The Diffuse Interstellar Bands: A Long-Running Mystery

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APO DIB Collaboration:

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Outline

- History of Diffuse Interstellar Bands
- Apache Point Observatory survey
- Correlations among DIBs
- Correlations with other species
- Evaluation of potential DIB carriers

Josef von Fraunhofer ~ 1814

* Optician who wanted to quantify the dispersion of different types of glasses

* Noticed emission lines in flames

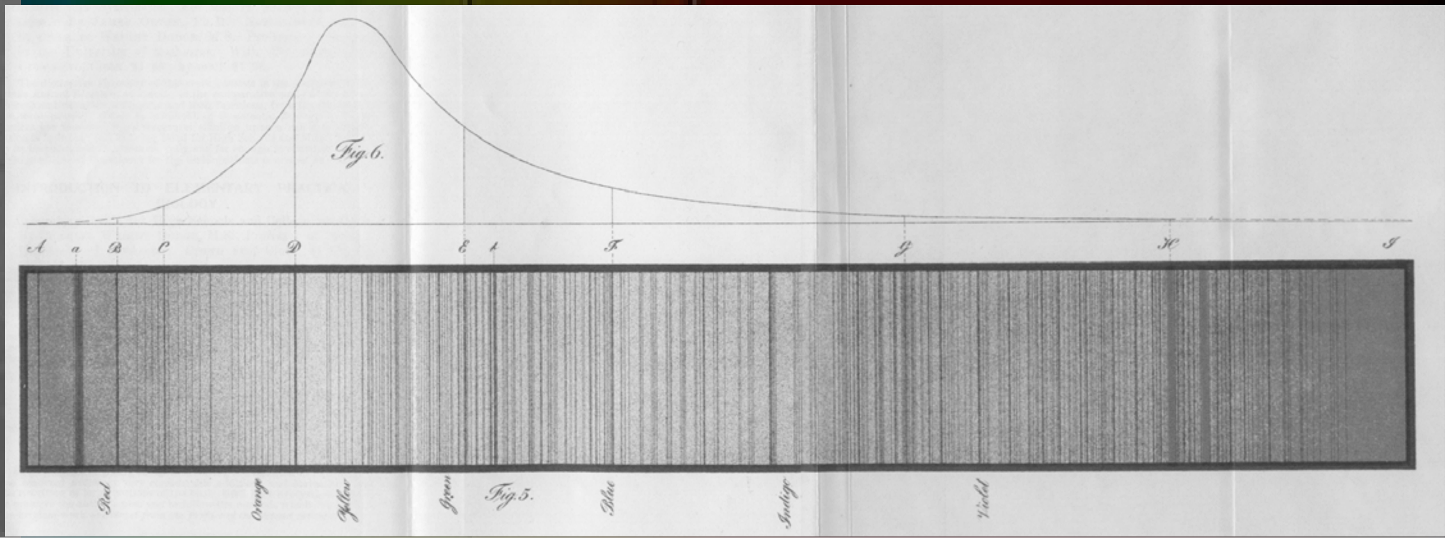
* Decided to look at sunlight

* Labels A, B, C, ...

* D doublet in flame

* Moon & Venus

* Bright stars



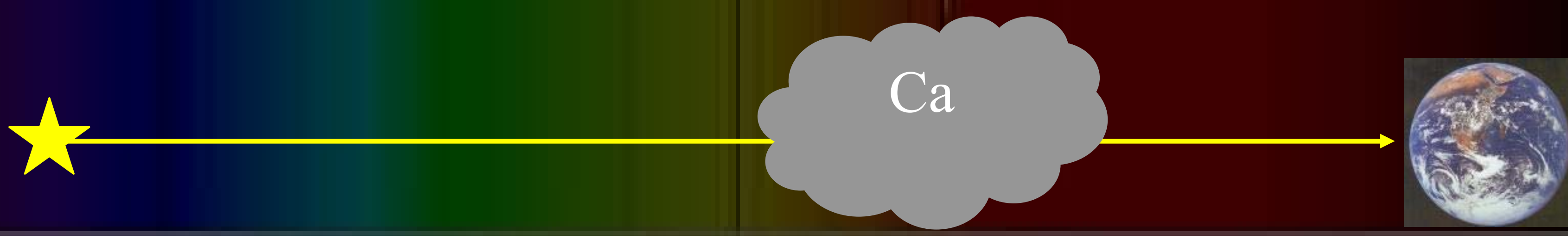
Interstellar Lines

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 Sodium Lines

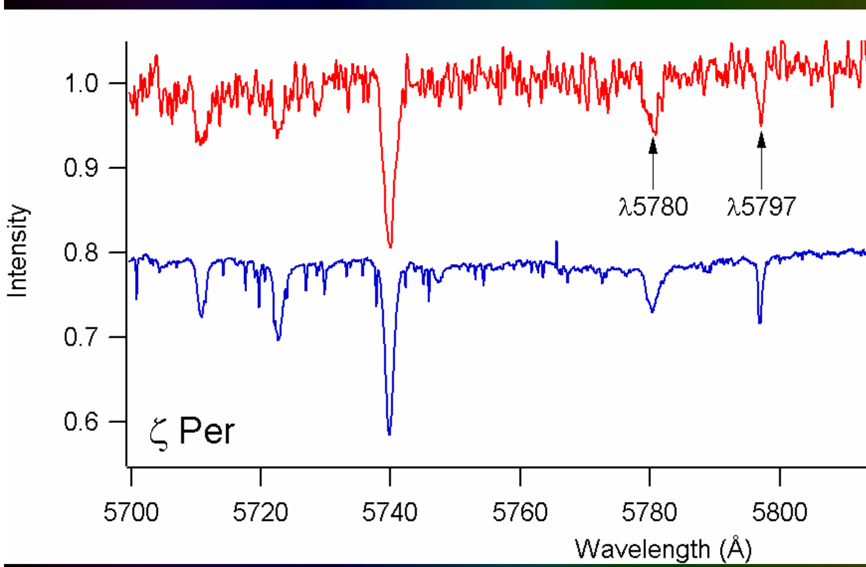
In 1919, Mary Lea Heger (Lick) found the sodium D lines are "stationary" in binaries β Sco & δ Ori.

> "The close relationship between the D lines of sodium and the H and K lines of calcium in the two stars...is very striking. Both in appearance and in behavior these lines are entirely comparable. 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?"

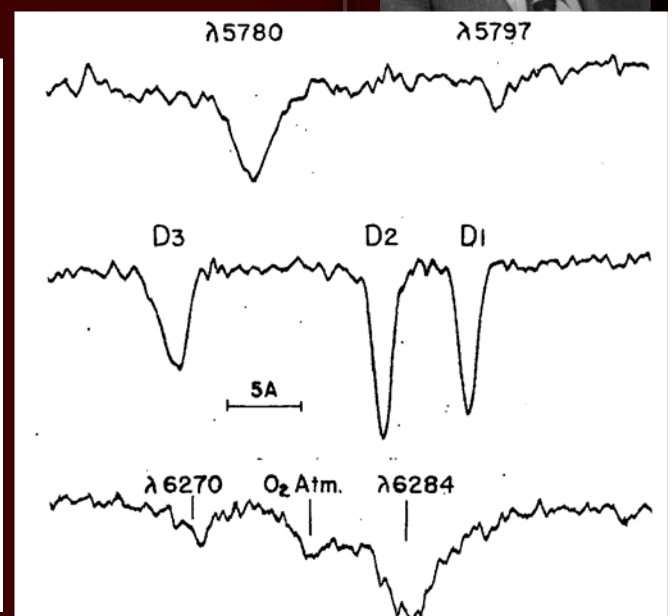
Discovery of the DIBs

- λλ5780, 5797 seen as unidentified bands
  - – ζ Per, ρ Leo (Mary Lea Heger, Lick, 1919)
- Six bands confirmed as interstellar
  - – Merrill & Wilson, Mt. Wilson, 1938
- Broad ("diffuse")



1960	10
1966	26
1975	39
1988	50
1994	229
today	400?

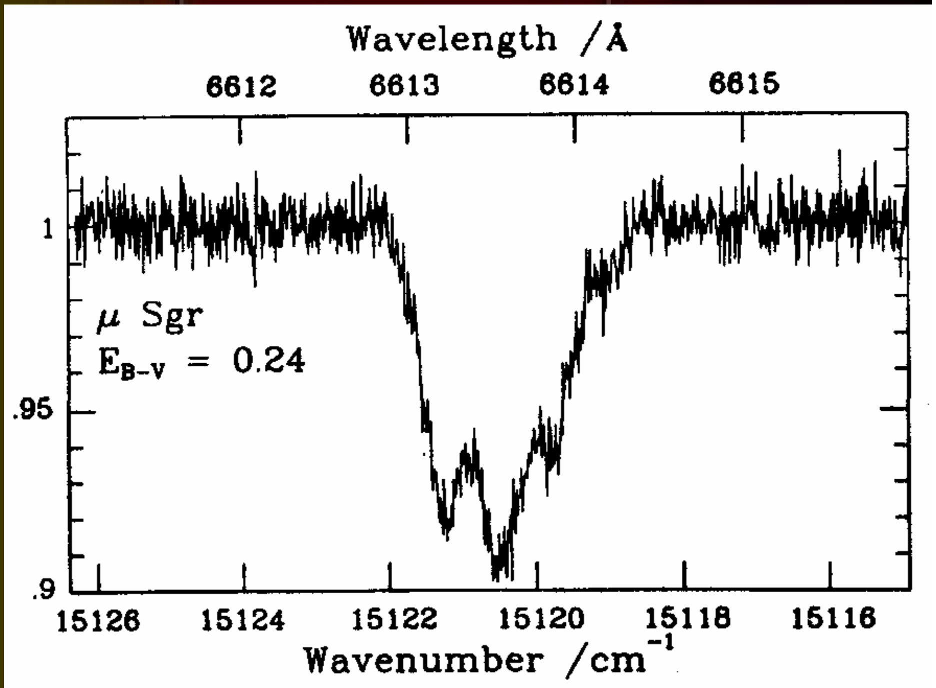
B. J. McCall, in preparation



Merrill & Wilson, ApJ 87, 9 (1938)

What are the DIBs?

- Reasonable correlation with dust extinction
  - but "level off" at high A_V → diffuse clouds only?
  - for a long time, solid state carriers favored
- Several characteristics argue against dust:
  - constancy of λ
  - lack of emission
  - fine structure!
- Present consensus:
  - gas-phase molecules
  - probably large
  - likely carbon-based
  - reservoir of organic material
- Greatest unsolved mystery in spectroscopy!



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

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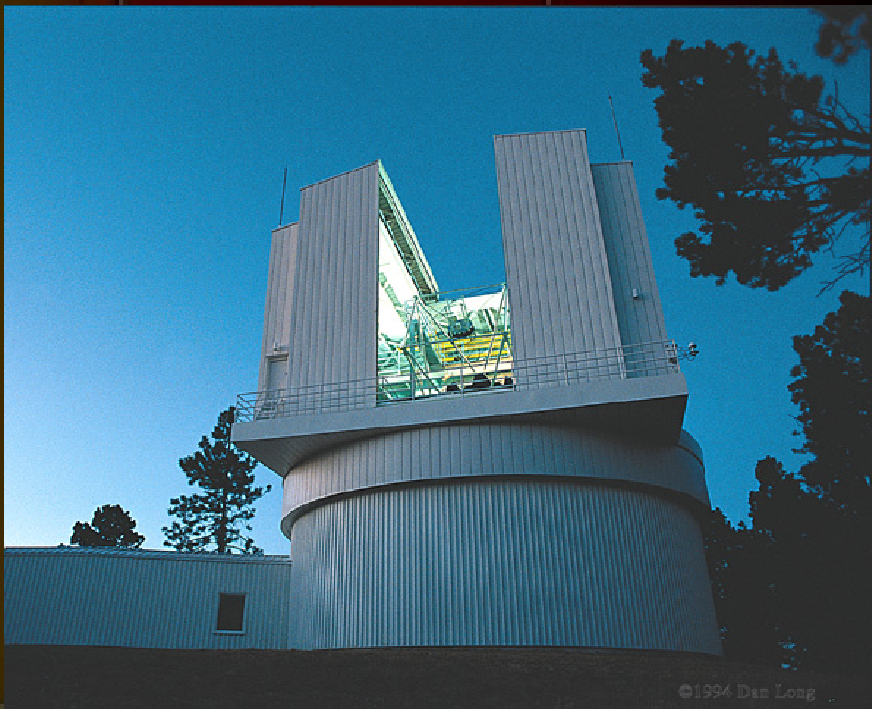
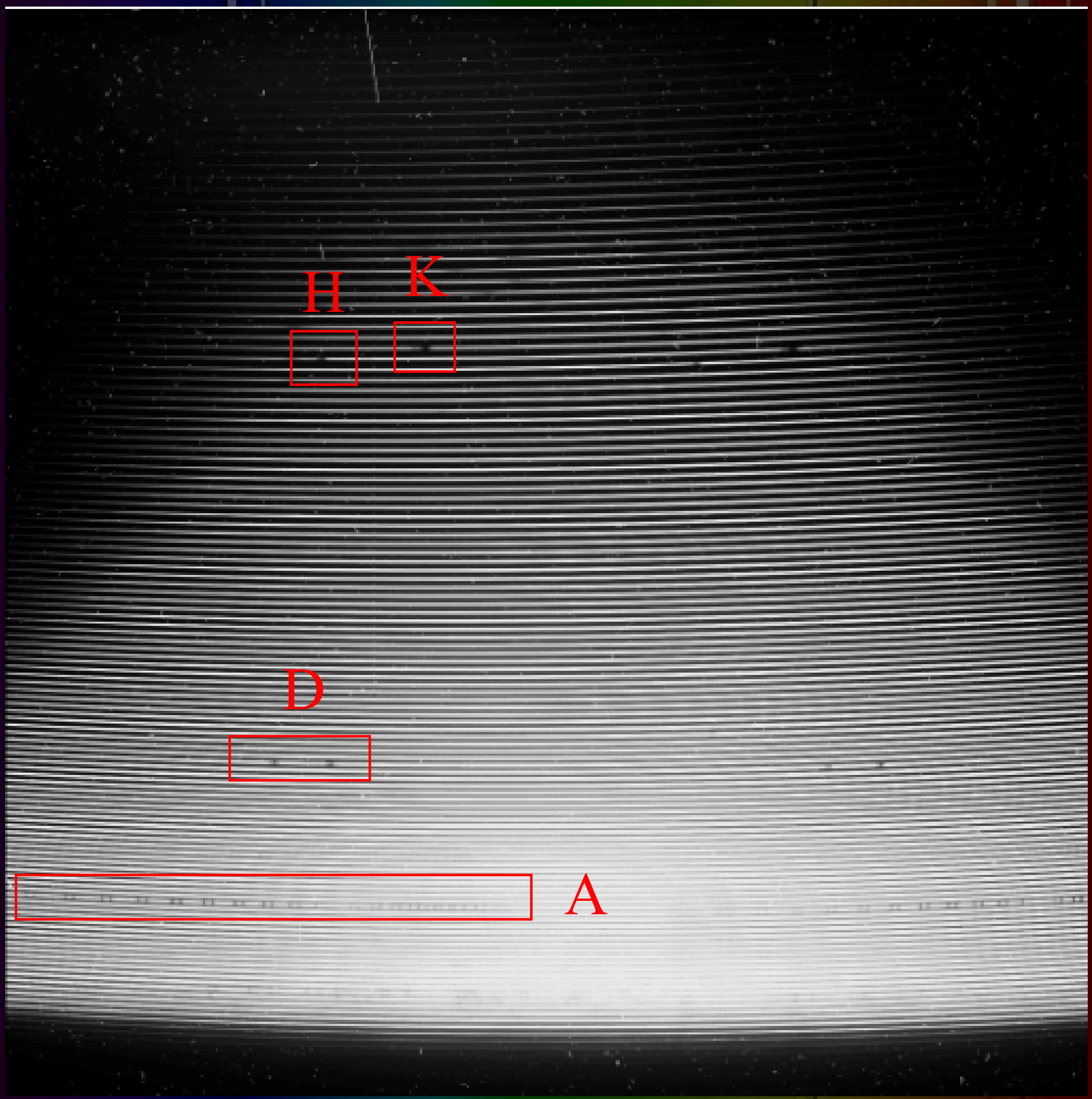
The APO DIB Survey

- Apache Point Observatory 3.5-meter
- 3,600–10,200 Å ; $\lambda/\Delta\lambda \sim 37{,}500$ (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



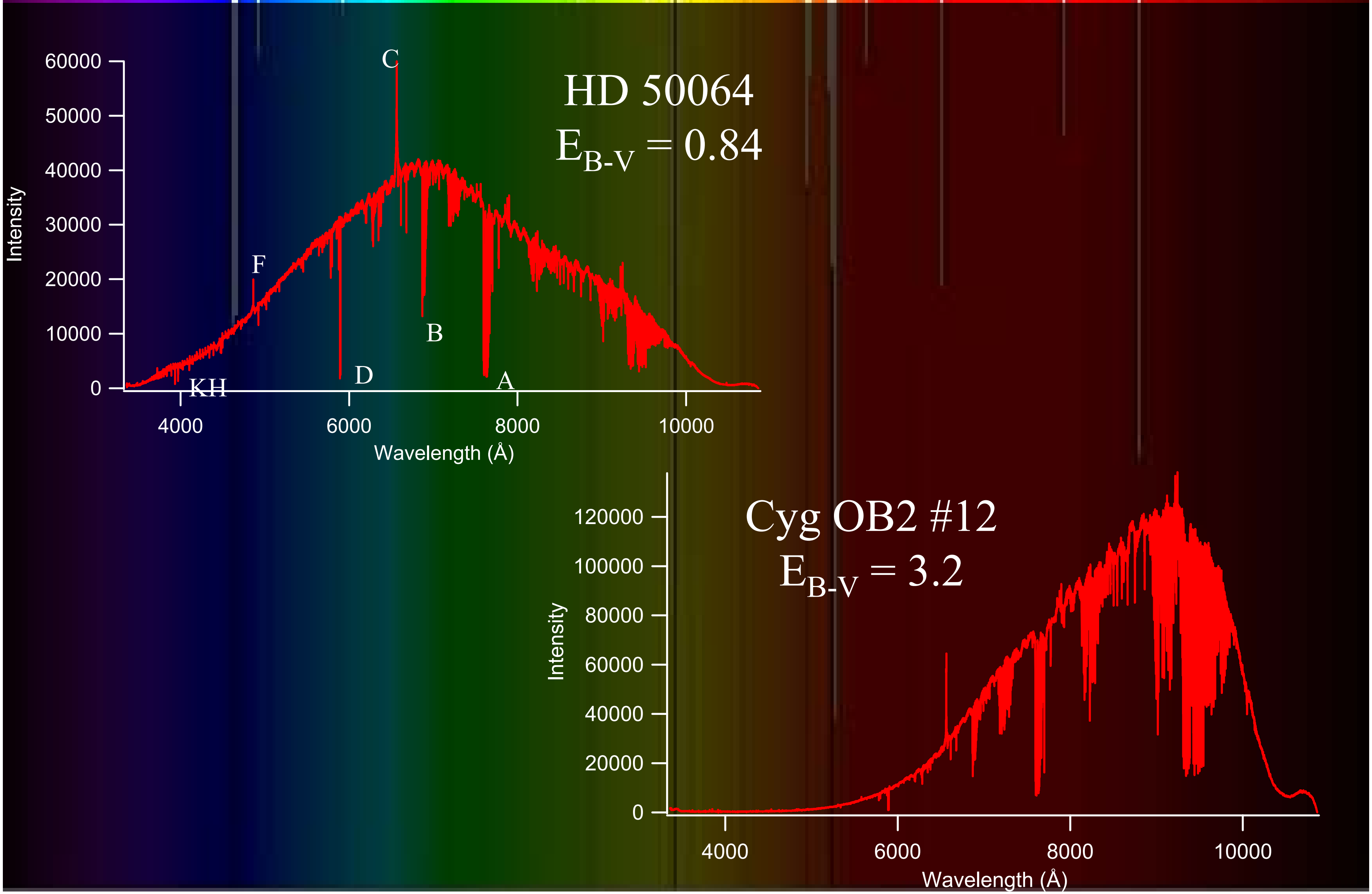
Fraunhofer Lines

H: Ca II ~ 3968 Å
K: Ca II ~ 3934 Å

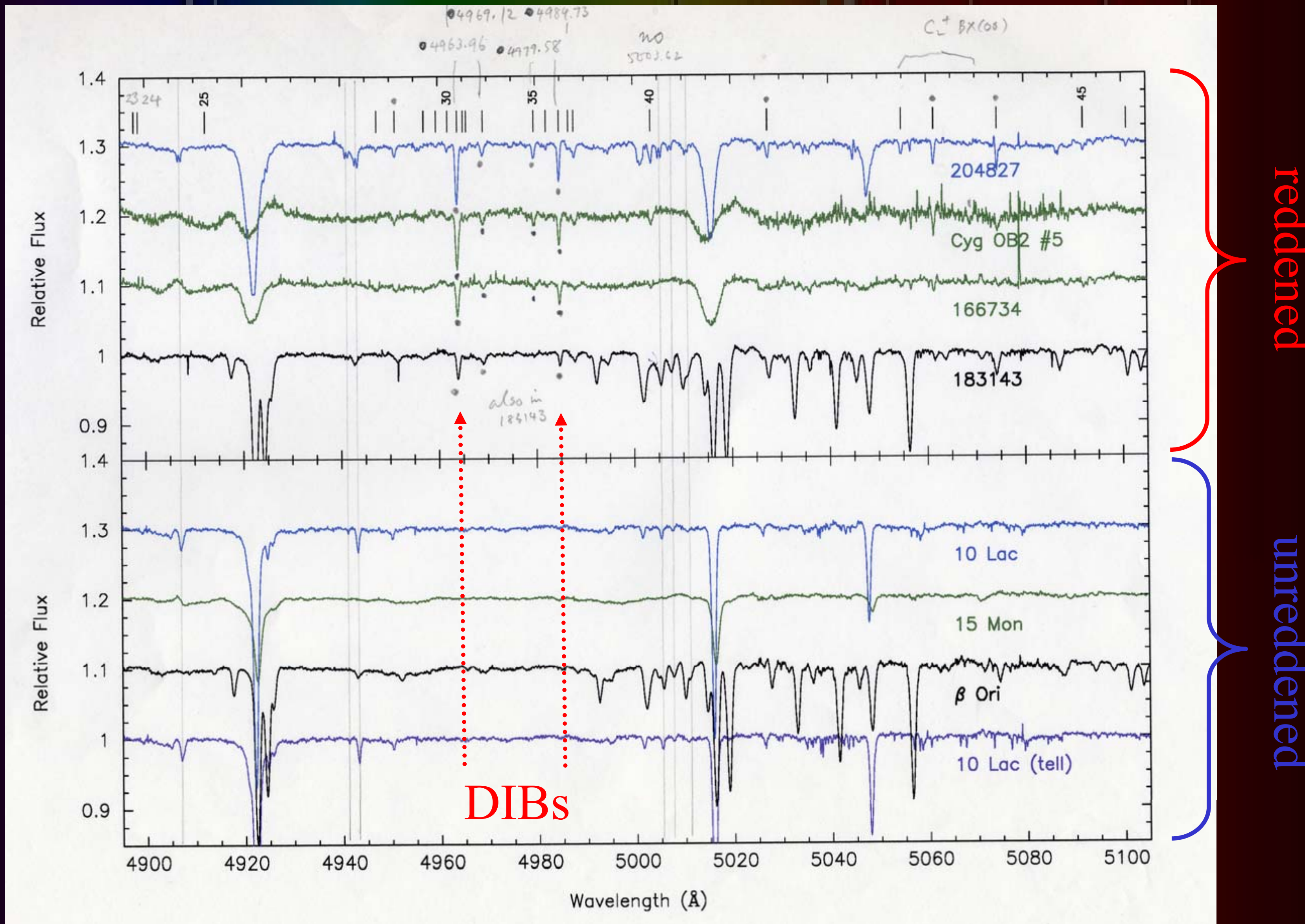
D: Na I ~ 5890 Å

A: O_2 ~ 7650 Å

Stellar Spectra



Stellar Spectra



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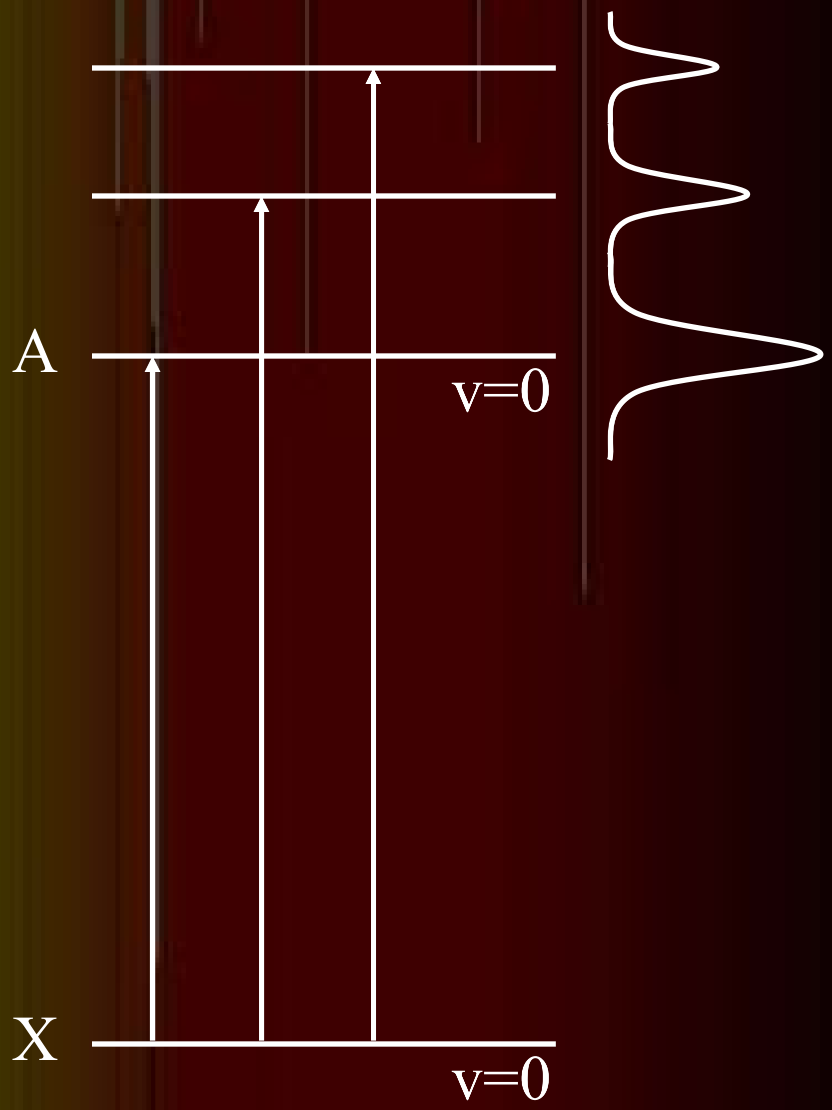
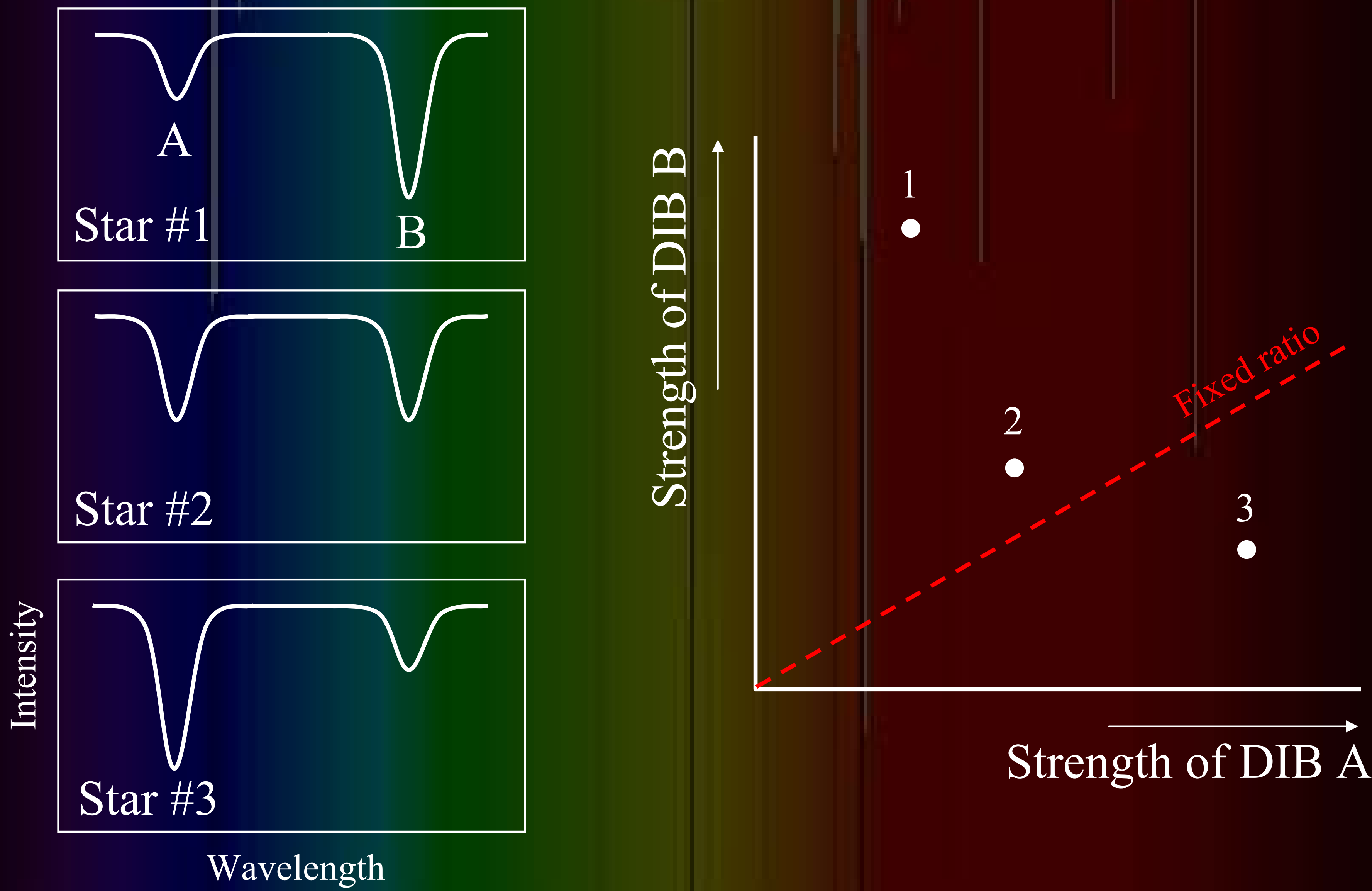
Search for a Common Carrier

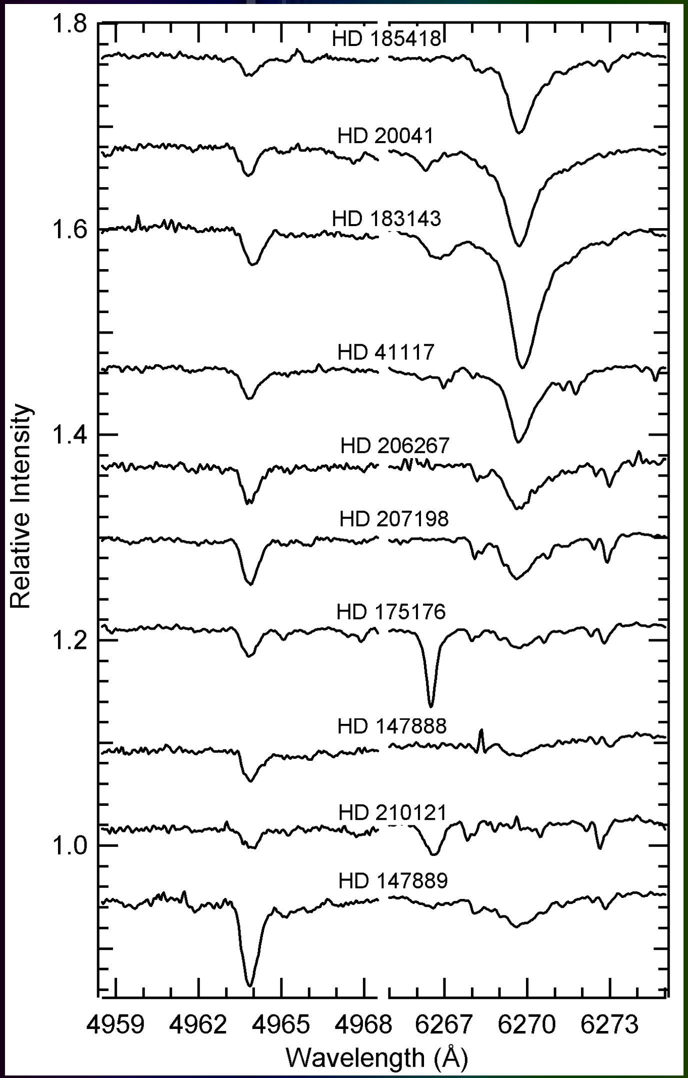
- Assumptions:
  - gas phase molecules
  - DIBs are vibronic bands
  - low temperature
    - carriers all in v=0
  - relative intensities fixed
    - Franck-Condon factors
    - independent of T, n
- Method:
  - look for DIBs with tight correlations in intensity
- Prospect:
  - identify vibronic spectrum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

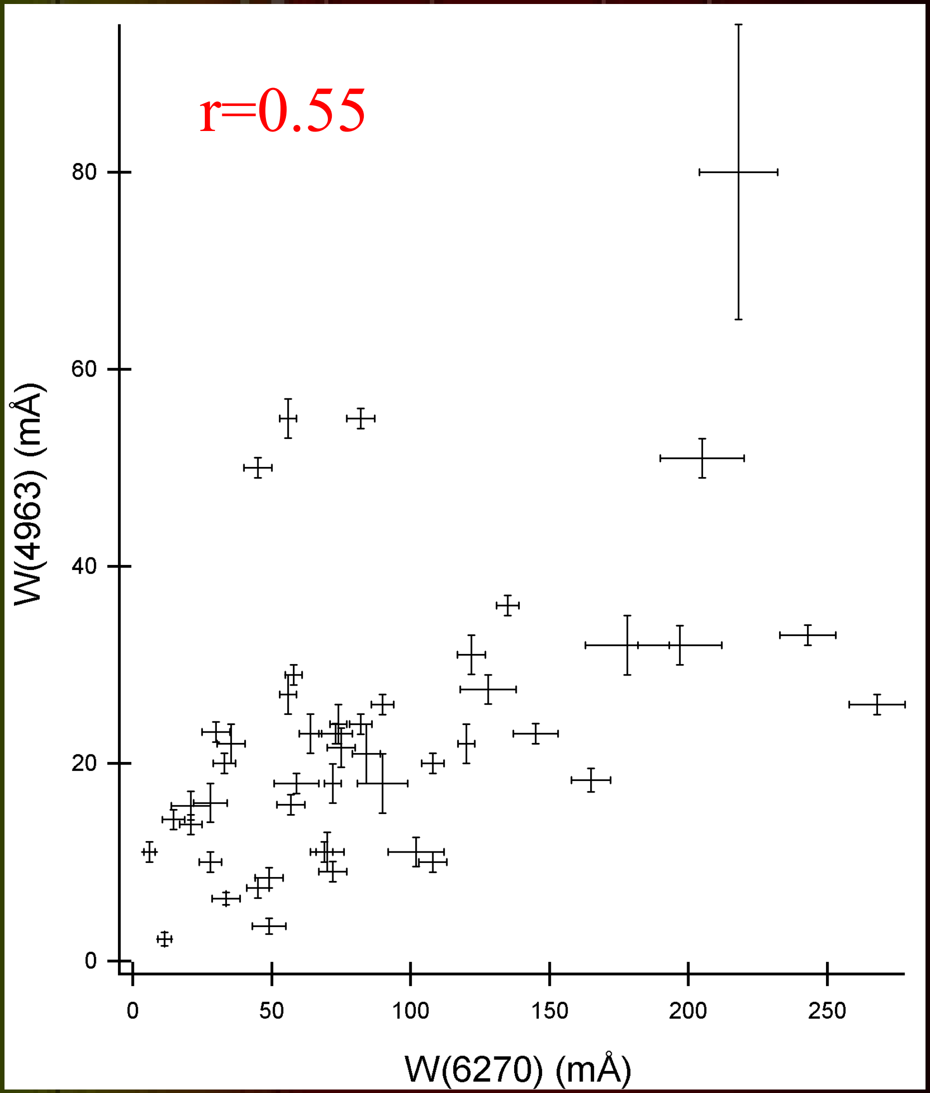


DIB Correlations

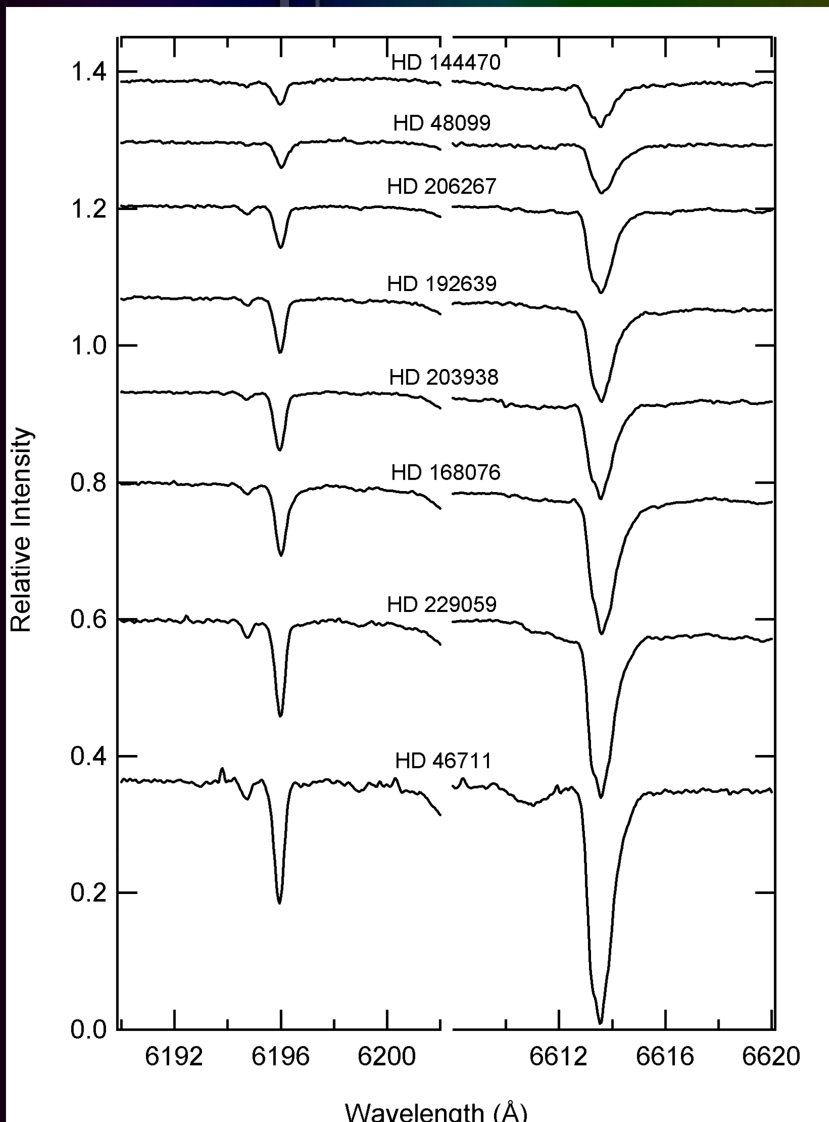


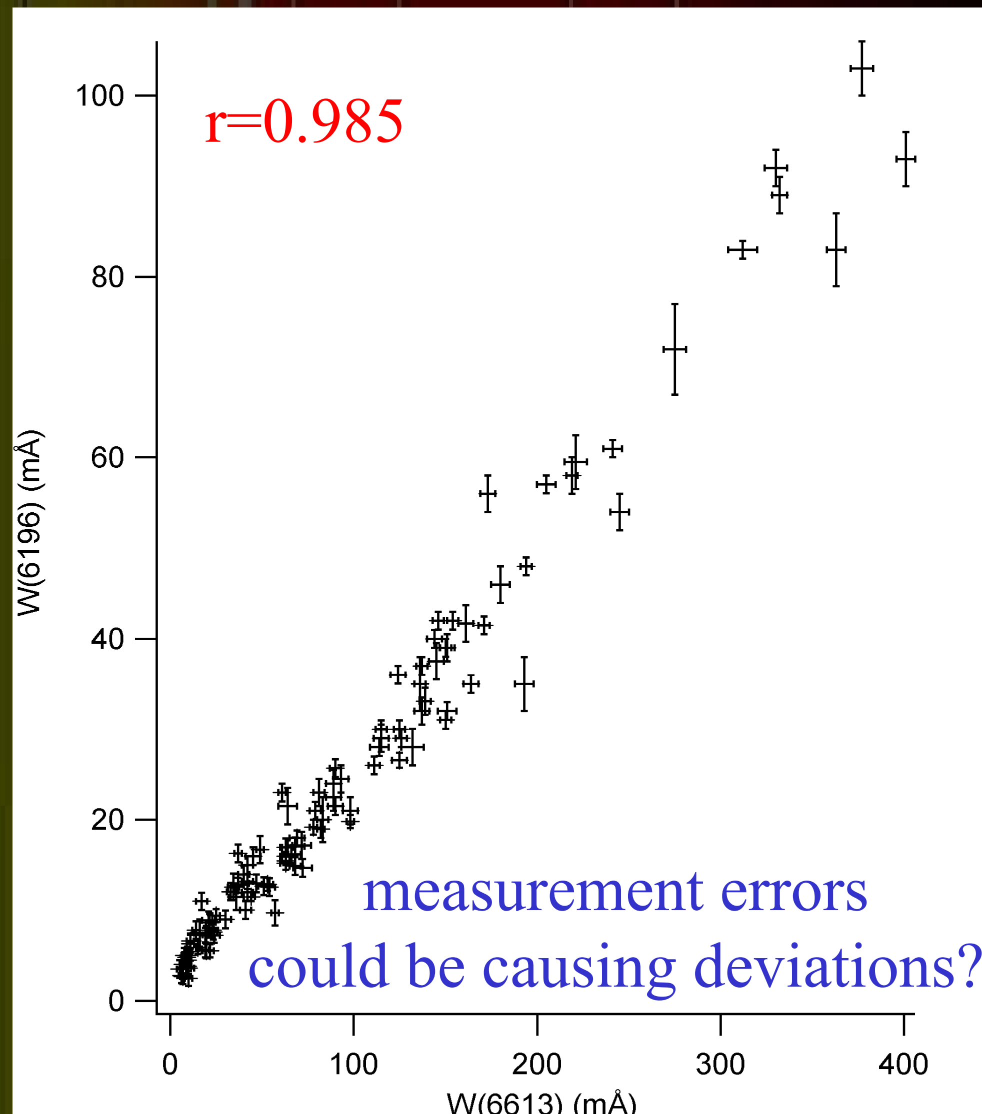
Example: Bad Correlation





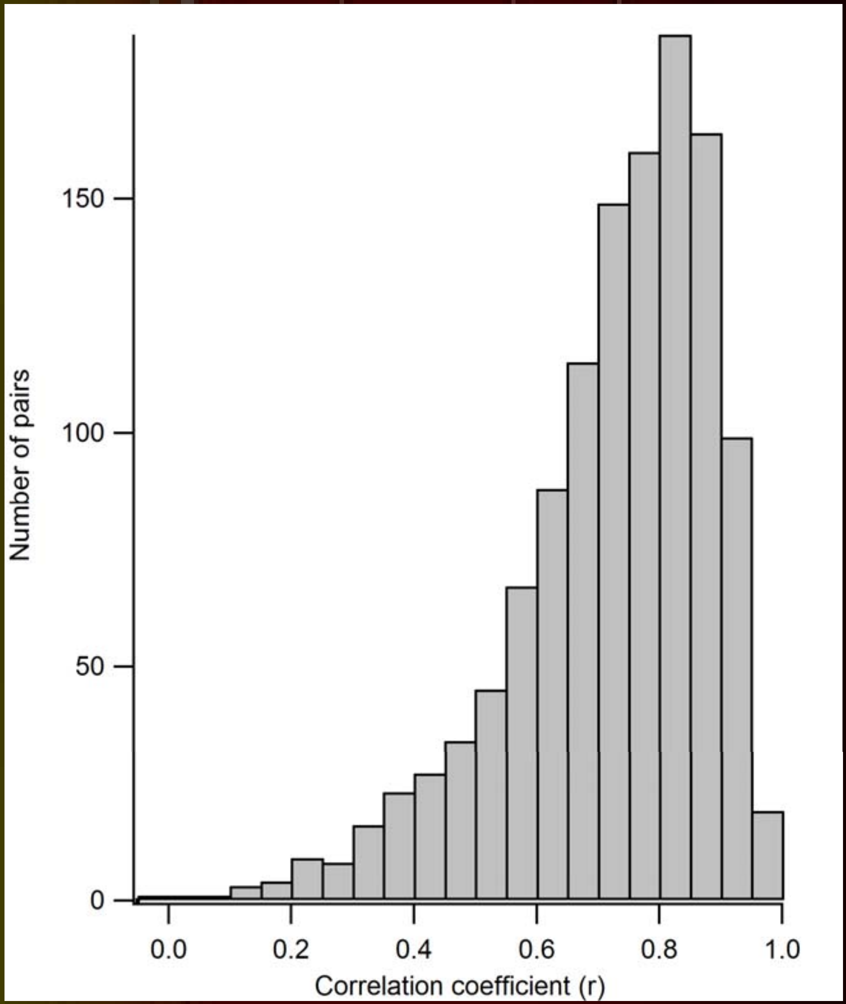
Example: Good Correlation





Statistics of Correlations

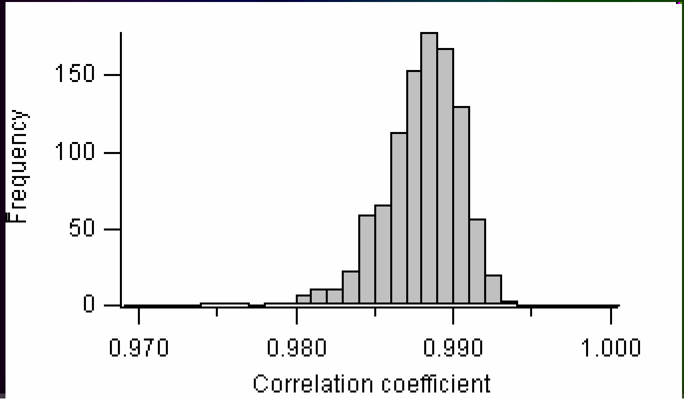
- Pairs of DIBs observed in >40 stars
- 1218 pairs
- 58 DIBs included
- Histogram of r
- Generally well correlated
- Few very good correlations
  - 118 with r > 0.90
  - 19 with r > 0.95

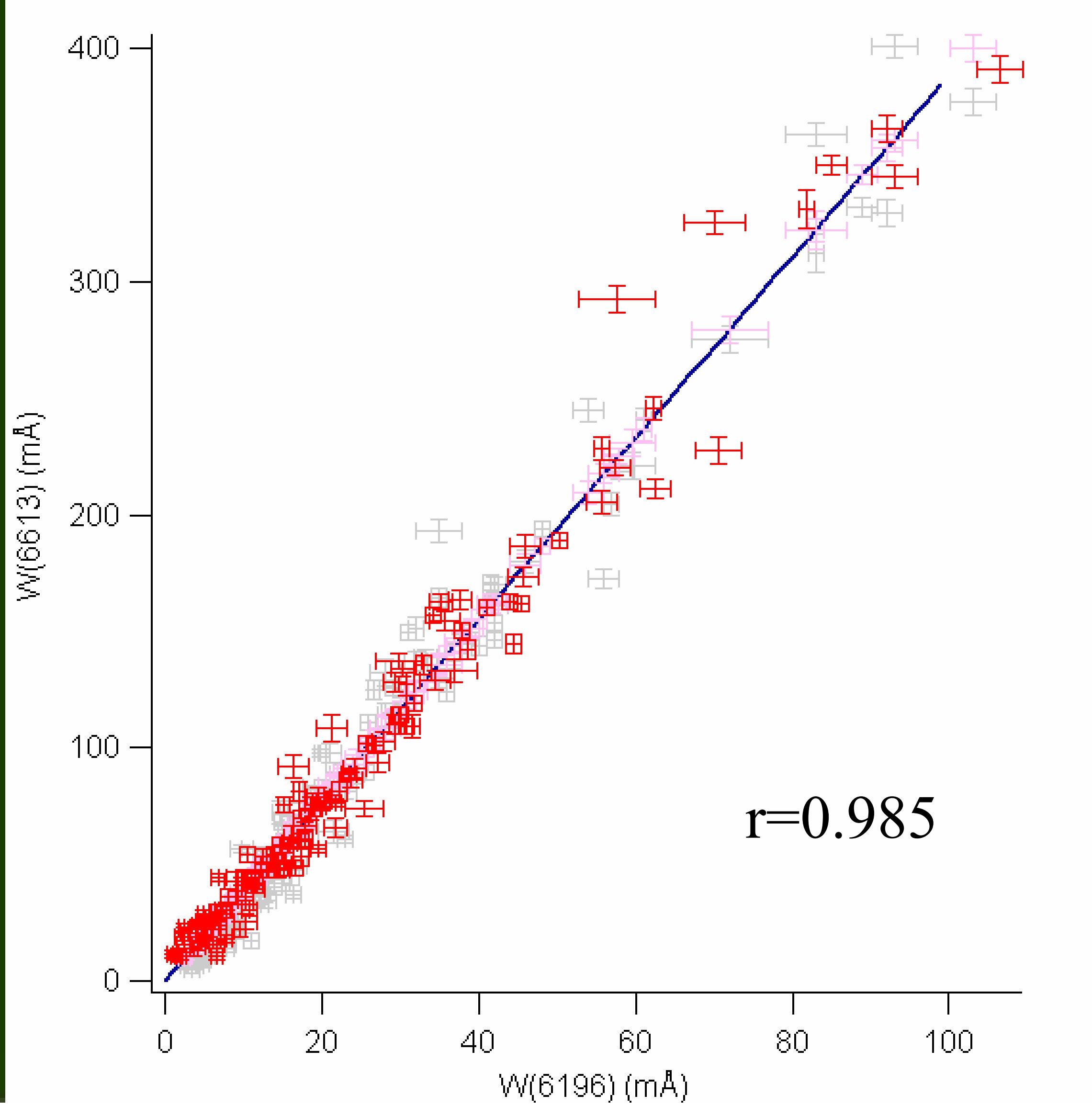


Revisiting λ6613 & λ6196

Can observed scatter be due to measurement errors?

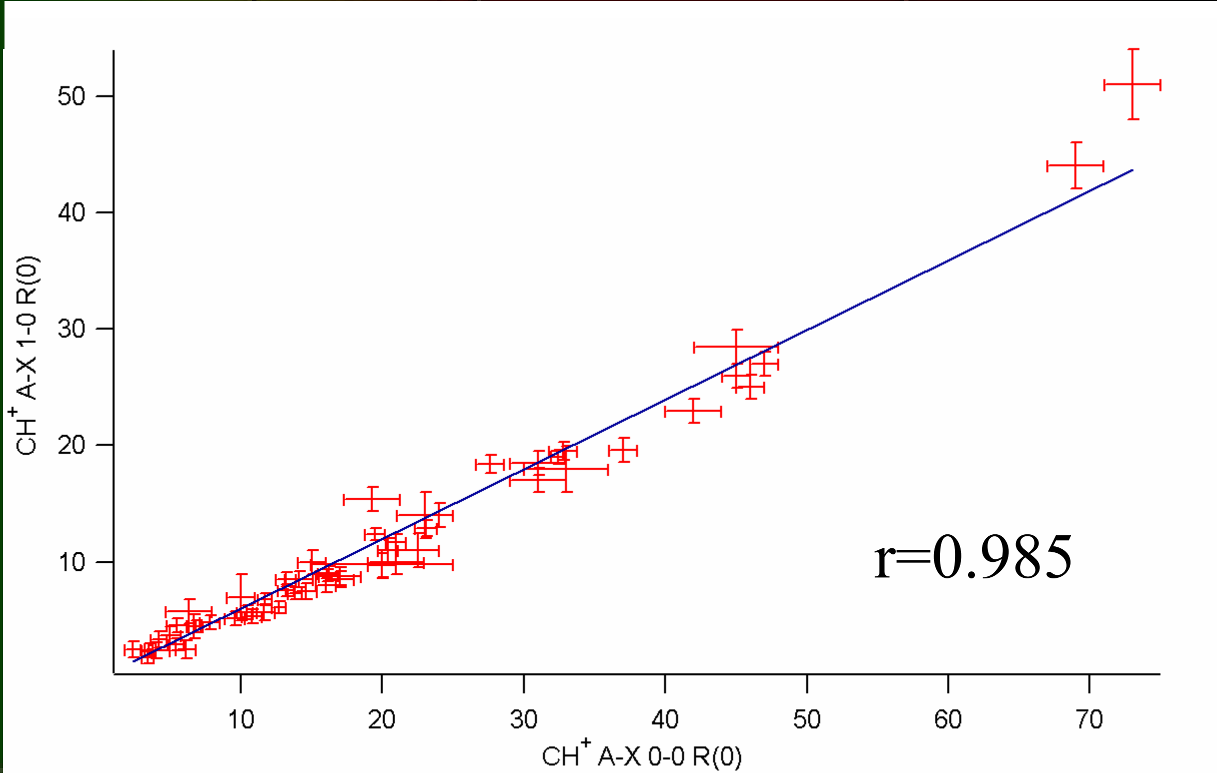
- Observed r=0.985
- Assume perfection
- Add Gaussian noise
- 1000 M.C. trials
- Double the noise
- 1000 M.C. trials
- Statistically OK if we underestimated errors





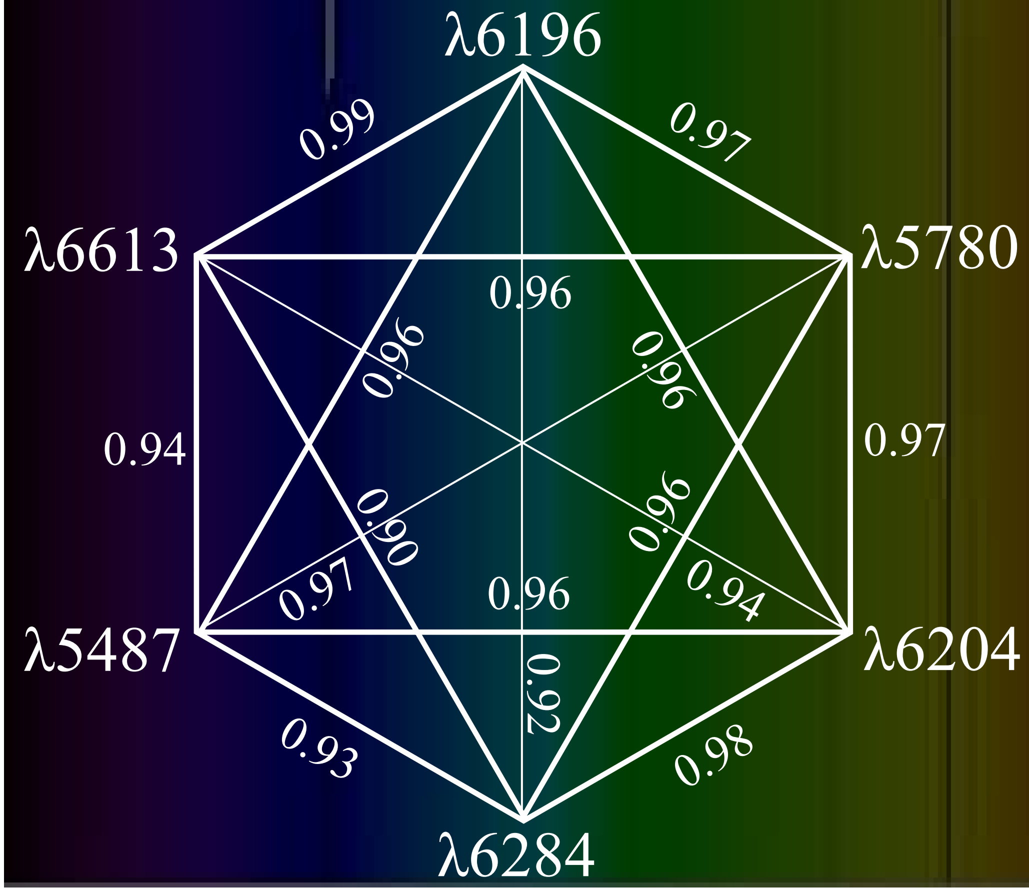
Measurement Errors

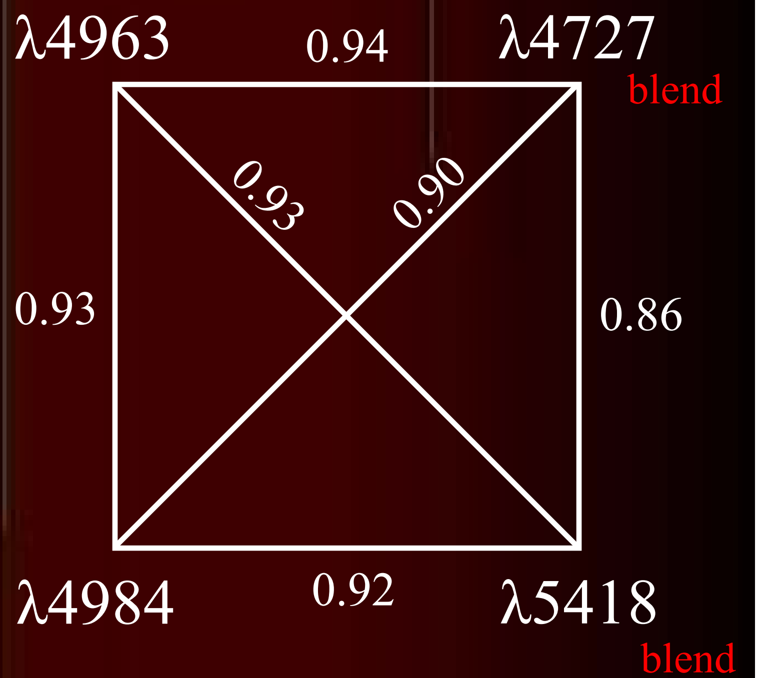
- Is doubling the error estimate reasonable?
- Error sources include:
  - finite S/N
  - unexpected structure
  - interfering DIBs?
  - continuum placement
- Agreement not always perfect!
  - CH^+ A-X band
- Hard to say; but it's certainly a very good correlation!



DIB "Families"

- Look for sets of DIBs in which all correlation coefficients are high





Why So Few Perfect Correlations?

- Assumption of a common ground state bad?
  - 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?

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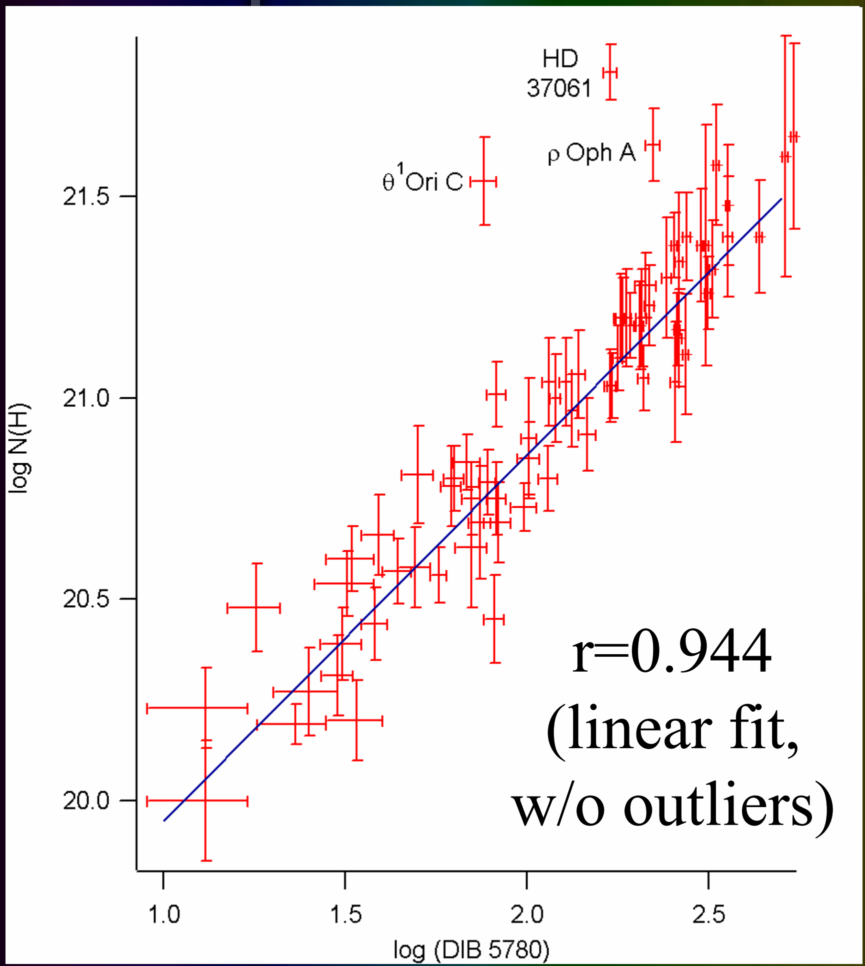
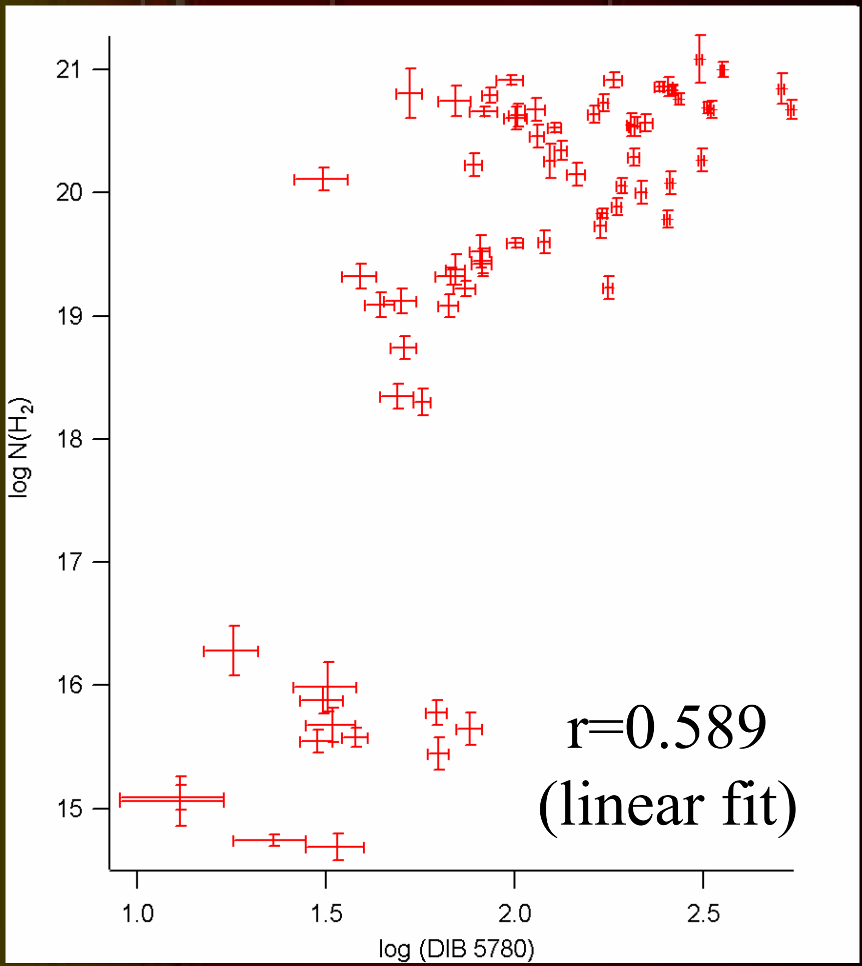
λ5780 and N(H)

well correlated with H

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



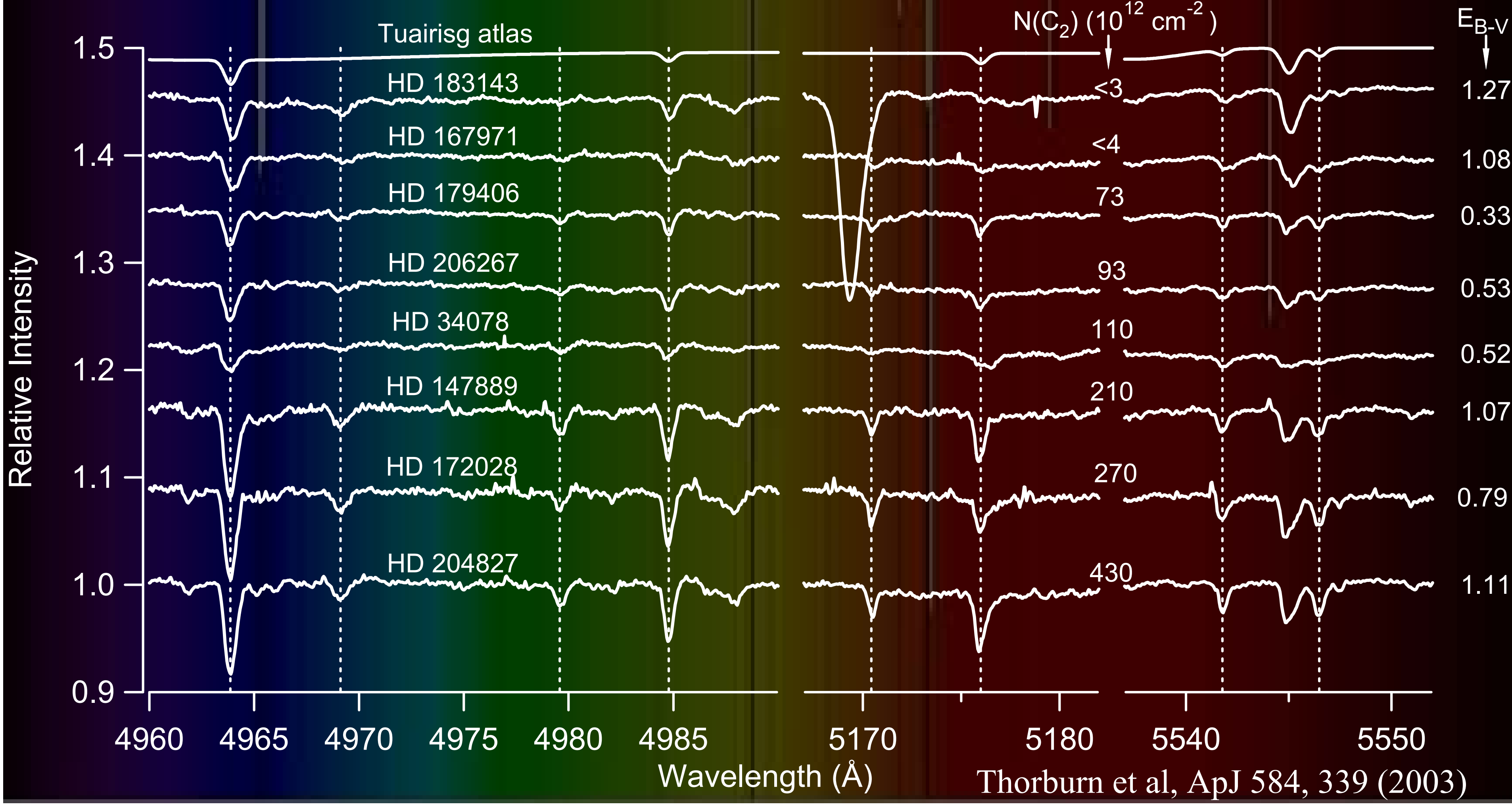
no correlation with H_2



York et al., in preparation

The "C_2 DIBs"

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

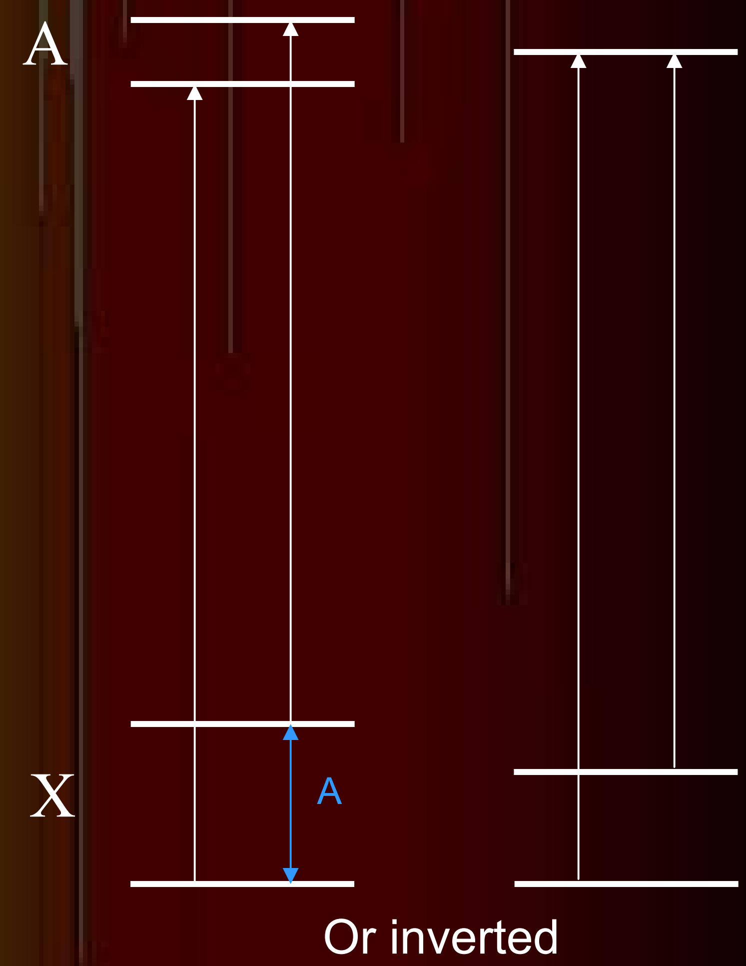


Thorburn et al, ApJ 584, 339 (2003)

C_2 DIB "Doublets"

λ (Å)	Δν	I_s / I_w	T_{ex}
4963.99 4969.24	21.3 cm^{-1}	4.0 3.8	22 K
4979.64 4984.82	20.9 cm^{-1}	2.4 1.8	34 K
5170.57 5176.04	20.4 cm^{-1}	3.1 2.8	26 K
5541.87 5546.48	15.0 cm^{-1}	1.0 1.1	[illegible]
5762.76 5769.16	19.1 cm^{-1}	1.5 2.0	

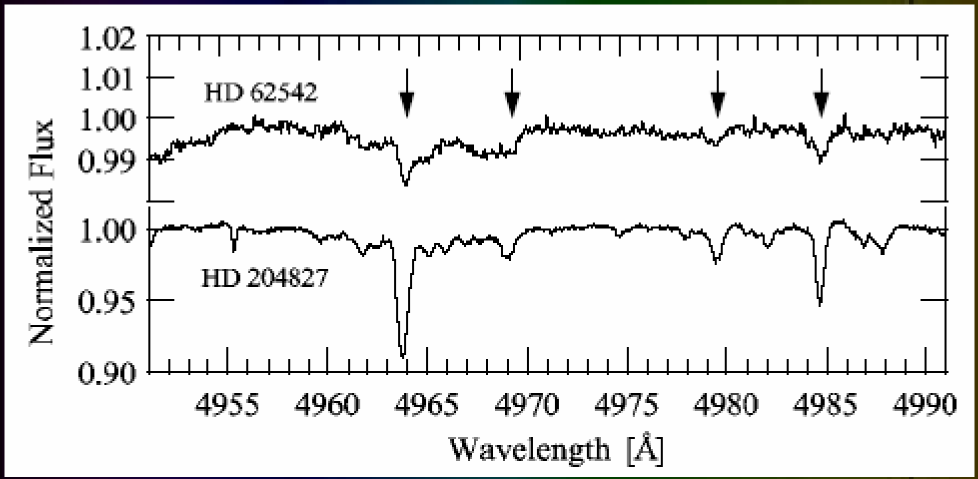
HD 204827
HD 147889



	HC_3	HC_5	HC_6	HC_7	HC_8	C_3^-	C_7^-
A (cm^{-1})	14.4	23.7	-15.1	26.2	-19.3	26.6	27.4

C_2 DIBs toward HD 62542

- Unusual sightline with only diffuse cloud "core"
  - outer layers stripped away by shock (?)
  - DIBs undetected [Snow et al. ApJ 573, 670 (2002)]
- Recent Keck observations (higher S/N)
  - Classical DIBs (e.g. λ5780) very weak
  - C_2 DIBs among the few DIBs observed
- C_2 DIBs evidently form in denser (molecular) regions



Ádámkovics, Blake, & McCall ApJ 625, 857 (2005)

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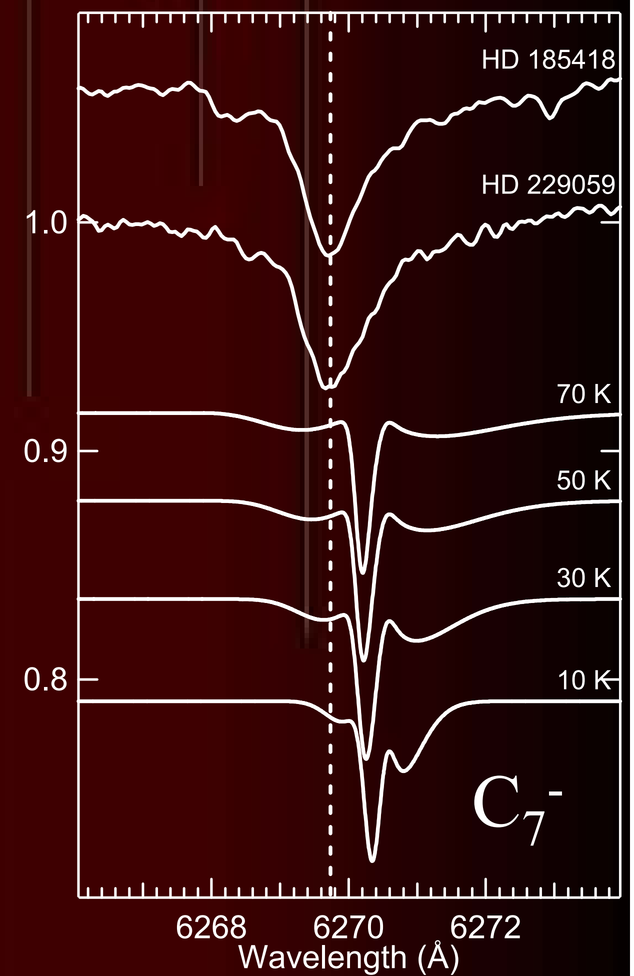
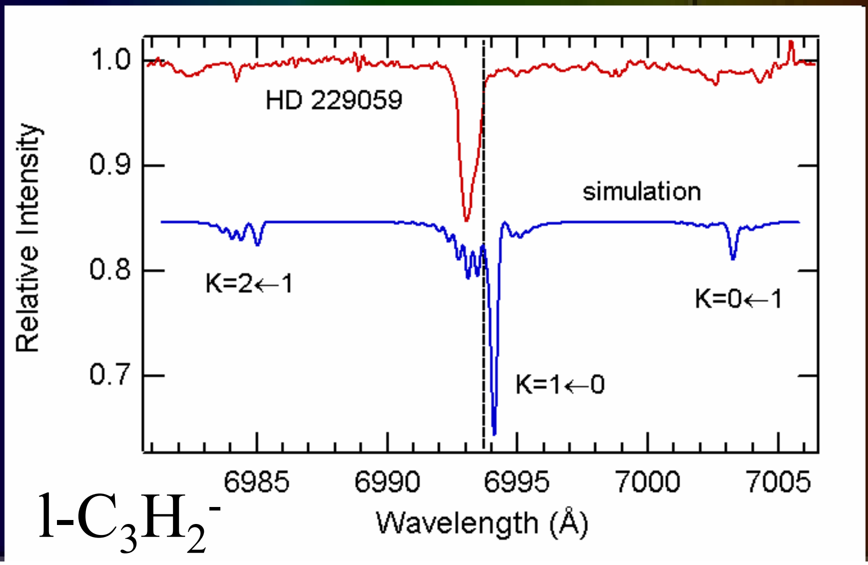
Evaluation of Proposed DIB Carriers

- Need a laboratory spectrum
  - gas phase (avoid matrix shifts)
  - rotationally resolved (or profile resolved)
- Need to be able to simulate spectrum
  - interstellar temperatures, excitation conditions
- DIB, simulated spectra must match exactly
  - central wavelength & profile
  - relative intensities & correlation
  - all laboratory bands present



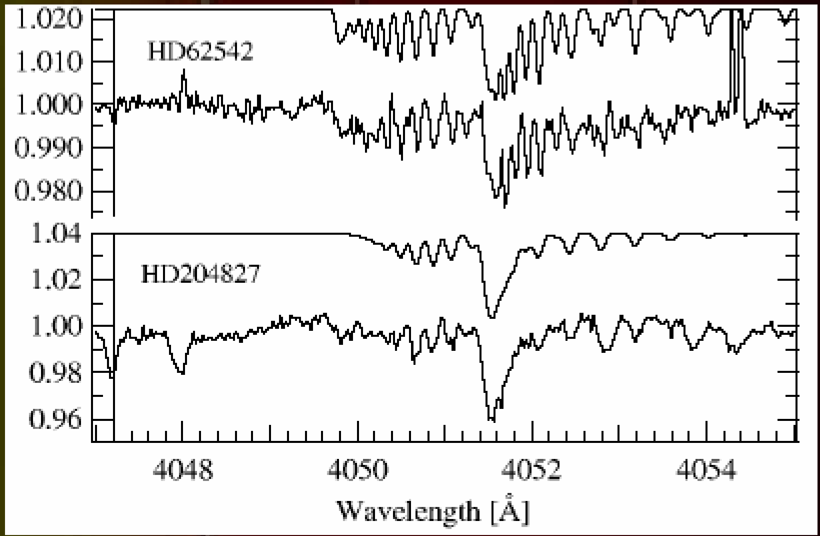
McCall et al., ApJ 559, L49 (2001)



McCall et al., ApJ 567, L145 (2002)

Carbon Chains as DIB Carriers?

- Some DIBs correlated with C_2
- C_3 widely observed in diffuse clouds
  - J. P. Maier 2001
- But, search for C_4, C_5 unsuccessful so far



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

- Conclusions:
  - Need high abundance, or
  - Large oscillator strength
  - Maier, Walker, & Bohlender [ApJ 602, 286 (2004)]:
    - Potential carbon chain DIB carriers must have >15 carbon atoms
    - C_{2n+1} (n=7-15); HC_nH (n>40); C_{2n} (n>10); C_nH; HC_nH^+; C_n^-
  - No lab spectra of long chains; very little of cations

PAHs as DIB Carriers?

- Polycyclic Aromatic Hydrocarbons
  - proposed by Leger & d'Hendecourt and by van der Zwet & Allamandola in 1985
- Would expect complex mixture
  - ionization stages (cation, neutral, anion?)
  - hydrogenation states
- So far, no spectroscopic match with DIBs
- Cation transitions observed so far in gas-phase are too broad!
- Still no convincing evidence

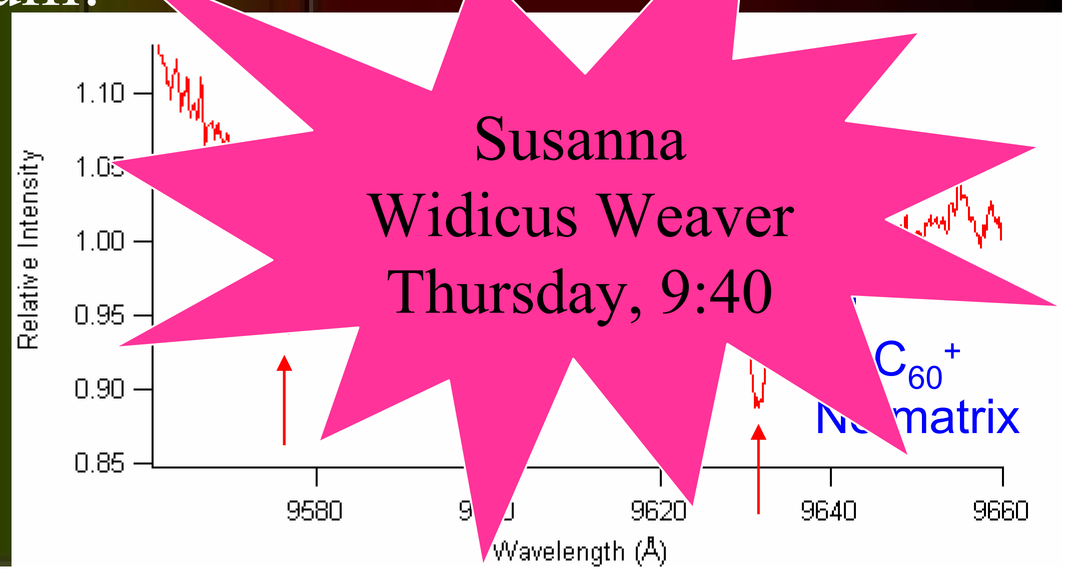
Fullerenes as DIB Carriers?

- Expected to form in carbon star outflows
- IP(C_{60}) = 7.6 eV
  - Ionized in diffuse clouds
- C_{60}^{+} in Ne matrix
  - two bands near 9600 Å
- Detection claimed in HD 183143
- Need gas-phase spectrum!
  - Experiment in progress

Fulara, Jakobi, & Maier
Chem. Phys. Lett. 211, 227 (1993)

Foing & Ehrenfreund
A&A 319, L59 (1997)

Susanna
Widicus Weaver
Thursday, 9:40



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!

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- McCall Group

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