



**Diffuse Interstellar Bands:
How Are They Related to Known
Gas-Phase Constituents of the ISM?**

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**data from ARCES, UVES, FEROS, HARPS, MIKE,
UCLES, KPNO, McDonald, *HST***



Gas-phase tracers of neutral ISM

Complexity (structure, processes)

Correlations

DIBs vs. atomic and molecular species

Historical overview (selective)

Correlations (and more correlations)

Special cases

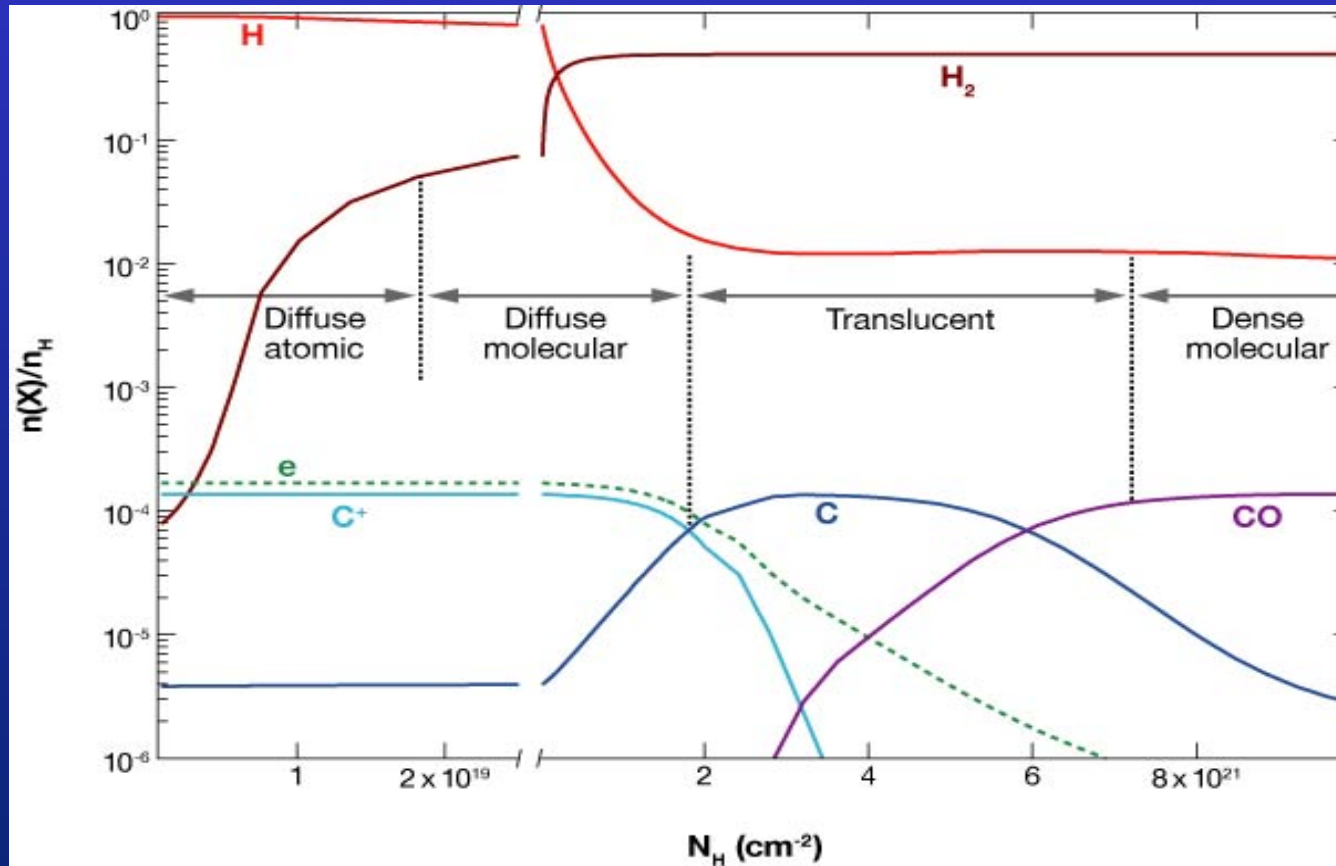
Objectives and opportunities

Identify DIB carriers

Understand their behavior

Large samples

Structure of Interstellar Clouds



$$n_H = 100 \text{ cm}^{-3}$$

$$I_{UV} = 1$$

AR Snow TP, McCall BJ. 2006.
Annu. Rev. Astron. Astrophys. 44:367–414

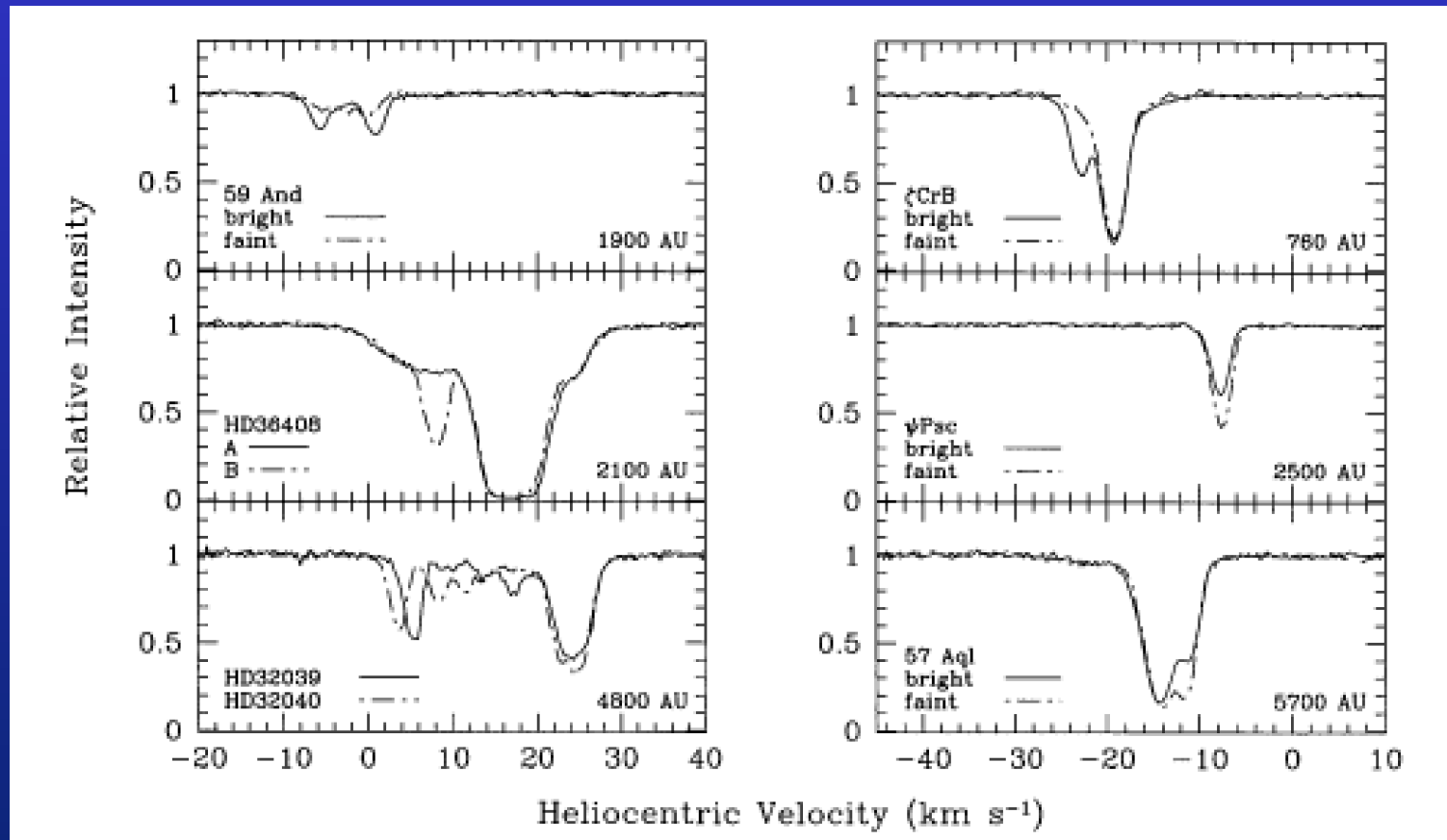
(Snow & McCall 2006; from Neufeld et al. 2005)

Carina Nebula



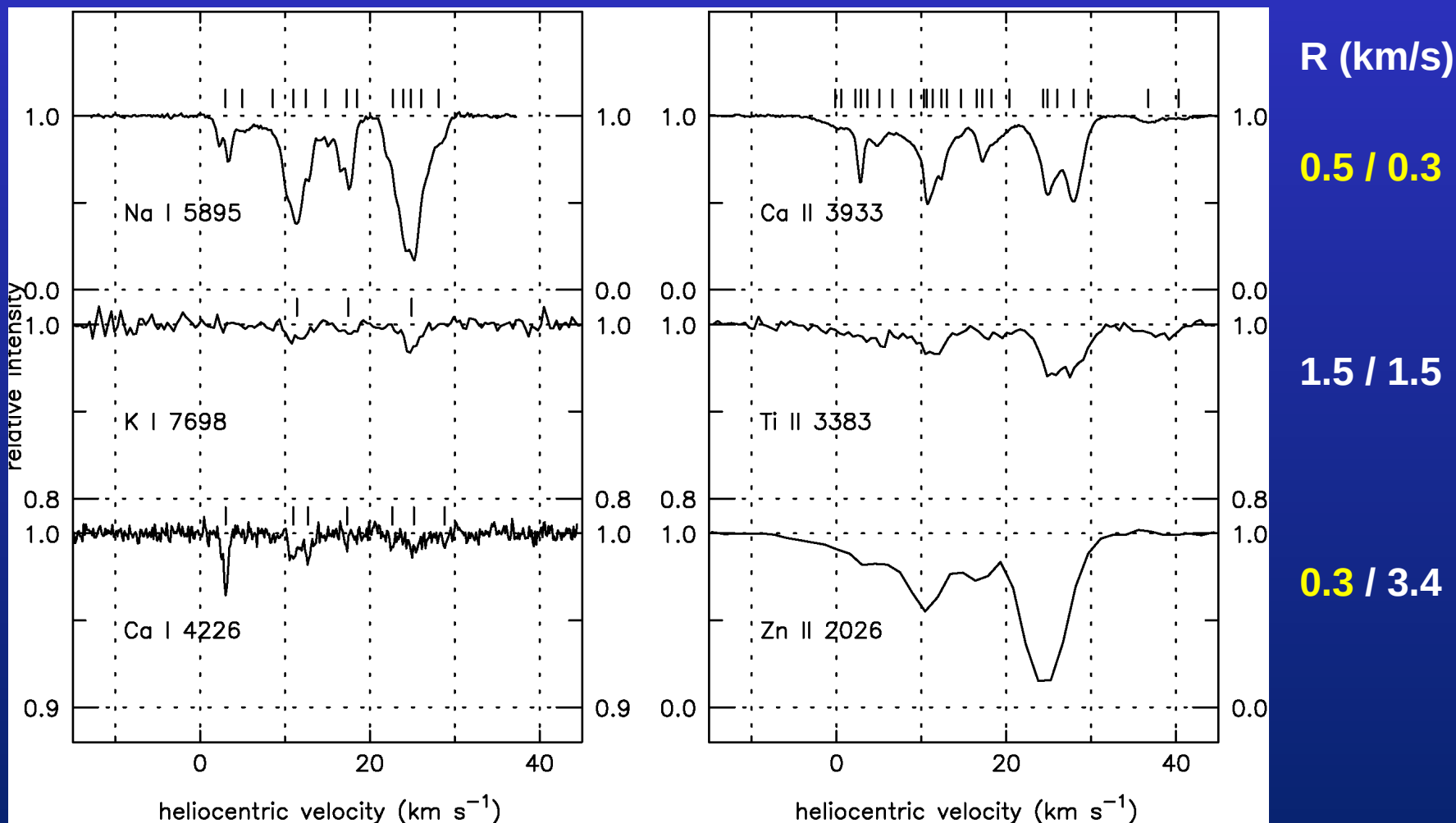


Small-scale Spatial Structure. I.



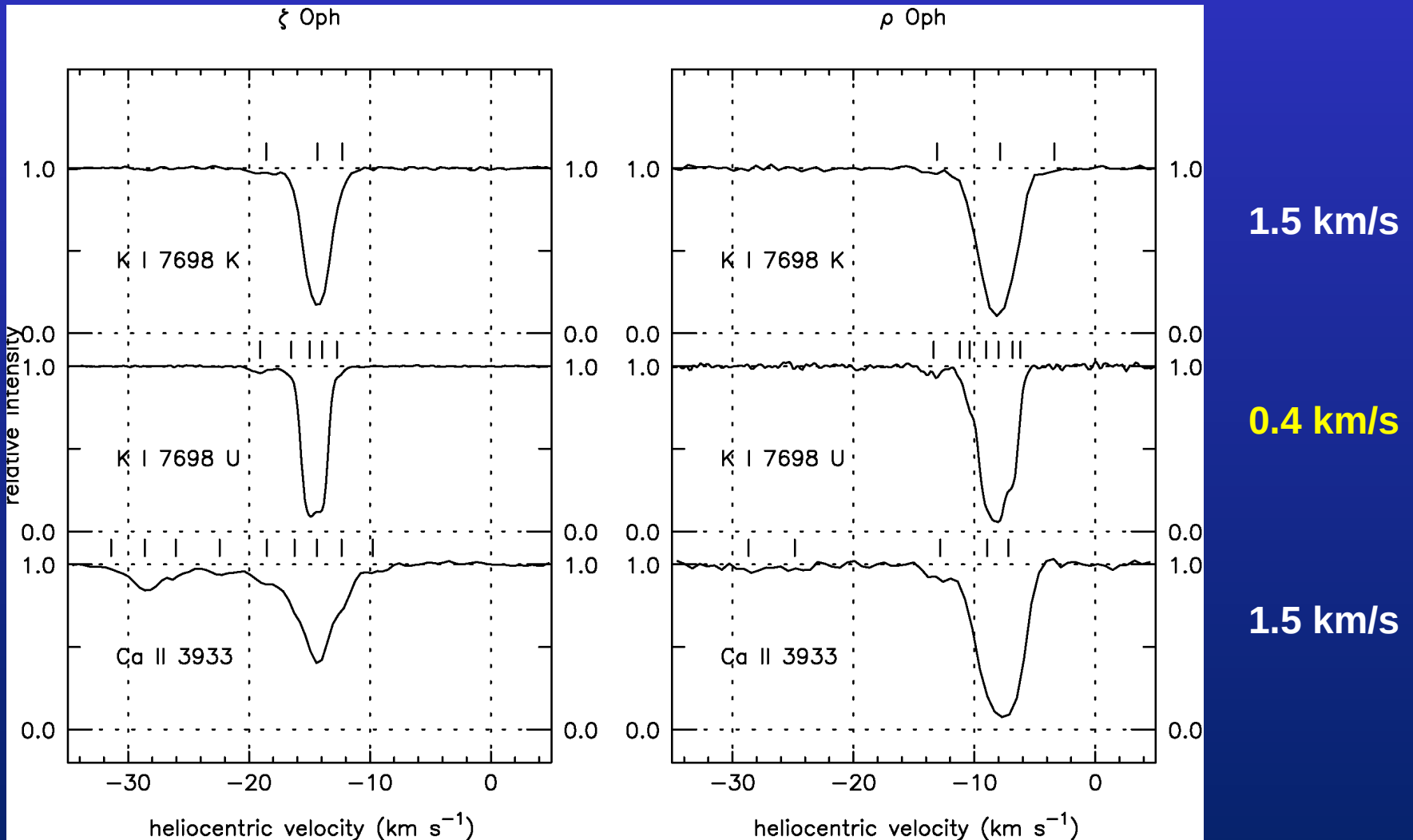
Watson & Meyer (1996) – Na I D for 17 systems; $d = 85\text{-}1200$ pc; separations 480-29000 AU; variations seen in Na I in all cases variations seen in H I ascribed to thin, dense filaments and/or sheets (Heiles 1997) – but Na I due to ionization (Welty 2007)

Complex Velocity Structure. I.



(Welty et al. 1994, 1996, 2003; Welty & Hobbs 2001; Welty & Crowther 2010)

Complex Velocity Structure. II.



(Welty et al. 1994; Welty & Hobbs 2001; see also Crawford, Barlow et al.)

Ionization Equilibrium / Electron Densities

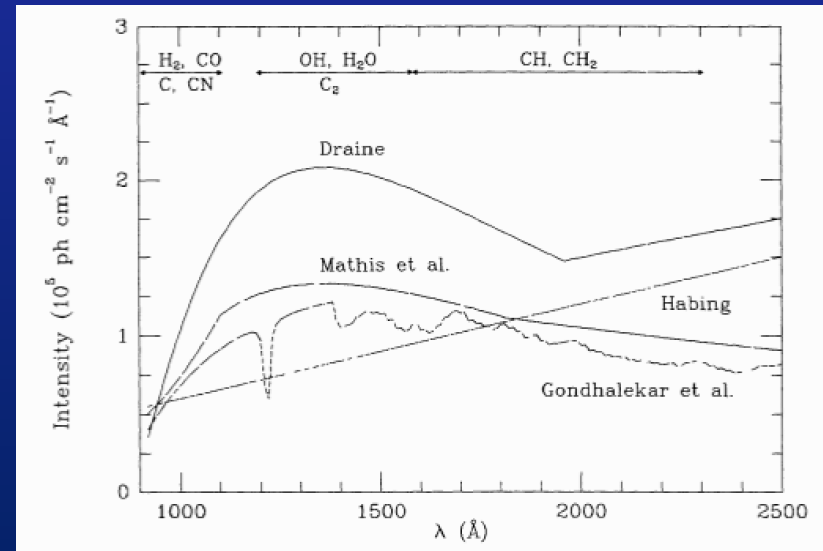
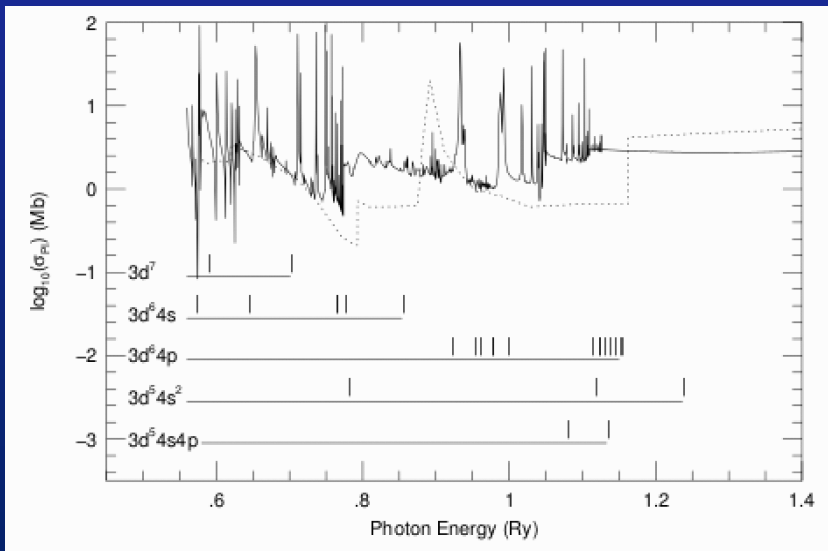
$$\Gamma_r n(X^0) = (\alpha_r + \alpha_d) n_e n(X^+)$$

Γ_r = photoionization rate

(cross-section, radiation field, extinction)

$\alpha(T)$ = recombination coefficients

(radiative, **dielectronic**; $\alpha_r = \alpha_0 T^{-\beta}$; $\beta \sim 0.6-0.8$)



Ionization Equilibrium / Electron Densities

$$(\Gamma_r + \Gamma_{cr}) n(X^0) = [(\alpha_r + \alpha_d) n_e + \alpha_g n_g] n(X^+)$$

Γ = ionization rates (radiative, **cosmic ray**)

$\alpha(T)$ = recombination coefficients (rad, diel, **grain-assisted**)

ionization via cosmic rays can be significant

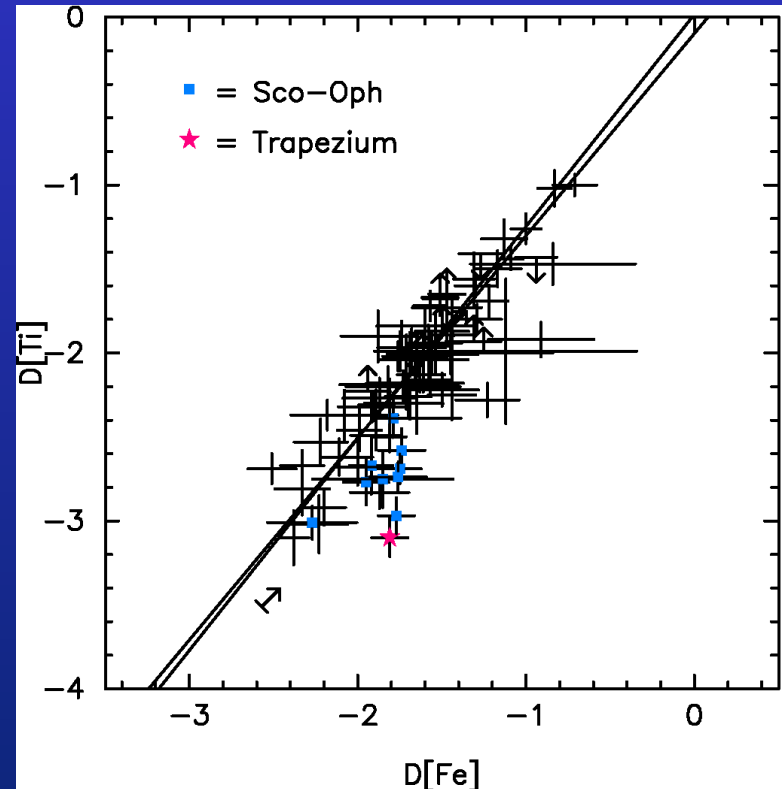
(H_3^+ : Indriolo & McCall 2012)

grain-assisted recombination can be significant / dominant –
depends on element, charge state of grains
(Weingartner & Draine 2001; Liszt 2003)

but even including GAR does not yield consistent n_e
from different X I/X II ratios – even for 'individual'
components (Welty et al. 2003)

Depletions / Chemistry / Turbulence / B / ...

Jenkins (2009): 17 elements,
243 sight lines; defines
depletion factor F_*
(depends on assumption
of consistent depletion
behavior in all sight lines)



database: ~480 MW (~170 with DIBs)
~290 SMC, LMC
high-res spectra / weak lines

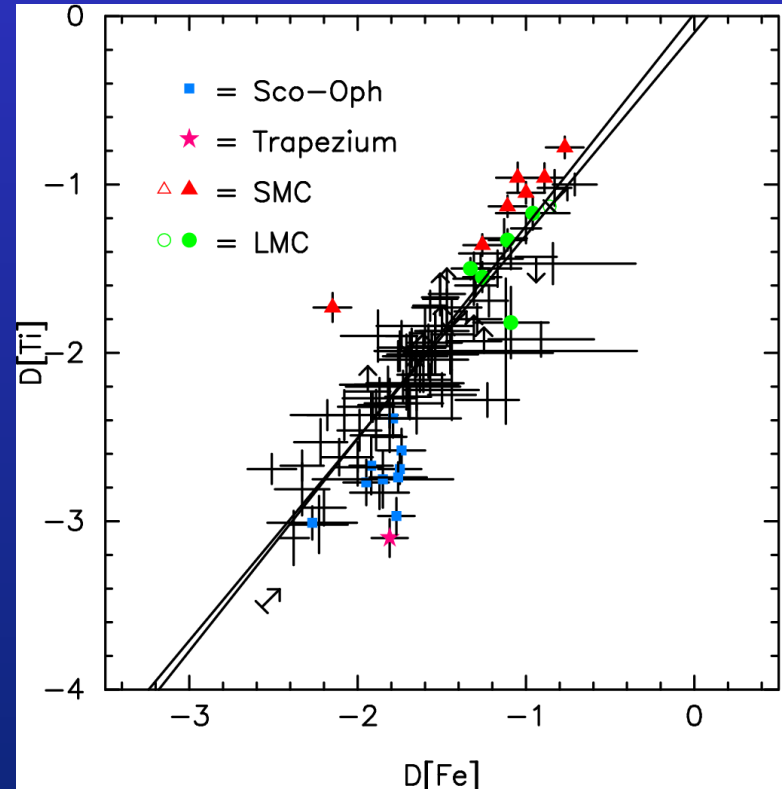
Depletions / Chemistry / Turbulence / B / ...

Jenkins (2009): 17 elements,
243 sight lines; defines
depletion factor F_*

but regional variations (i.e.,
differences in patterns)?

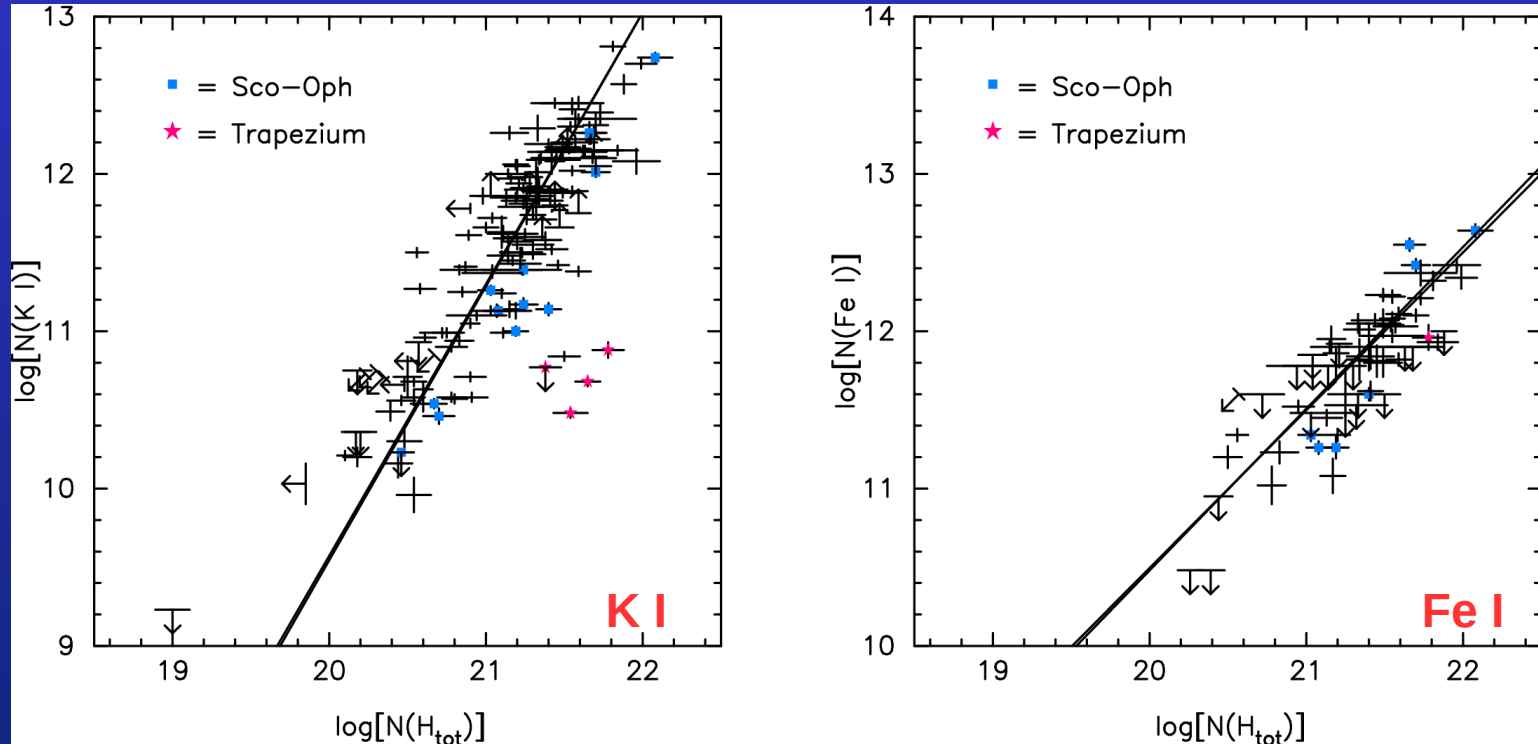
thought to depend on local
density – but no obvious
trends, where estimates
for n_H are available

any implications for DIBs?



Chemistry: Liszt; Wakelam; Roueff; Federman; others

Correlations: Trace Species K I, Fe I vs. H_{tot}

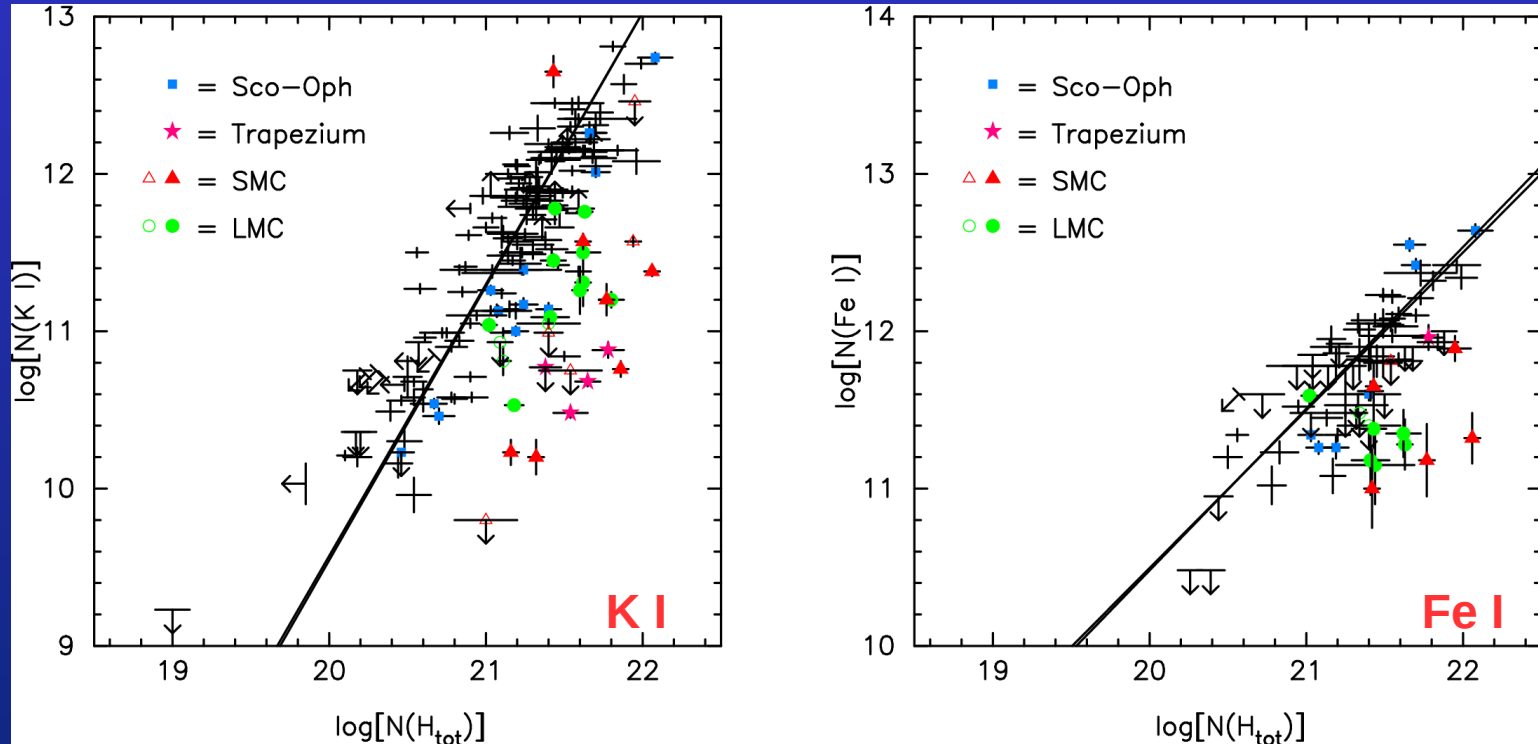


K I: **slope ~ 1.7** (nearly quadratic) – trace species, little depleted; Sco-Oph slightly low, Orion Trapezium very low (radiation)

Fe I: **slope ~ 1.0** – trace species, increasing depletion at higher $N(\text{H})$

(Welty & Hobbs 2001; Welty, Hobbs, & Morton 2003)

Magellanic Clouds – Lower Metallicities

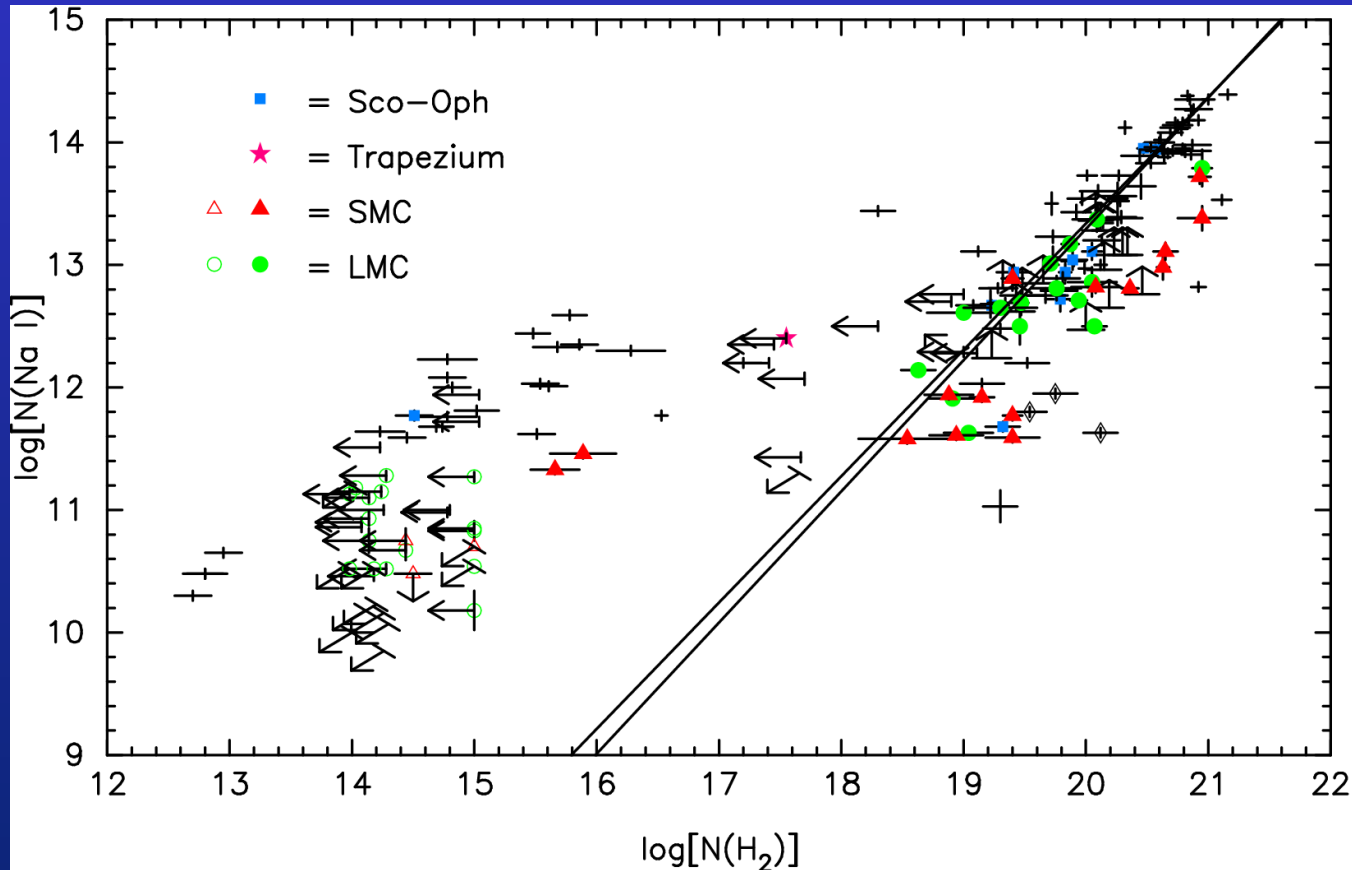


K I: roughly parallel trends for LMC, SMC – but at lower $N(K I)$; differences greater than differences in metallicity – less GAR?

Fe I: lower $N(\text{Fe I})$ for most LMC, SMC

(Welty & Crowther, in prep.)

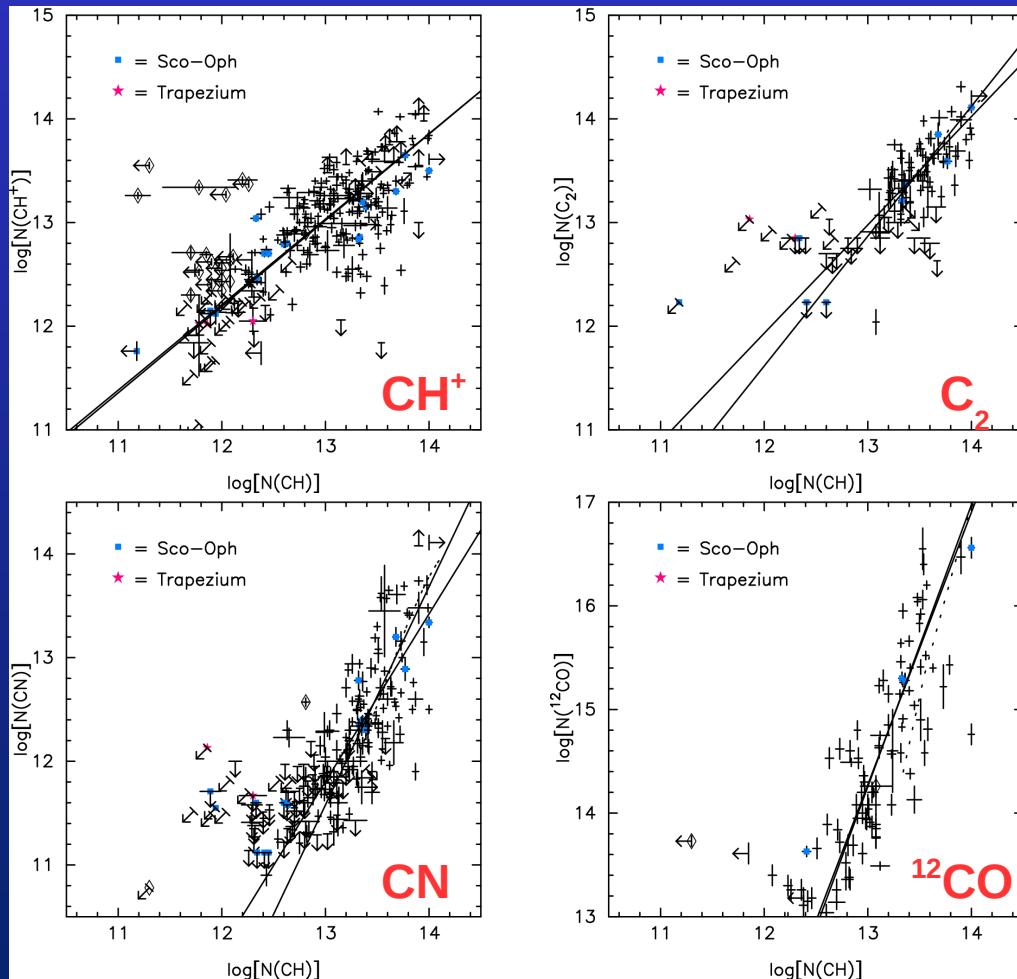
Correlations: Trace Species Na I vs. H_2



roughly linear trends for both low, high $N(H_2)$; H_2 self-shielding;
some regional variations (Pleiades, SMC)

(Welty & Crowther, in prep.)

Correlations between Molecular Species



CH^+ (not well correlated)

increasing slope vs. H_2 :

$\text{OH}, \text{CH}, (\text{H}_2) \sim 1.0-1.2$

$\text{C}_2, \text{C}_3 \sim 1.2-1.5$

$\text{NH}, \text{HD}, \text{CN} \sim 1.5-2.5$

$^{12}\text{CO}, ^{13}\text{CO} \sim >2.5 (3-5?)$

(self-shielding)

Consistent with
chemical networks?

Indicative of relative
distributions?

(Welty, Federman, Roueff, & Ritchey, in prep.;
Pan et al. 2005; Sheffer et al. 2008)

Summary: Atomic and Molecular Species

K I, Na I – trace species; mild depletion; strong and weak lines; roughly quadratic vs. H_{tot} ; scatter at low H_{tot}

Ca I, Fe I – trace species; variable depletion; weak lines

Ca II – trace or dominant species; variable depletion; more broadly distributed (spatial, velocity)

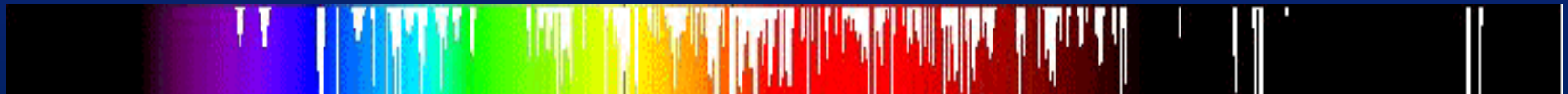
Ti II – dominant species; variable depletion

CH – good correlation with H_2 ; can be produced thermally or non-thermally (with CH^+)

CH^+ – not well correlated with any other species; more broadly distributed (spatially), in more diffuse gas?

CN – tracer of relatively dense gas; more localized

correlation slopes: clues to distribution, processes

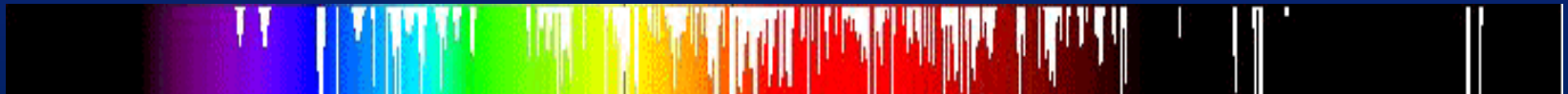


DIBs vs. Atomic and Molecular Species

Correlations of total line of sight values (most cases)

Multiple variables (abundances, physical conditions, history)

- DIB equivalent widths vs. column densities (saturation?)
- $\log(W)$ vs. $\log(N)$ – can reveal physical relationships
- How large is the sample? selection effects?
- How strong is the correlation? (r , rms, mad, ...)
- What is the slope of the relationship? breaks?
- Fits should account for reasonable errors (in both x and y)
- Look at scatter, residuals – trends w/ other quantities?
- Look for regional trends, outliers – special conditions?

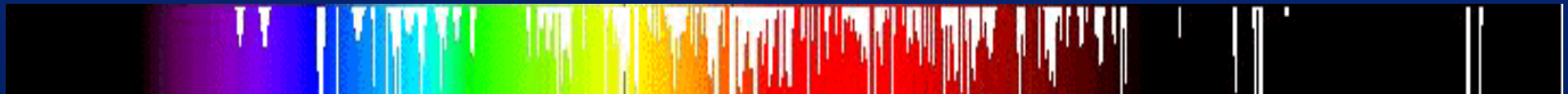


Herbig (1993) – An Early Correlation Study

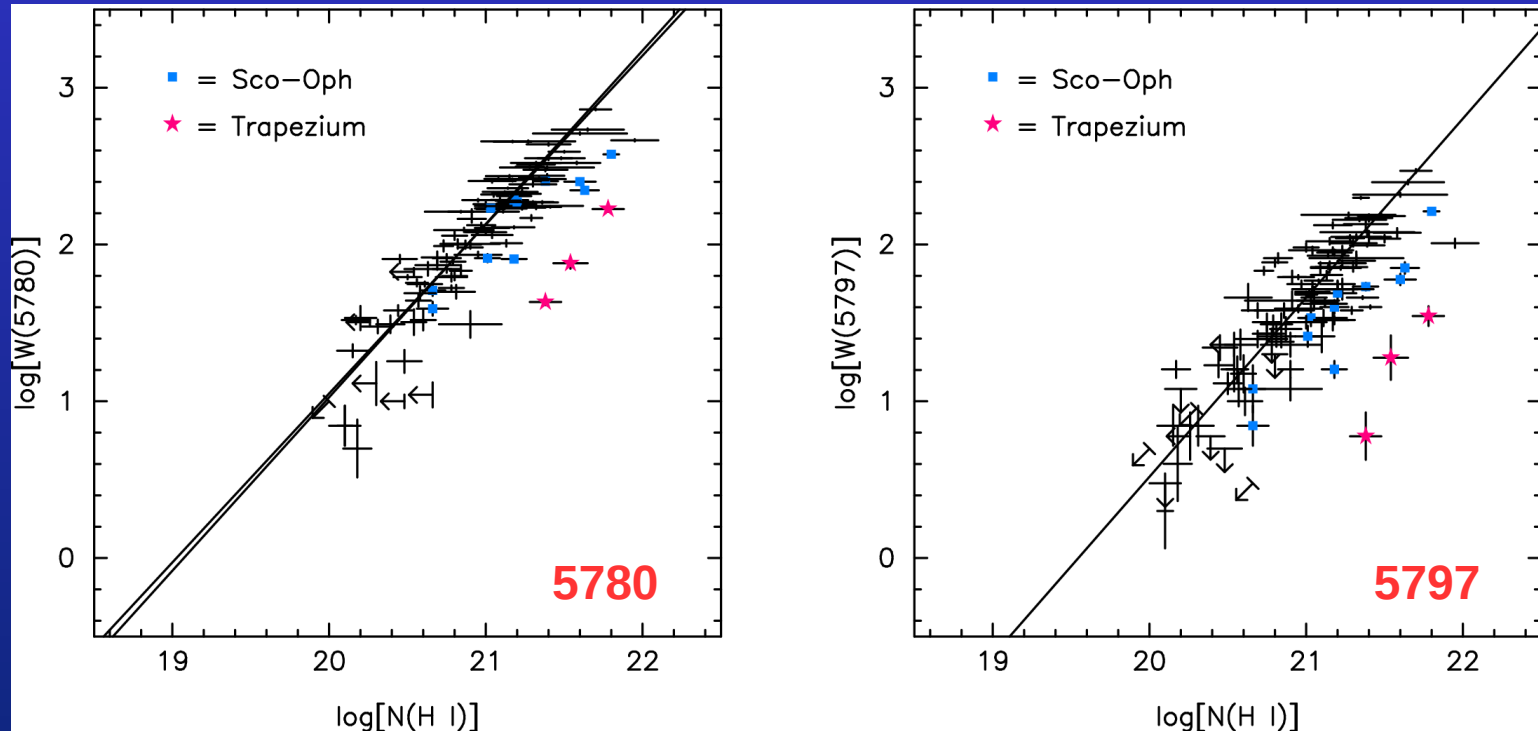
observations of 5780, 5797, Na I D lines (93 stars)

- 5780 correlated with H (slope ~ 1.35); residuals not related to H_2 ; several outliers
- 5780 not correlated with D(Ti) or CH^+
- 5780 correlated with Na I and K I (slopes ~ 0.7)
- 5780, 5797 well correlated with $E(B-V)$ (slopes ~ 1.0), but not with small grain population or R_v

conclusion: carrier of 5780, 5797 “behaves like a free neutral species in the gas ... (with an) ionization / dissociation threshold > 5 eV”

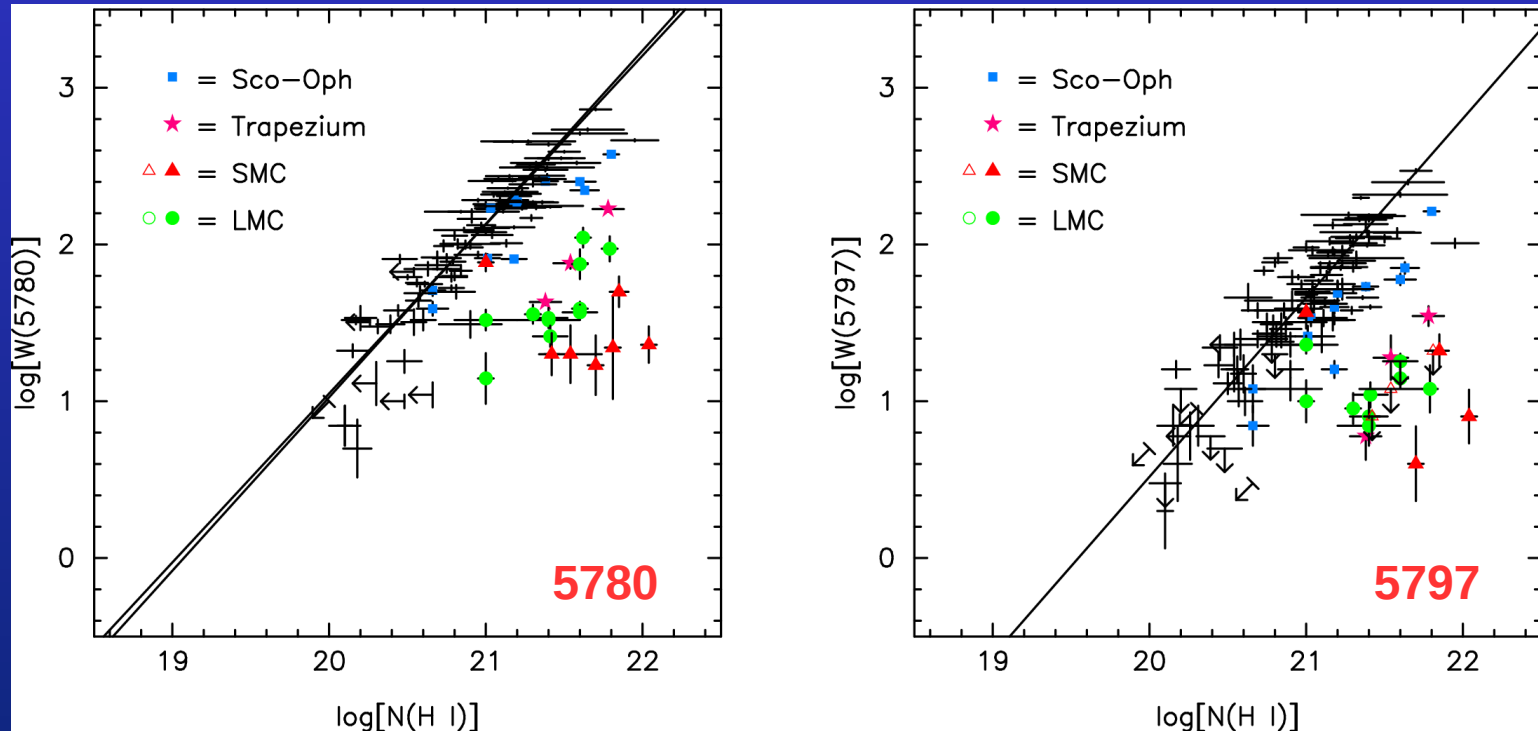


Herbig (today) – 5780, 5797 vs. H



slopes ~ 1.1 for both 5780, 5797 vs. H ($r \sim 0.91, 0.85$)
lower W for both DIBs in Sco-Oph, Trapezium, few others –
enhanced radiation fields?

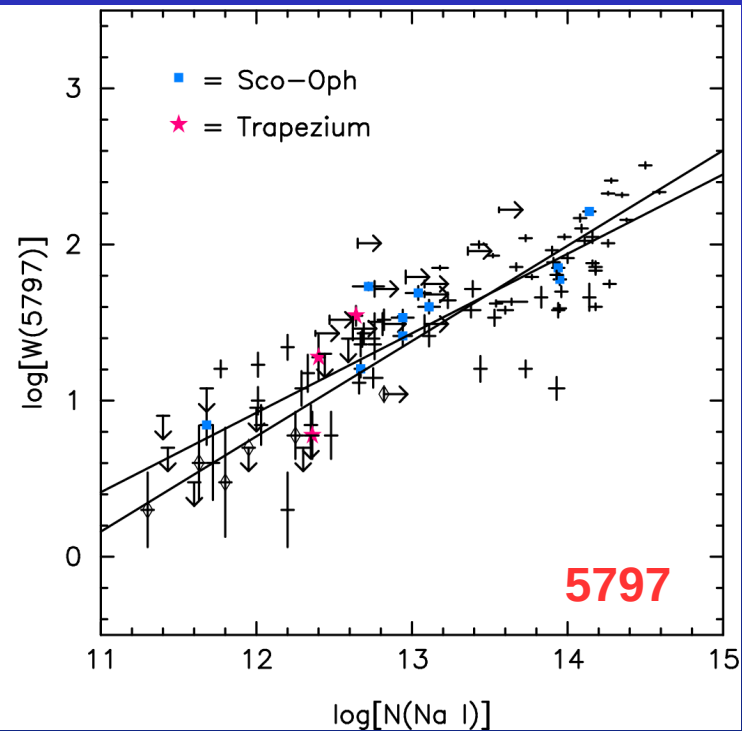
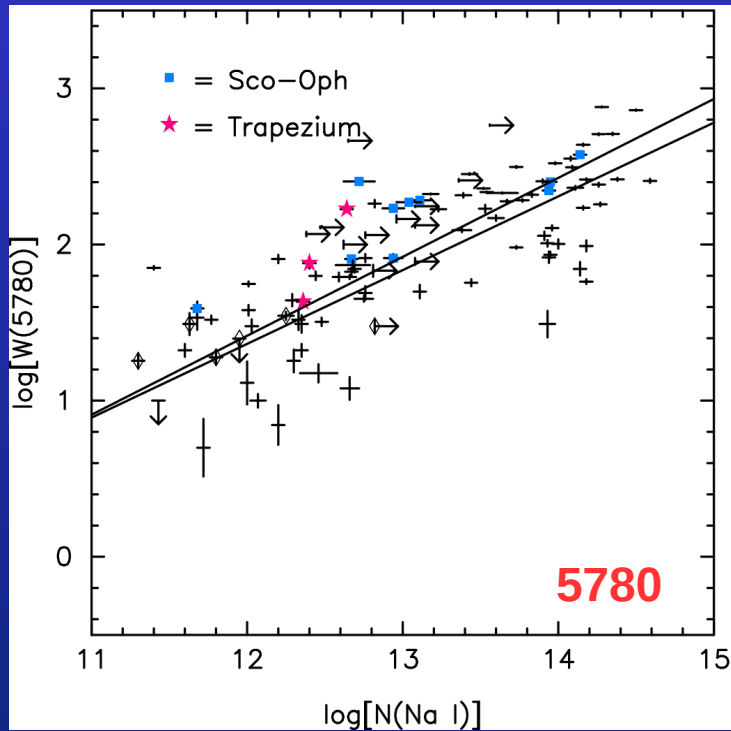
Herbig (LMC/SMC) – 5780, 5797 vs. H



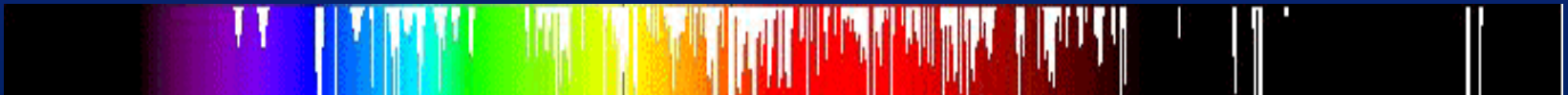
roughly parallel trends for LMC, SMC – but at lower $W(\text{DIB})$;
differences greater than differences in metallicity – due to
enhanced radiation fields in MC? cloud structure?

(Cox et al. 2006, 2007; Welty et al. 2006)

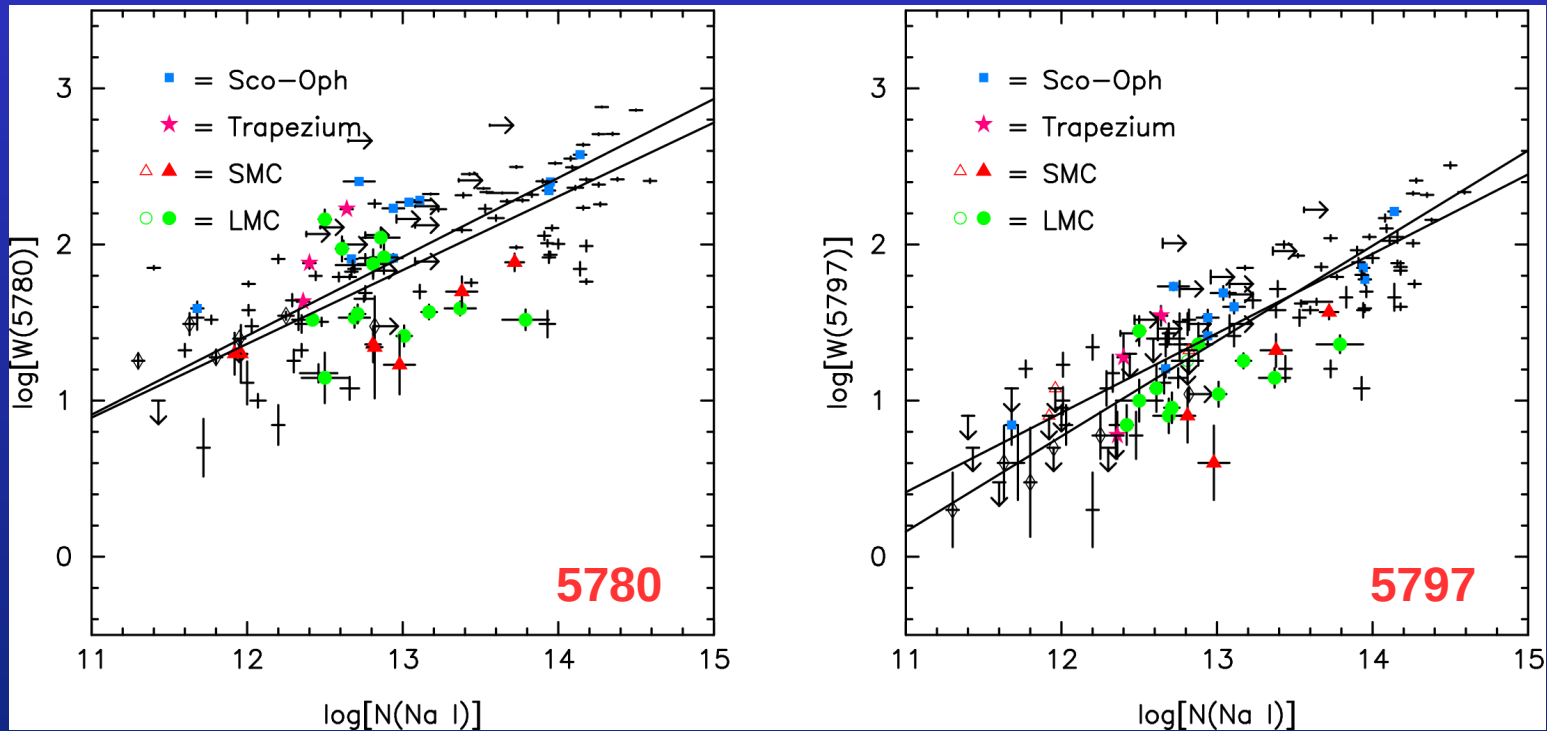
Herbig (today) – 5780, 5797 vs. Na I



slopes ~ 0.5-0.6 for both 5780, 5797 vs. Na I ($r \sim 0.77, 0.85$)
both DIBs 'normal' in Sco-Oph, Trapezium? – but several
sight lines low; more scatter



Herbig (today) – 5780, 5797 vs. Na I

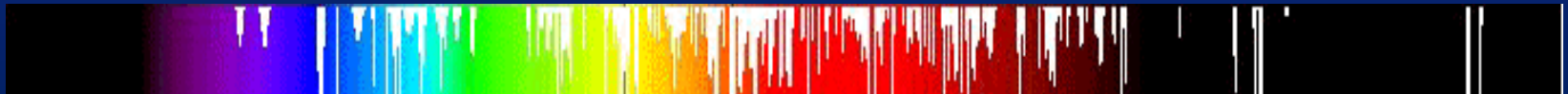


DIBs 'normal' vs. Na I in most LMC/SMC sight lines?

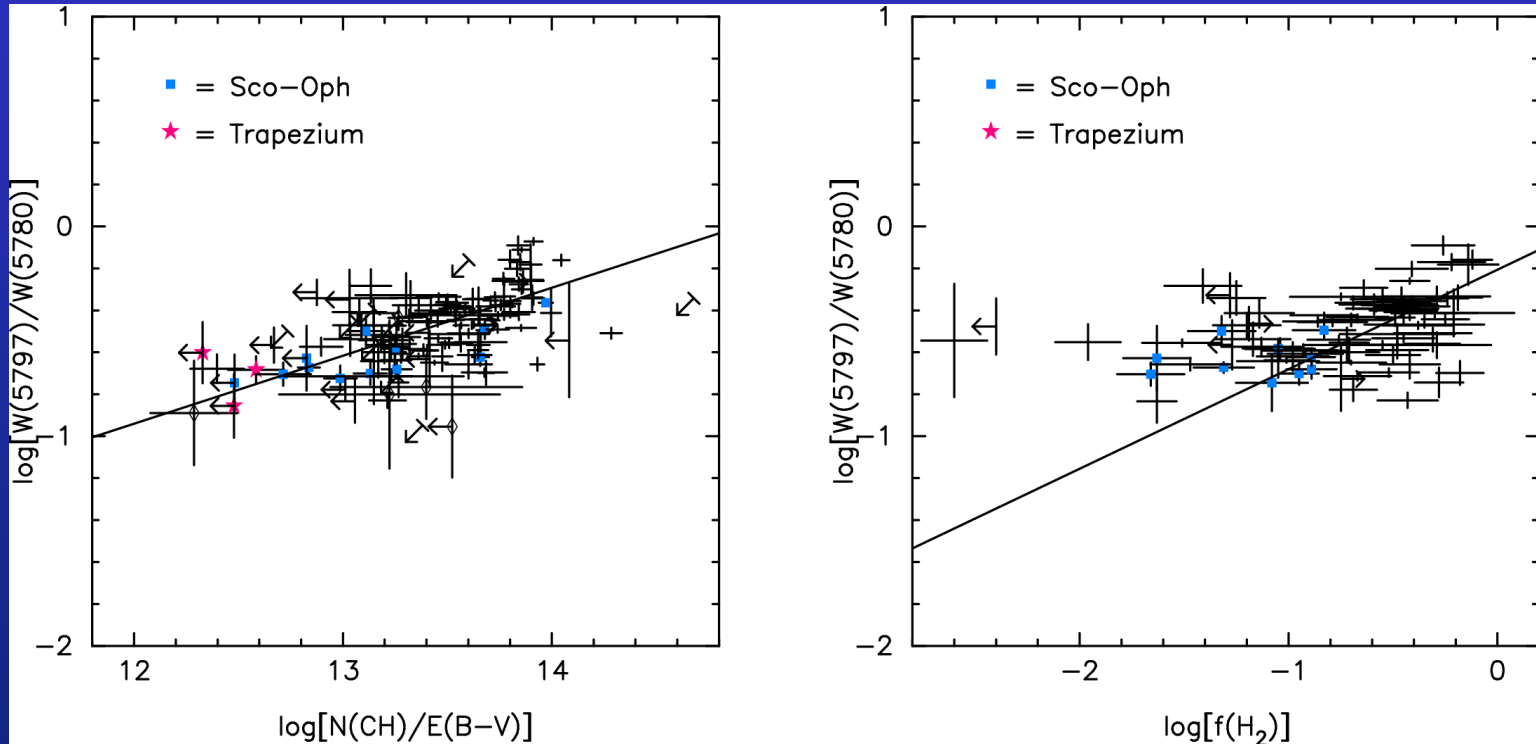
conclusion: either carriers are dominant species or they are trace species that can be depleted / altered / destroyed at higher $N(\text{H})$ and/or in strong radiation fields

Krełowski / Galazutdinov / Weselak

- 1992K: CH, CN present when $d(5797) > d(5780)$ [6]
- 1997G: $d(5780)$, $d(5797)$ vary less than $d(\text{CH}^+)$, $d(\text{CH})$ [12]
- 1998K: $d(\text{K I})$ correlated with $d(5797)$, $d(6379)$, but not
with broader $d(5780)$, $d(6284)$ [45]
- 1999K: $W(5797)/W(5780)$ correlated with $W(\text{CH})/E(\text{B-V})$,
not with $W(\text{CH}^+)/E(\text{B-V})$ [70]
- 2004W: $W(5797)/W(5780)$ correlated with $f(\text{H}_2)$ [38]
- 2004G: $W(5780, 5797, 5850, 6614)$ correlate better with
 $W(\text{K I})$ than with $W(\text{Ca II})$ [35]
- 2008W: $W(5797)/W(5780)$ correlate better with
 $N(\text{CH})/E(\text{B-V})$ than with $N(\text{CN})/E(\text{B-V})$ [84]

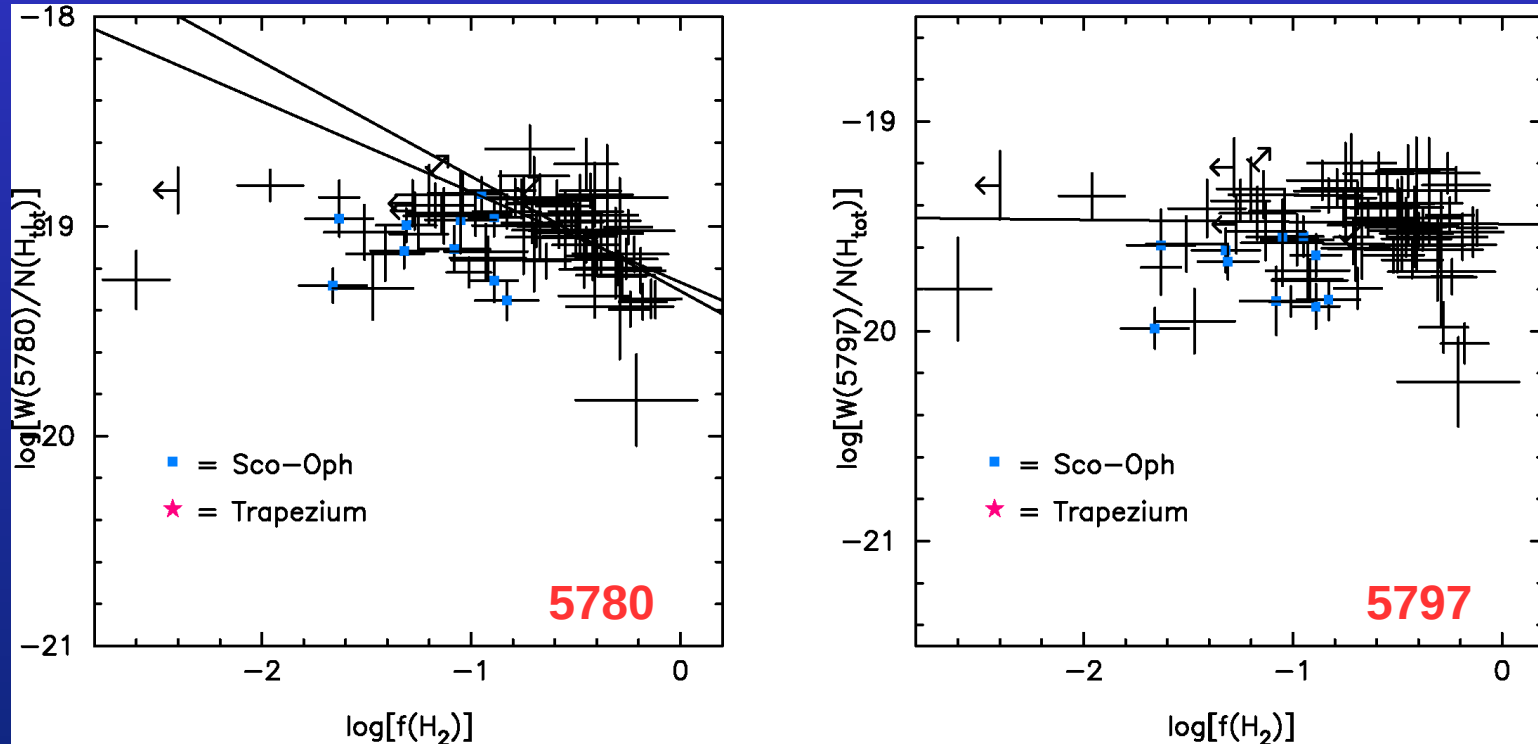


$W(5797)/W(5780)$ vs. $N(\text{CH})/E(\text{B-V})$, $f(\text{H}_2)$

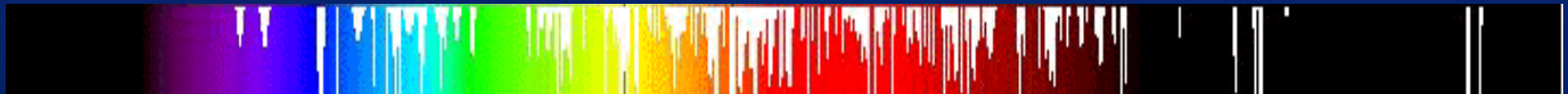


relatively weak trends with both $N(\text{CH})/E(\text{B-V})$ and $f(\text{H}_2)$,
with significant scatter – so some tendency for 5797
to be associated with somewhat denser material and/or
for 5780 to be associated with more diffuse gas

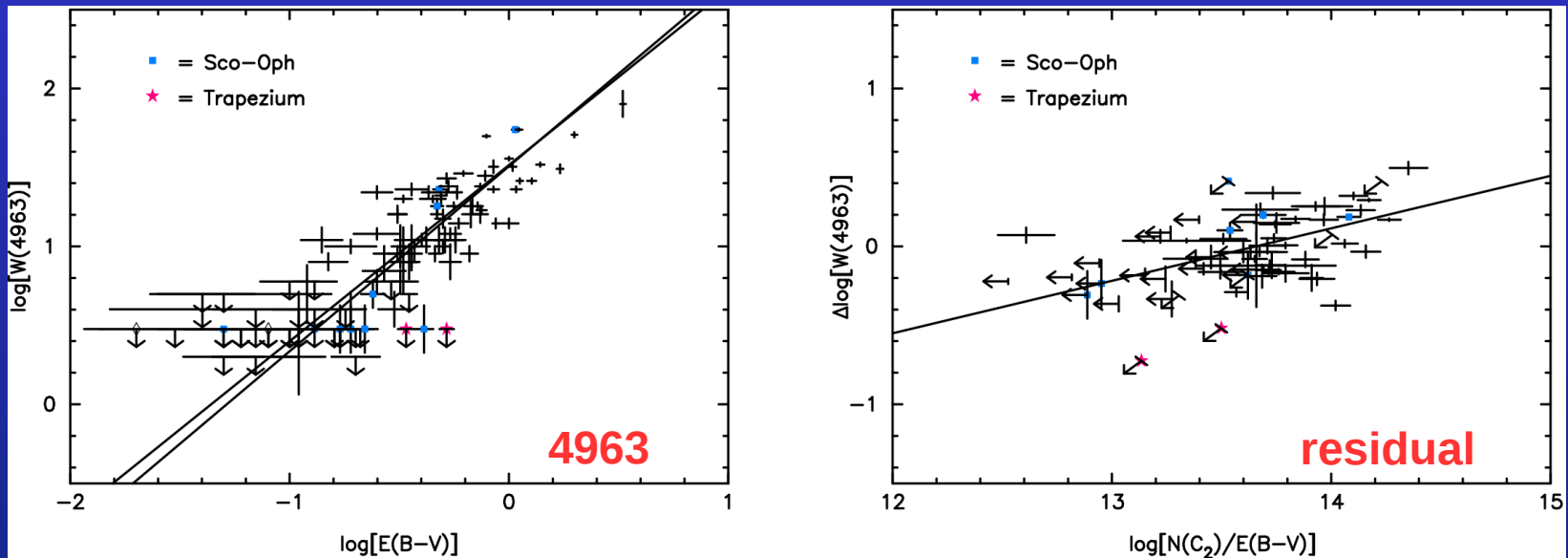
$W(5780)/N(H_{\text{tot}})$, $W(5797)/N(H_{\text{tot}})$ vs. $f(H_2)$



$W(5780)/N(H_{\text{tot}})$ declines for $f(H_2) > 0.1$ (as do most DIBs?)
any such trend for $W(5797)/N(H_{\text{tot}})$ much weaker



Thorburn et al. (2003) – C₂ DIBs

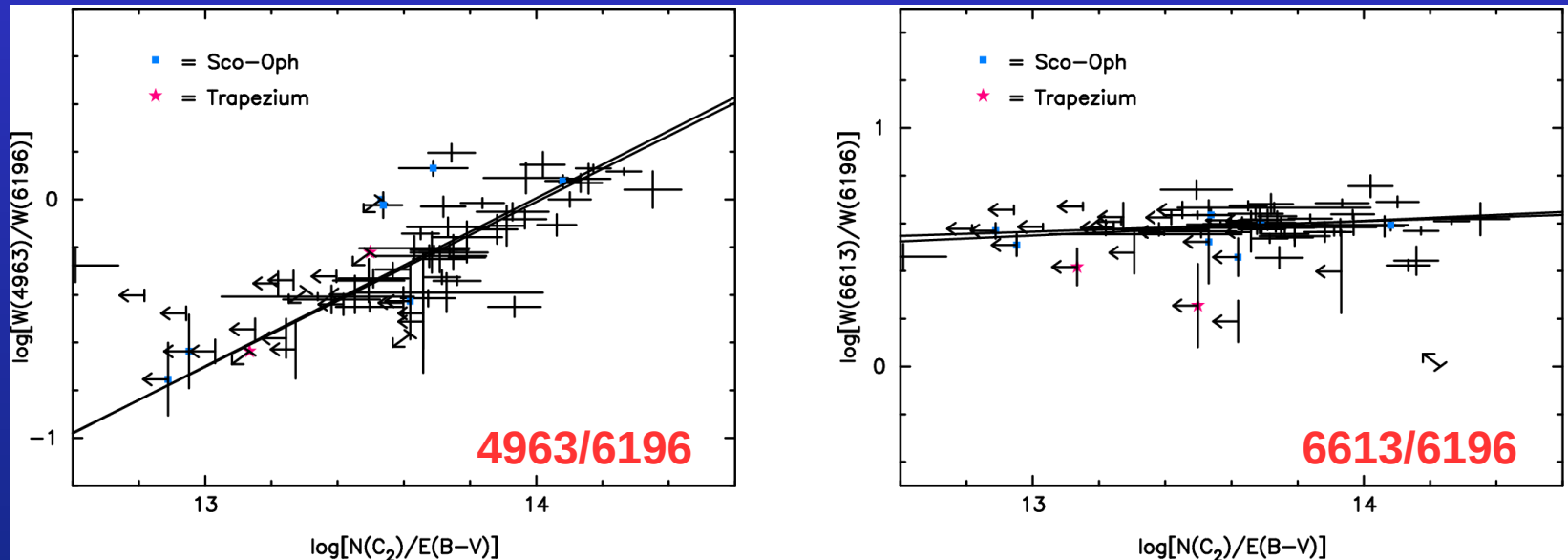


ARCES (8 km/s; S/N ~ 1000); 53 stars; 21 isolated DIBs

start with $\log[W(\text{DIB})]$ vs. $\log[E(B-V)]$ – 'expected' 1st order trend;
for some DIBs, residuals vs. best fit exhibit relationship with
 $\log[N(C_2)/E(B-V)]$ – 2nd order effect

no trend for 6196, so look at $W(\text{DIB})/W(6196)$ vs. $N(C_2)/E(B-V)$ –
a crude multivariate analysis

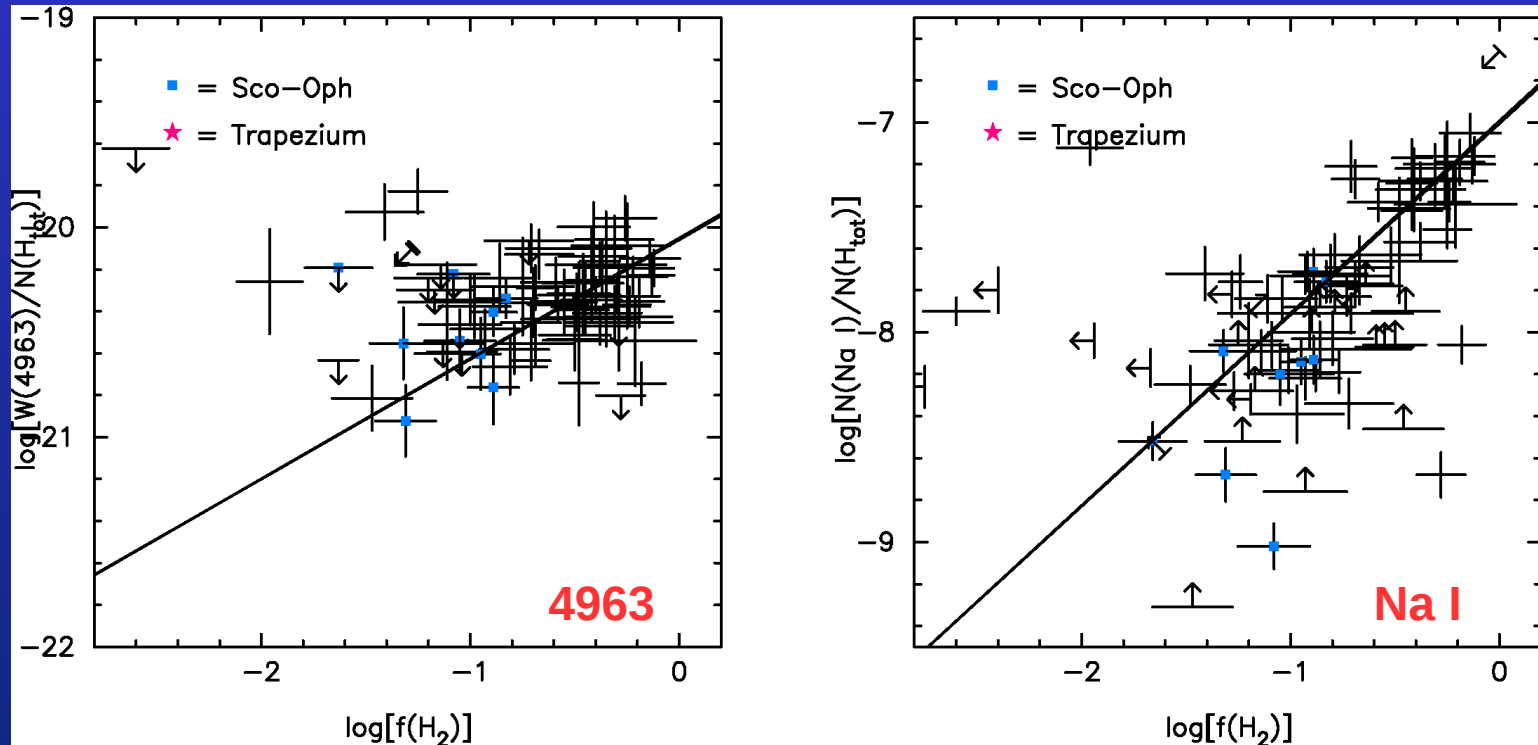
Thorburn et al. (2003) – C₂ DIBs



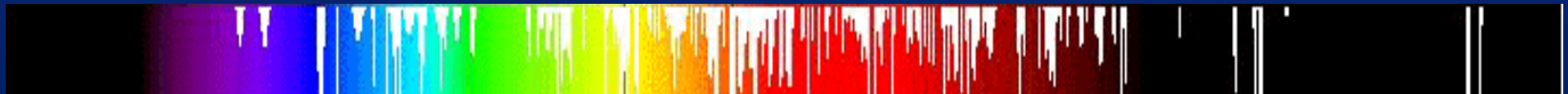
7 DIBs exhibit significant positive trend; 14 other DIBs do not;
11 other DIBs subsequently identified
correlations also with $N(CN)/E(B-V)$, $N(CH)/E(B-V)$
all are relatively narrow ($FWHM < 1 \text{ \AA}$)
several pairs with $\Delta\sigma \sim 20 \text{ cm}^{-1}$

conclusion: conditions that enhance C₂ also enhance some DIBs

Thorburn et al. (2003) – C₂ DIBs



unlike most other DIBs, the C₂ DIBs exhibit positive trends with $f(\text{H}_2)$ – intermediate between Na I, K I and Fe I, Ca I



Friedman et al. (2011) – 8 DIBs vs. H, H₂, E(B-V)

ARCES spectra; 133 stars; **correlation coefficients:**

DIB	FWHM	r[H]	r[H2]	r[E(B-V)]	r[Na I]	r[K I]
4963.9	0.62	0.62	0.53	0.79	0.80	0.84
5487.7	5.20	0.60	0.47	0.79	0.56	0.58
5705.1	2.58	0.73	0.56	0.80	0.69	0.68
5780.5	2.11	0.90	0.65	0.82	0.78	0.71
5797.1	0.77	0.72	0.79	0.84	0.87	0.84
6196.0	0.42	0.79	0.74	0.85	0.89	0.84
6204.5	4.87	0.84	0.60	0.83	0.64	0.55
6283.8	4.77	0.87	0.46	0.82	0.71	0.67
6613.6	0.93	0.77	0.80	0.83	0.88	0.85

most uniform correlations are with E(B-V) [not for A_v ?]

several of the narrower DIBs are well correlated with Na I, K I

Friedman et al. (2011) – 8 DIBs vs. H, H₂, E(B-V)

correlation slopes (log[W(DIB)] vs. log[x]):

DIB	FWHM	s[H]	s[H ₂]	s[E(B-V)]	s[Na I]	s[K I]	s(Fe I)	s(Ca I)
6283.8	4.77	0.86	0.25	0.82	0.39	0.39	0.76	0.70
5487.7	5.20	0.93	0.29	0.90	0.49	0.41	1.01	0.75
6204.5	4.87	0.93	0.29	0.89	0.40	0.42	0.87	0.75
5705.1	2.58	1.01	0.41	0.82	0.44	0.42	0.72	0.70
5780.5	2.11	1.05	0.34	0.94	0.44	0.48	0.91	0.87
6196.0	0.42	1.04	0.40	0.95	0.51	0.52	0.87	0.71
5797.1	0.77	1.05	0.41	0.99	0.56	0.57	0.86	0.77
4963.9	0.62	1.04	0.43	1.07	0.83	0.70	0.90	0.71
6613.6	0.93	1.40	0.54	1.20	0.67	0.72	0.98	1.09

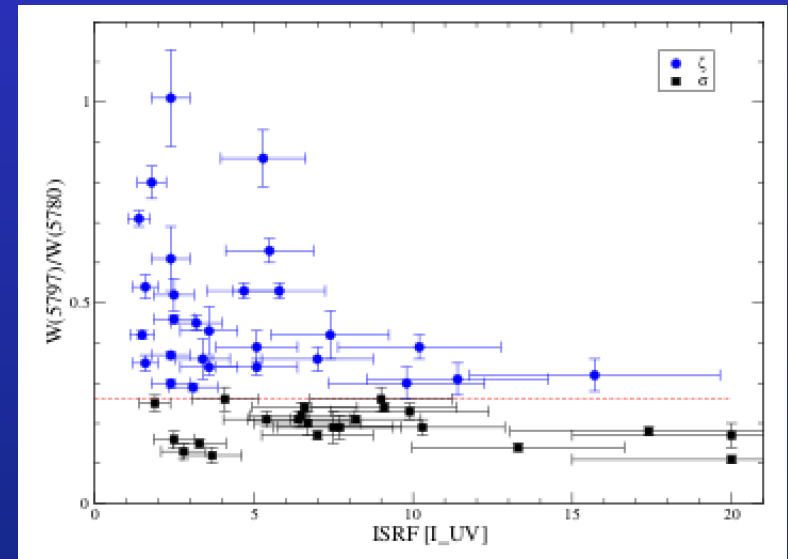
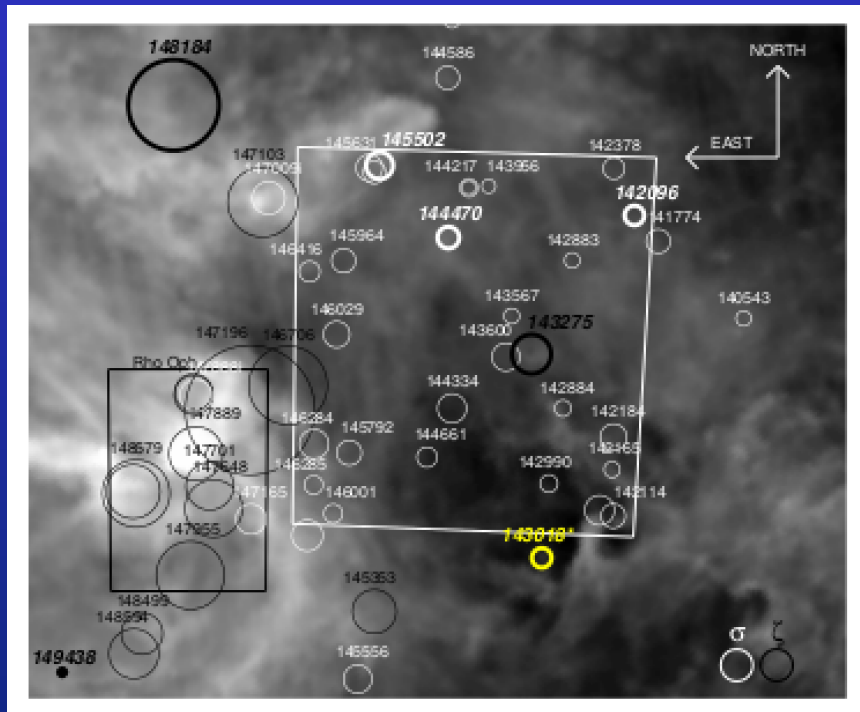
trends: broader DIBs have shallower slopes

6613, 4963, 5797 steepest; 6283 most shallow

steepest slopes for H and E(B-V), then Fe I and Ca I

any implications for relative spatial distributions of these DIBs?

Vos et al. 2012 – DIBs in Upper Scorpius

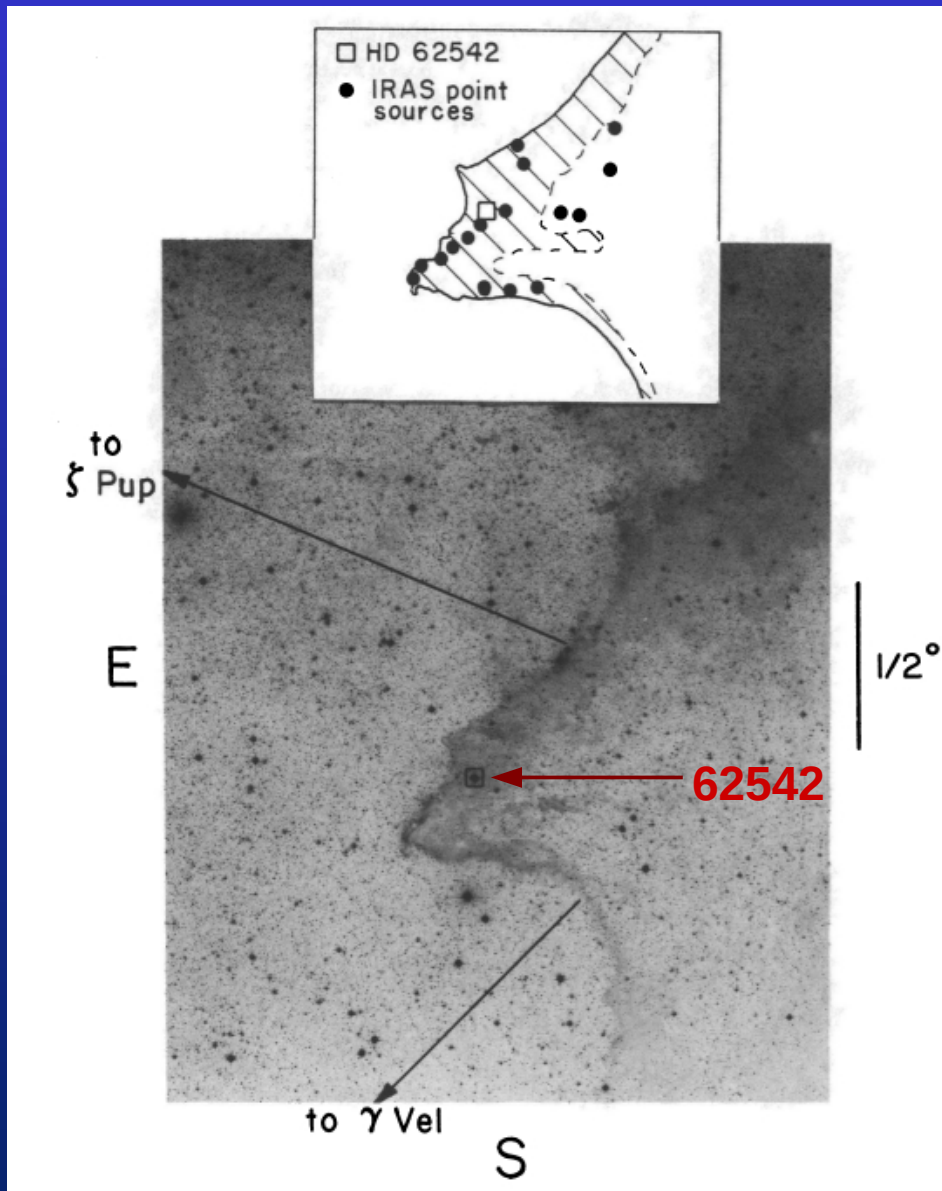


FEROS spectra of 89 stars in Upper Scorpius measured 5780, 5797, 6196, 6379, 6613, CH, CH⁺, CN, K I, Ca I confirm some previous correlations (separate sigma, zeta) estimate ISRF using model to reproduce observed CN, CH: **higher 5797/5780 generally associated with weaker ISRF**

HD 62542

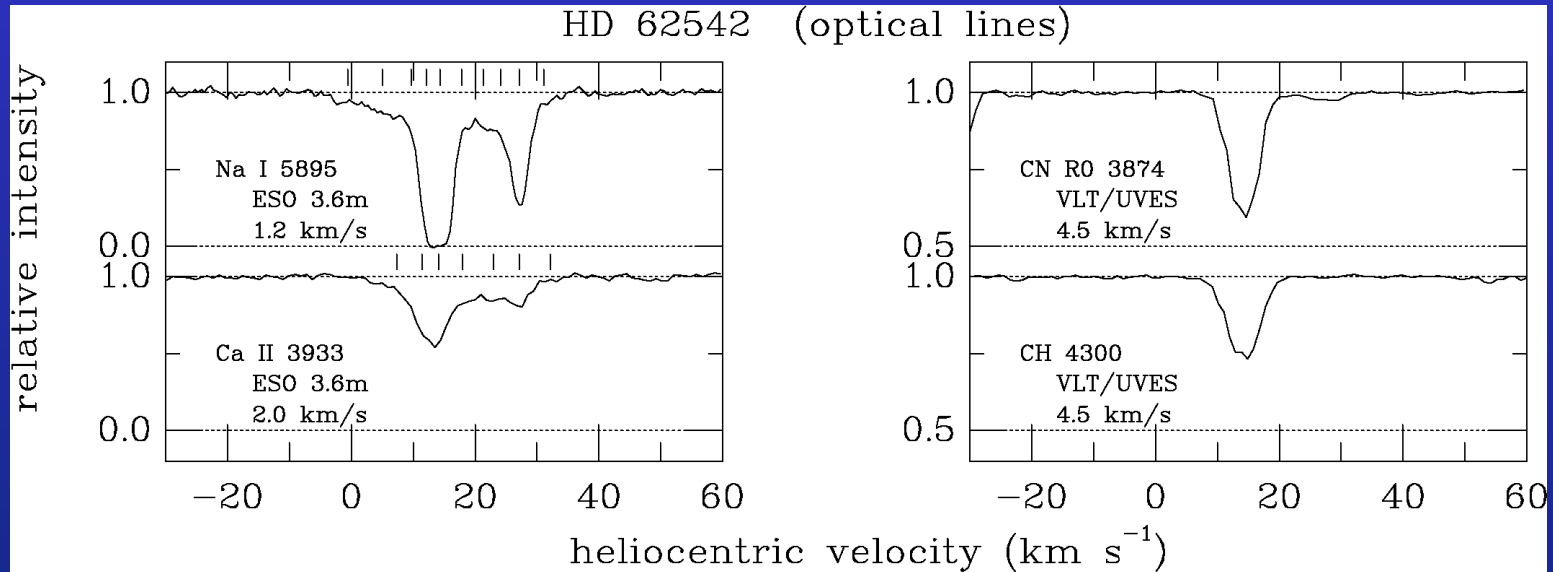
B5 V; behind Vela SNR
 $E(B-V) = 0.35$
 $A_v = 1.02$
steep far-UV extinction
weak, shifted 2175 Å bump
strong CN, high CN/CH
very weak CH⁺
 $f(H_2) = 0.64-0.78$ (higher?)
 $n_H \sim 500-1000 \text{ cm}^{-3}$

**a bare, dense core, with
most of outer atomic
envelope stripped by
stellar winds, radiation?
(Cardelli et al. 1990)**



(Cardelli & Savage 1988)

HD 62542 – Optical Interstellar Absorption



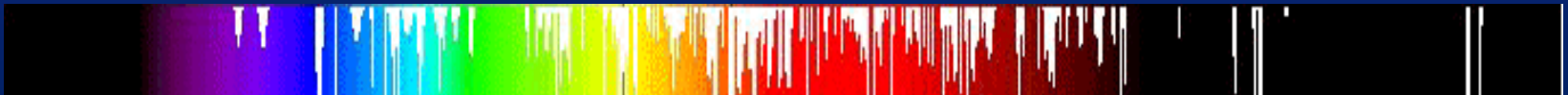
most in single narrow ($b \sim 0.8 \text{ km s}^{-1}$) component at 14 km s^{-1}

Na I/Ca II very high

CN/CH very high

CH⁺ very weak

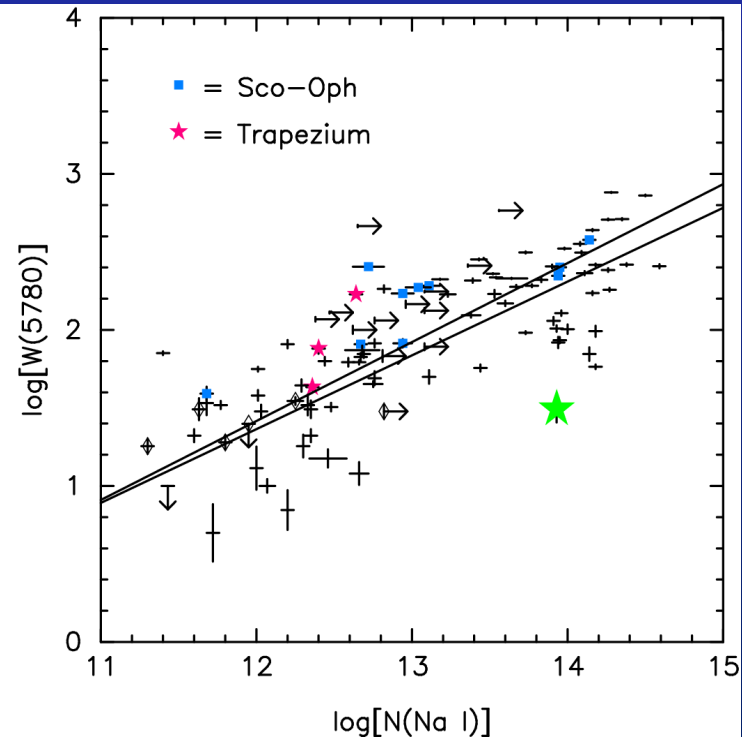
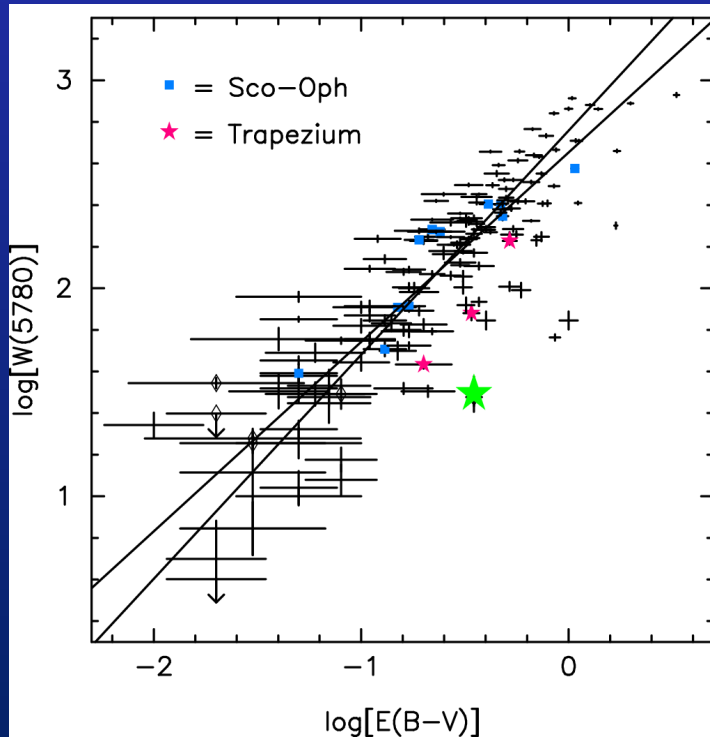
Ti II: severe depletions in main component



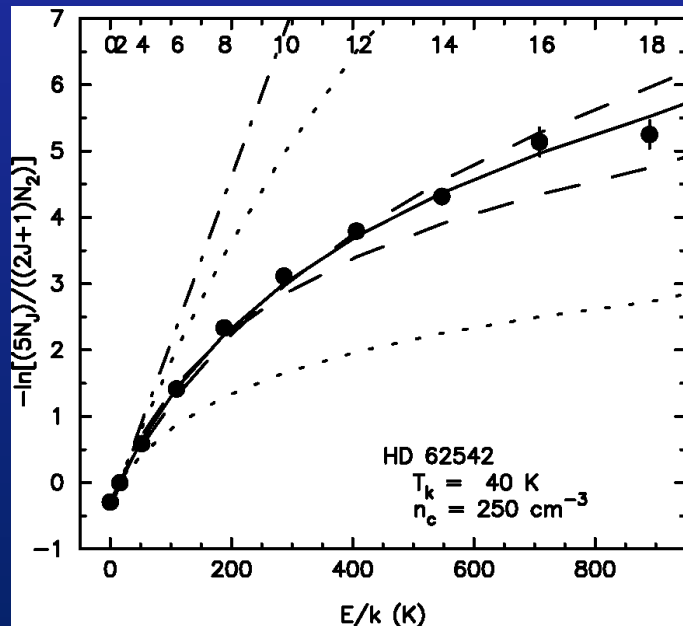
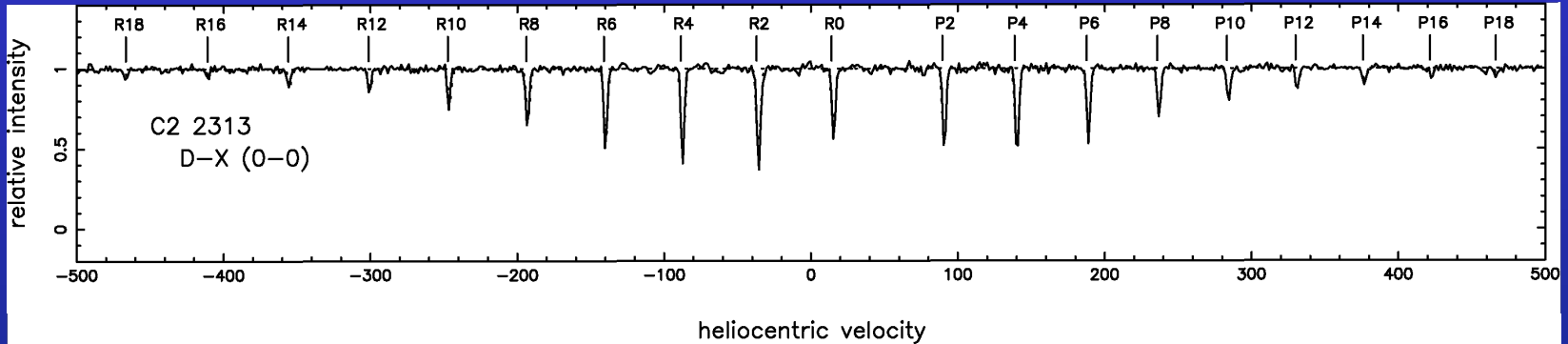
HD 62542 – DIBs in a Bare, Dense Core

commonly observed DIBs (5780, 5797, 6283) very weak, but C_2 DIBs present (Snow et al. 2002; Ádámkóvics et al. 2005)

measured 5780, inferred $N(H)$ could be entirely due to weaker component seen in Na I – velocity shift (5780 vs. C_2 DIBs)?



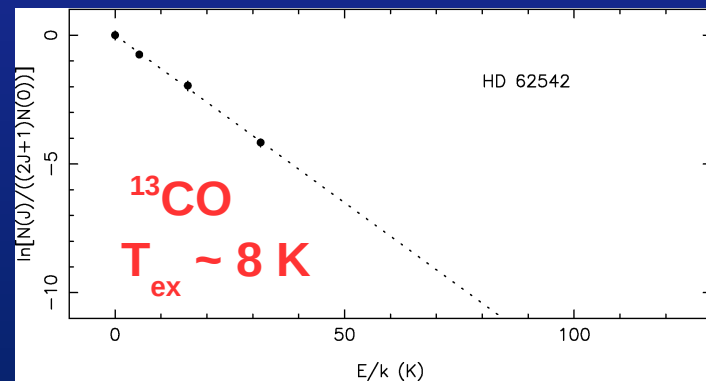
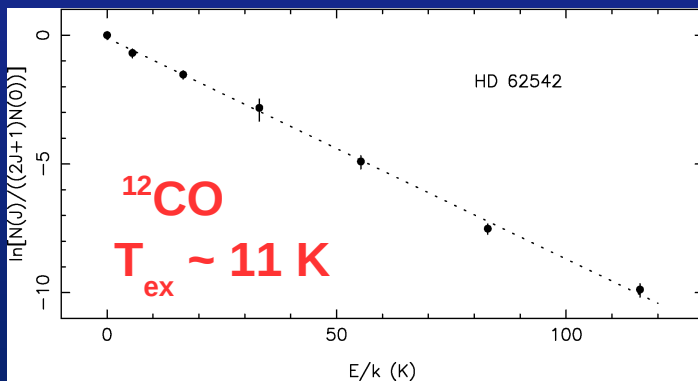
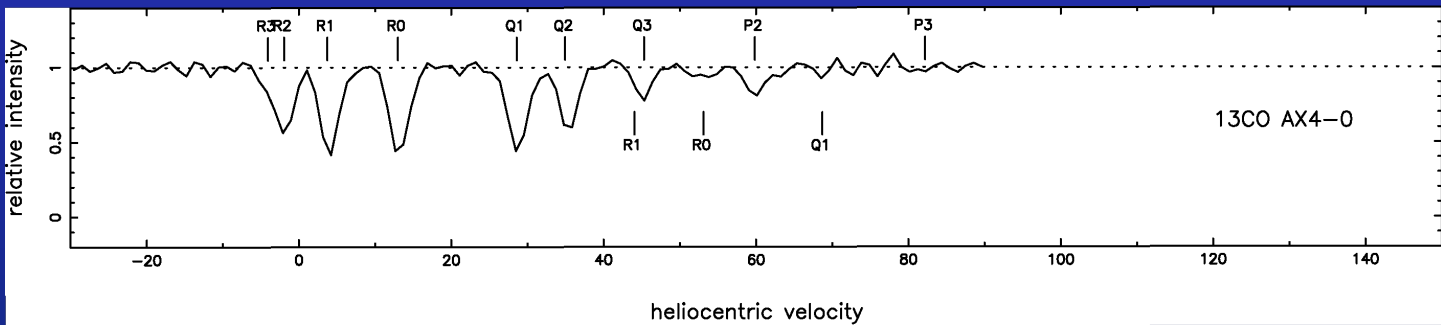
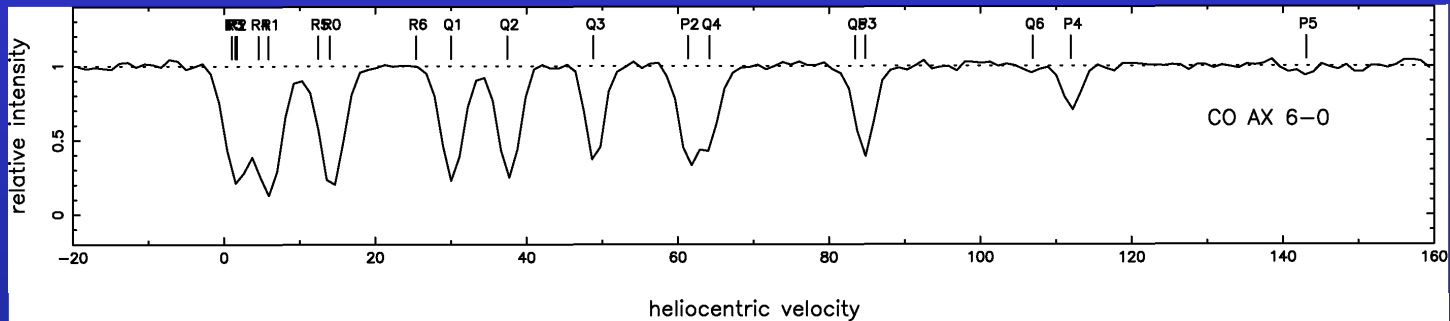
HD 62542 – C₂ D-X (0,0) Band



C₂ excitation: upper electronic levels radiatively excited (near-IR), then cascade down; lower J levels influenced by collisions (H, H₂); excitation depends on $n\sigma/l$

T_k (from lower levels) ~ 40 K
 $n_H \sim 385 \text{ cm}^{-3}$

HD 62542 – ^{12}CO , ^{13}CO , C^{18}O A-X Bands



relatively high T_{ex} – high density and/or local CO emission

FWHM(6196) vs. Temperature

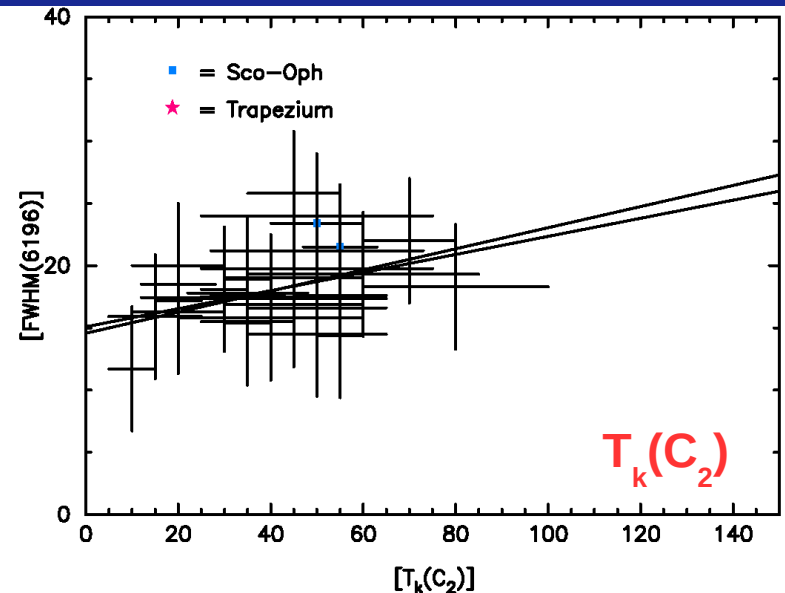
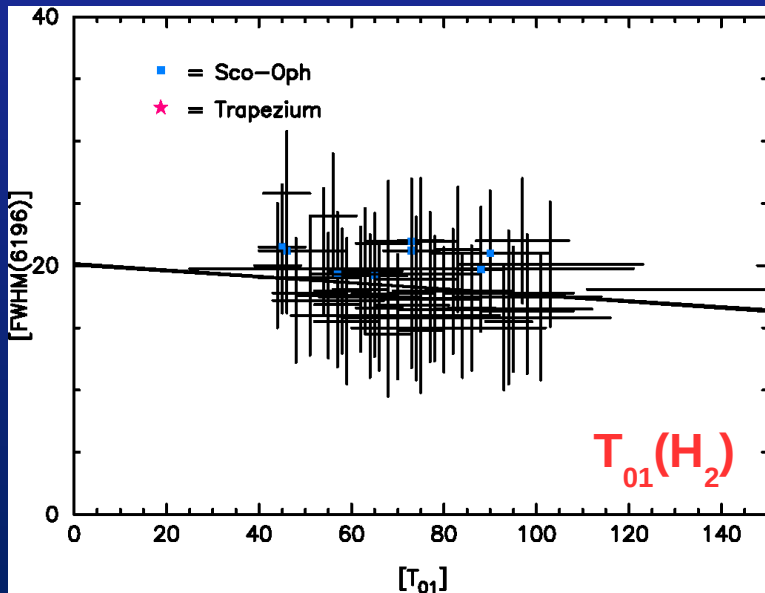
possible correlation between FWHM(6196, 5797) and $T_{\text{ex}}(\text{C}_2)$

(Kazmierczak et al. 2009, 2010)

sample fairly small; most of high FWHM in Sco-Oph region, where some 6196 profiles exhibit fine structure (G2002)

no correlation seen for 4963 (a C_2 DIB)

larger sample: no correlation with $T_{01}(\text{H}_2)$, marginal for $T_k(\text{C}_2)$?



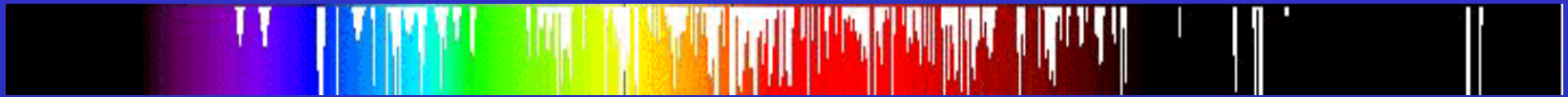


**Complexity of ISM (spatial & velocity structure, processes)
keep that in mind when interpreting correlations –
the DIB abundances depend on several variables**

Different DIBs exhibit different correlation strengths and slopes with the various atomic and molecular species (and derived quantities) – differences in distribution, sensitivity to physical conditions (n , T , radiation, ...)

Such comparisons can help determine DIB behavior in various environments – and (ultimately) enable use of DIBs as widespread diagnostics of physical conditions (but for total sight line, not individual components)

Special cases (unusual environments) can yield useful insights (Herschel 36, HD 62542, Trapezium, ...)



Use correlations appropriately – be aware of regional effects, recognize trends in residuals with other parameters

Large data sets – should enable more sophisticated statistical methods for unraveling dependencies on multiple variables (PCA?) – but will not have as precise atomic and molecular abundances, in general (lower resolution, S/N)

Obtain optical spectra for sight lines with good UV spectra (e.g., Jenkins sample – have estimates of pressures, radiation fields)

Detailed investigation of other special cases

Make the data public – many eyes and minds will be needed