The Enigmatic Diffuse Interstellar Bands

Ben McCall

Department of Chemistry and Department of Astronomy

University of Illinois at Urbana-Champaign

<u>Apache Point Observatory DIB Collaboration</u>:

Meredith Drosback (Colorado), Scott Friedman (STScI), Lew Hobbs (Yerkes), Ben McCall (UIUC), Takeshi Oka (Chicago), Brian Rachford (ERAU), Ted Snow (Colorado), Paule Sonnentrucker (JHU), Julie Thorburn (Yerkes), Dan Welty (Chicago), Don York (Chicago)

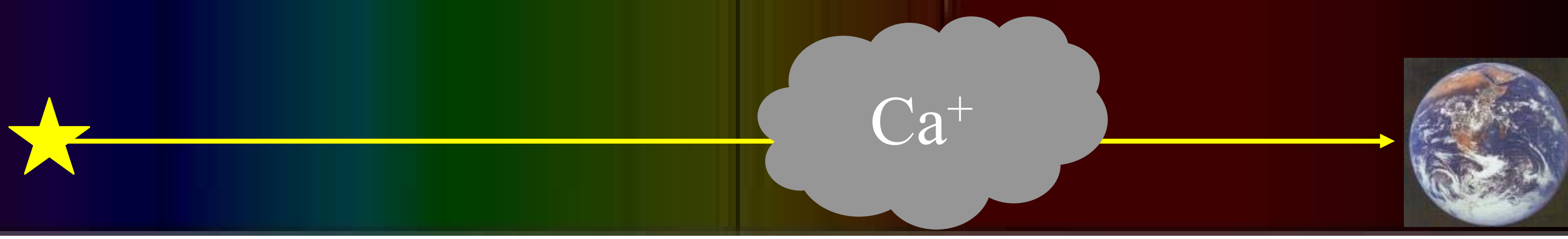
The First Interstellar Radical

As of 1900, two types of lines known in stellar spectra: stellar lines or atmospheric lines

In 1904, J. Hartmann (Potsdam) studied the binary star δ Orionis and observed velocity variations in stellar lines.

"Among the lines...the calcium line at λ3934 [K] exhibits a very peculiar behavior. It...does not share in the periodic displacements of the lines caused by the orbital motion of the star."

"We are thus led to the assumption that at some point in space in the line of sight between the Sun and δ Orionis there is a cloud which produces that absorption...we admit the further assumption, very probable from the nature of the observed line, that the cloud consists of calcium vapor."



Interstellar Na·

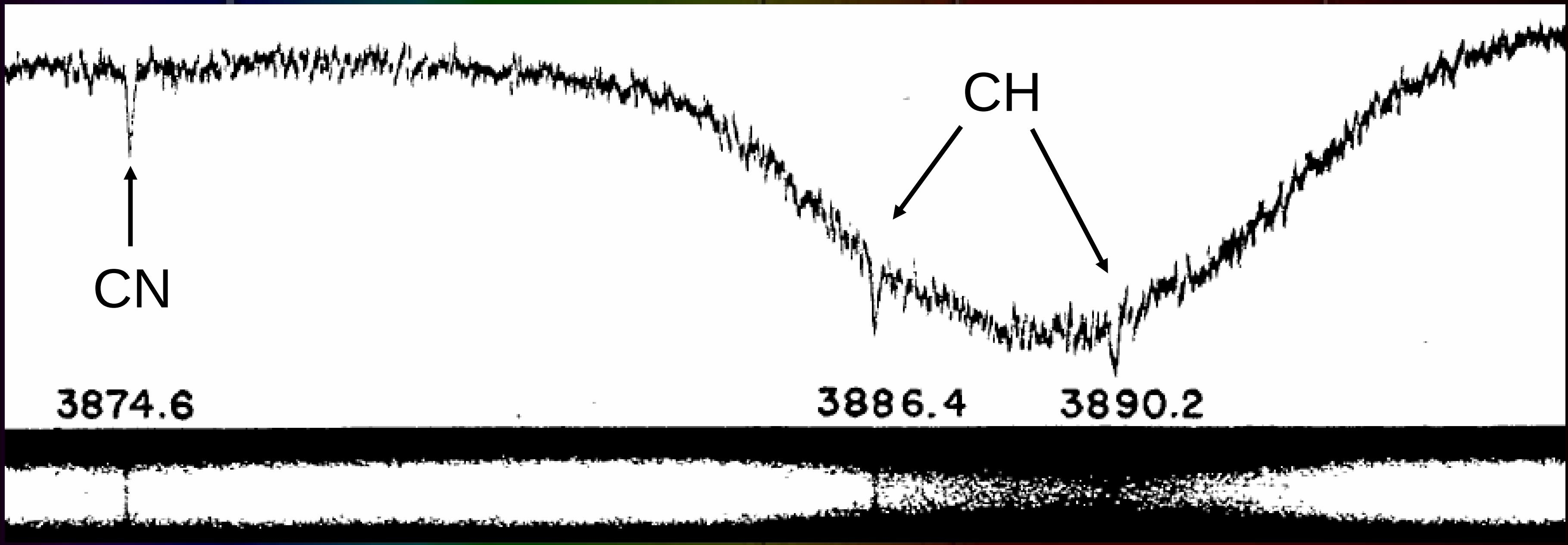
In 1919, Mary Lea Heger (Lick) found the sodium D lines are "stationary" in binaries β Sco & δ Ori.

> "The close relationship between the D lines of sodium and the H and K lines of calcium in the two stars...is very striking. We have still to look for an explanation of the peculiarity in these lines."

> "Do sodium clouds similar to the hypothetical calcium clouds exist in space?...Are there any other star lines which we might suspect of a behavior similar to that shown by the H and K and the D lines?"

Molecular Radicals

- Unidentified lines observed in late 1930s
- Assigned to CH, CH^+, CN in the early 1940s



Adams, ApJ 93, 11 (1941)

Interstellar H· (21 cm)

356 NATURE September 1, 1951 VOL. 168

OBSERVATION OF A LINE IN THE GALACTIC RADIO SPECTRUM

Radiation from Galactic Hydrogen at 1,420 Mc./sec.

THE ground-state of the hydrogen atom is hyperfine doublet the splitting of which, d termined by the method of atomic beams, 1,420·405 Mc./sec.[1]. Transitions occur between t upper ($F = 1$) and lower ($F = 0$) components b

me 150 kc. above the shift varied during an shift and its variation ted for by the earth's ion of the solar system riod of reception shifts lar time, as it ought to. ady be drawn from these

declination $-5°$; scanning is effected by the earth rotation.

The line was first detected on March 25, 1951. appeared in emission with a width of about 80 kc and was most intense in the direction 18 hr. right ascension. Many subsequent observations have established the following facts. At declination $-5°$ the line is detectable, by our equipment, over a period of about six hours, during which the apparent temperature at the centre of the line rises to a

H. I. EWEN
E. M. PURCELL

Lyman Laboratory,
Harvard University,
Cambridge,
Mass.

June 14.

Ubiquity of H·

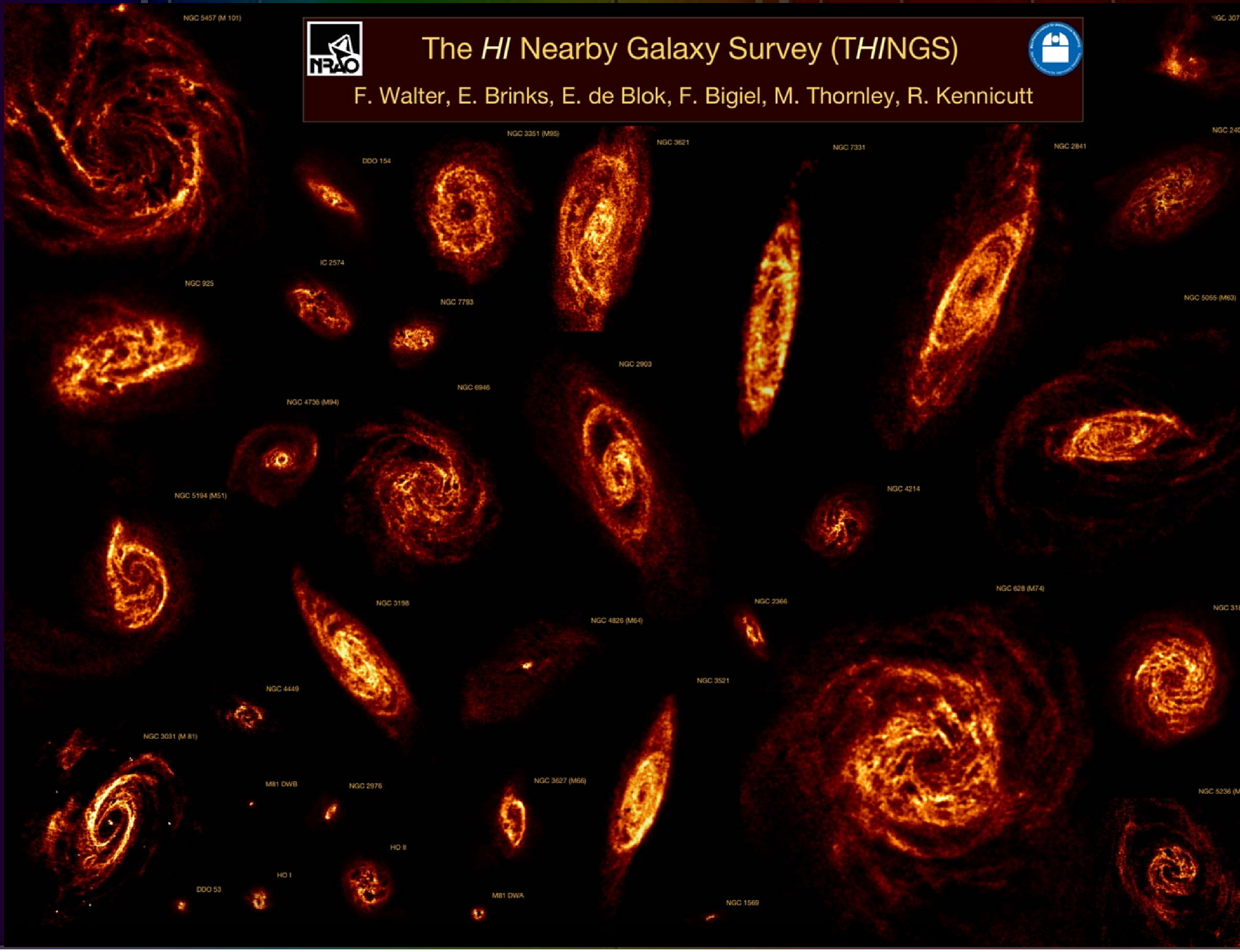


Image courtesy of NRAO/AUI and Fabian Walter, Max Planck Institute for Astronomy

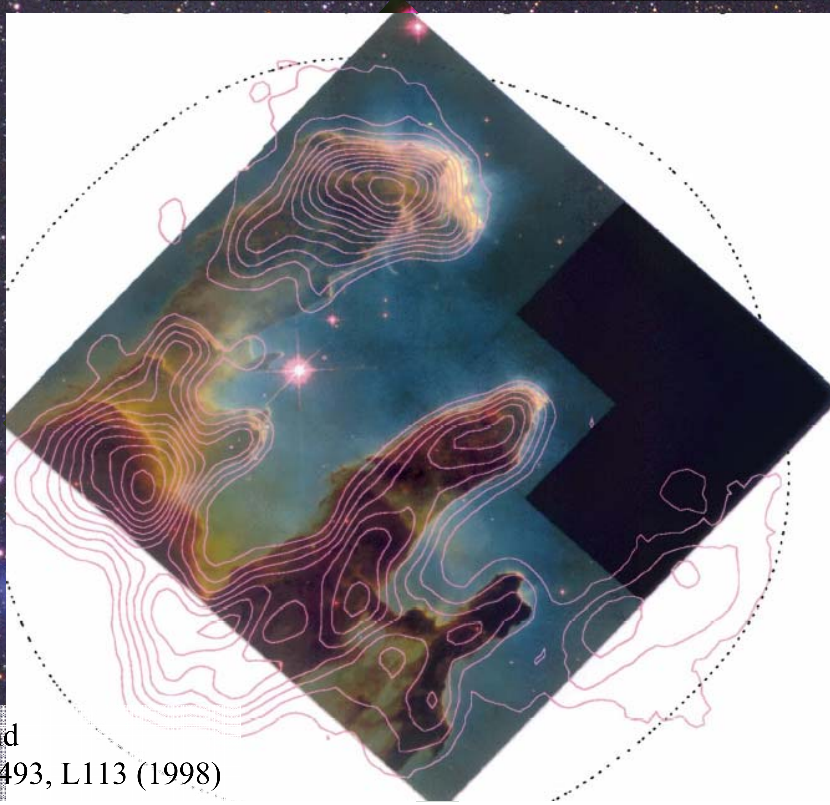
Dense vs. Diffuse Clouds

Dense molecular clouds:

- $H \rightarrow H_2$
- $C \rightarrow CO$
- $n(H_2) \sim 10^4\text{–}10^6\ cm^{-3}$
- $T \sim 20$ K

Diffuse clouds:

- $H \leftrightarrow H_2$
- $C \rightarrow C^+$
- $n(H_2) \sim 10^1\text{–}10^3\ cm^{-3}$
- $T \sim 50$ K



Pound
ApJ 493, L113 (1998)

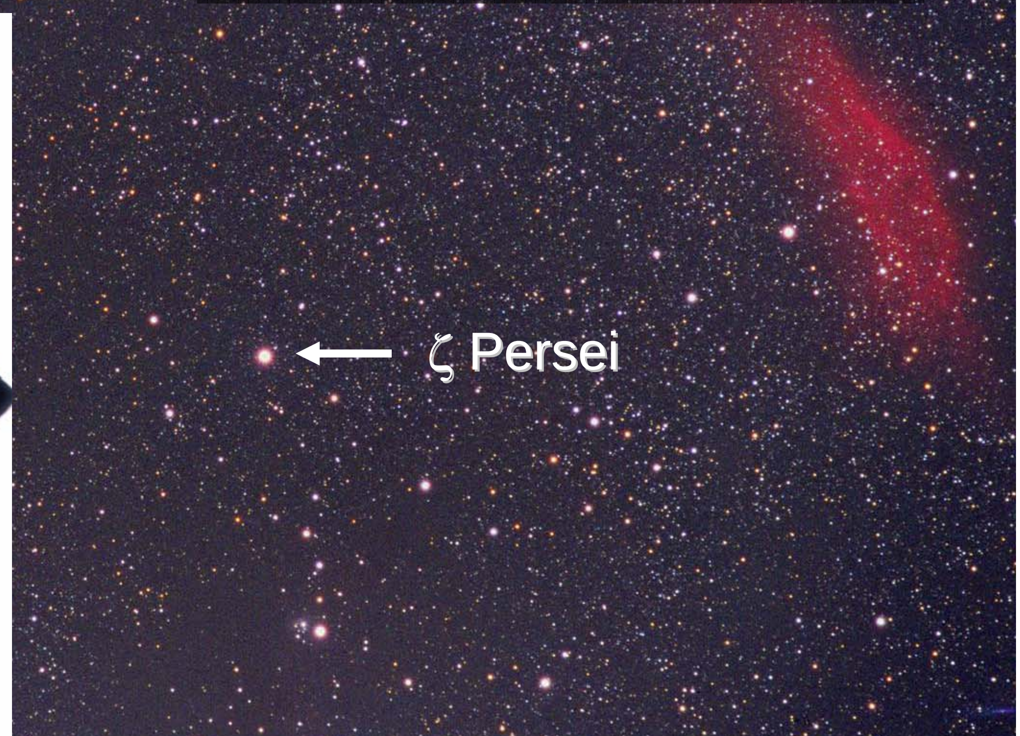


Photo: Jose Fernandez Garcia

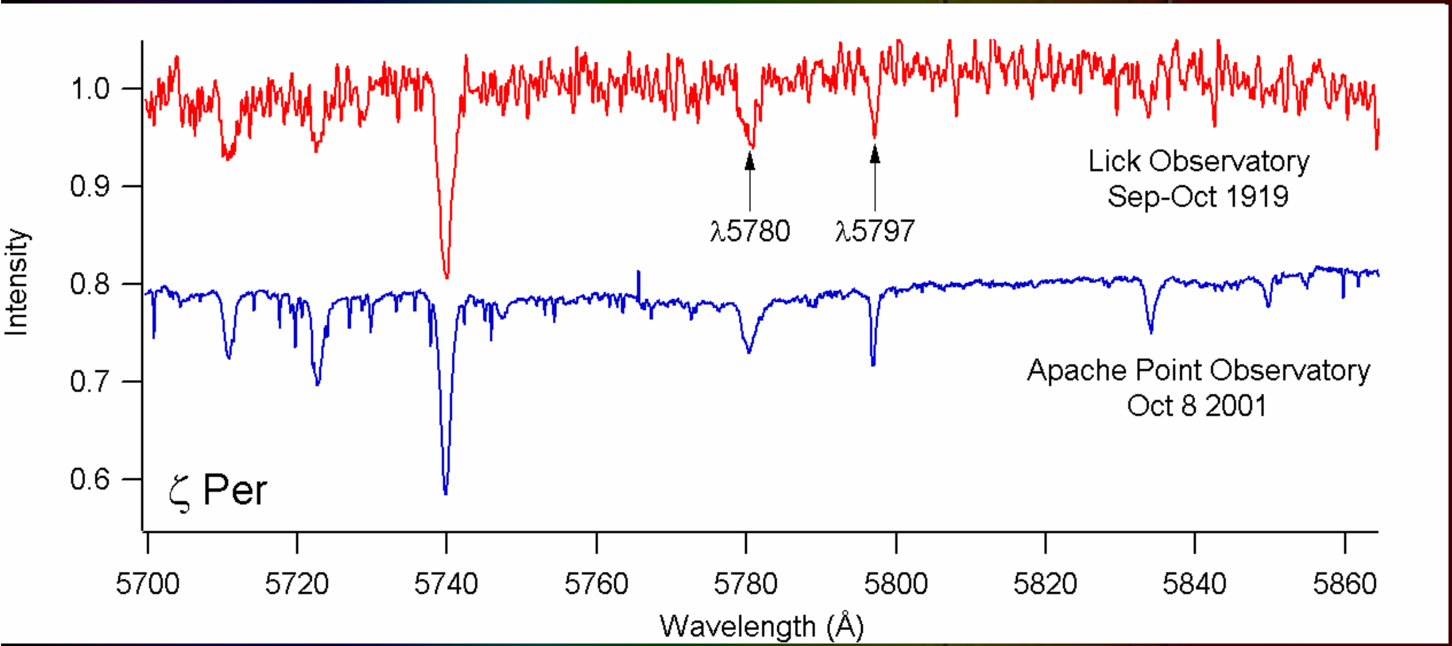
A Census of Galactic Radicals

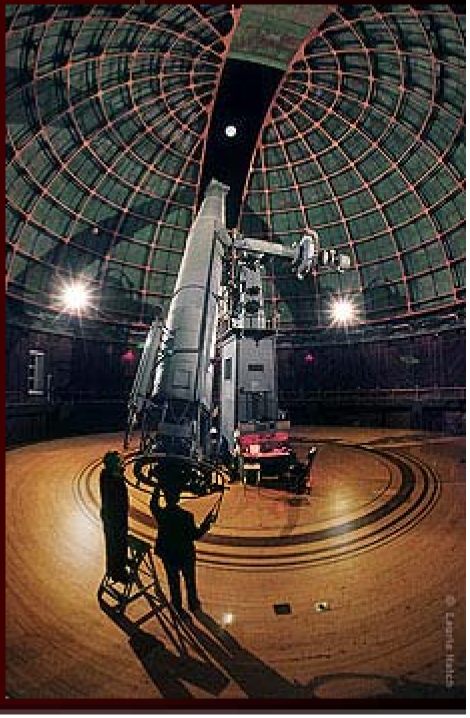
- H· $3\times10^{9}\ M_{\odot} = 6\times10^{42}$ g ~ 3×10^{66} radicals
- Optical studies:
  - CH ~ 5×10^{57}
  - CH^+ ~ 8×10^{58}
  - CN ~ 7×10^{57}
  - OH ~ 1×10^{59}
  - NH ~ 2×10^{57}
  - C_2 ~ 5×10^{58}
  - C_3 ~ 4×10^{57}
  - DIBs ~ 10^{58} ?
- Radio studies:
  - C_2H ~ 3×10^{58}
  - C_3H_2 ~ 2×10^{57}
  - (HCO^+) ~ 5×10^{57}
  - (HOC^+) ~ 8×10^{55}
- Infrared studies:
  - (H_3^+) ~ 2×10^{59}

Based on abundances from Snow & McCall, ARAA 44, 367 (2006)

Discovery of the DIBs

- λλ5780, 5797 seen as unidentified bands
  - ζ Per, ρ Leo (Mary Lea Heger, Lick, 1919)
- Broad ("diffuse")
- Possibly "stationary"





B. J. McCall, in preparation

Interstellar Origin

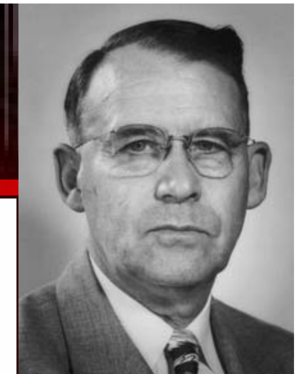


TABLE I

MEASUREMENTS IN THE SPECTRUM OF BOSS 6142

G.M.T.	Plate	Star Obs. km/sec	Star Comp. km/sec	D1,2 km/sec	λ 5780 I.A.	λ 5797 I.A.	λ 6278 I.A.	λ 6284 I.A.
1928 Dec. 1.66	G 214*	− 57	− 77	(−18)	....	....	(6277.7)	(6283.5)
1932 Oct. 13.79	620	−145	−127	20	....	....	7.4	3.9
1934 Jan. 2.60	970†	− 33	− 17	17	....	....	....	....
July 31.96	1058	−150	−126	20	5780.6	....	....	3.6
Aug. 27.85	1063	−124	−127	18	0.3	5796.6	7.6	3.9
27.94	1064	−130	−128	21	0.4	7.2	7.8	4.2
28.91	1069	−112	−129	16	0.8	6.7	7.6	4.7
28.97	1070	−118	−129	18	0.6	7.2	7.9	3.9
Sept. 29.78	1078†	+ 65	+ 78	(26)	(0.5)	....	....	(4.4)
30.73	1082	+105	+104	23	0.6	....	7.5	3.7
30.86	1083	+132	+105	19	0.8	....	7.6	3.9
Oct. 1.74	1087	+ 88	+ 97	−20	0.5	6.9	7.9	4.2
Mean	....	....	....	−19.5	0.58	6.9	7.67	4.02
High velocity	....	+108	+102	−20.7	0.63	(6.9)	7.65	3.93
Low velocity	....	−130	−128	−18.9	0.54	6.9	7.67	4.05
Other stars	....	....	....	....	5780.44	5796.88	6277.70	6283.91

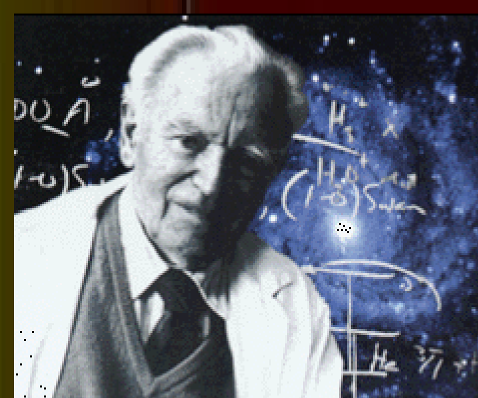
P. W. Merrill, ApJ 83, 126 (1936)

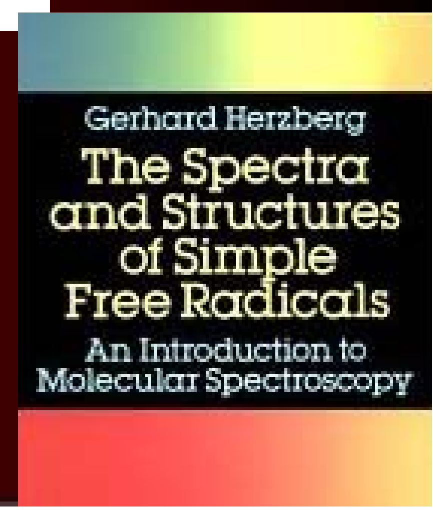
	Assumed Stellar		Assumed Interstellar	
High-velocity group ...	5779.7	6283.3	5780.4	6284.0
Low-velocity group	5781.1	6284.6	5780.6	6284.1
Difference	+1.4	+1.3	+0.2	+0.1
For Comparison				
Boss 6142			5780.5	6284.0
Other stars			5780.4	6283.9

P. W. Merrill, PASP 483, 179 (1936)

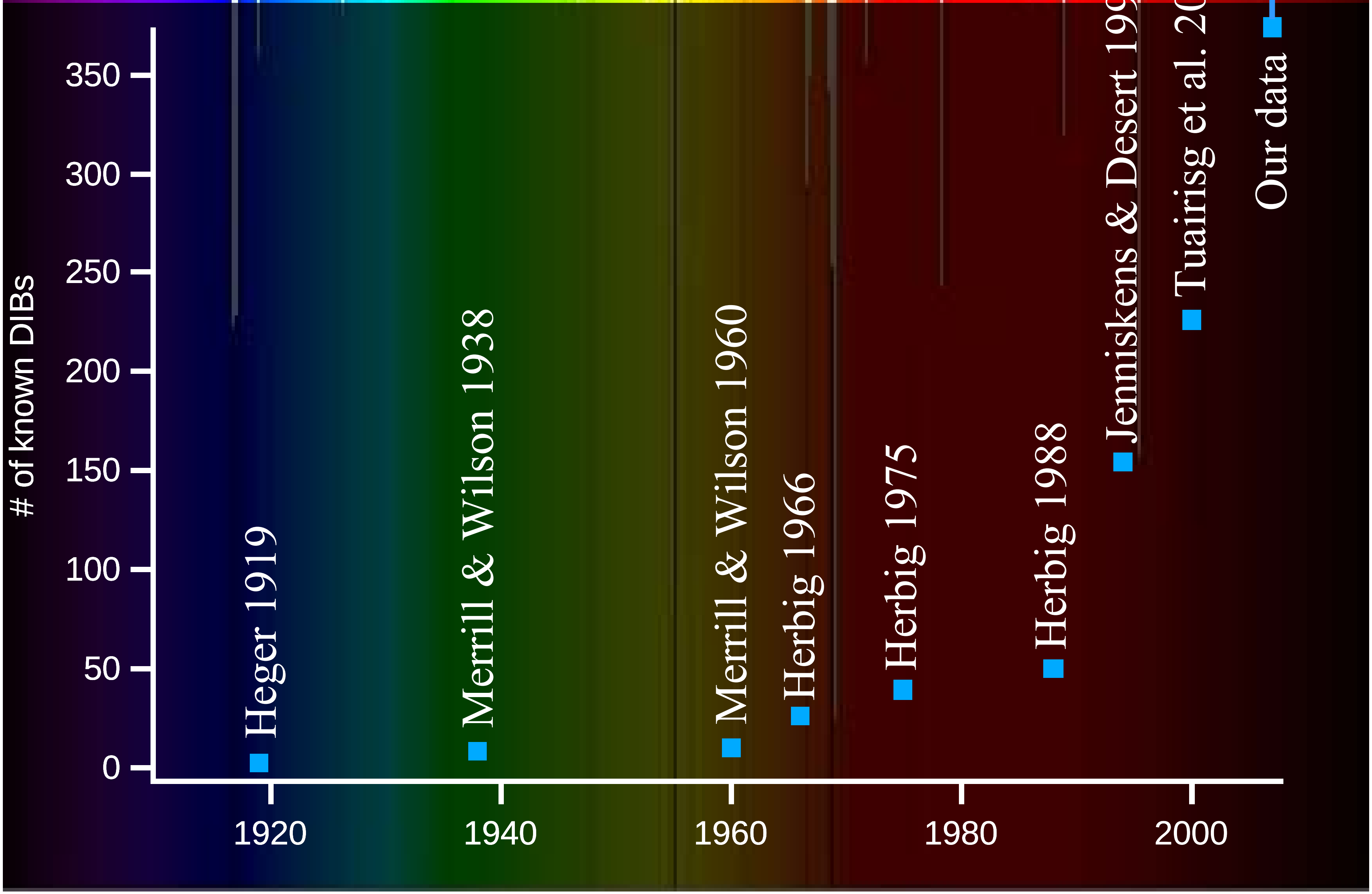
DIBs as Radicals?

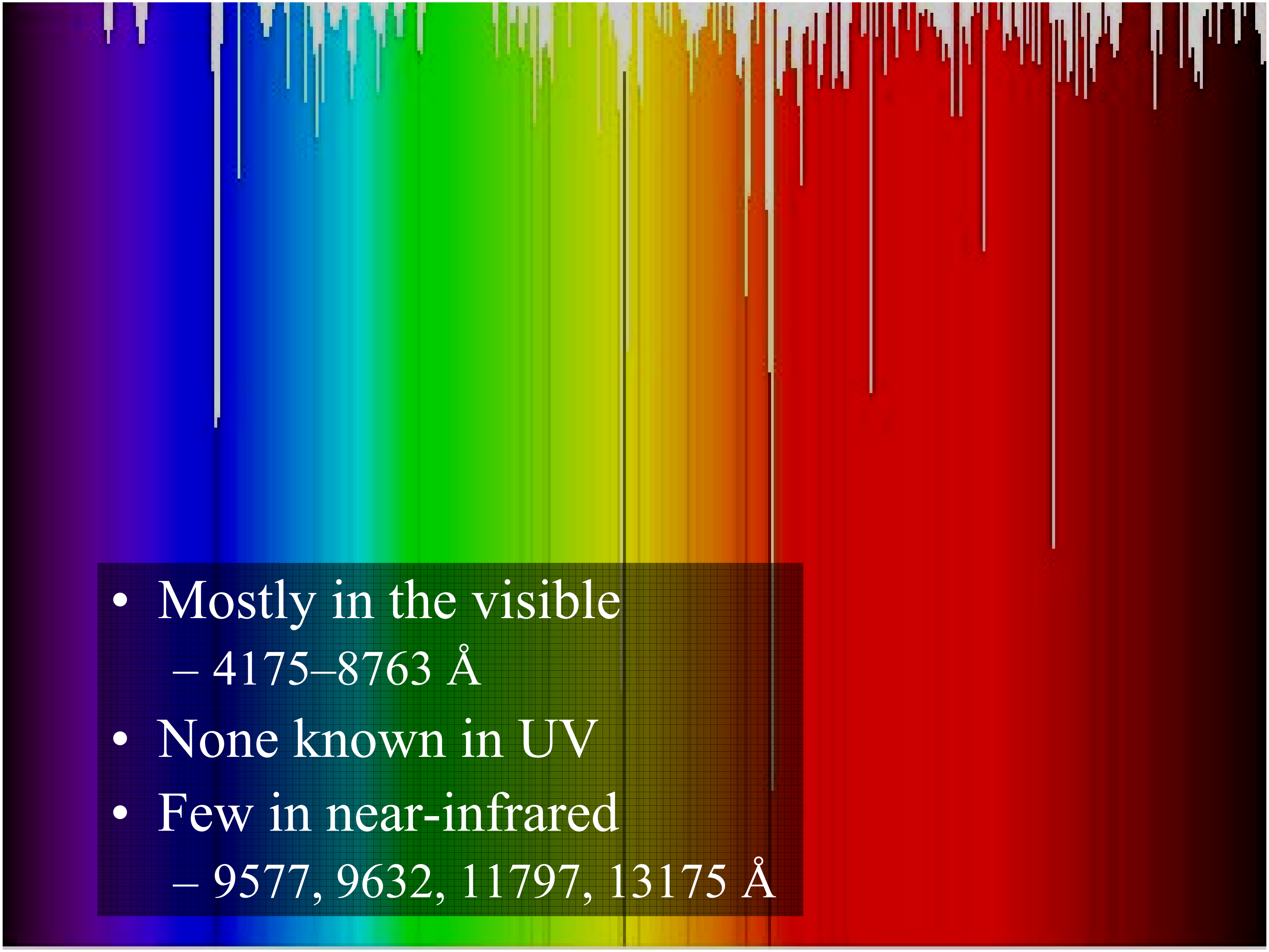
Finally I should like to mention still another method of obtaining free-radical spectra in absorption: the study of the spectra of distant stars. These spectra show features that can be definitely ascribed to absorption in the *interstellar medium*. In addition to a number of free atoms, the radicals CH, CH^+, CN, and OH have been unambiguously identified in the interstellar medium. Their concentration is of course extremely small, of the order of one molecule per cubic meter. A number of additional features observed in interstellar absorption have resisted all attempts at identification, but they are, at least in my opinion, very likely due to some free radical or ion present in the interstellar medium.





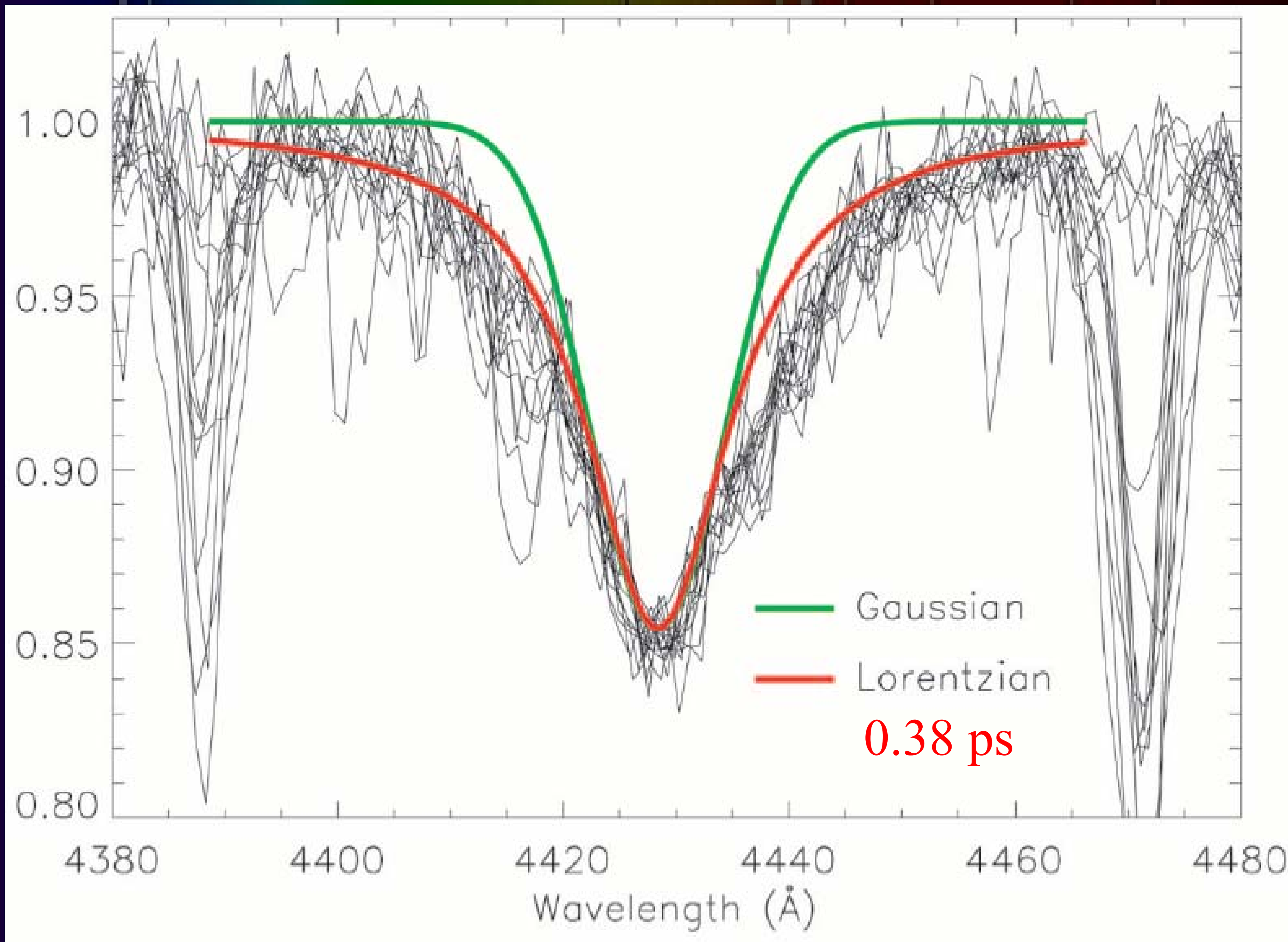
A Growing Problem





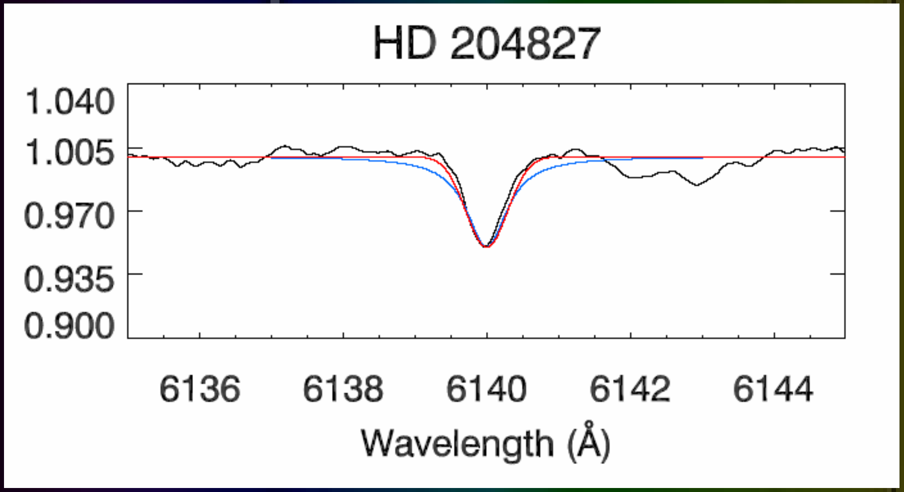
- Mostly in the visible
  - 4175–8763 Å
- None known in UV
- Few in near-infrared
  - 9577, 9632, 11797, 13175 Å

Examples: Lorentzian Profiles

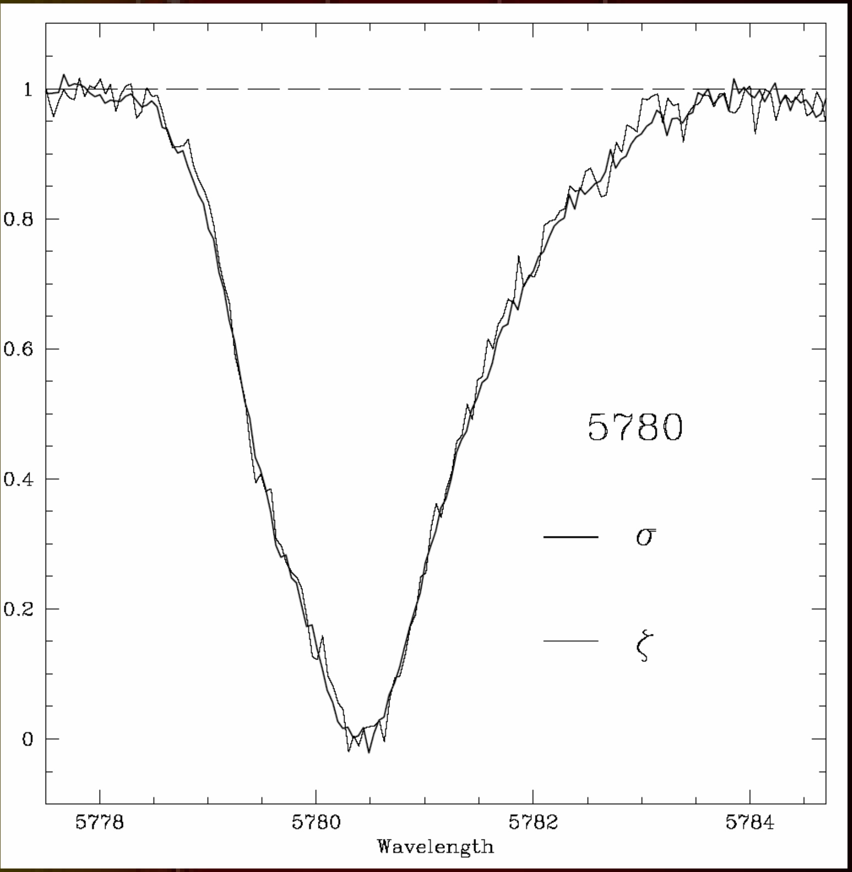


Snow, Zukowski, & Massey, ApJ 578, 877 (2002)

Examples: Smooth Profiles

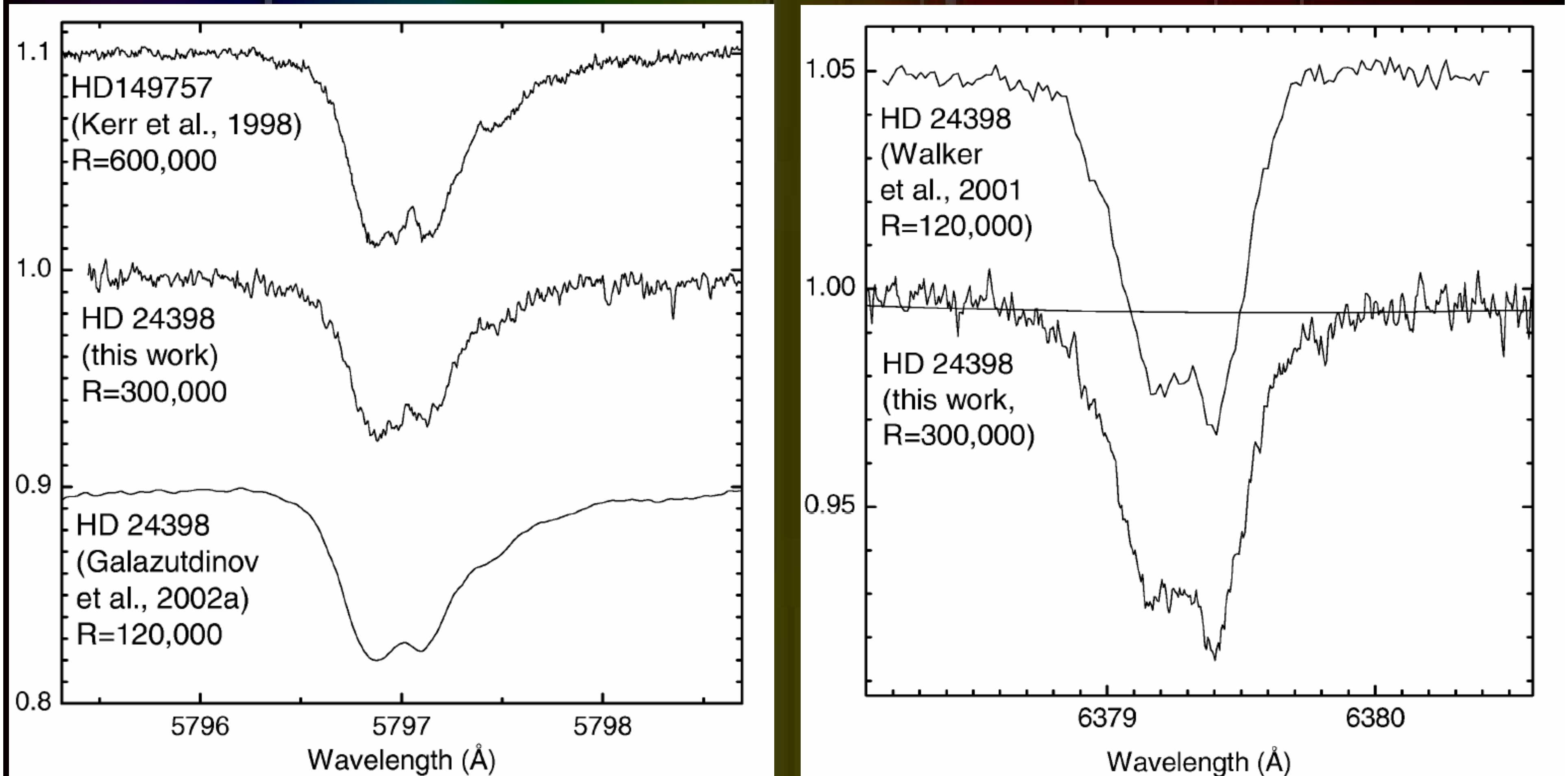


M. Drosback, Ph.D. Thesis (2006)



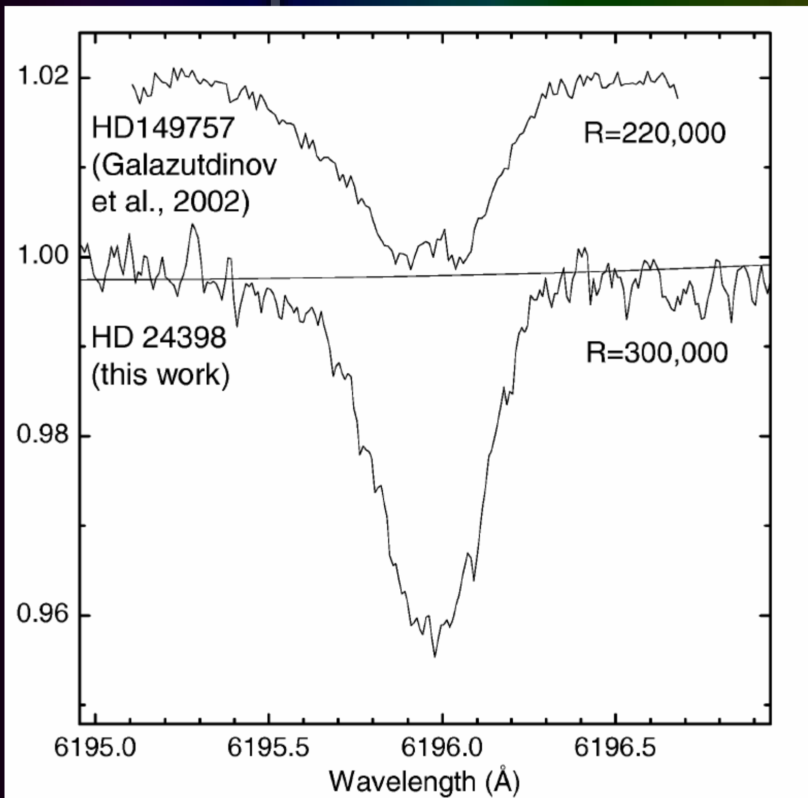
Krelowski & Schmidt, ApJ 477, 209 (1997)

Examples: Fine Structure

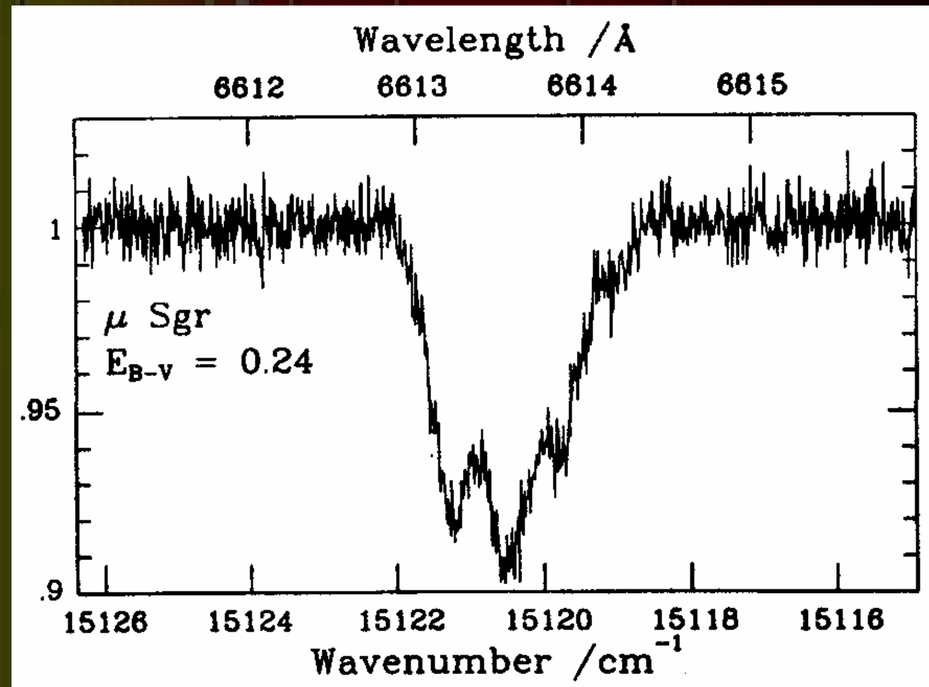


Galazutdinov et al., MNRAS 345, 365 (2003)

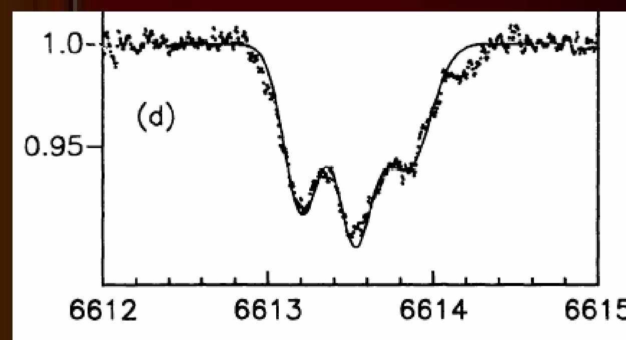
Examples: Molecular Structure?



Galazutdinov et al., MNRAS 345, 365 (2003)



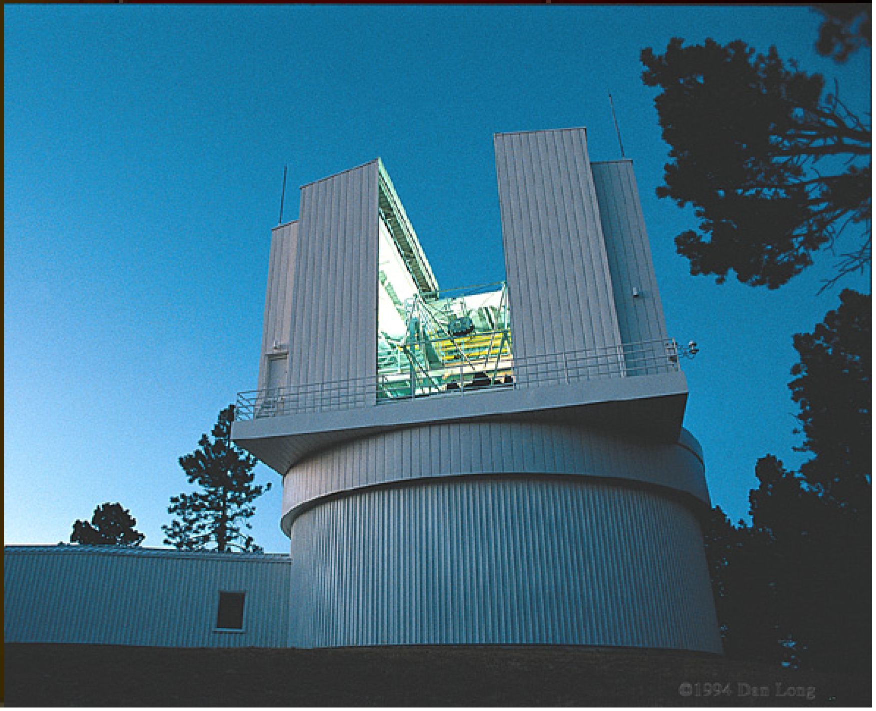
Sarre et al., MNRAS 277, L41 (1995)



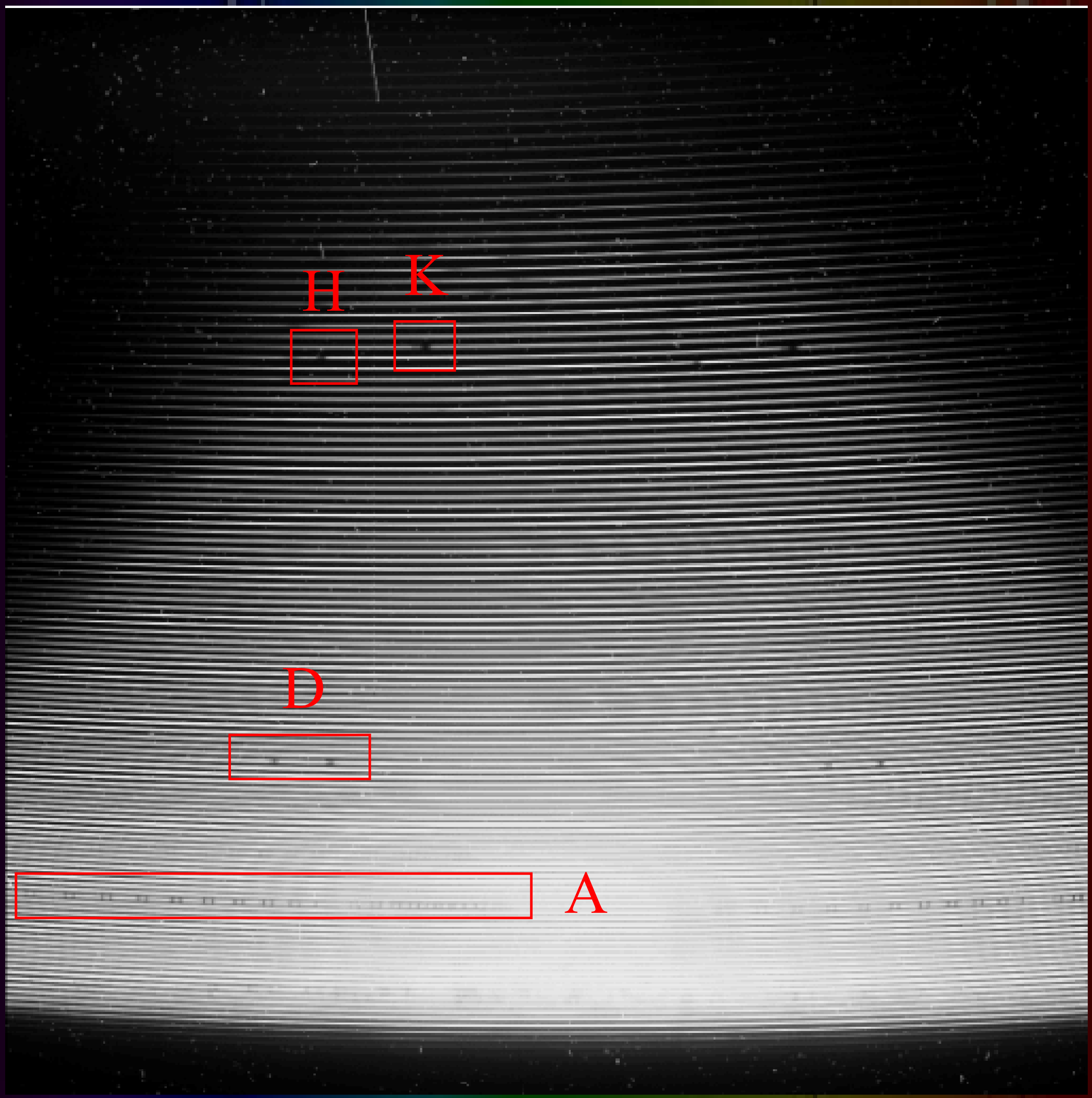
Kerr et al., MNRAS 283, L105 (1996)

The APO DIB Survey

- Apache Point Observatory 3.5-meter
- 3,600–10,200 Å ; λ/Δλ ~ 37,500 (8 km/s)
- 119 nights, from Jan 1999 to Jan 2003
- S/N (@ 5780Å) > 500 for **160** stars (115 reddened)
- Measurements & analysis still underway



Echelle Image



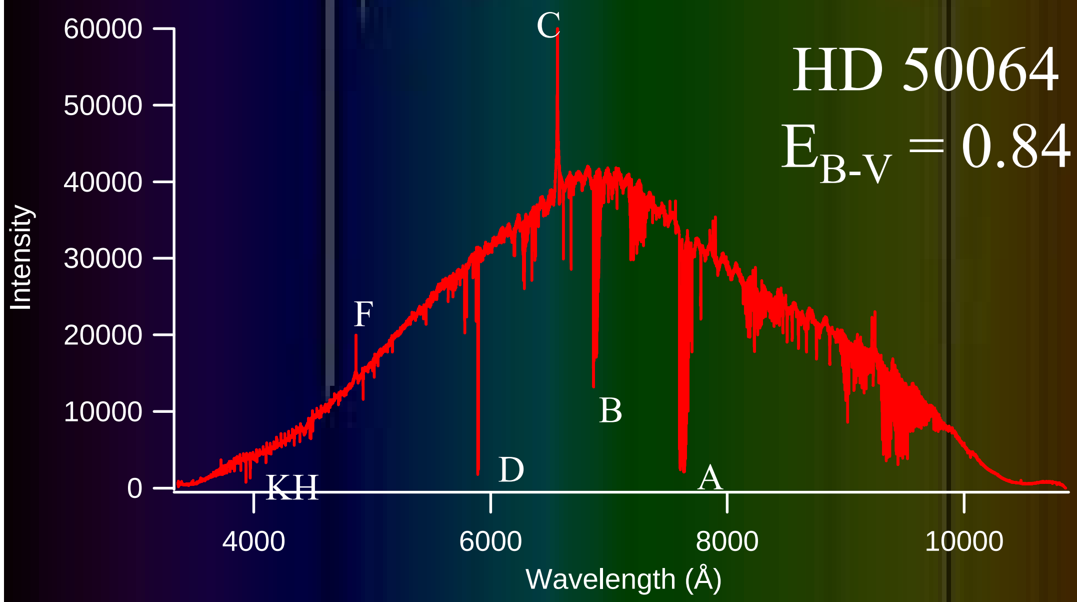
Fraunhofer Lines

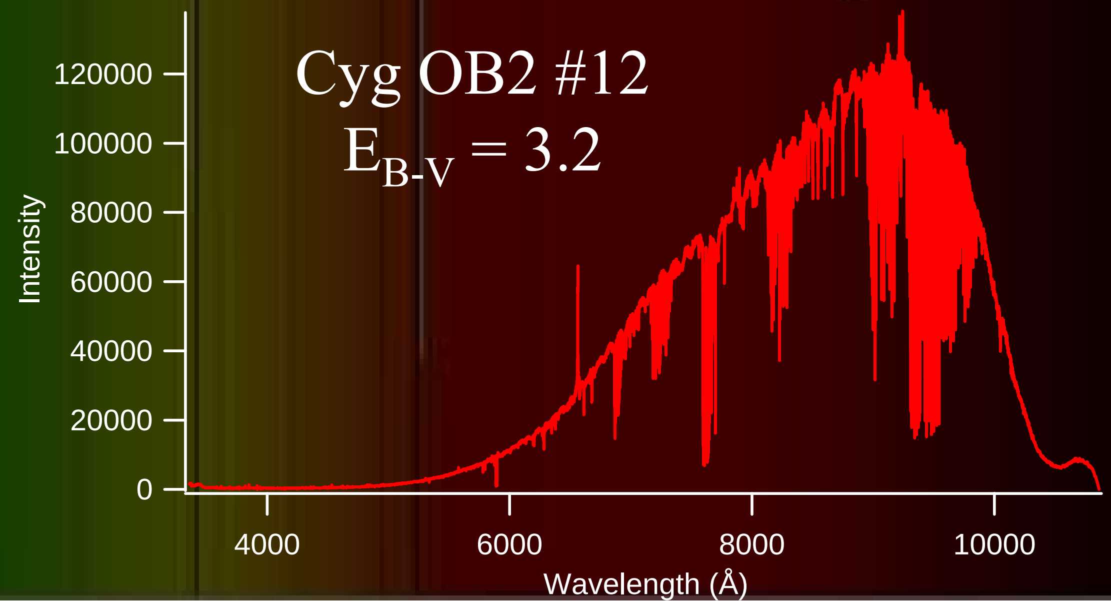
H: Ca II ~ 3968 Å
K: Ca II ~ 3934 Å

D: Na I ~ 5890 Å

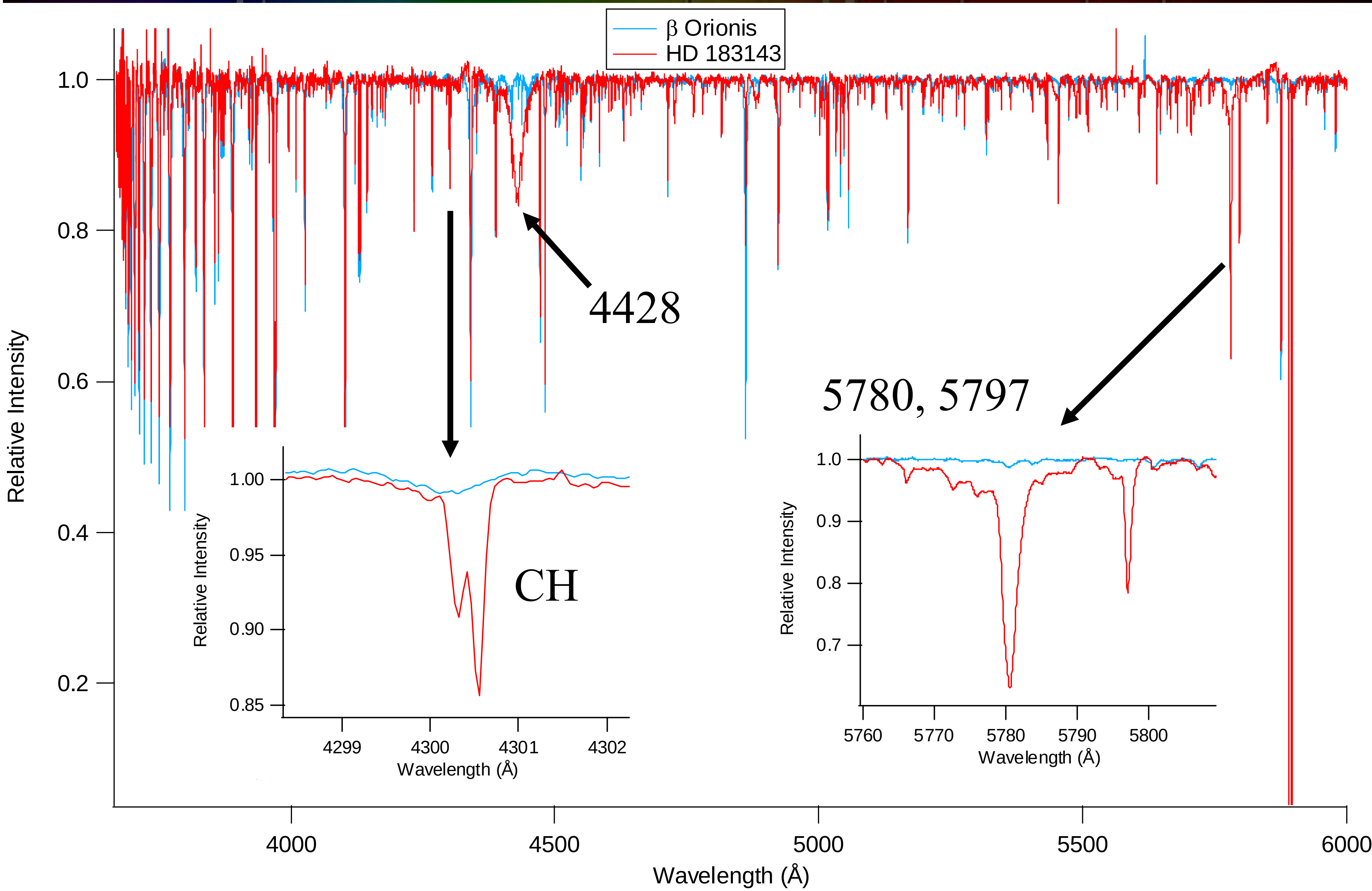
A: O_2 ~ 7650 Å

Stellar Spectra





Stellar Spectra

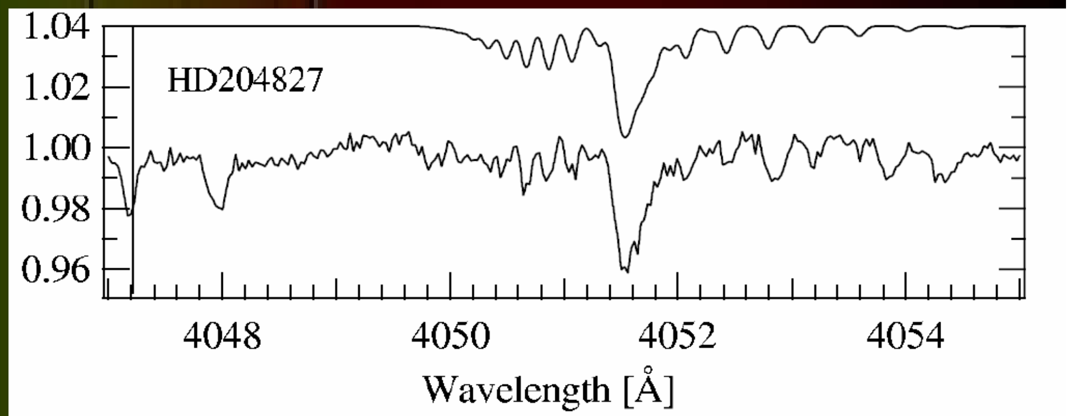


Overview of Preliminary Results

- Spectral atlas of DIBs
  - for comparison to laboratory spectra
  - Version 1: HD 204827
  - Version 2: Four reddened stars
- DIB correlations
  - between DIBs & other species
    - → chemistry, environment of carriers
  - among DIBs
    - → spectra of carriers

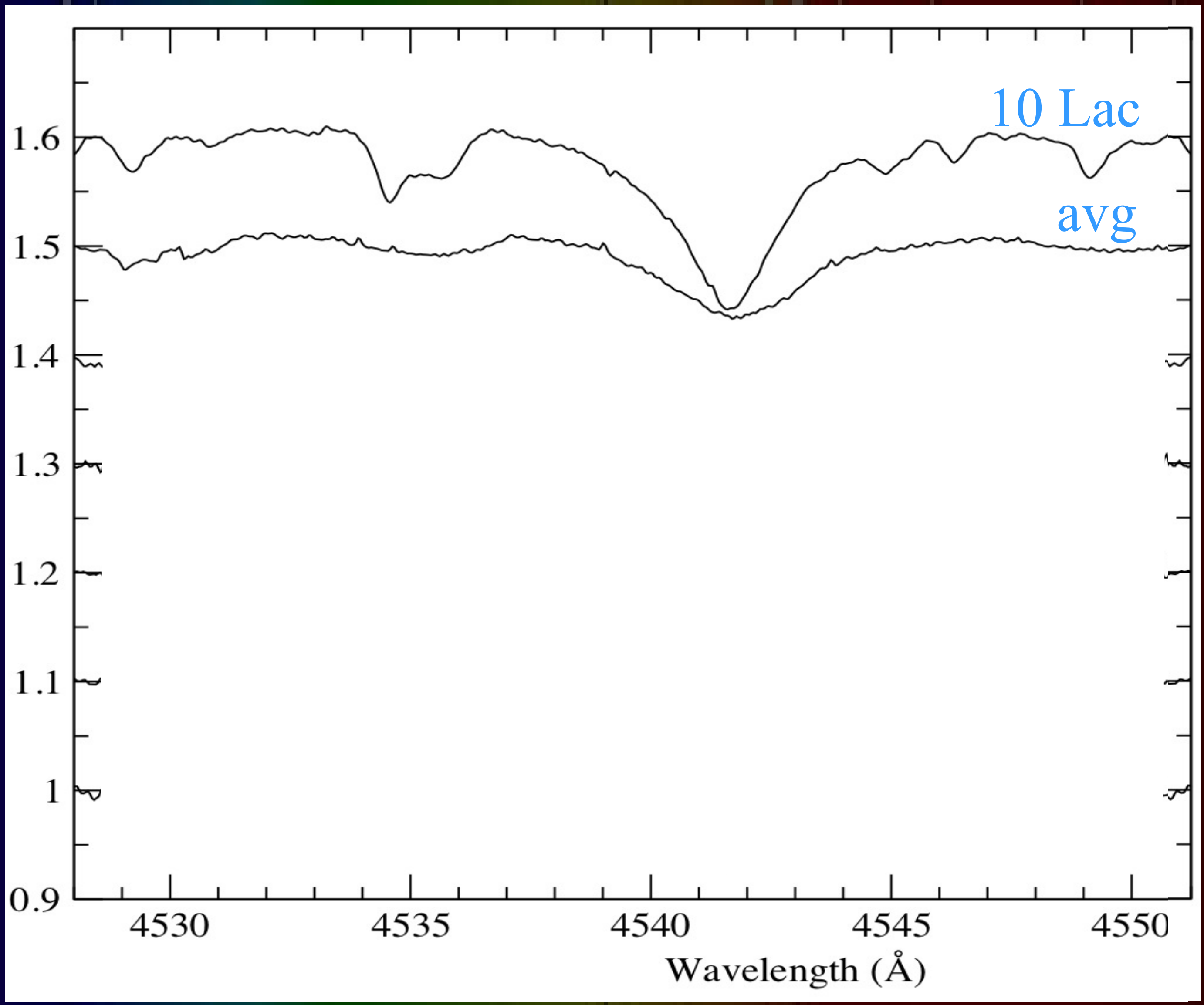
DIB Spectral Atlas: Version 1

- Initial target: HD 204827
  - heavily reddened: E_{B-V}=1.11
  - early spectral type: ~B0V
  - fairly bright: V=7.94
  - member of open cluster Trumpler 37
    - in Cepheus OB2 association
- Abundant C_2
- Champion of C_3

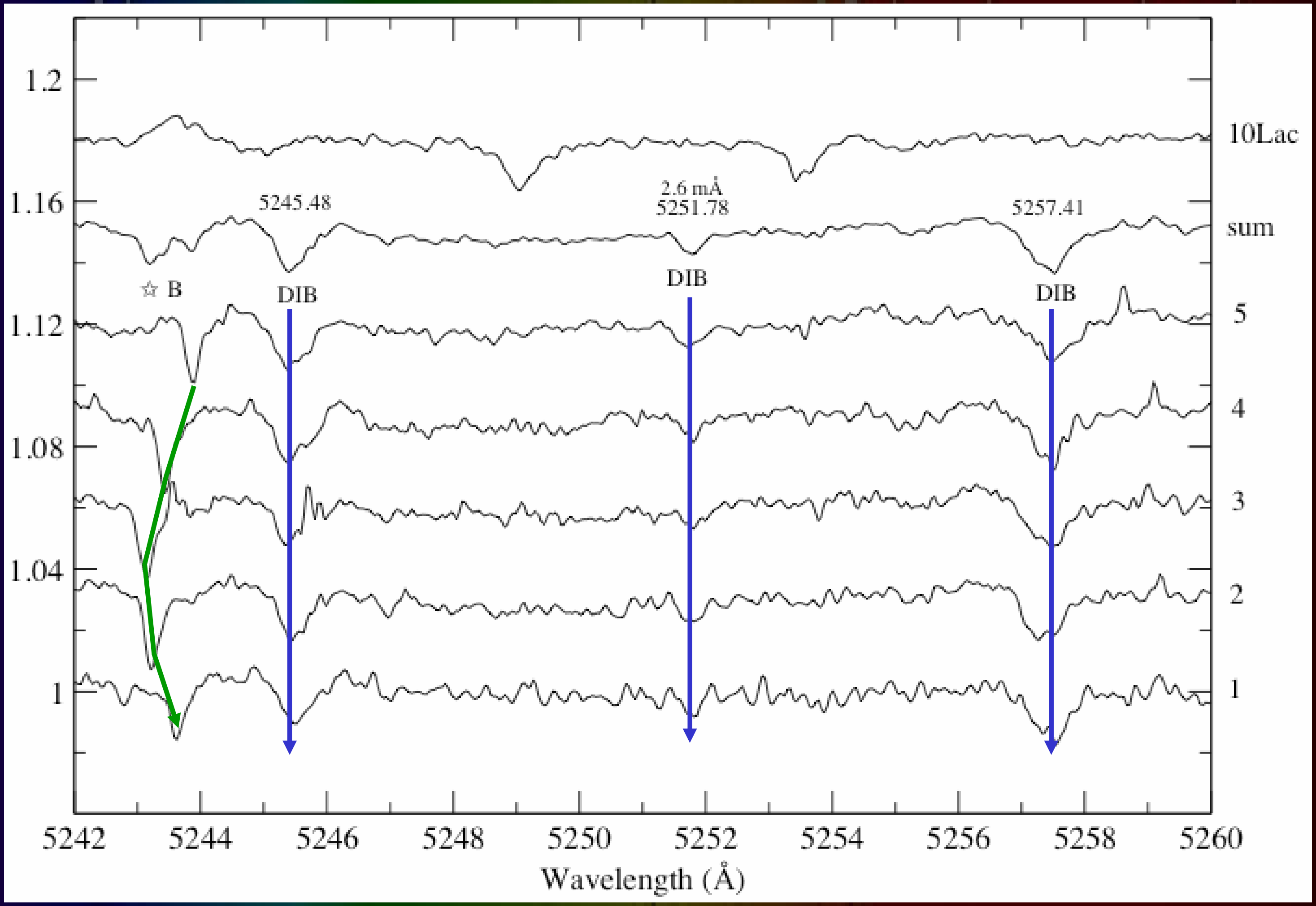


Adamkovics, Blake, & McCall, ApJ 595, 235 (2003)

Spectroscopic Binary!



Great Test for DIBs



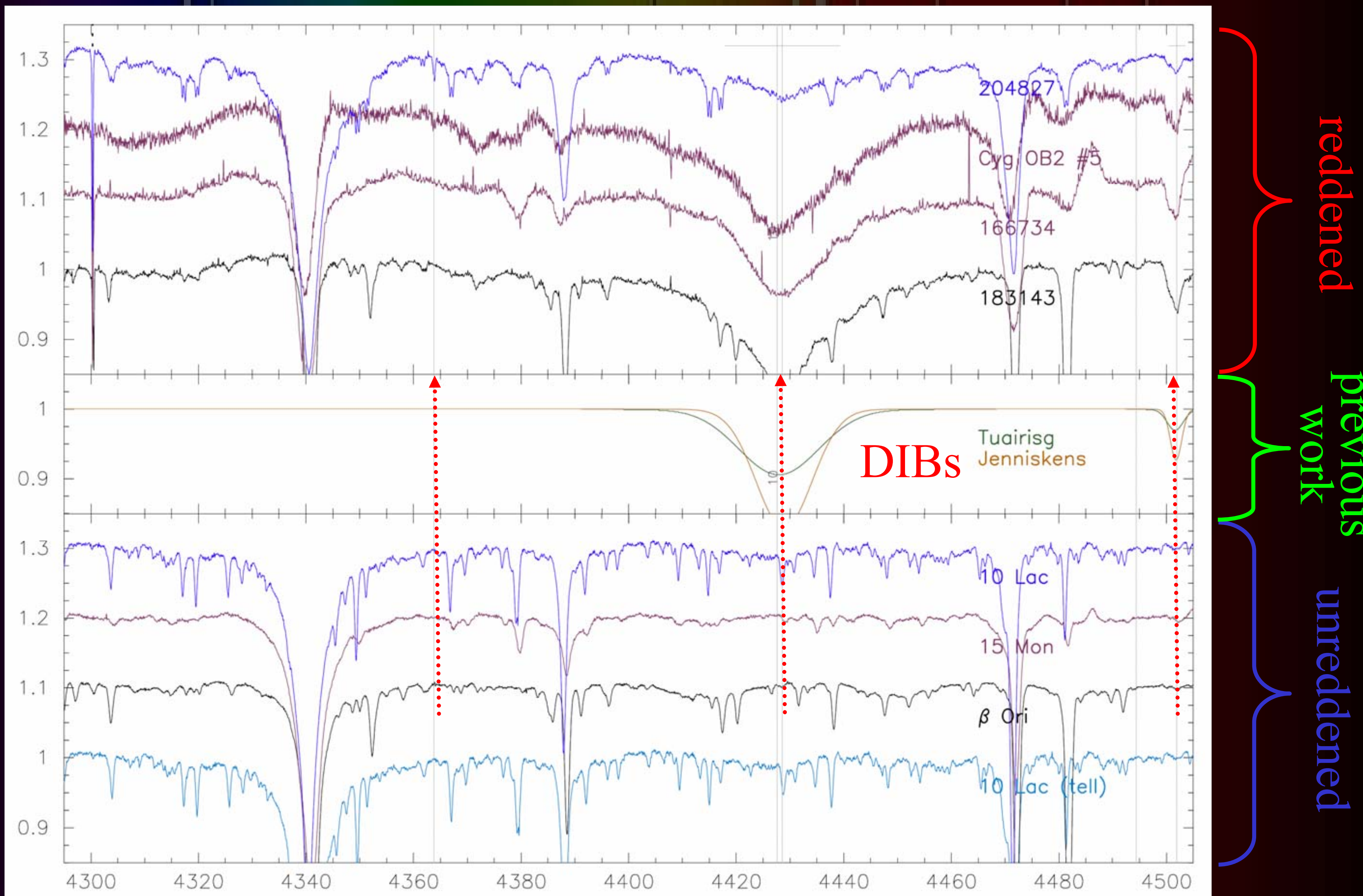
- DIB count: 259 confirmed, 115 new, 374 total!
- Atlas to be released late 2007 or early 2008

DIB Spectral Atlas: Version 2

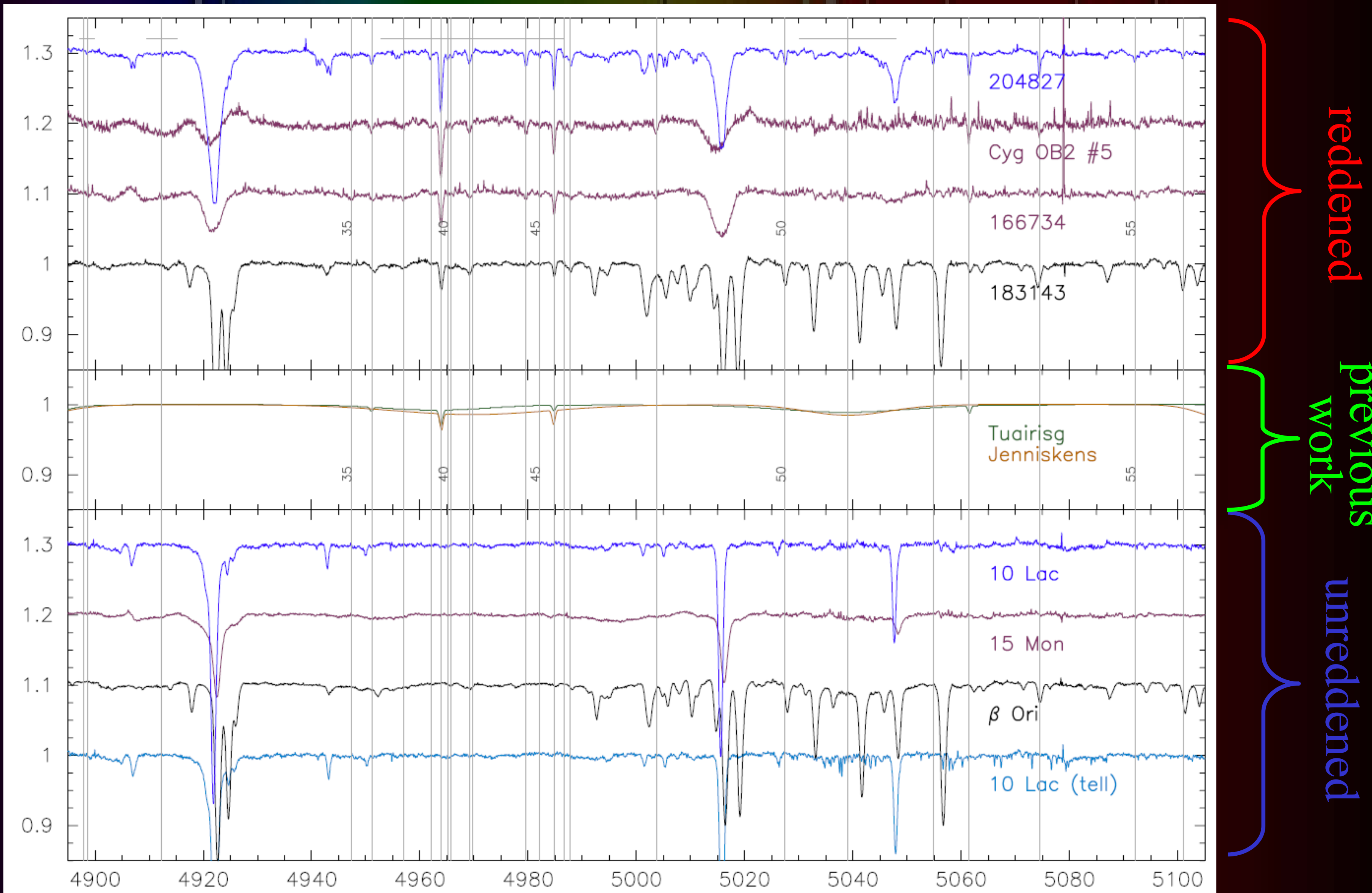
Four heavily reddened stars:

Star	**Sp. Type**	$\mathbf{E_{B-V}}$	$\mathbf{N(C_2)}$
HD 204827	B0V	1.11	440×10^{12}
Cyg OB2 5	O7f	1.99	200×10^{12}
HD 166734	O8e	1.39	160×10^{12}
HD 183143	B7Iae	1.27	$< 6\times10^{12}$

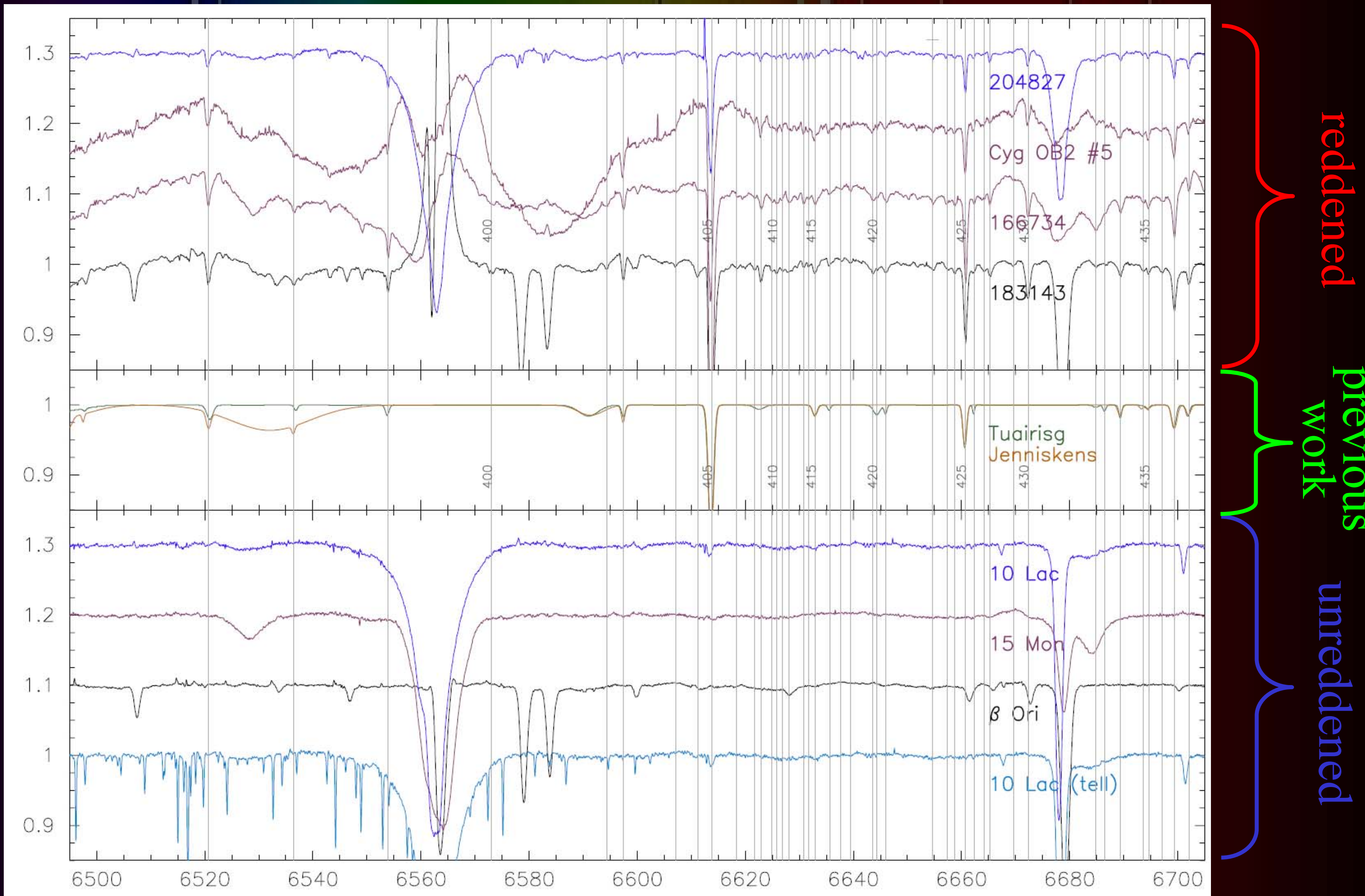
Atlas Plots: 4300–4500 Å



Atlas Plots: 4900–5100 Å



Atlas Plots: 6500–6700 Å



Statistics & Status

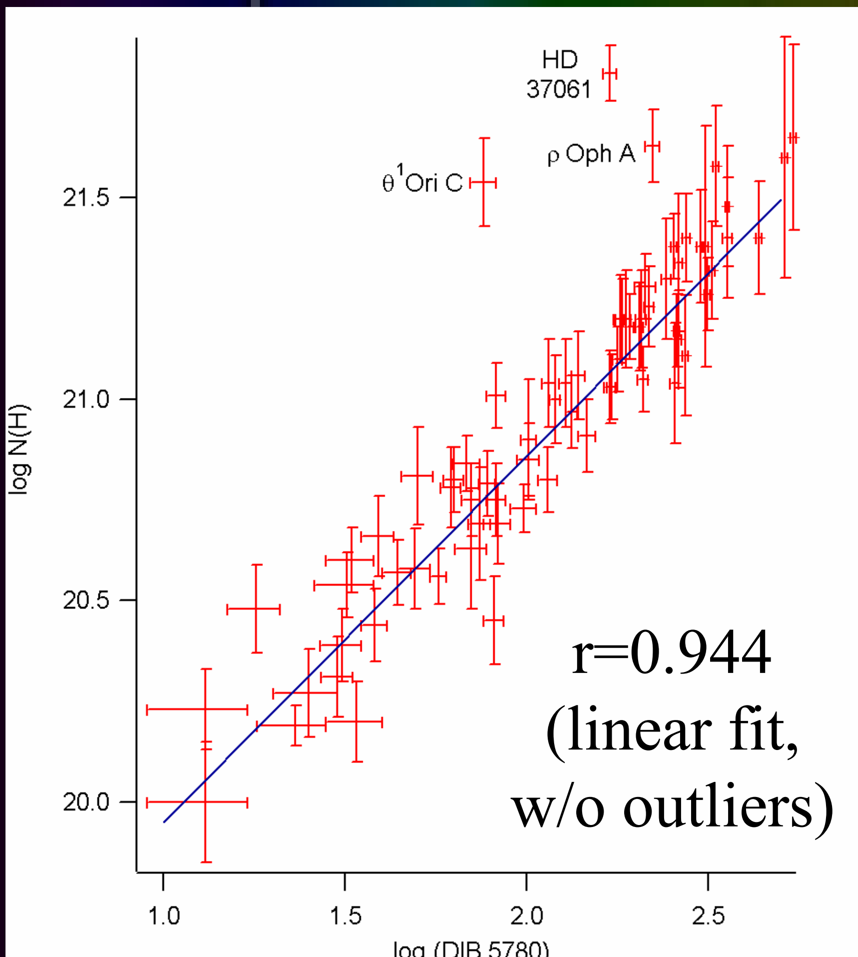
Criterion (2 stars)	Criterion (4 stars)	New DIBs	Confirmed DIBs	Total DIBs
10 σ	5 σ	111	270	381
8 σ	4 σ	151	291	442
4 σ	—	284	350	634

- Issues still to address:
  - defining the continuum
  - blends of DIBs with each other
- Complete atlas sometime in 2008

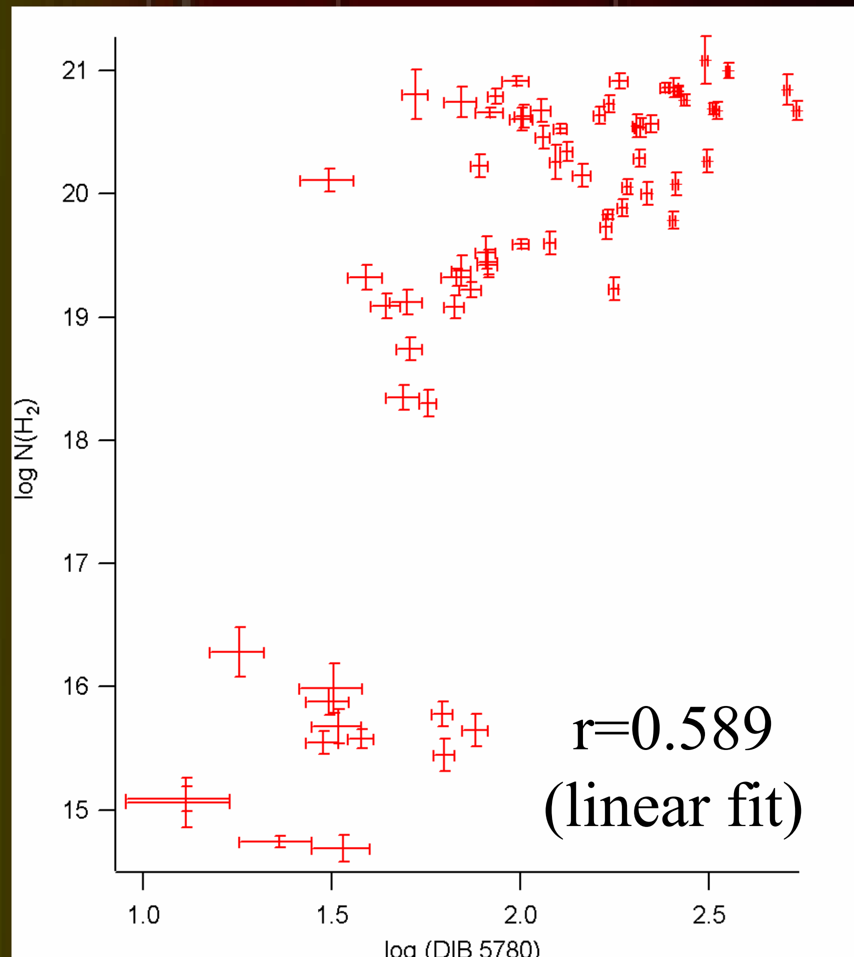
DIB Correlations: H & H_2

λ5780 well correlated with H

[a la Herbig ApJ 407, 142 (1993)]



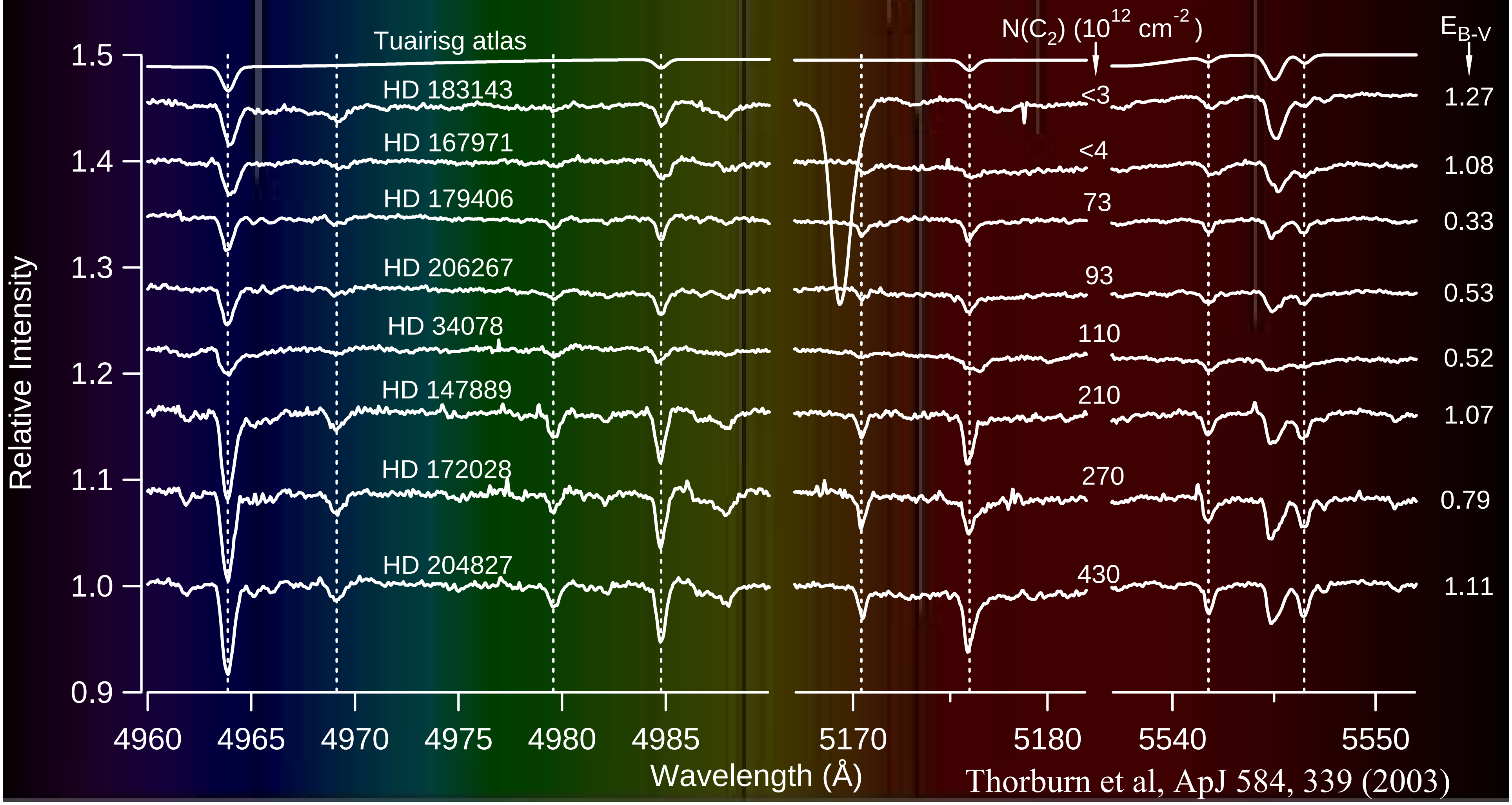
no correlation with H_2



York et al., in preparation

The "C_2 DIBs"

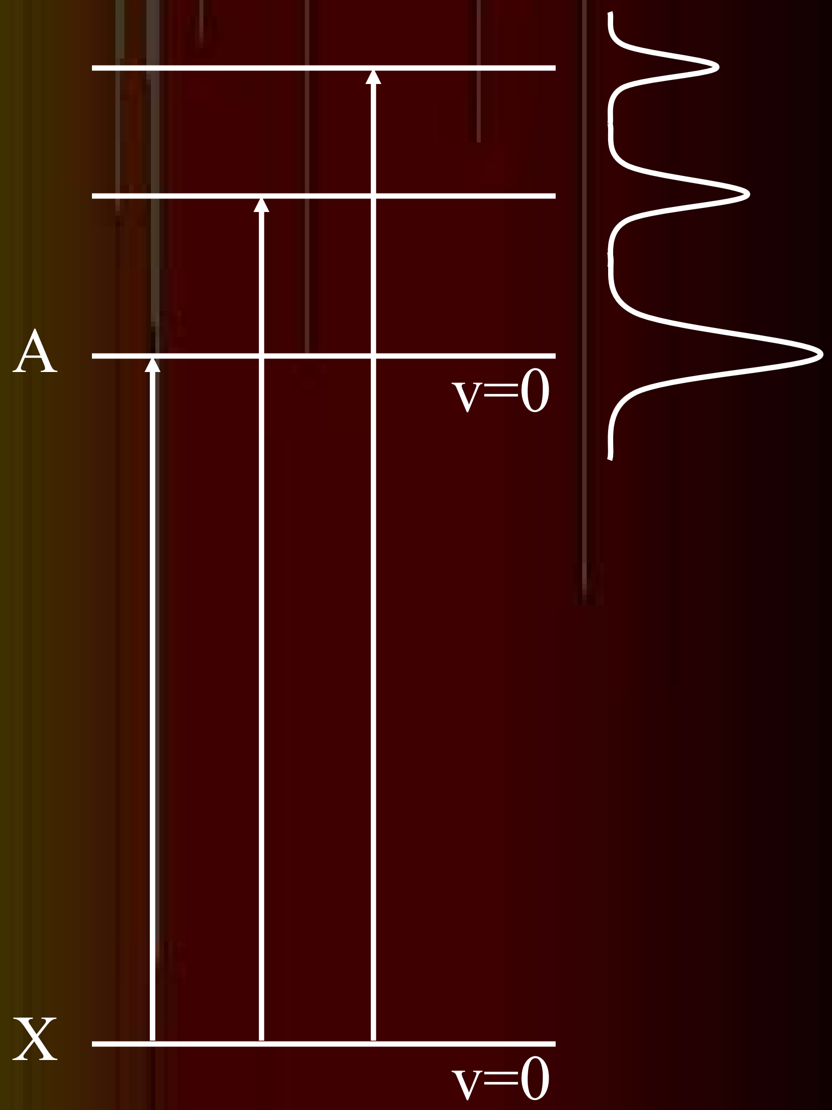
- First set of DIBs known to be correlated with a known species!



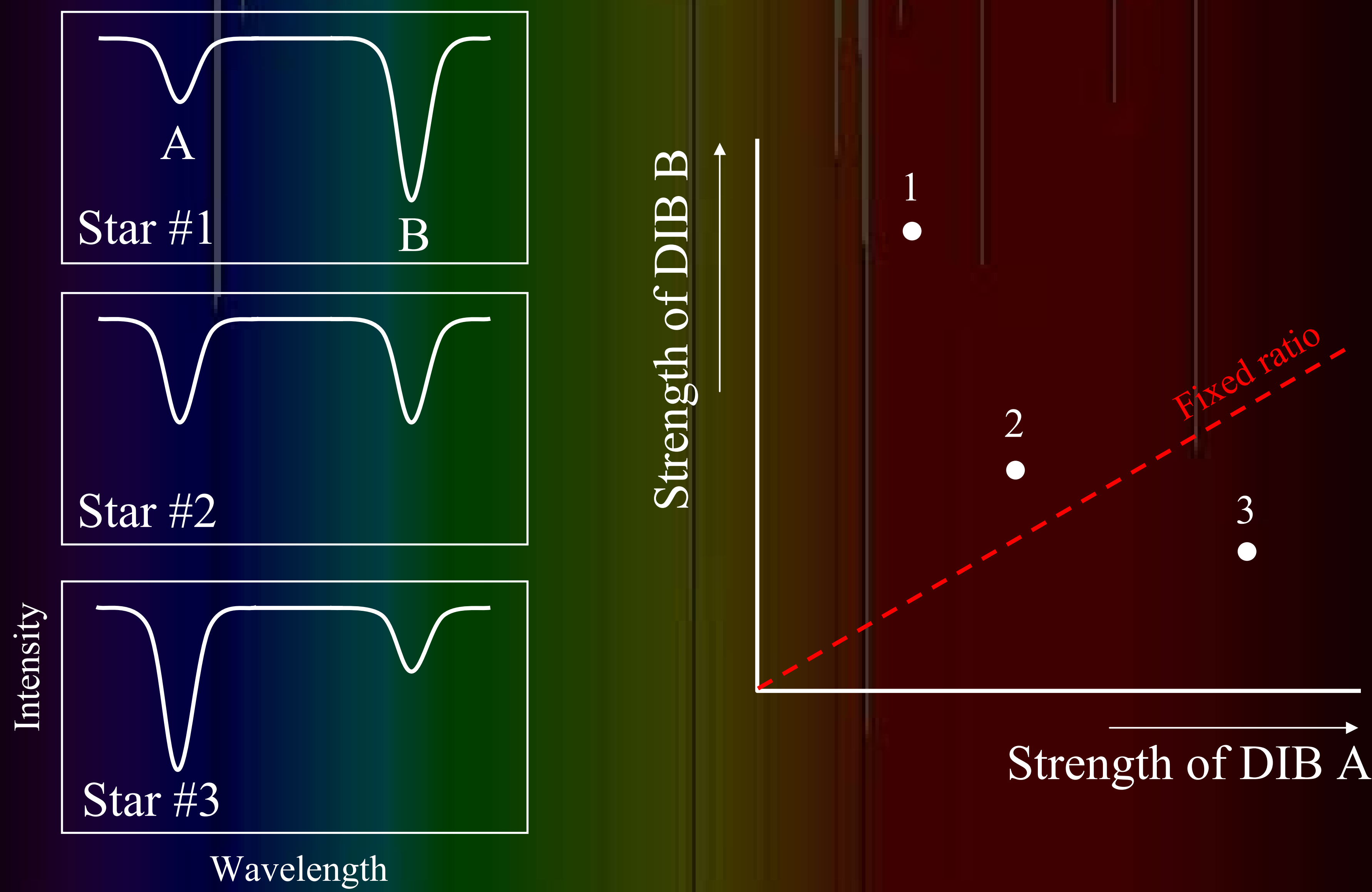
Thorburn et al, ApJ 584, 339 (2003)

Correlations Among DIBs

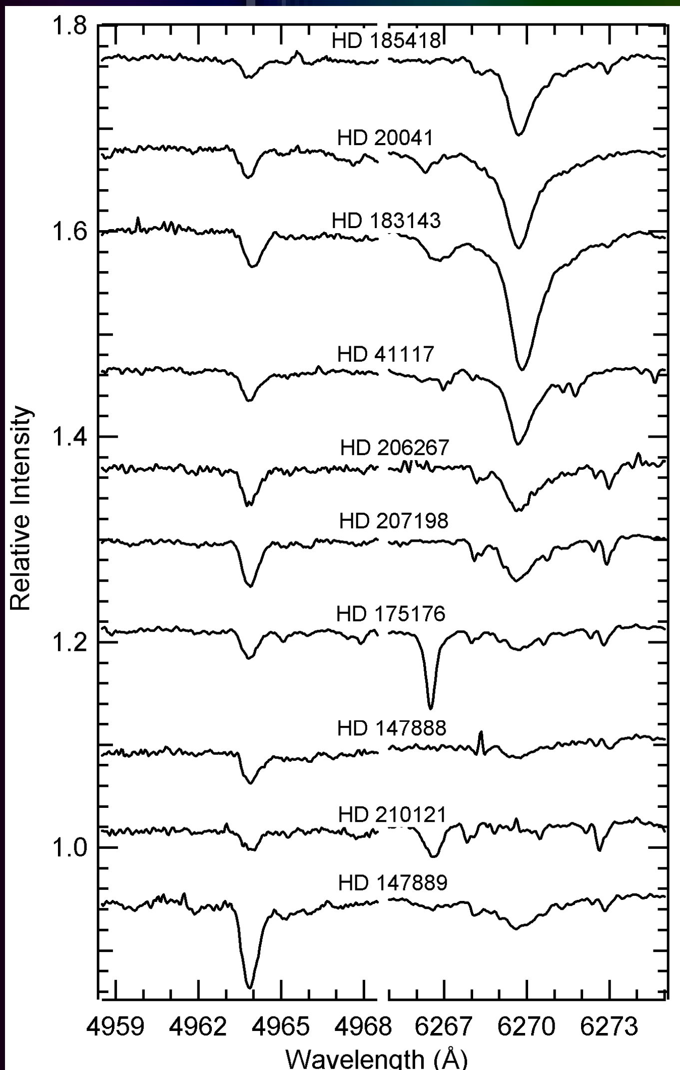
- Assumptions:
  - gas phase molecules
  - DIBs are vibronic bands
  - low temperature
    - carriers all in v=0
  - relative intensities fixed
    - Franck-Condon factors
    - independent of T, n
- Method:
  - look for DIBs with tight correlations in intensity
- Prospect:
  - identify vibronic spectrum of single carrier
  - spacings may suggest ID

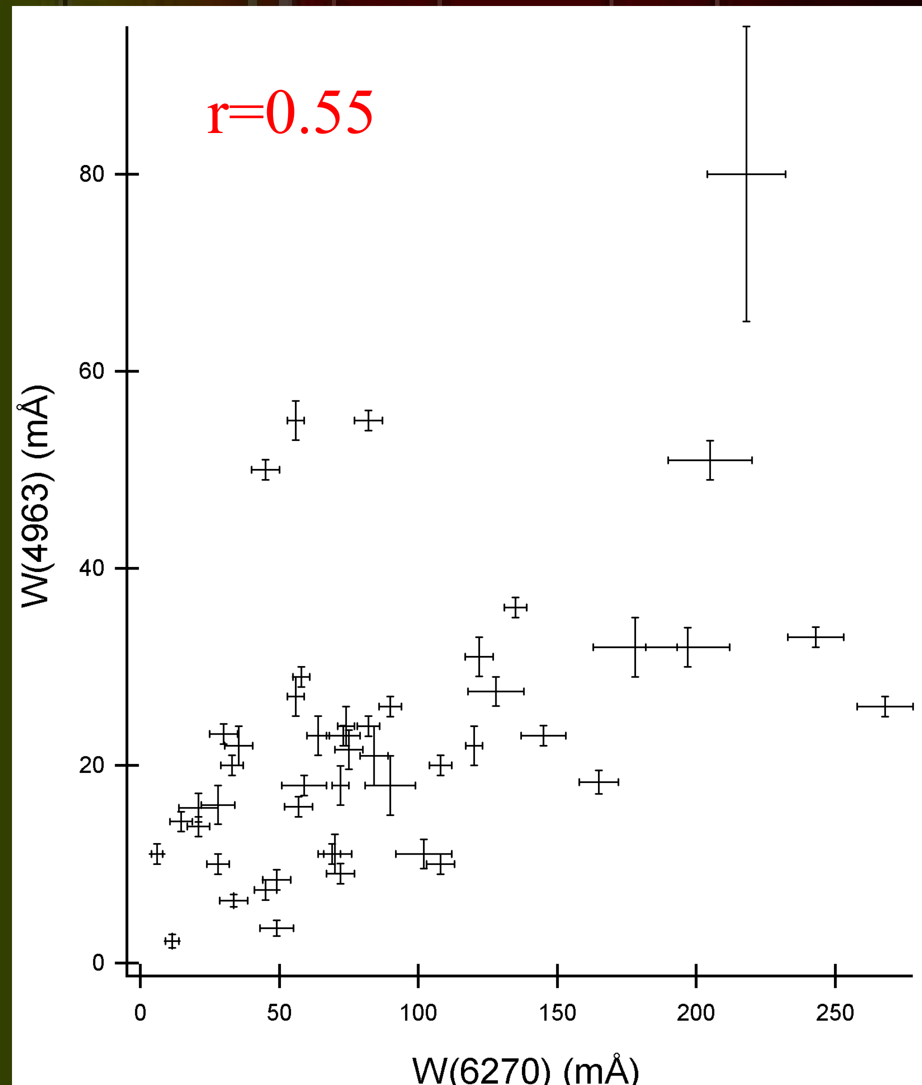


Correlation Plots

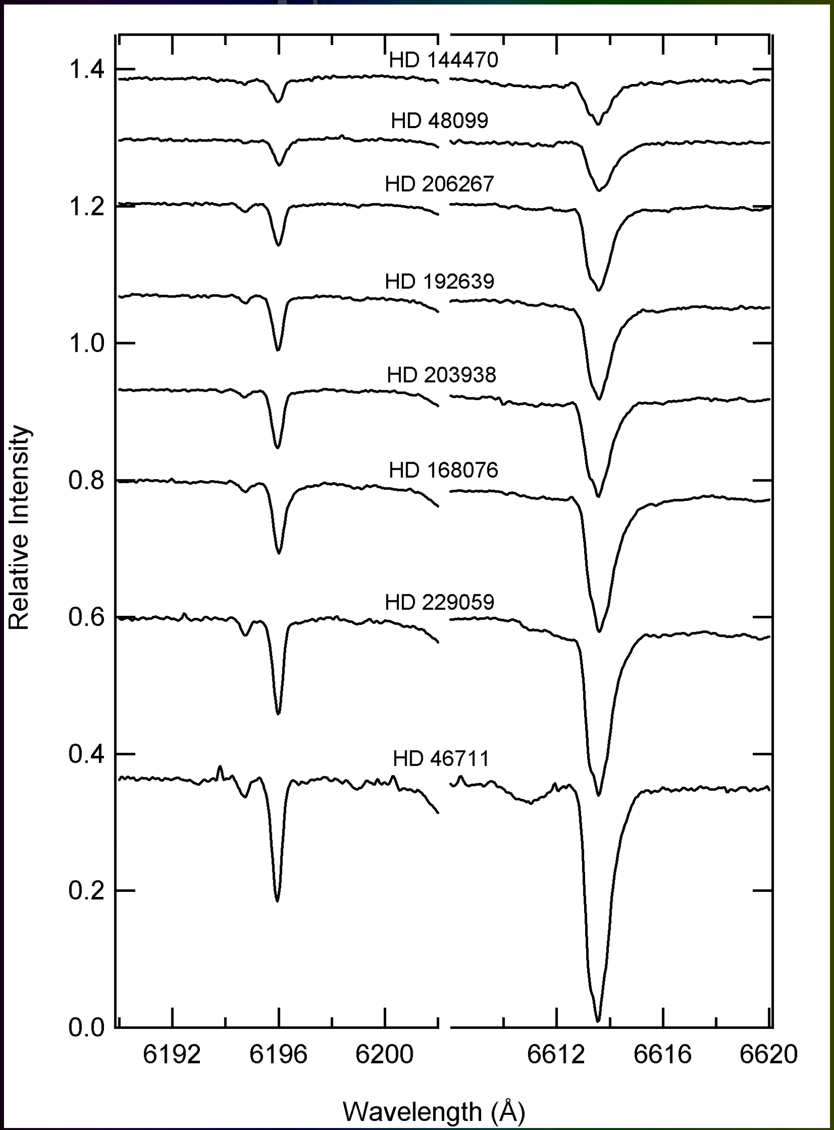


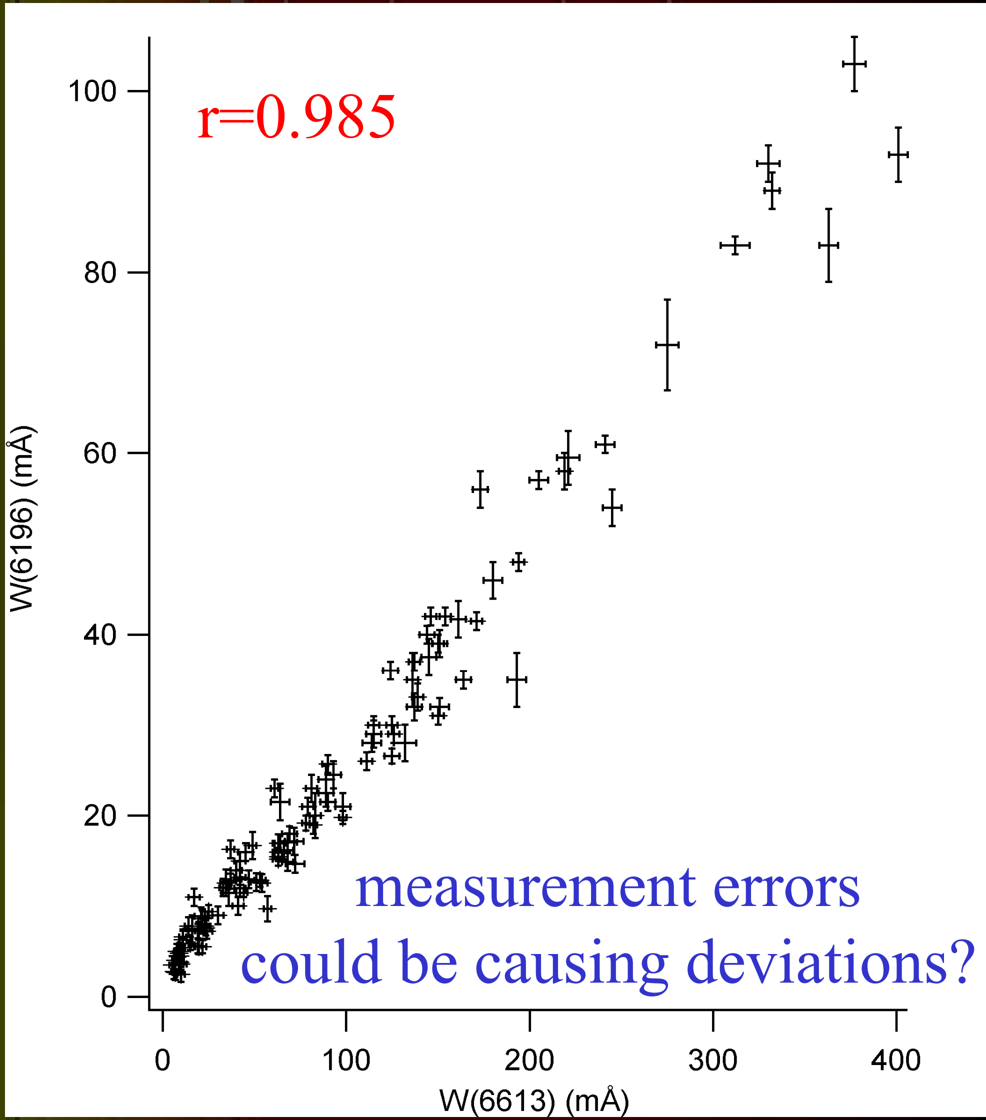
Example: Bad Correlation





Example: Good Correlation

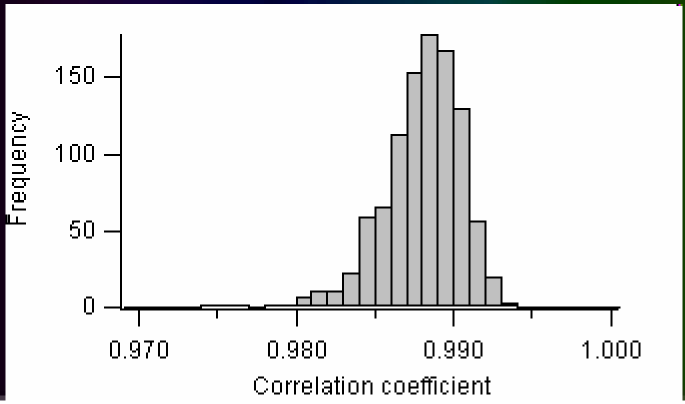


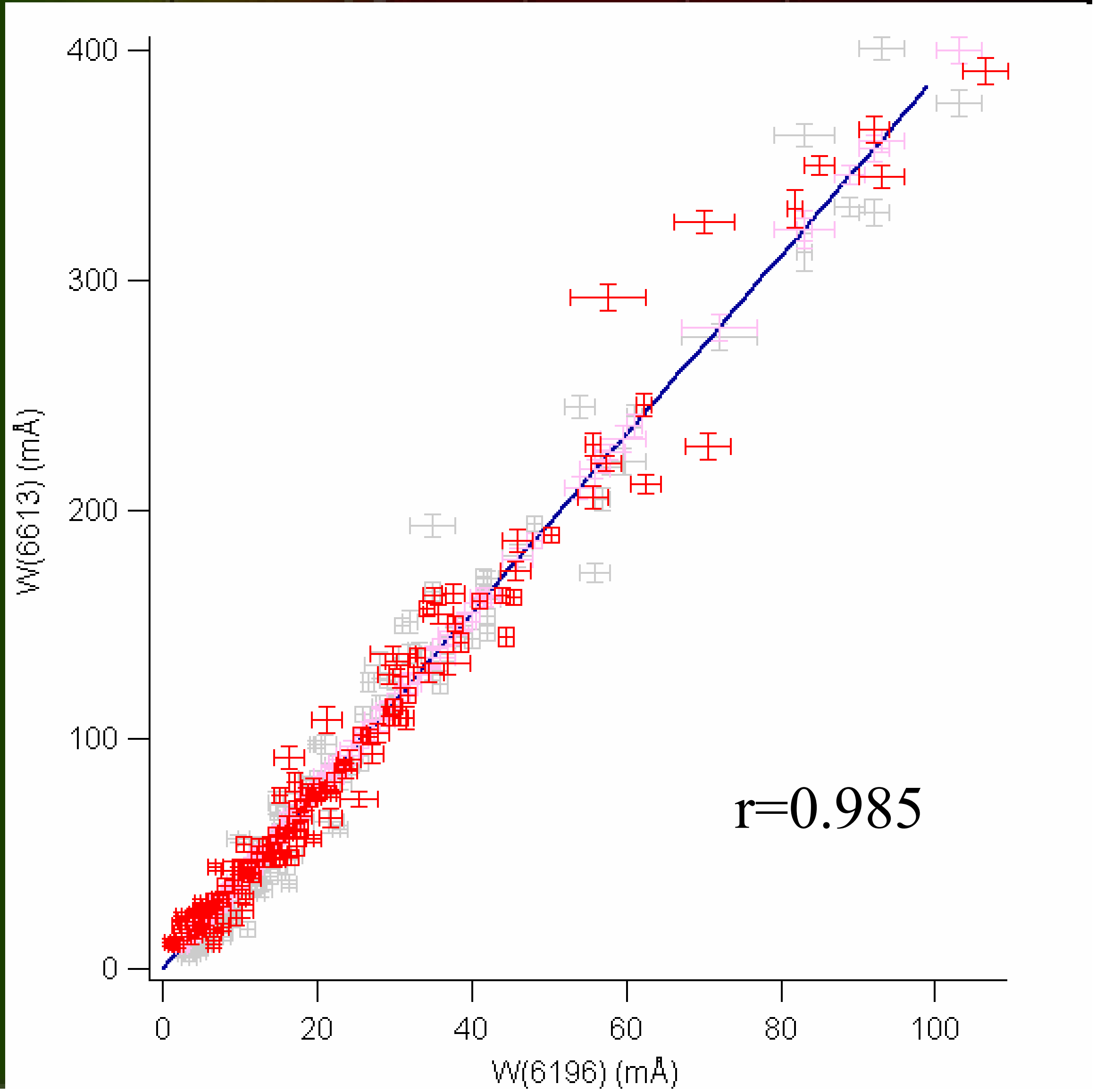


More on λ6613 & λ6196

Can observed scatter be due to measurement errors?

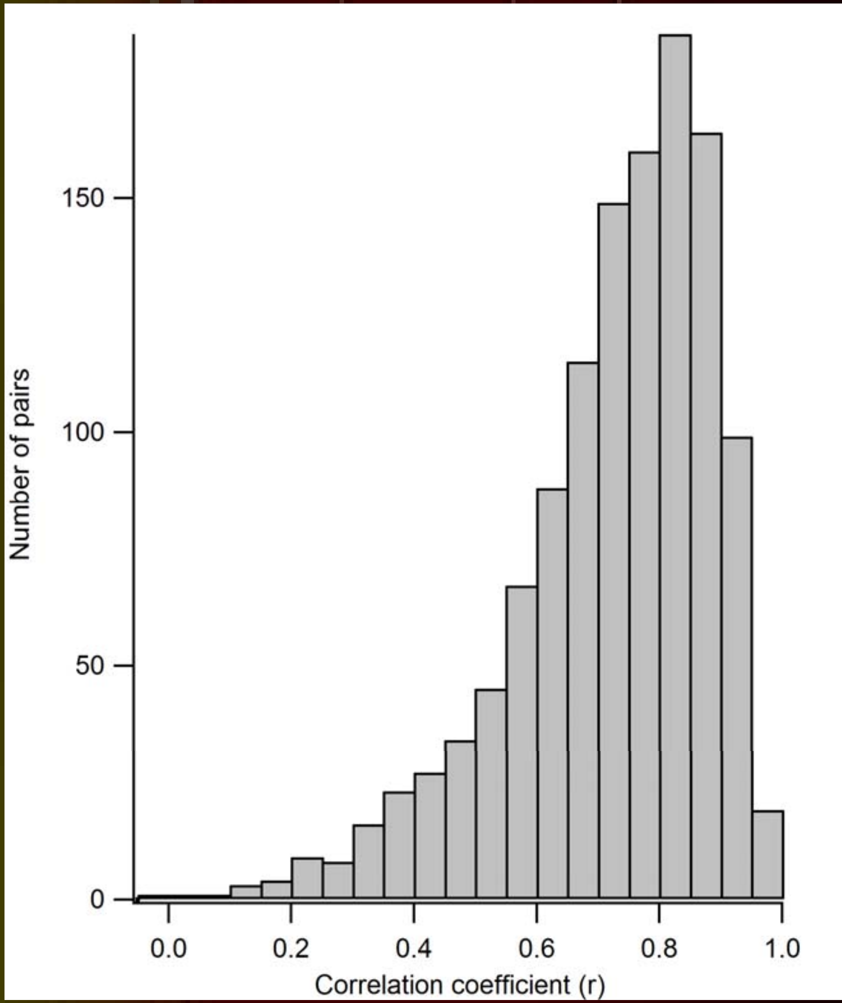
- Observed r=0.985
- Assume perfection
- Add Gaussian noise
- 1000 M.C. trials
- Double the noise
- 1000 M.C. trials
- Statistically OK if we underestimated errors





Statistics of Correlations

- 58 strong DIBs
- Pairs of DIBs observed in >40 stars
- 1218 pairs
- Generally well correlated
- Few very good correlations
  - 118 with r > 0.90
  - 19 with r > 0.95



Why So Few Perfect Correlations?

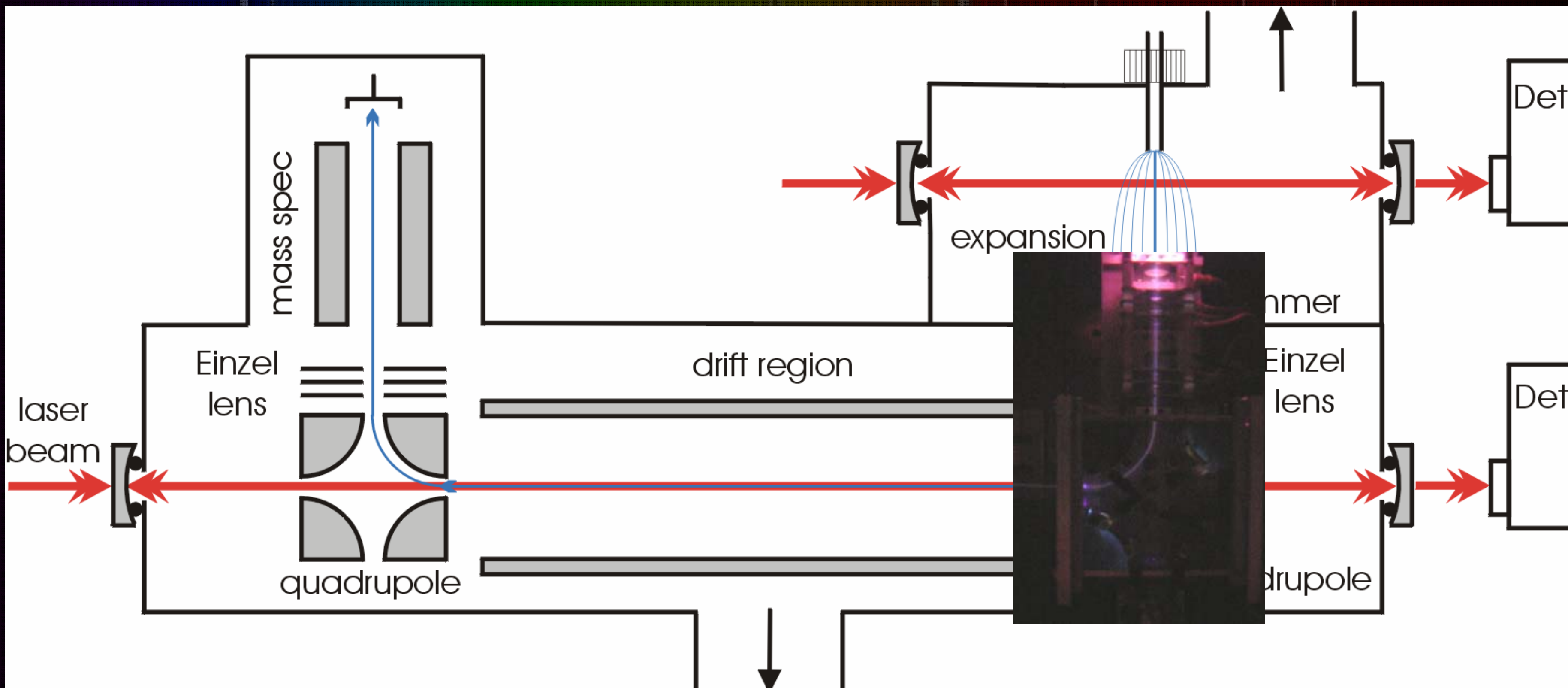
- Assumption of a common ground state bad?
  - energetically accessible excited states?
    - spin-orbit splitting?
      - if linear molecules
    - low lying vibrationally excited states?
      - if very large molecules
- “Vertical” transitions?
  - intense origin band
  - weaker vibronic bands
    - correlations could be seen with weaker bands?

The Road to a Solution

- Laboratory spectroscopy is essential!
- Blind laboratory searches unlikely to work
  - ~10^7 organic molecules known on Earth
  - ~10^{200} stable molecules of weight < 750 containing only C, H, N, O, S
- Observational constraints & progress are also essential!
- Computational chemistry will play an important role
- Close collaborations needed!

Advertisement

SCRIBES: Sensitive Cooled Resolved Ion BEam Spectroscopy



- Infrared spectra of ions important in:
  - astrochemistry
  - atmospheric chemistry
  - propulsion/combustion

- Optical spectra → DIBs ?

Acknowledgments

ACS Petroleum Research Fund

Dreyfus New Faculty Award

NASA Laboratory Astrophysics

NSF Divisions of Chemistry & Astronomy

Packard Fellowship

Air Force Young Investigator Award

Cottrell Scholarship

http://astrochemistry.uiuc.edu