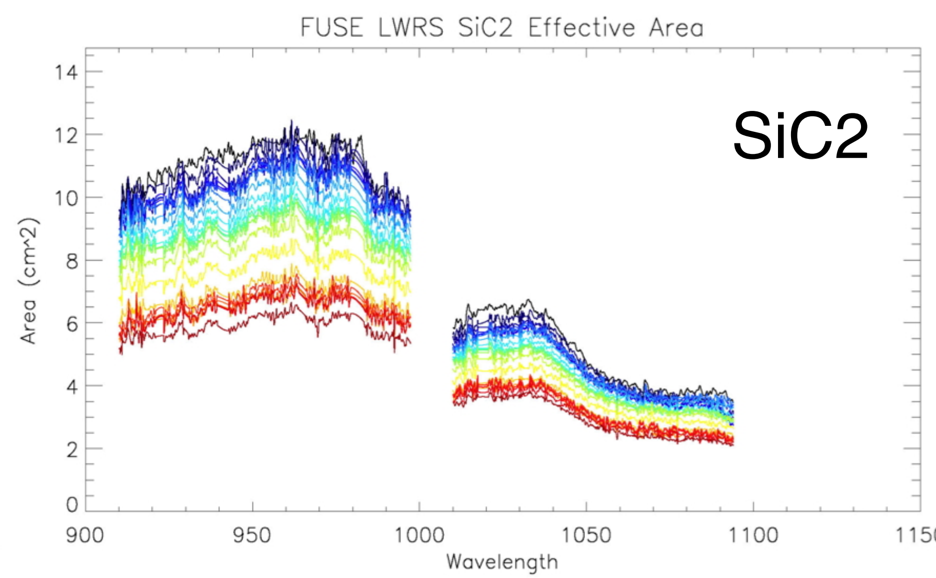
Instrument performance

<50% sensitivity loss in 8 years









Instrument Performance

- Excellent sensitivity history attributed to meticulous pre-launch environmental control and in-orbit ram avoidance
- Far UV absolute flux calibration based on white dwarf models
  - Excellent agreement, after including quasi-molecular satellite lines of H
  - <5% uncertainty
  - G191-B2B could not be used as high-precision standard due to forest of weak metal lines in stellar spectrum

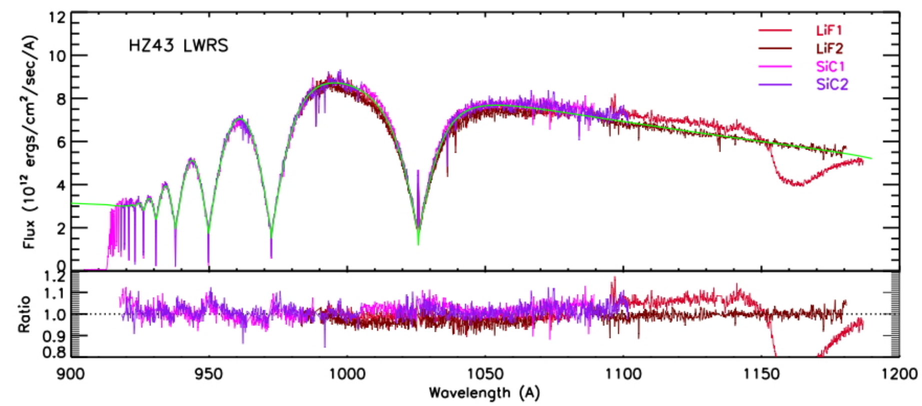


FIGURE 1. The observed and model spectra of HZ 43 are plotted; the model is the smooth green curve. Except for LiF1b, agreement is better than 10% and usually better than 5%.

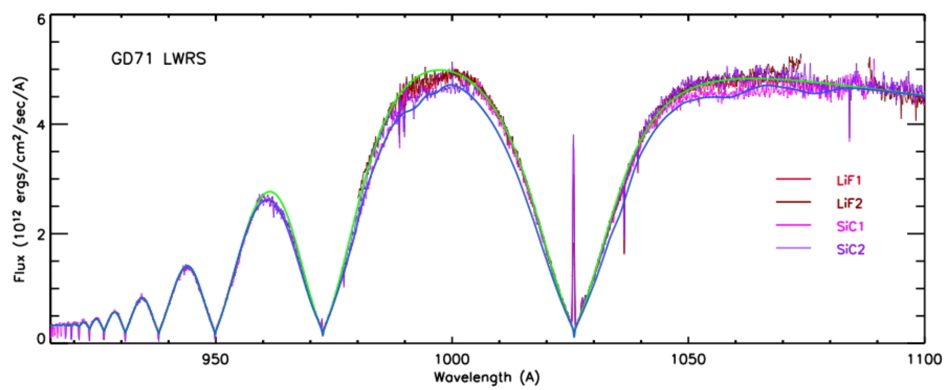


FIGURE 2. The FUSE spectrum of GD 71 is plotted, along with the normal pure H model (green curve) and the model including quasi-molecular states in the line profile (blue curve). The QM states improve the match at 960Å, and have mixed results elsewhere; see text.

Summary

- The FUSE deuterium program was a big success, although the story concluded not exactly as predicted
- O VI has had a major impact across astrophysics
- H_2 is everywhere, although we still do not understand its origin and physical processes; higher resolution needed
- The combination of wavelength coverage, sensitivity, and spectral resolution allowed FUSE observers to make discoveries across the HR diagram, the Galaxy, the Local Group, and into the intergalactic medium.