The Cold ISM

1. Observational Examples
2. History
3. Molecular Spectroscopy
4. H_2 and CO
5. Molecular Clouds
6. Dust and Molecule Formation
7. Starformation

Literature:

Rohlfs & Wilson: Tools of Radio Astronomy, Springer
Cowley: An Introduction to Cosmochemistry, CUP

M51, NOAO, T. Rector

Whirlpool Galaxy • M51

Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-10

NGC 4565, McLaughlin

Edge-On Galaxy NGC 4013

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

Star Forming Region RCW 108 in ARA
(MPG/ESO 2.2-m + WFI)

ESO PR Photo 21a/99 (30 April 1999)

The Horsehead Nebula
(VLT KUEYEN + FORS 2)

ESO PR Photo 02a/02 (25 January 2002)

The Orion Nebula and Trapezium Cluster
(VLT ANTU + ISAAC)

ESO PR Photo 03a/01 (15 January 2001)

Reflection Nebula NGC 1999

PRC00-10 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI)

Milky Way: Overview

General properties of the Galaxy:

Hubble Type	SBb
Diameter of disk	35 kpc
Thickness of bulge	6 kpc
Thickness of disk	1 kpc
Diameter of halo	$\gtrsim$50 kpc
Mass	$4 \times 10^{12}\,M_\odot$
Mean Density	$0.1\,M_\odot\,\mathrm{pc}^{-3}$
Stellar mass fraction	90%
Gas mass fraction	10%
Dust	0.1%

This and the following lectures will look at the properties of the ISM.

General context: formation of stars.

Milky Way: ISM

The ISM of the Milky Way consists of the following phases

Name	Type	n cm^{-3}	T K	Filling Factor Vol-%	Mass % ISM	Comments
HIM	H II	10^{-2}–10^{-4}	10^6–10^8	20–60	<1	SNR, wind, shocks
WIM	H II	10^{-1}–10^{-4}	10^4	1–10	<1	photoionized by O/B-stars
WNM	H I	1–10	10^4	20–30	20-50	21cm clouds, shells
CNM	H I	10–10^2	100	10–20	20-50	HI envelopes, shells
MC	H I	10^2–10^4	10	1	40-50	IR, dust

HIM: Hot Ionized Medium, WIM: Warm Ionized Medium, WNM: Warm Neutral Medium, CNM: Cool Neutral Medium, MC: Molecular Clouds

courtesy J. Bally

Molecules: History

- Secchi, 1878: First notice of molecular features in stellar spectra (class III and IV; no explanation)

  Today known as TiO, C_2, and CN bands

- 1930s: Molecular lines in spectra of planetary atmospheres and comets as well as low temperature stars

- 1941: Interstellar absorption lines due to CN, CH, and CH^+ in optical spectrum of ζOph

- Weinreb et al, 1963: Radio absorption lines at $\lambda = 18\,\mathrm{cm}$ from OH towards SNR Cas A (not associated with Cas A, but with foreground clouds). Discovery of masers (=non-LTE!)

- Cheung et al., 1968: First multi-atom molecules: NH_3 and H_2O ($\lambda = 1.35\,\mathrm{cm}$).

- Snyder et al., 1969: Formaldehyde (H_2CO).

- Today (2002 April 11): 123 different molecules known

Molecular Hamiltonian, I

Simplest case: diatomic molecule

Hamiltonian: due to motion of nuclei and electrons.

Assume molecular size a ($\sim$ 1 Å).

Heisenberg:

$$\Delta p \Delta q \geq \hbar \tag{10.1}$$

such that typical energy spacing

$$\Delta E \sim \frac{\Delta p^2}{2m} \sim \frac{\hbar^2}{2ma} \tag{10.2}$$

since $\Delta q \sim a$.

For electrons: $\Delta E \sim$ 1 eV ($\widehat{=}$ 10^4 K),

for nuclei: $\Delta E \sim$ 0.001 eV ($\widehat{=}$ 10 K)

$\Longrightarrow$ To first order, kinetic energy of nuclei can be ignored.

In other words: electrons move much faster than nuclei $\Longrightarrow$ can make assumption of quasi-stationarity.

QM: Computation in "Born-Oppenheimer approximation", i.e., factorize wave-function $\Psi = \Psi_{\mathrm{e}}\Psi_{\mathrm{nucl}}$ and compute Ψ_{e} using the assumption that the nuclei are fixed.

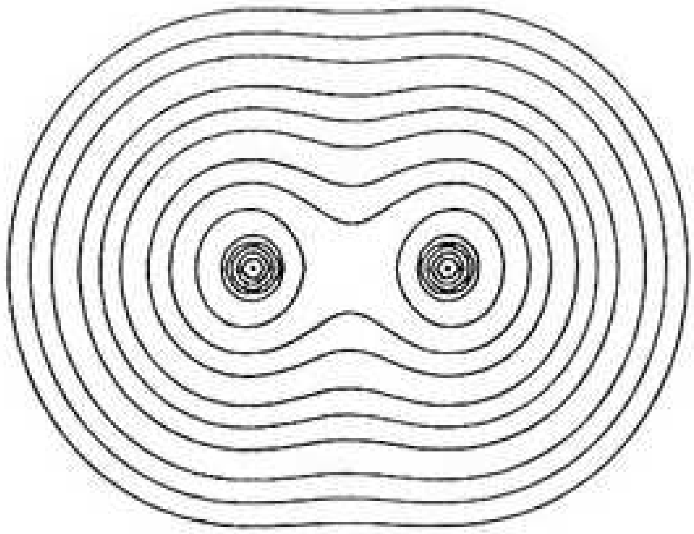
Molecular Hamiltonian, II

Transitions in molecule due to three different categories:

- electronic transitions between different levels, typical energies: $\sim$ eV $\Longrightarrow$ visual or UV
- vibrational transitions due to oscillation of nuclei, typical energies of 0.1 to 0.01 eV $\Longrightarrow$ infrared
- rotational transitions due to rotation of nuclei around common, 10^{-3} eV axis $\Longrightarrow$ cm and mm wavebands

Will now look at these in (some) detail.

Electronic States, I



O_2

Basic building-block: electronic states.

Generally, in molecules, distinction between "state", "level", and "term" from atomic spectra is *not* made!

Diatomic molecules: classify electron angular momentum along internuclear axis.

Wavefunction in this case will have φ-symmetry, and $\Psi \propto \exp(im\varphi)$, functions for other two coordinates depend on m^2 only $\Longrightarrow$ electronic states independent of sign of m.

Therefore use

$$\lambda = |m|, \quad \lambda = 0, 1, 2, \ldots \tag{10.3}$$

to describe wave functions. Electronic states with $\lambda = 0, 1, 2, 3, \ldots$ are called σ, π, δ, ϕ.

Electronic States, II

State of molecule: sum of orbital angular momenta, $\mathbf{L}$. Projection of L onto axis gives M_L, characterized by quantum number Λ.
$\Lambda = 0, 1, 2, 3, \ldots$ are called Σ, Π, Δ, Φ,$\ldots$,

Finally, multiplicity: Total electronic angular momentum (quantum number S). Write as in atoms, $^{2S+1}\Sigma$, such as $^2\Sigma$, $^4\Pi$, etc.

Sometimes, sum of Λ and Σ appended to term symbol.
For example, for $^4\Pi$:
$\Lambda = 1$ and
$\Sigma = -3/2, -1/2, 1/2, 3/2$,
such that

$$^4\Pi_{5/2}, {}^4\Pi_{3/2}, {}^4\Pi_{1/2}, {}^4\Pi_{-1/2}$$

Individual states are sorted in a weird way. X is ground state (sometimes addtl. $_g$ appended), higher states are A, B, C, other terms a, b,$\ldots$(e.g., ground state of CN is $X\,^2\Pi$, ground state of H_2 is $X\,^1\Sigma_g$).

Electronic States, III

Energy of electronic state:

In molecular spectroscopy, use wavenumber $\tilde{\nu}$ instead of Energy:

$$E = h\nu = \frac{hc}{\lambda} = hc\tilde{\nu} \qquad (10.4)$$

Energy expressed in terms of wavenumber is called a term value (not to be confused with "terms" of atomic physics!).

The electronic term value is

$$T_e = T_0 + A \cdot \Lambda \cdot \Sigma \qquad (10.5)$$

where Σ is projection of $\mathbf{S}$ on the internuclear axis, and A, T_0 are constants.

$\Longrightarrow$ Spin has large influence on energy!

Typical energies on order of several eV.

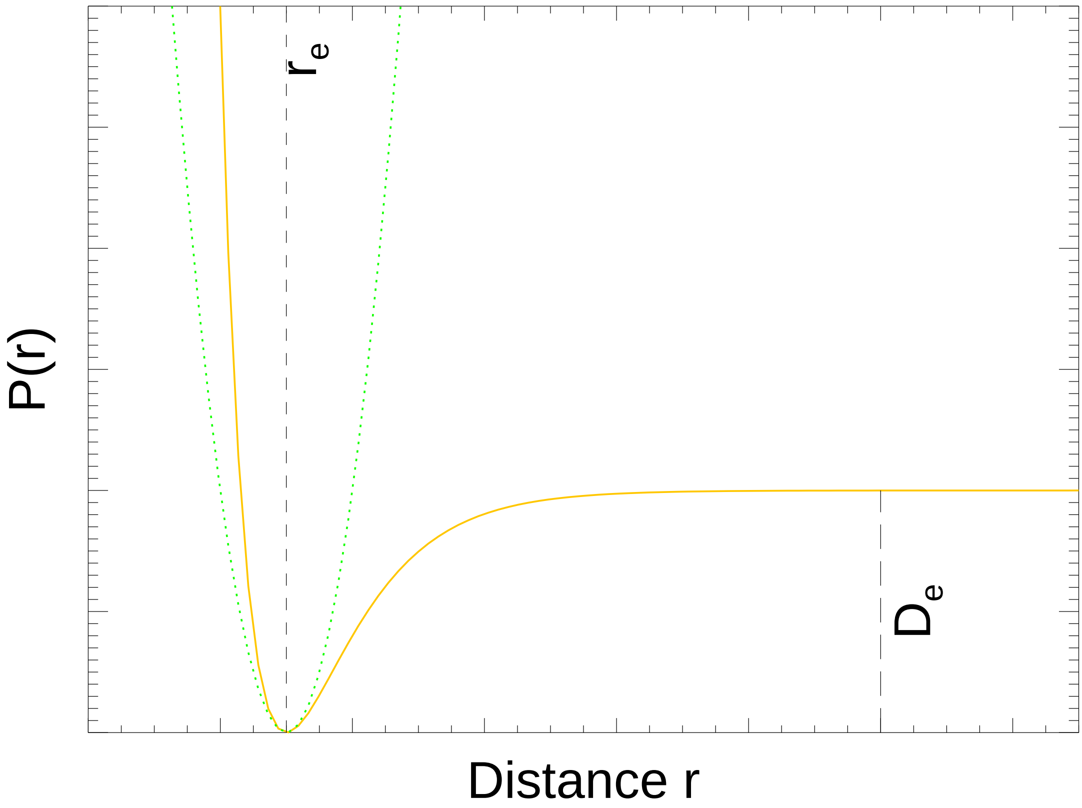
Sign of A determines order of energies.

$A > 0 \Longrightarrow$ Regular multiplet

$A < 0 \Longrightarrow$ Inverted multiplet

append r or i to designation of state

Vibrations



Internuclear potential $P(r)$ similar to Morse potential,

$$P(r) = D_\mathrm{e}\left(1 - \exp(-a(r - r_\mathrm{e}))\right)^2 \quad (10.6)$$

$$\sim a^2 D_\mathrm{e}(r - r_\mathrm{e})^2 \quad (10.7)$$

where D_e potential energy at large distances (=dissociation energy), r_e minimum of potential energy (distance of nuclei). Schrödinger equation gives vibrational energies

$$E(v) = h\nu_\mathrm{osc}(v + 1/2), \quad \text{with} \quad \nu_\mathrm{osc} = \frac{a}{2\pi}\sqrt{\frac{2D_\mathrm{e}}{m}} \quad (10.8)$$

where $v = 0, 1, 2, \ldots$ is called the vibrational quantum number.

Rotational Spectra, I

Kinetic energy of rotation:

$$H_{\mathrm{rot}} = \frac{1}{2}\Theta\omega^2 = \frac{\mathbf{J}^2}{2\Theta} \tag{10.9}$$

where J is angular momentum and where Θ is the moment of inertia.

For a diatomic molecule with nuclei A and B,

$$\Theta = m_A r_A^2 + m_B r_B^2 =: m r_e^2 \tag{10.10}$$

where

$$\mathbf{r}_e = \mathbf{r}_A - \mathbf{r}_B \tag{10.11}$$

and where the reduced mass is

$$m = \frac{m_A m_B}{m_A + m_B} \tag{10.12}$$

Finally, the angular momentum is

$$\mathbf{J} = \Theta\omega \tag{10.13}$$

Normally, the moment of inertia is a tensor $\Longrightarrow$ use value appropriate for direction of ω...

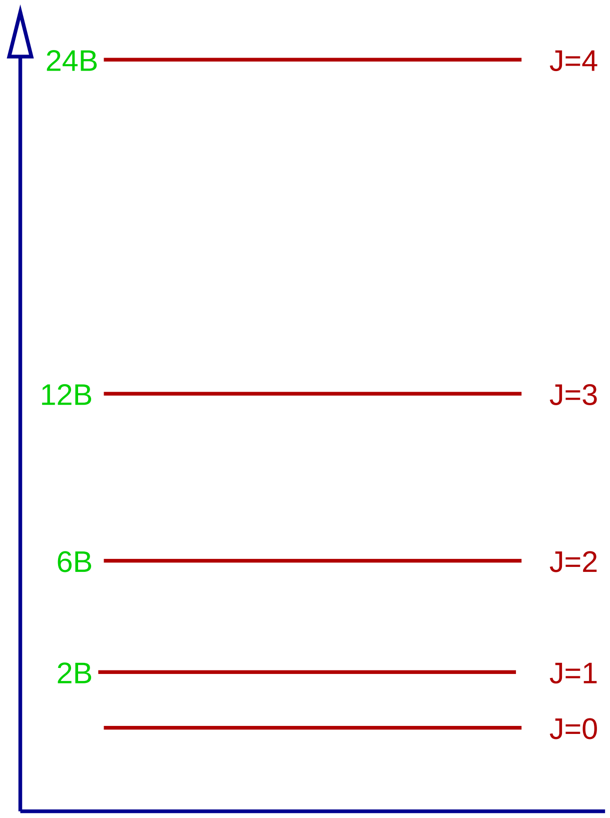
Rotational Spectra, II

Solution of the Schrödinger equation for the angular momentum gives

$$E_{\text{rot}}(J) = \frac{\hbar^2}{2\Theta} J(J+1) \qquad (10.14)$$

where J is quantum number of angular momentum, and where

$$J = 0, 1, 2, \ldots$$



Or in units of wave-number:

$$\begin{aligned} F(J) &= \frac{E_{\text{rot}}}{hc} \\ &= \frac{h}{8\pi^2\Theta c} J(J+1) \\ &= B \cdot J(J+1) \end{aligned} \qquad (10.15)$$

Rotational Spectra, III

Actual molecules have centrifugal stretching due to rotation.

To first order, gives energy correction, therefore for rotational terms in general:

$$F(J) = BJ(J+1) - D\left[J(J+1)\right]^2 \qquad (10.16)$$

with some constant $D \ll B$.

Order of magnitude of B: Typical separation of nuclei in molecule $a \sim 1\,\text{Å} \sim 10^{-8}$ cm. For CO, reduced mass is about 10 amu, or 1.6×10^{-23} g. Therefore

$$\Theta = 1.6 \times 10^{-23} \cdot 10^{-16} = 1.6 \times 10^{-39}\,\mathrm{g\,cm^2}$$

such that

$$B = 1.75\,\mathrm{cm^{-1}}$$

Wavenumber of transition between $J = 1$ and $J = 0$ therefore:

$$\tilde{\nu}_{J=1\rightarrow J=0} = 3B - 1B = 2B = 3.5\,\mathrm{cm^{-1}}$$

corresponding to $\lambda = 3$ mm, or $\nu = 100$ GHz.

Reality

In reality, rotators vibrate $\Longrightarrow$ rotations and vibrations are coupled $\Longrightarrow$ All constants are not constants...

Rotations:

$$F(J) = J(J+1)B_v - (J(J+1))^2 D_v \qquad (10.17)$$

where

$$B_v = B - \alpha_e(v + 1/2) \qquad (10.18)$$

with some correcting constant α_e. In principle similar equation for D_v, with constant β_e, but usually setting $D_v = D$ is sufficient.

Vibrations:

$$G(v) = \omega_e(v+1/2) - \omega_e x_e(v+1/2)^2 + \\ + \omega_e y_e(v+1/2)^3 + \dots \qquad (10.19)$$

where ω_e, $\omega_e x_e$, etc. are constants.

Typically, all constants (α_e, D_v, ω_e,...) are tabulated (determined from experiments)

Table 11.1. *Selected Constants for Diatomic Molecules. (Units are* cm^{-1} *except as indicated.)*

State	Te	ω_e	$\omega_e x_e$	B_e	α_e	D_e	r_e(Å)
		$^1H_2$	$D_0^0 = 4.4781_3$ eV				
$C\,^1\Pi_u 2p\pi$	100 089.8	2 443.77	69.524	31.362$_9$	1.664$_7$	2.23	1.03
$B^1\Sigma_u^+ 2p\sigma$	91 700.0	1 358.09	20.888	20.15$_4$	1.184 5	1.625	1.29
$X\,^1\Sigma_g^+ 1s\sigma^2$	0.0	4 401.21$_3$	121.33$_6$	60.853$_0$	3.062$_2$	4.71	0.74
		$^{12}C_2$	$D_0^0 = 6.21$ eV				
$d^3\Pi_g$	20 022.50	1 788.22	16.440	1.752 7	0.016 08	6.7$_4$	1.27
$c^3\Sigma_u^+$	13 312.$_1$	1 961.$_6$	13.$_7$	1.87			1.23
$A^1\Pi_u$	8 391.00	1 608.35	12.07$_8$	1.616 3$_4$	0.016 8$_6$	6.44	1.32
$b^3\Sigma_g^-$	6 434.2$_7$	1 470.4$_5$	11.1$_9$	1.485$_2$	0.016 34	6.22	1.37
$a^3\Pi_u$	716.2$_4$	1 641.35	11.67	1.632 4$_6$	0.016 61	6.44	1.31
$X^1\Sigma_g^+$	0.0	1 854.71	13.34$_0$	1.819 8$_4$	0.017 6$_5$	6.92	1.24
		$^{12}C\,^{14}N$	$D_0^0 = 7.7_6$ eV				
$D^2\Pi_i$	54 486.3	1 004.7$_1$	8.7$_8$	1.162	0.013	7.	1.50
$a^4\Sigma^{(+)}$	(32 400.)						
$B^2\Sigma^+$	25 752.0	2 163.9	20.2	1.973	0.023	[6.6]	1.15
$A^2\Pi_i$	9 245.28	1 812.5$_6$	12.60$_9$	1.715 1	0.017 08	5.93	1.23
$X^2\Sigma^+$	0.0	2 068.59	13.087	1.899 7$_4$	0.017 36$_9$	6.40	1.17
		$^{12}C\,^{16}O$	$D_0^0 = 11.09_2$ eV				
$a'^3\Sigma^+$	55 825.4$_9$	1 228.60	10.468	1.344 6	0.018 9$_2$	6.41	1.352 3
$a^3\Pi_r$	48 686.70	1 743.4$_1$	14.3$_6$	1.691 24	0.019 04	6.36	1.205 74
$X^1\Sigma^+$	0.0	2 169.814	13.288 3	1.931 3	0.017 5	6.121	1.128
		$^{16}O\,^1H$	$D_0^0 = 4.392$ eV				
$X\,^2\Pi_i$	0.0	3 737.76$_1$	84.881$_3$	18.910$_8$	0.7242	19.38	0.969 66
		$^{48}Ti\,^{16}O$	$D_0^0 = 6.87$ eV				
$C\,^3\Delta_r$	1 9617.0	838.26	4.76	0.489 89	0.003 06	6.7	1.69
	19 525.5						
	19 427.12						
$B^3\Pi_r$	16 331.$_3$	875.	5.	[0.506 17]		[6.86]	[1.67]
	16 315.$_1$						
	16 293.$_5$						
$b^1\Pi$	$a + 11\,322.0_3$	[911.20]	(3.7$_2$)	0.513 37	0.002 9$_1$	6.1	1.65
$A^3\Phi_r$	14 431.0	867.78	3.942	0.507 39	0.003 15	6.92	1.66
	14 262.8						
	14 089.91						
$E^3\Pi$	12 025.	924.$_2$	5.1				
$d^1\Sigma^+$	$a + 2\,215.6$	[1 014.6]	(4.6$_4$)	0.549 22	0.003 37	[6.0]	1.60
$a^1\Delta$	a	[1 009.3]	3.9$_3$	0.537 60	0.002 98	5.9	1.62
$X^3\Delta_r$	197.5	1 009.02	4.498	0.535 41	0.003 01	6.03	1.62
	96.4						
	0.0						

Cowley, Tab. 11.1

Selection Rules

Total energy of a molecular level of a diatomic molecule:

$$T(v, J) = T_e + G(v) + F(J) \qquad (10.20)$$

Compute line wavenumbers from differences of levels obeying selection rules.
Most important for spectroscopy: rotational-vibrational transitions.
For these the following selection rules apply:

- Selection rule for J:
  $\Delta J = 0, \pm 1$,
  $J = 0 \not\to J = 0$.
- Selection rule for v:
  $\Delta v \neq 0$ (only true for pure harmonic oscillator)

Also need finite dipole moment for these dipole-transitions to be possible

Note: homonuclear molecules have no dipole moment $\Longrightarrow$ only quadrupole lines possible ($\Delta J = \pm 2$).

Most common:
$J' = J'' + 1$: R-Branch
$J' = J''$: Q-Branch
$J' = J'' - 1$: P-Branch

Note: $J = 0 \not\to J = 0$ means that there is no Q-branch for most ground states.

Molecular Hydrogen

Because of high abundances: most molecular gas is H_2.

For review of properties of H_2, see Shull & Beckwith, 1982, Ann. Rev. Astron. Astrophys. 20, 163

H_2 is homonuclear $\Longrightarrow$ no permanent dipole moment $\Longrightarrow$ no rotational dipole transitions.
Only transitions observable are vibrational or electronic.
Vibrational: $\lambda \sim 6\,\mu\mathrm{m}$, in the infrared.

Problem: Dust extinction in IR severe

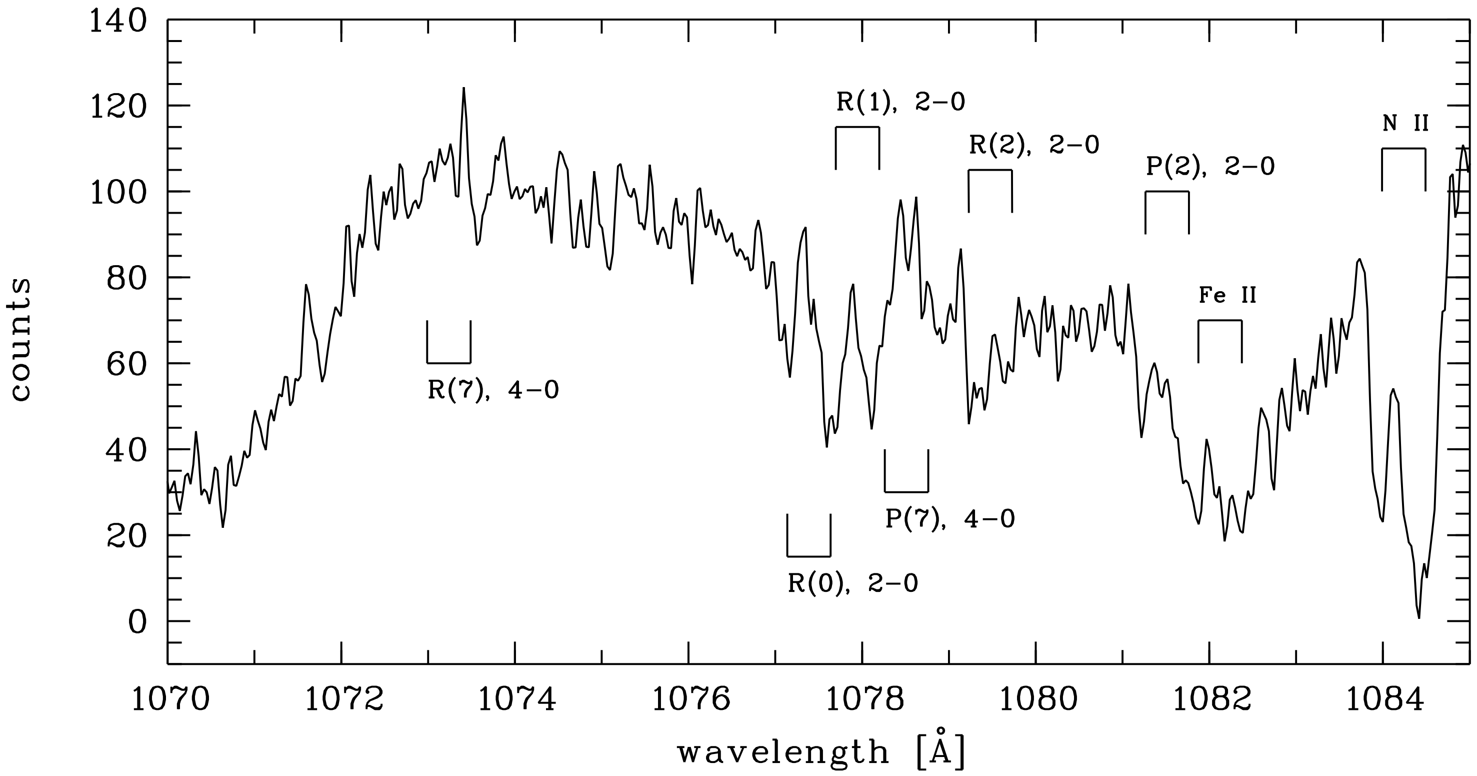
Once H is molecular, it is very difficult to see.

Alternative: Observation of electronic transitions of H_2 in absorption against hot UV-Stars ("Werner-bands").

Note that excitation of transitions requires lots of energy which cannot be produced otherwise.

Unfortunately, no relation to K.W. :-)

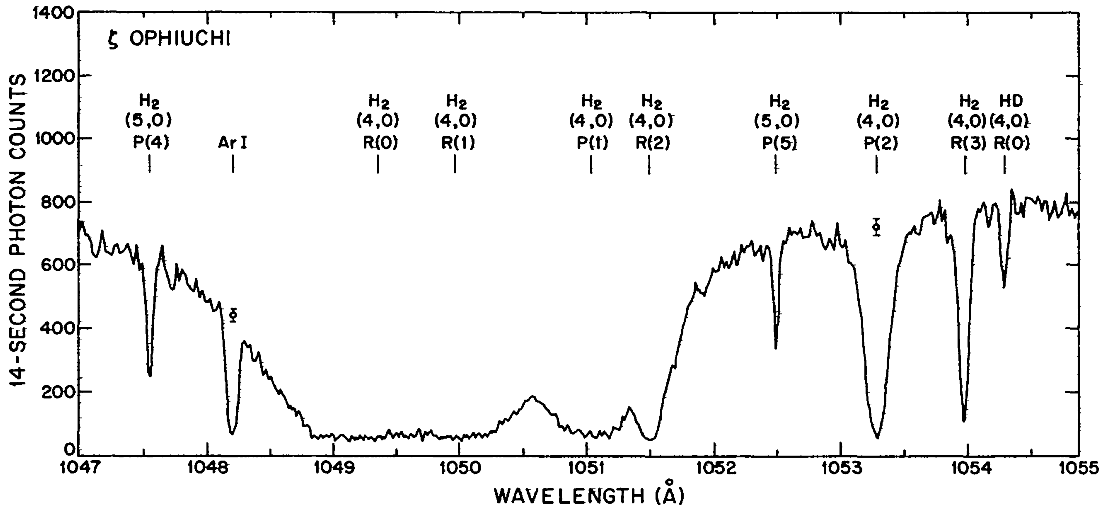
Molecular Hydrogen



Richter et al., 1998, A&A

ORFEUS: Discovery of H_2 bands in absorption in direction towards SMC $\Longrightarrow$ H_2 also present in diffuse ISM, not only in clouds (agrees with *Copernicus* measurements in milky way; Spitzer, 1974).

Molecular Hydrogen



Spitzer & Jenkins, 1975, ARAA 13, 133

Observation of $J = 1 \longrightarrow J = 0$ transition can be used to deduce temperature:

Boltzmann gives:

$$\frac{N(J)}{N(0)} = (2J+1)\exp\left(-J(J+1)\frac{85\,\mathrm{K}}{T}\right) \tag{10.21}$$

Typical temperatures for the diffuse medium are between 45 K and 130 K.

For low-density clouds, $N(1)/N(0)$ might be non-thermal, because molecules have tendency to be in high-J states when relaxing after photon excitation, thermal ratio only good for $n < 10^{18}\,\mathrm{cm}^{-3}$.

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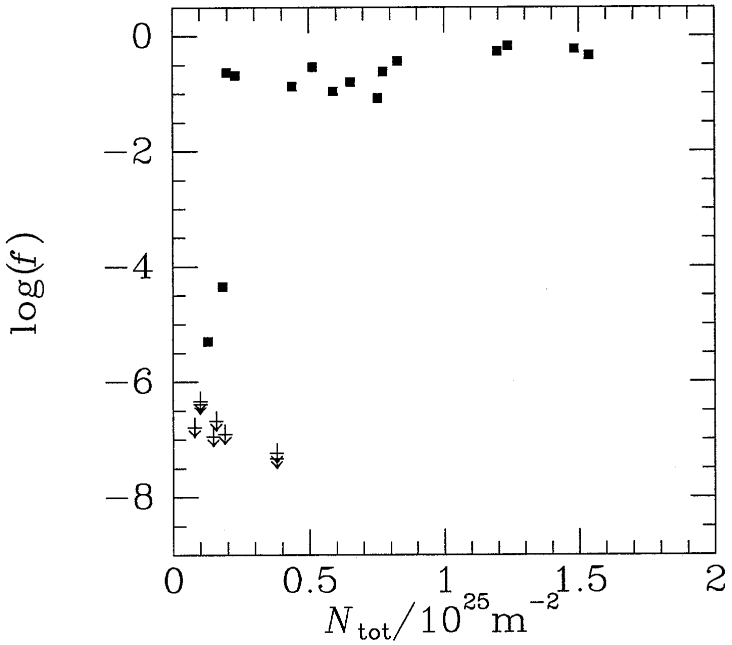
Molecular Hydrogen



Binney&Merrifield, Fig. 8.5

Compute total Hydrogen-density obtained from

$$N(\mathrm{H_{tot}}) = N(\mathrm{HI}) + 2N(\mathrm{H_2}) \tag{10.22}$$

and molecular fraction

$$f_{\mathrm{H_2}} = \frac{2N(\mathrm{H_2})}{N(\mathrm{H_{tot}})} \tag{10.23}$$

For $N(\mathrm{H_{tot}}) < 2 \times 10^{18}\,\mathrm{cm}^{-2}$, i.e., low columns, H is atomic, above that molecular $\Longrightarrow$ More molecules in denser parts of ISM.

Carbon Monoxide

Better than observing H_2 directly is to deduce its presence *indirectly* using other molecules with rotational positions $\Longrightarrow$ use heteronuclear molecules, e.g., CO, CS, HCN.

Candidate Number 1: CO, rotational transitions at 1.3 mm ($J = 2 \rightarrow J = 1$) and 2.6 mm ($J = 1 \rightarrow J = 0$).

Notation: CO(2-1) and CO(1-0)

CO is less abundant than H_2 (see later), but A-coefficients of lines very large; $\tau = 1$ reached at CO-column $\sim 6 \times 10^{15}\,\mathrm{cm}^{-2}$, corresponding to $N_\mathrm{H} \sim 8 \times 10^{19}\,\mathrm{cm}^{-2}$

$\Longrightarrow$ Cannot use "standard" CO to look into thick clouds.

$\Longrightarrow$ Use some tricks: Isotope effects!

CO: Isotope Effects

CO occurs in several forms:

- $^{12}C^{16}O$ (= ^{12}CO)
- $^{13}C^{16}O$ (= ^{13}CO)
- $^{12}C^{18}O$ (= $C^{18}O$)

because of slightly different reduced masses, wavelength of transitions slightly different $\Longrightarrow$ can separate emission lines from these species.

Relative abundances:
$^{12}CO : {}^{13}CO : C^{18}O = 500 : 65 : 1$

By using ^{13}CO or $C^{18}O$, can look deeper in molecular cloud.

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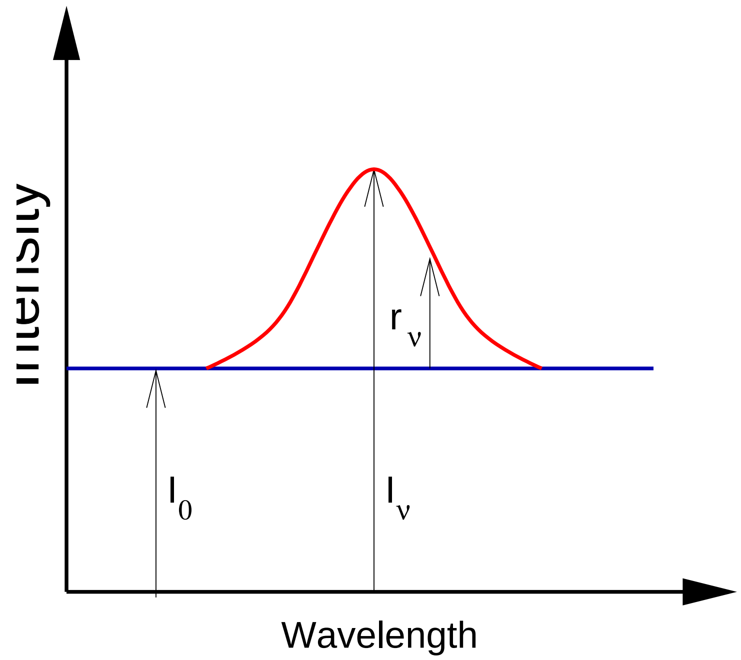
Column from Lines



after Cowley, Fig. 14.5

To measure mass from emission line, determine number of emitting atoms, N.

Observed intensity not trivially $\propto N$ because of self-absorption.

Excess in line:

$$r_\nu = \frac{I_\nu - I_0}{I_0} = \frac{S_\nu - I_0}{S_\nu}\left(1 - \exp\left(-\frac{\tau_\nu}{\mu}\right)\right) \quad (10.24)$$

where τ: optical depth, I_0: background intens., $\mu = \cos\theta$

Inserting τ in terms of transition probability f_{nm} and expanding the exponential gives for the equivalent width

$$W_\nu = \int r_\nu \, \mathrm{d}\nu \sim \frac{\pi e^2}{mc} r_0 f_{nm} \frac{N_n}{\mu} \quad (10.25)$$

where $r_0 = (S_\nu - I_0)/S_\nu$.

NGC 2024, II

For a case study: use NGC 2024 (flame nebula, bright star is Alnitak [ζ Ori]; close to horsehead).

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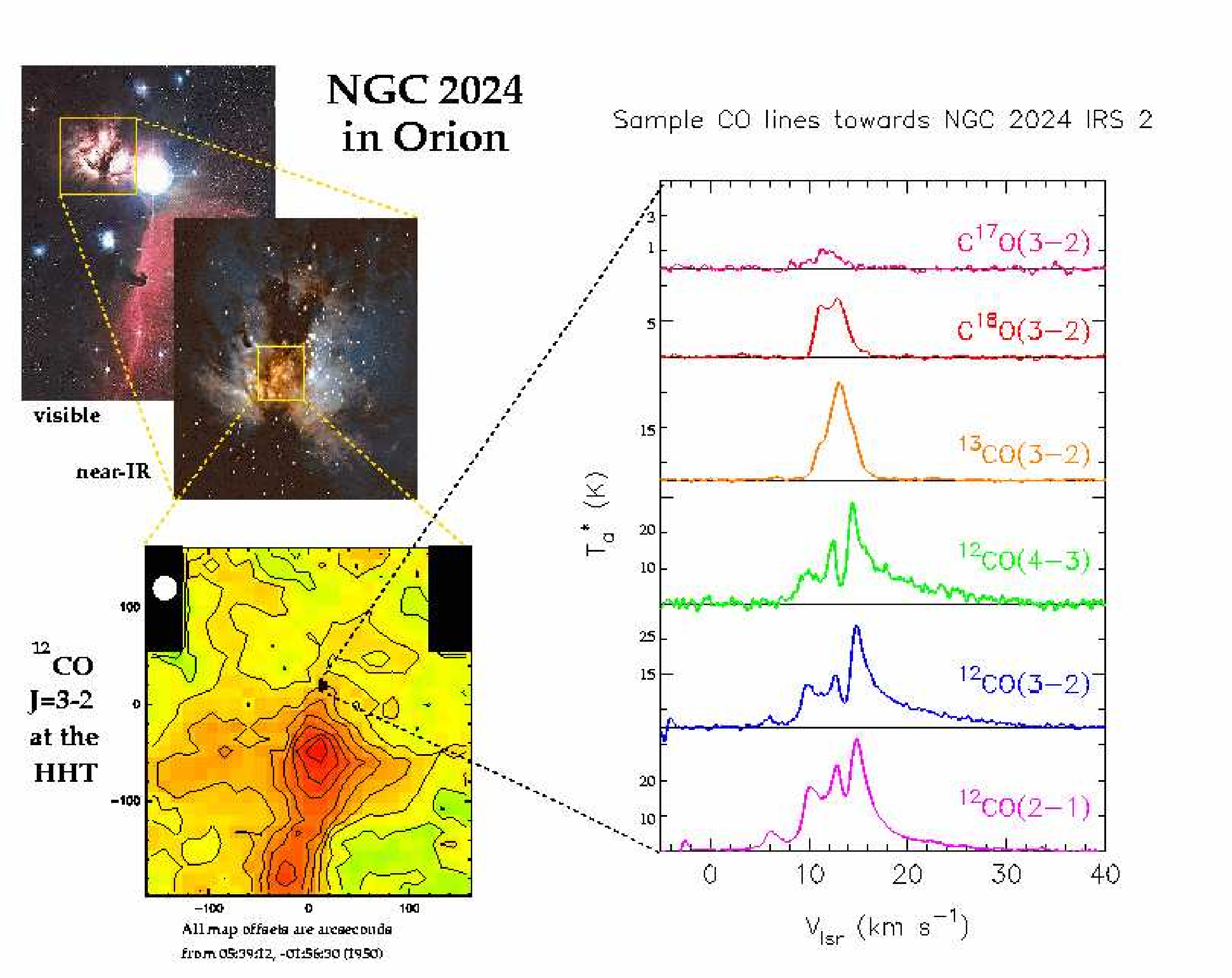
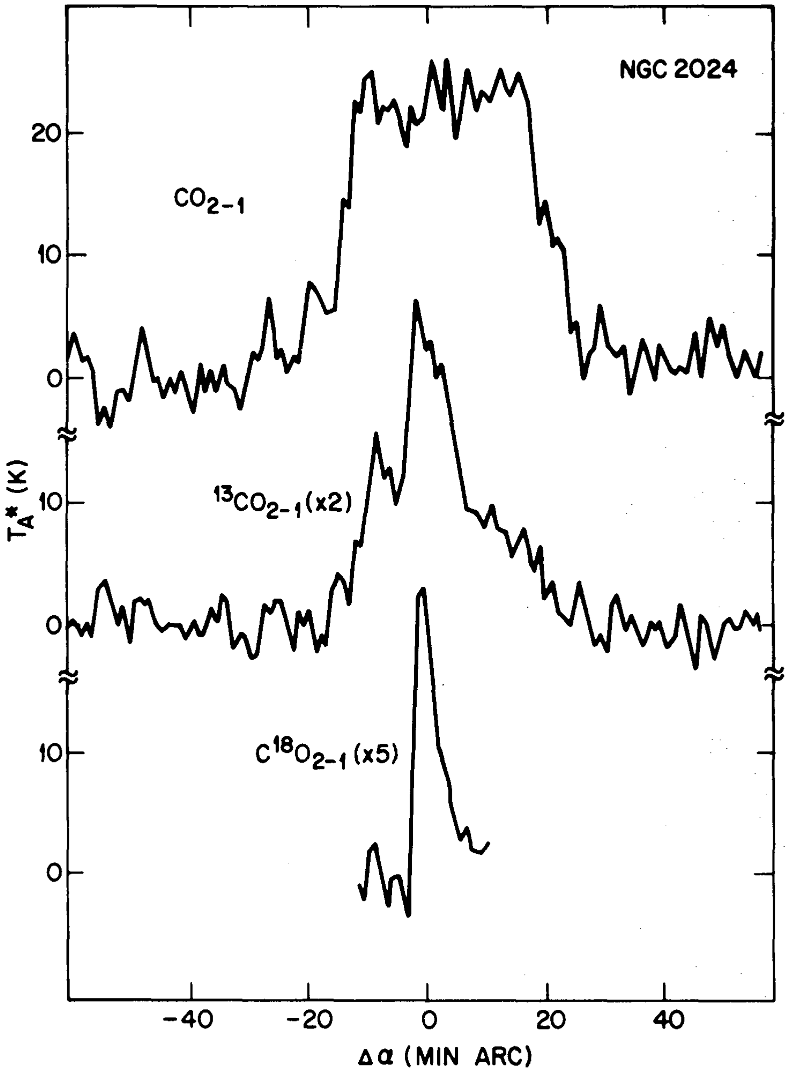
NGC 2024, III



(courtesy Craig Kulesa)

NGC 2024, IV



(Phillips et al., 1979, Fig. 3b)

Intensity given as antenna temperature, $I = 2kT\nu^2/c^2$

Right-ascension strip maps over NGC 2024: peak intensities ^{12}CO, ^{13}CO, and C^{18}O scale as 5:2:1 $\Longrightarrow$ cloud is optically thick (lines should scale as the abundances, and they don't).

Last step to get N_{CO}*:* use Boltzmann if (and only if) LTE is appropriate. . .

From CO to H

Once $N(\text{CO})$ has been determined: Infer H_2 column using some "standard" ratio. Typical assumptions:

$$\frac{N(^{13}\text{CO})}{N(\text{H}_2)} \sim 0.5\ldots 2.0 \times 10^{-6} \qquad (10.26)$$

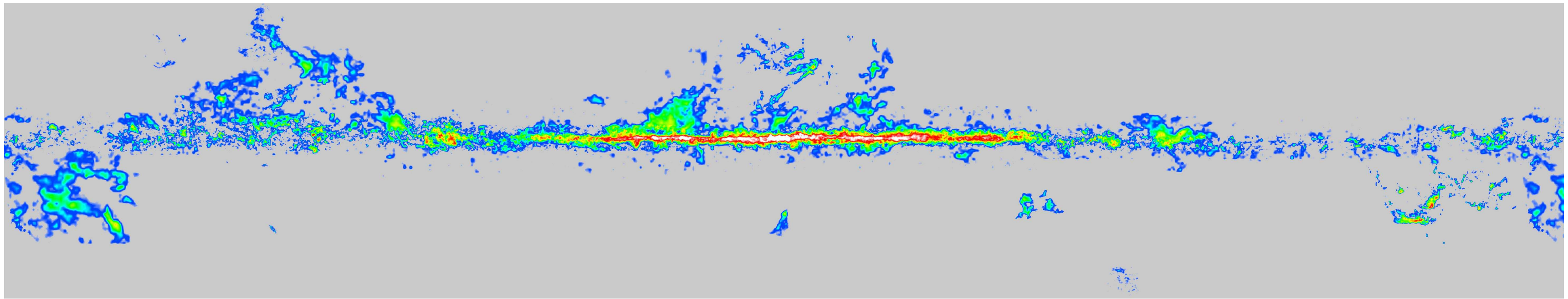
Ratio determined from UV-data on hydrogen and CO measurements at cloud edges (low τ).

Caveats:

- CO usually *not* in LTE for higher J
- $n(\text{H}_2)/n(^{12}\text{C})$, $n(^{12}\text{C})/n(^{13}\text{C})$ affected by astration (passage of ISM through stars), $\Longrightarrow$ $n(^{12}\text{C})/n(^{13}\text{C}) = 20$ at GC, 90 at large Galactic radii,
- Clumpy clouds? Shadowing? (fi nite beamsize of telescope. . .),
- Isotope ratios very different between different cloud complexes
- . . .

H_2 mass only determinable to factor of a few!

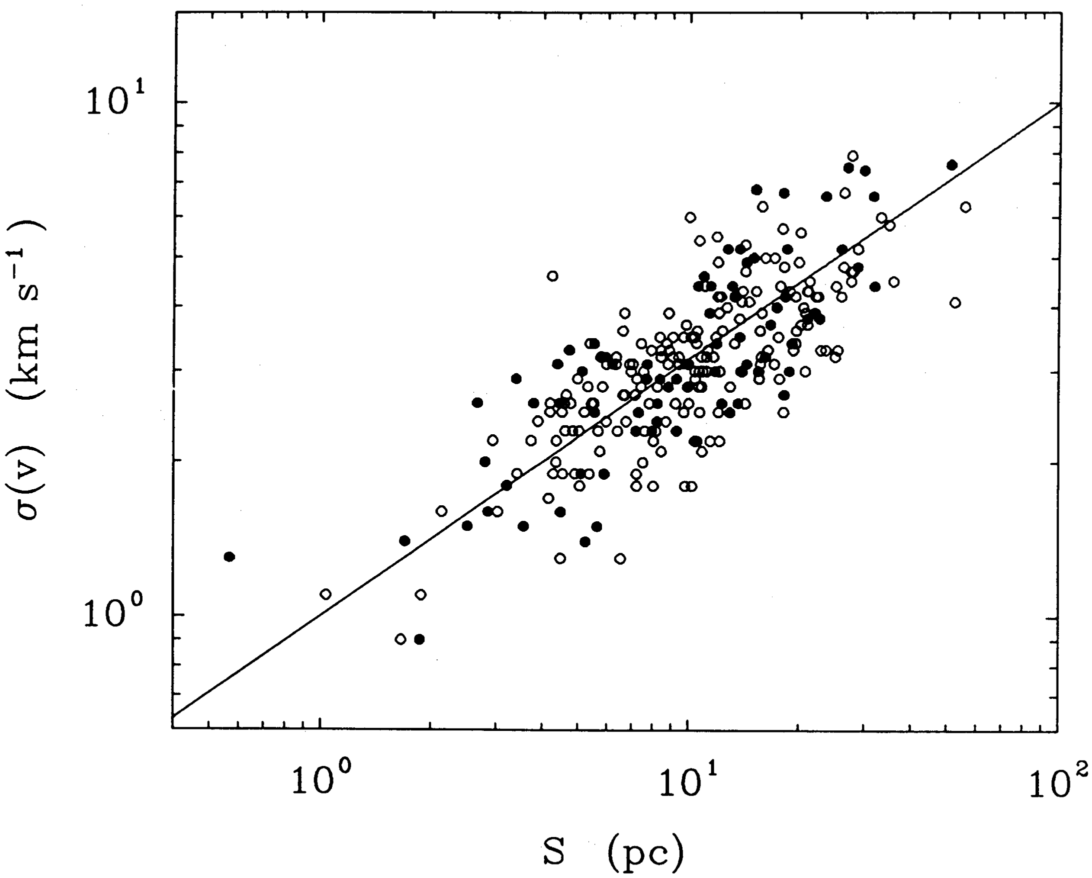
Cloud Properties, I



Dame et al., CfA; Columbia 1.2 m telescope

CO distribution in galactic coordinates: concentration of clouds on plane; high speed at center not yet understood.

Cloud Properties, II



(Solomon et al., 1987, Fig. 1)

Solomon et al. (1987): 2.6 mm ^{12}CO survey of $>$ 200 molecular clouds within solar circle.

Relationship between velocity dispersion, σ_v, (from line width) and cloud size, S:

$$\sigma_v = (1 \pm 0.1)\,\mathrm{km\,s^{-1}} \left(\frac{S}{\mathrm{pc}}\right) \qquad (10.27)$$

Cloud Properties, III

Median linewidth in Solomon survey:

$$\sigma_v \sim 3\,\mathrm{km\,s^{-1}} \tag{10.28}$$

Compare to sound-speed, assuming $kT \sim 30\,\mathrm{K}$

$$c_\mathrm{s} \sim \sqrt{\frac{kT}{m_\mathrm{p}}} \sim 0.5\,\mathrm{km\,s^{-1}} \sqrt{\frac{T}{30\,\mathrm{K}}} \tag{10.29}$$

σ_v dominated by turbulent velocity within clouds, not by sound speed...

Turbulent pressure $P \sim nm\sigma_v^2$, with $n \gtrsim 10^2\,\mathrm{cm^{-3}}$, much higher than confi ning pressure in intra-cloud medium (there: $n \sim 1\,\mathrm{cm^{-3}}$, $c_s \sim 10\,\mathrm{km\,s^{-1}}$) $\Longrightarrow$ clouds confi ned by gravity!

Use virial theorem to get mass:

$$M \sim \mathrm{const.}\frac{\sigma_v^2 S}{G} \tag{10.30}$$

where const. ~ 8.7, depending on geometry.

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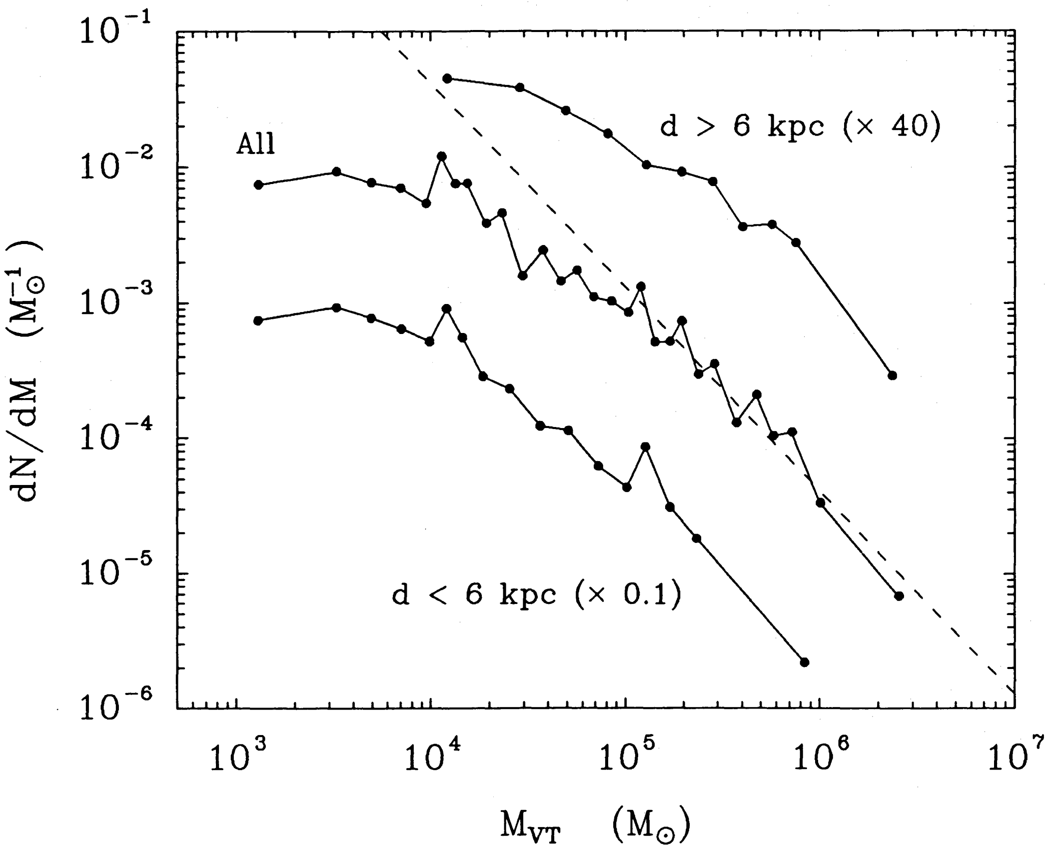
Cloud Properties, IV



(Solomon & Rivolo, 1989, Fig. 1)

Mass spectrum of molecular clouds is roughly

$$\frac{\mathrm{d}N}{\mathrm{d}M} \propto M^{-1.7} \qquad (10.31)$$

for $2000\,\mathrm{M}_\odot < M < 40000\,\mathrm{M}_\odot$.

At low masses selection effect (biasing).

Integrating over mass distribution shows

Most of the Galaxy's molecular gas is in the most massive clouds

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All Molecules

List of all interstellar and circumstellar molecules observed (`http://www.cv.nrao.edu/~awootten/allmols.html`; as of 2002 April 11)

Molecules with Two Atoms : AlF, AlCl, C_2, CH, CH^+, CN, CO, CO^+, CP, CS, CSi, HCl, H_2, KCl, NH, NO, NS, NaCl, OH, PN, SO, $S0^+$, SiN, SiO, SiS, HF, SH, FeO(?)

Molecules with Three Atoms: C_3, C_2H, C_20, C_2S, CH_2, HCN, HCO, HCO^+, HCS^+, HOC^+, H_20, H_2S, HNC, HNO, MgCN, MgNC, N_2H^+, N_2O, NaCN, OCS, $S0_2$, c-SiC_2, CO_2, NH_2, H_3^+, AlNC

Molecules with Four Atoms: c-C_3H, l-C_3H, C_3N, C_3O, C_3S, C_2H_2, CH_2D^+?, HCCN, HCNH+, HNCO, HNCS, HOCO+, H_2CO, H_2CN, H_2CS, H_30^+, NH_3, SiC_3

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All Molecules

Molecules with Five Atoms: C_5, C_4H, C_4Si, l-C_3H_2, c-C_3H_2, CH_2CN, CH_4, HC_3N, HC_2NC, HCOOH, H_2CHN, H_2C_20, H_2NCN, HNC_3, SiH_4, H_2COH^+

Molecules with Six Atoms: C_5H, C_50, C_2H_4, CH_3CN, CH_3NC, CH_30H, CH_3SH, HC_3NH^+, HC_2CHO, $HCONH_2$, l-H_2C_4, C_5N

Molecules with Seven Atoms: C6H, CH_2CHCN, CH_3C_2H, HC_5N, $HCOCH_3$, NH_2CH_3, c-C_2H_4O

Molecules with Eight Atoms: CH_3C_3N, $HCOOCH_3$, CH_3COOH, C7H, H_2C6, CH_2OHCHO

Molecules with Nine Atoms: CH_3C_4H, CH_3CH_2CN, $(CH_3)_20$, CH_3CH_20H, HC7N, C8H

Molecules with Ten or More Atoms: CH_3C_5N?, $(CH_3)_2CO$, NH_2CH_2COOH?, HC_9N, $HC_{11}N$

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The Problem

Formation of molecules in dense media (e.g., Earth's atmosphere) is no problem. This is very different from the rest of the universe!

Assume two-body collision of two (neutral) atoms: typical interaction timescale 10^{-13} s (1 vibration timescale).

To form molecule, need to get rid of excess energy!

Problem: Typical time for radiative relaxation given by A-coefficient ($\sim 10^{8}\,\mathrm{s}^{-1}$)

$\Longrightarrow$ Typical collisional time-scale too low
$\Longrightarrow$ cannot form molecules!

On Earth, excess energy carried away by triple-collisions, these are too rare in the ISM...

Further complication: UV-dissociation of molecules.

The Solution, I

Solution: "nonstandard chemistry"

- Atom-ion reactions
- dust as catalyst

Atom-ion reactions are, e.g.,

$$\mathrm{O}^{+} + \mathrm{H}_2 \longrightarrow \mathrm{OH}^{+} + \mathrm{H} \qquad (10.32)$$

These reactions are very effective.

Reason: ion polarizes molecule.

Langevin theory:

Assume charge q_1 approaches molecule; represent induced dipole-moment by charge q_2 separated by distance p. Then

$$q_2 p = \alpha E \qquad (10.33)$$

where E electric field, α polarizability.

Since $E = q_1/r^2$, this means

$$p = \frac{\alpha q_1}{q_2 r^2} \qquad (10.34)$$

and the attractive force is

$$F_r = -\frac{2 q_1 q_2 p}{r^3} = -\frac{2 q_1^2 \alpha}{r^5} \qquad (10.35)$$

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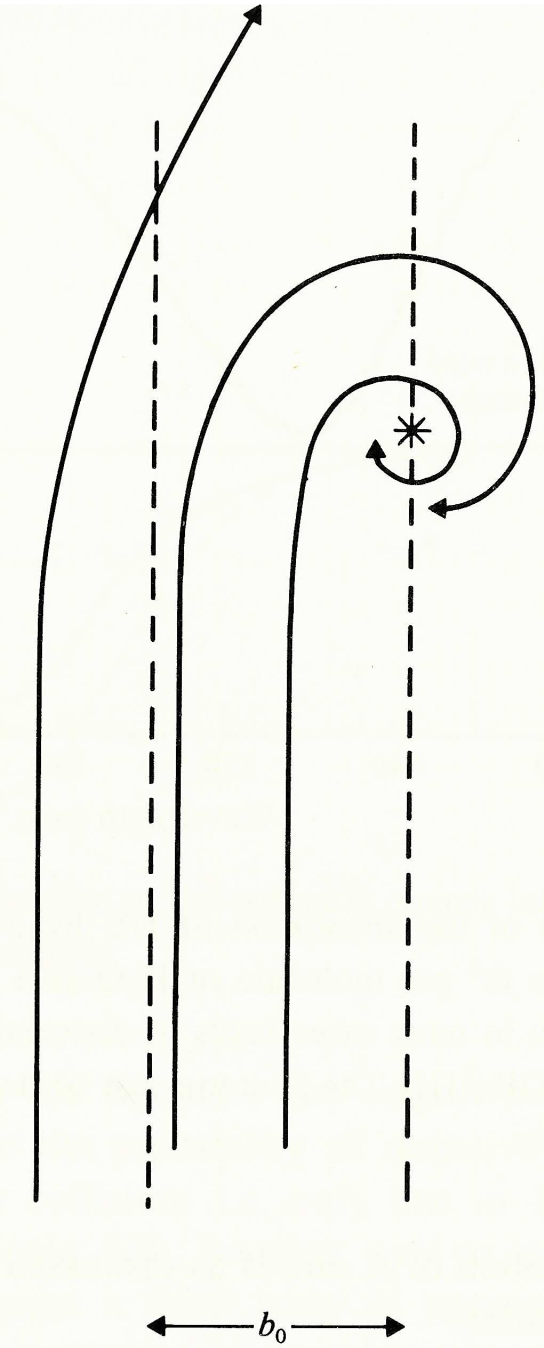
The Solution, II



Thus potential energy is

$$V(r) = \int_r^\infty F_r \, \mathrm{d}r = \frac{q_1^2 \alpha}{2r^4} \qquad (10.36)$$

Motion in such a potential allows spiral-in (F can not always be balanced by centrifugal force).

This happens for impact parameters $b < b_0$ where

$$b_0 = q_1 \left(\frac{4\alpha}{\mu v^2} \right)^{1/4} \qquad (10.37)$$

where μ reduced mass.

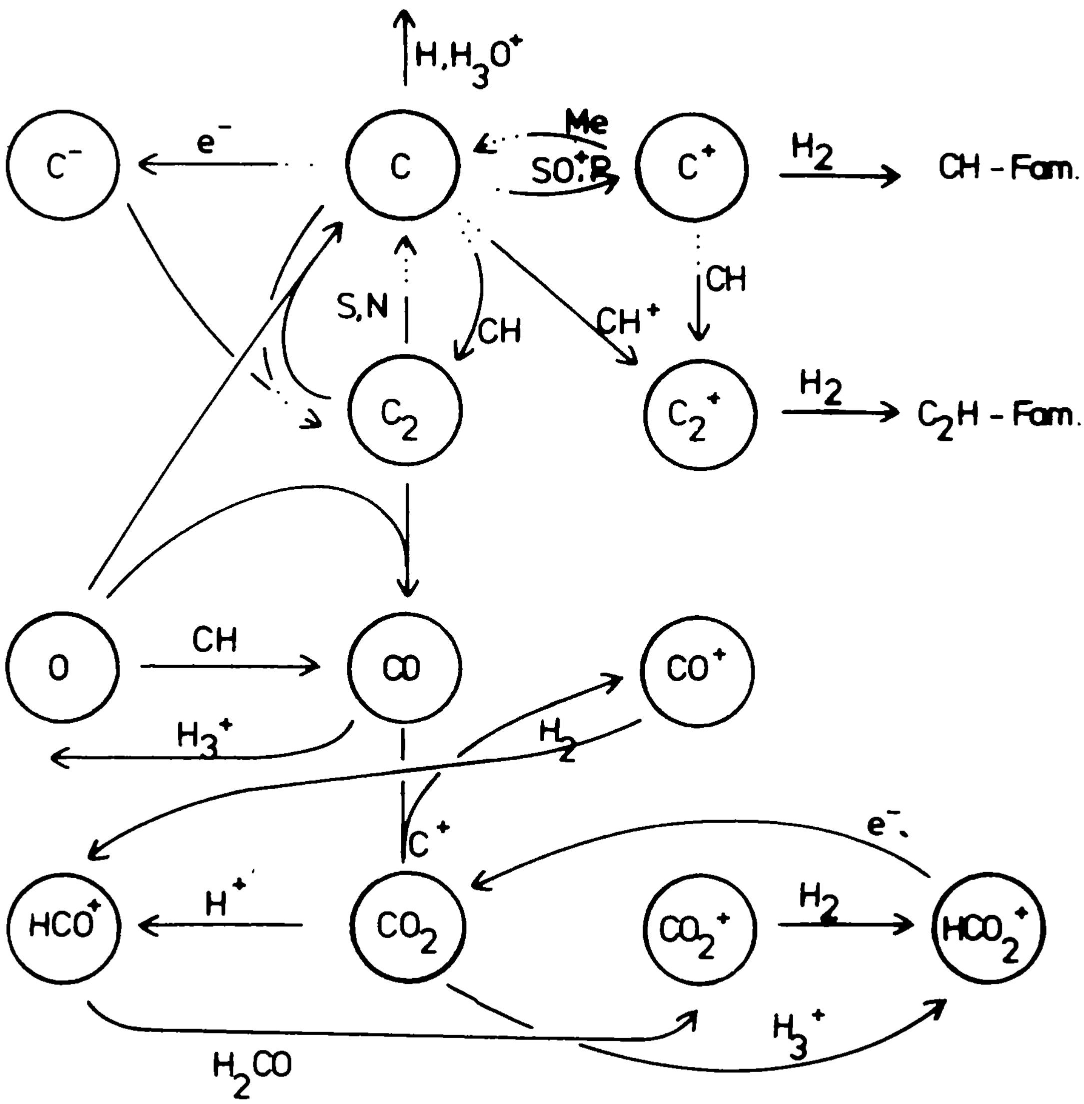
$\Longrightarrow$ Langevin cross section

$$Q = \pi b_0^2 \propto \frac{1}{v_\infty} \qquad (10.38)$$

Since collision frequency $\propto \langle Qv \rangle$, collision frequency independent of energy

Not really true in full theory, but dependence small for regime of astrophysical interest.

The Solution, III



Henning, 1981

Typical theory of molecular formation: reaction networks with ∼1000 and more different reactions.

Hydrogen Molecule

One unavoidable fact: cannot produce H_2 in gas phase $\Longrightarrow$ must occur on surface of dust grains.

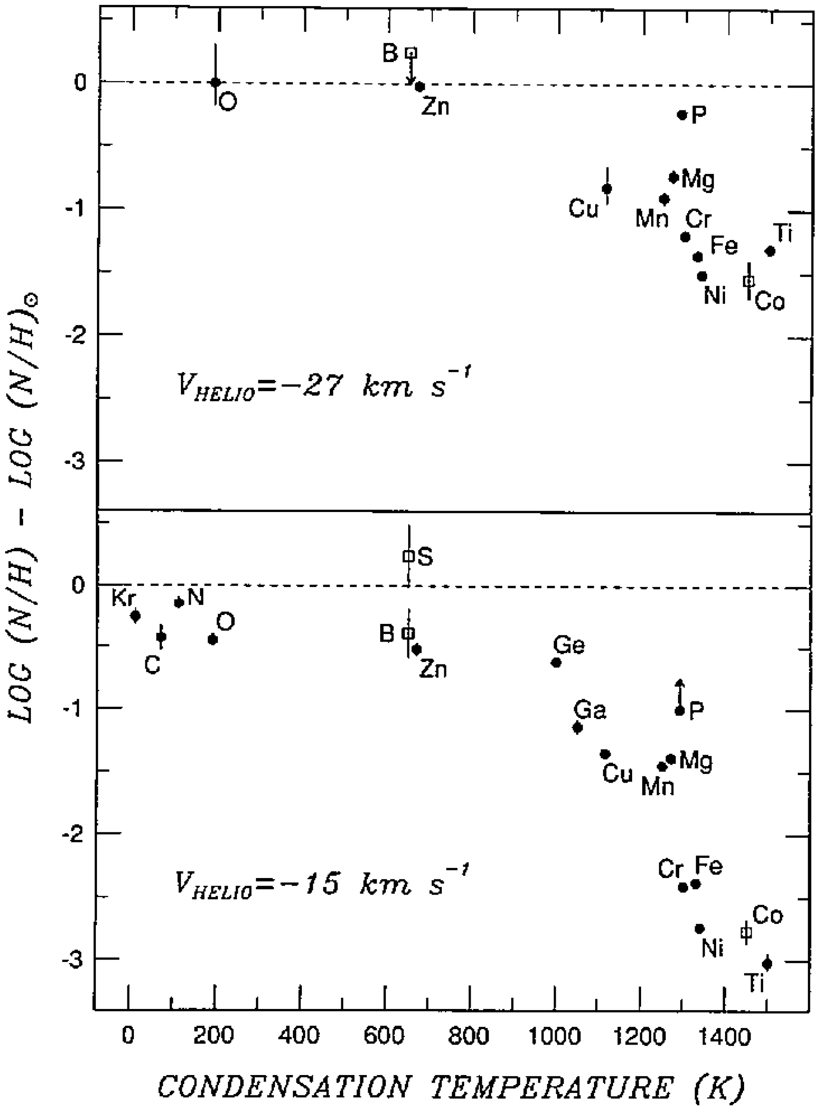
Why?

Two-body recombination not possible because no dipole moment $\Longrightarrow$ radiative relaxation would go via quadrupole terms, which is very slow.

Therefore: general picture:
adsorption of H on grain surface (e.g., ice, silicate) $\Longrightarrow$ proton will thermally "hop" over surface (tunnel through lattice structure,. . .) $\Longrightarrow$
Two H-atoms meet $\Longrightarrow$ formation of H_2

Detailed theory requires knowledge about grains.

Depletion of Elements



Abundances in direction to ζ Oph (Federman et al., 1993)

Evidence for existence of solid state material in universe comes mainly from two observations:

1. Depletion of elements in ISM gas phase wrt. solar abundances
2. Reddening of stars

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Extinction, I

Extinction = dimming of starlight by dust

How is this measured?

Assume two stars, 1,2, at distances d_1, d_2, with same physical spectral shape, $F(\lambda)$. Medium to star 2 has optical depth $\tau(\lambda)$. Observed spectral fluxes are

$$F_1(\lambda) = \frac{F(\lambda)}{d_1^2} \quad \text{and} \quad F_2(\lambda) = \frac{F(\lambda)}{d_2^2} e^{-\tau(\lambda)} \tag{10.39}$$

Compare fluxes at wavelength λ_1:

$$\frac{F_1(\lambda_1)}{F_2(\lambda_1)} = \frac{F(\lambda_1)/d_1^2}{F(\lambda_2)/d_2^2} e^{\tau(\lambda_1)} = \frac{d_2^2}{d_1^2} e^{\tau(\lambda_1)} \tag{10.40}$$

Same at λ_2:

$$\frac{F_1(\lambda_2)}{F_2(\lambda_2)} = \frac{d_2^2}{d_1^2} e^{\tau(\lambda_2)} \tag{10.41}$$

Therefore

$$\frac{F_1(\lambda_1)/F_1(\lambda_2)}{F_2(\lambda_1)/F_2(\lambda_2)} = e^{\tau(\lambda_1)-\tau(\lambda_2)} \tag{10.42}$$

Take the logarithm of both sides and multiply with -2.5:

$$-2.5\log\left(\frac{F_1(\lambda_1)}{F_1(\lambda_2)}\right) - \left(-2.5\log\left(\frac{F_2(\lambda_1)}{F_2(\lambda_2)}\right)\right) = \text{const.}\cdot(\tau(\lambda_1)-\tau(\lambda_2)) \tag{10.43}$$

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Extinction, II

Now remember defi nition of magnitude

$$m(\lambda_1) - m(\lambda_2) = -2.5 \log \frac{F(\lambda_1)}{F(\lambda_2)} \quad (10.44)$$

Therefore Eq. (10.43) reads

$$(m_1(\lambda_1) - m_1(\lambda_2)) - (m_2(\lambda_1) - m_2(\lambda_2)) = \text{const.} \cdot (\tau_1 - \tau_2) \quad (10.45)$$

In astronomy, a color is defi ned as a difference of magnitudes, e.g. for the B and V fi lters:

$$\text{B} - \text{V} = m(\text{B}) - m(\text{V}) \quad (10.46)$$

Thus, Eq. (10.45) is difference between colors, or color excess

$$E_{\lambda_1 - \lambda_2} := (m_1(\lambda_1) - m_1(\lambda_2)) - (m_2(\lambda_1) - m_2(\lambda_2)) \quad (10.47)$$

Note that because of Eq. (10.45)

$$E_{\lambda_1 - \lambda_2} \propto \tau_1 - \tau_2 \quad (10.48)$$

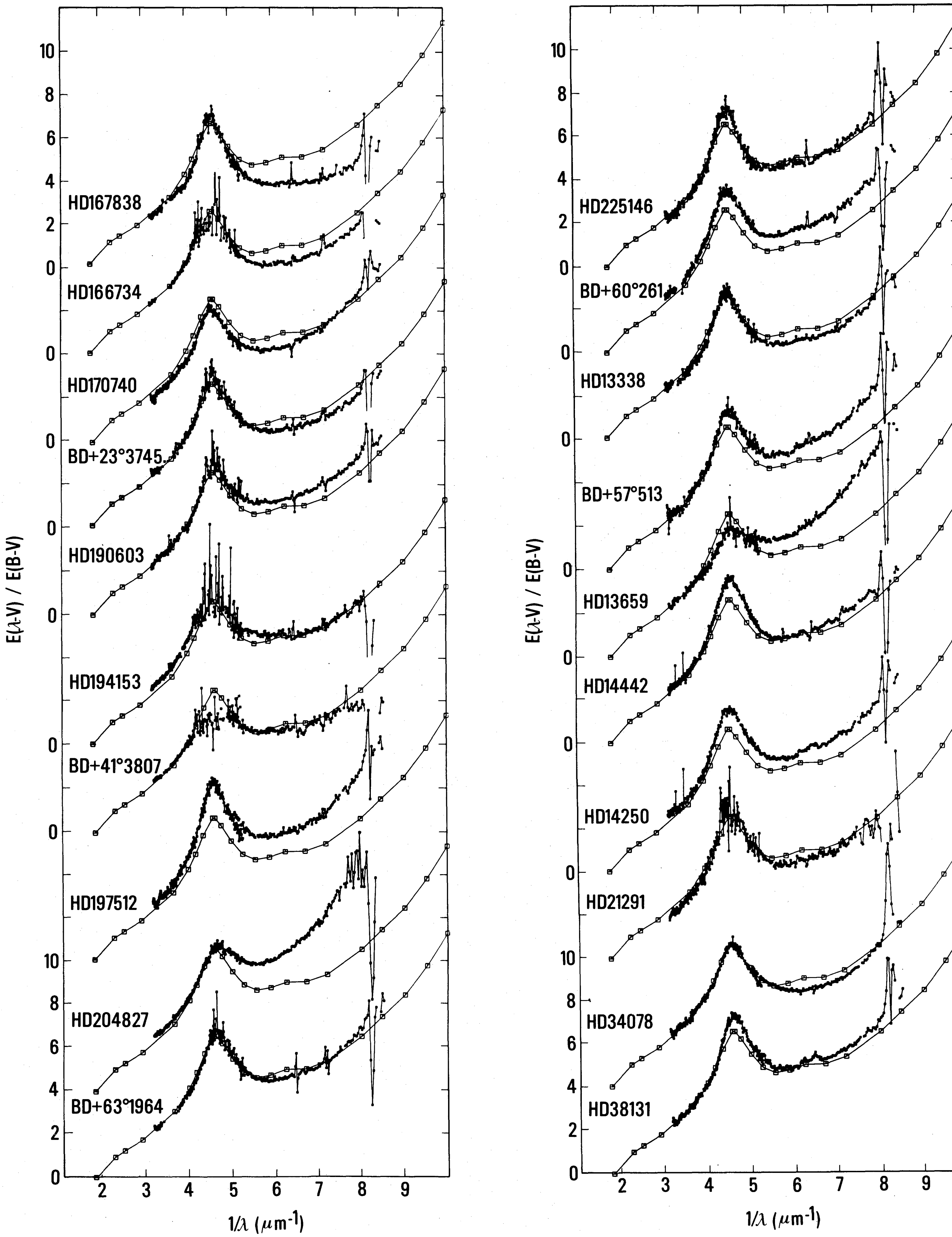
Generally use normalized color excess,

$$\frac{E(\lambda - \text{V})}{E(\text{B} - \text{V})} = \frac{\tau(\lambda) - \tau(\text{V})}{\tau\text{B} - \tau\text{V}} \quad (10.49)$$

$$\propto \frac{\tau(\lambda) - \tau(\text{V})}{\tau(\text{B}) - \tau(\text{V})} \quad (10.50)$$

$$\propto \tau(\lambda) \quad (10.51)$$

$$\propto \sigma_{\text{sca}}(\lambda) \quad (10.52)$$



Stellar spectra in the UV (Witt et al., 1984)

Overall extinction very similar, prominent feature at $1/\lambda \sim$ 4.6 ($\lambda = 2170\,$Å), strength of feature varies, position ver stable.

Extinction, IV

Observationally important is relationship between reddening $E(\mathrm{B}-\mathrm{V})$ and extinction in V-band.
Extinction defi ned via

$$A_{\mathrm{V}} = \mathrm{V} - \mathrm{V}_0 \qquad (10.53)$$

Now, normalized extinction was

$$\frac{E(\lambda - \mathrm{V})}{E(\mathrm{B}-\mathrm{V})} = \frac{(m_\lambda - m_{\mathrm{V}}) - (m_\lambda - m_{\mathrm{V}})_0}{E(\mathrm{B}-\mathrm{V})} \qquad (10.54)$$

$$= \frac{m_\lambda - m_{\lambda,0} - (m_{\mathrm{V}} - m_{\mathrm{V},0})}{E(\mathrm{B}-\mathrm{V})} \qquad (10.55)$$

$$= \frac{A_\lambda - A_{\mathrm{V}}}{E(\mathrm{B}-\mathrm{V})} \qquad (10.56)$$

But for $\lambda \to \infty$:

$$\frac{E(\lambda - \mathrm{V})}{E(\mathrm{B}-\mathrm{V})} \to \text{const.} =: R \qquad (10.57)$$

where $R \sim 3.1 \pm 0.1$.
$\Longrightarrow$ A_{V} known if $E(\mathrm{B}-\mathrm{V})$ known!

Note also that $A_{\mathrm{V}}/E(\mathrm{B}-\mathrm{V}) \propto r$ since $\tau = n\sigma_{\mathrm{scat}} r$
$\Longrightarrow$ can measure distance! Generally, $A_{\mathrm{V}} \sim 1 \ldots 2\,\mathrm{mag\,pc}^{-1}$.

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Extinction, V

Normalized reddening observed roughly $\propto 1/\lambda$.

Explanation: scattering of radiation on grains.

Overall theory very complicated...
In scattering, intensity will be

$$I = I_0 \exp(-n\pi a^2 Q l) \tag{10.58}$$

where the quality factor Q has two components:

$$Q = Q_{\text{abs}} + Q_{\text{sca}} \tag{10.59}$$

Q_{abs}: absorption,
Q_{sca}: scattering.
(see next slide)

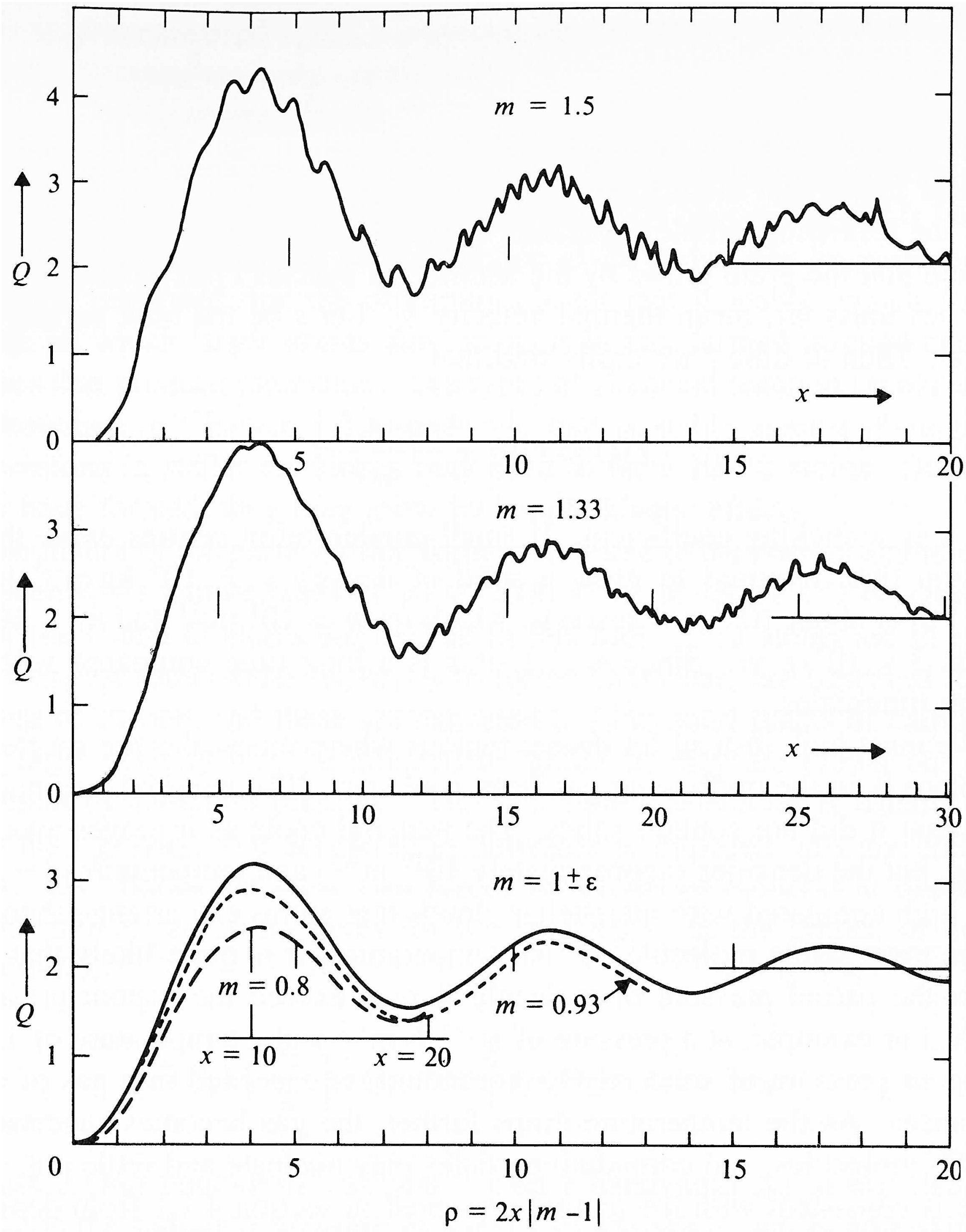
Note that Q is proportional to the optical depth...

Defi ne Albedo of particles

$$\gamma = \frac{Q_{\text{sca}}}{Q_{\text{abs}} + Q_{\text{sca}}} \tag{10.60}$$

(note that angular dependence in principle possible)

Extinction, VI



Q_{sca} as function of $x = 2\pi a/\lambda$ for several dielectric constants m (Dyson& Williams, Fig. 4.5; $m = 1.33$ is water ice)

Detailed theory: Mie scattering; gives $Q \propto 1/\lambda$ for small diameters $a \implies$ as observed!

Extinction, VII

For detailed theory also need size distribution of grains.

Common assumption:

$$n(a) = Aa^{-3.5} \tag{10.61}$$

("MRN distribution"; Mathis, Rumpl, Nordsieck; $0.005\,\mu\text{m} < a < 0.25\,\mu\text{m}$) determined from fitting extinction curves.

Overall $1/\lambda$-behavior understood with Mie scattering

2200 Å feature:

- graphite grains? Optical constants change dramatically around 2200 Å for small graphite grains.
- Silicate grains?
- Polycyclic aromatic hydrocarbons (PAHs)?

Solution not yet known, graphite seems slightly preferred

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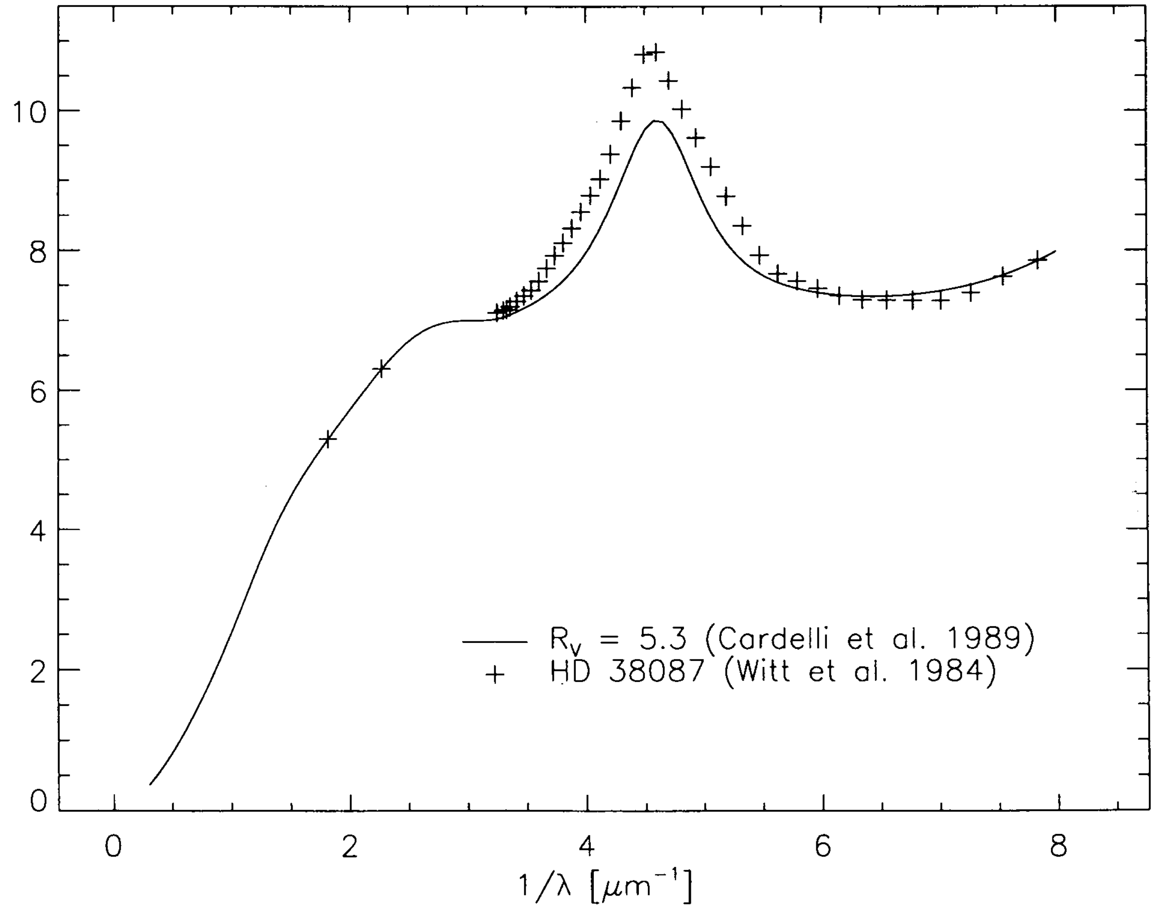
Scattering Halos: IC 435, I



IC 435 (reflection nebula close to horsehead;
Calzetti et al., 1995, Fig. 1)

IC 435: Reflection nebula: reflection of star light in shell of dust surrounding the star.

IUE Observations of IC 435: Extinction $A(\lambda)/E(\mathrm{B}-\mathrm{V})$ stronger than "standard" $\Longrightarrow$ Evidence for concentration of dust.

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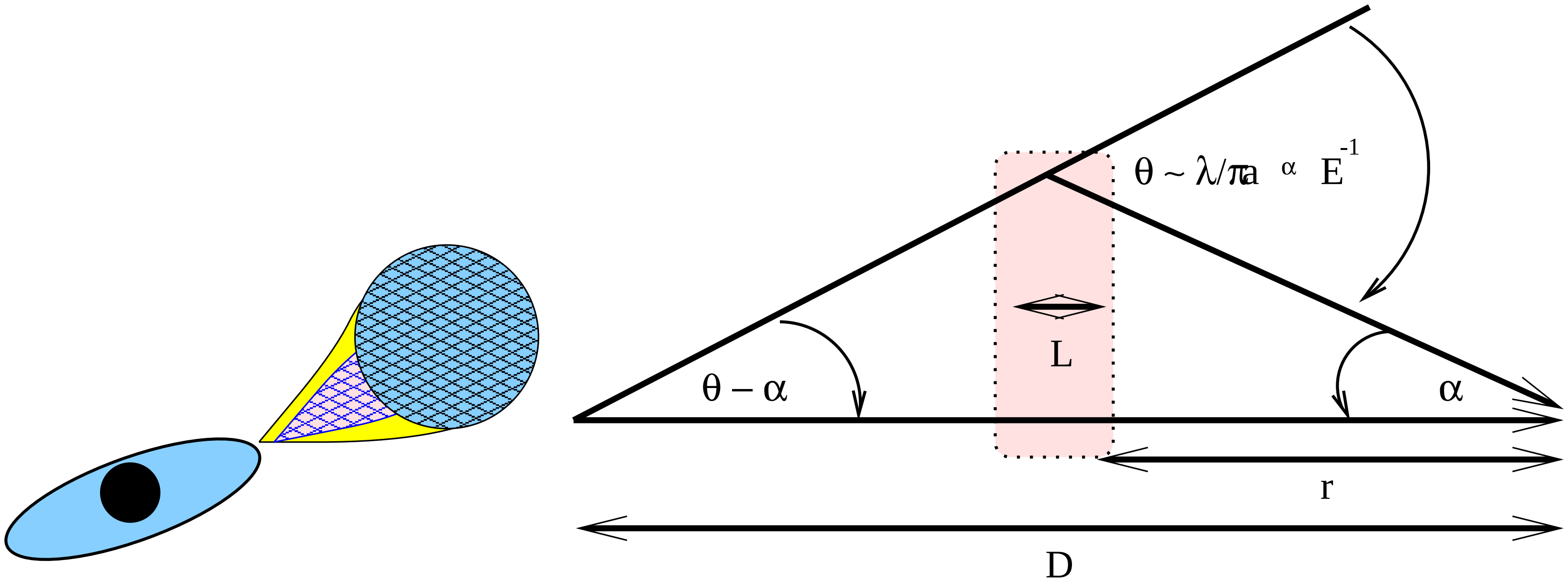
Scattering Halos: IC 435, II

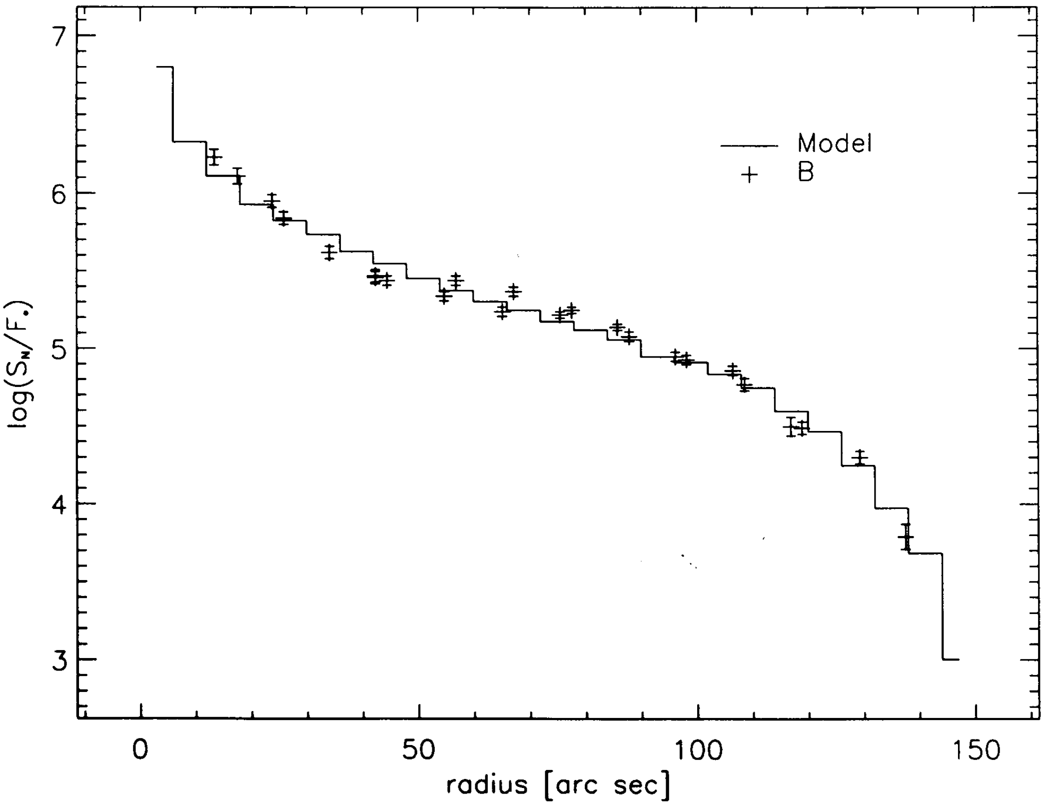


To obtain information on dust: perform Monte Carlo simulations of scattering in dust.

(use correct prescription for scattering off the dust grains).

Output of simulation: intensity profile, and scattered and absorbed fraction of radiation as function of wavelength.

Scattering Halos: IC 435, III

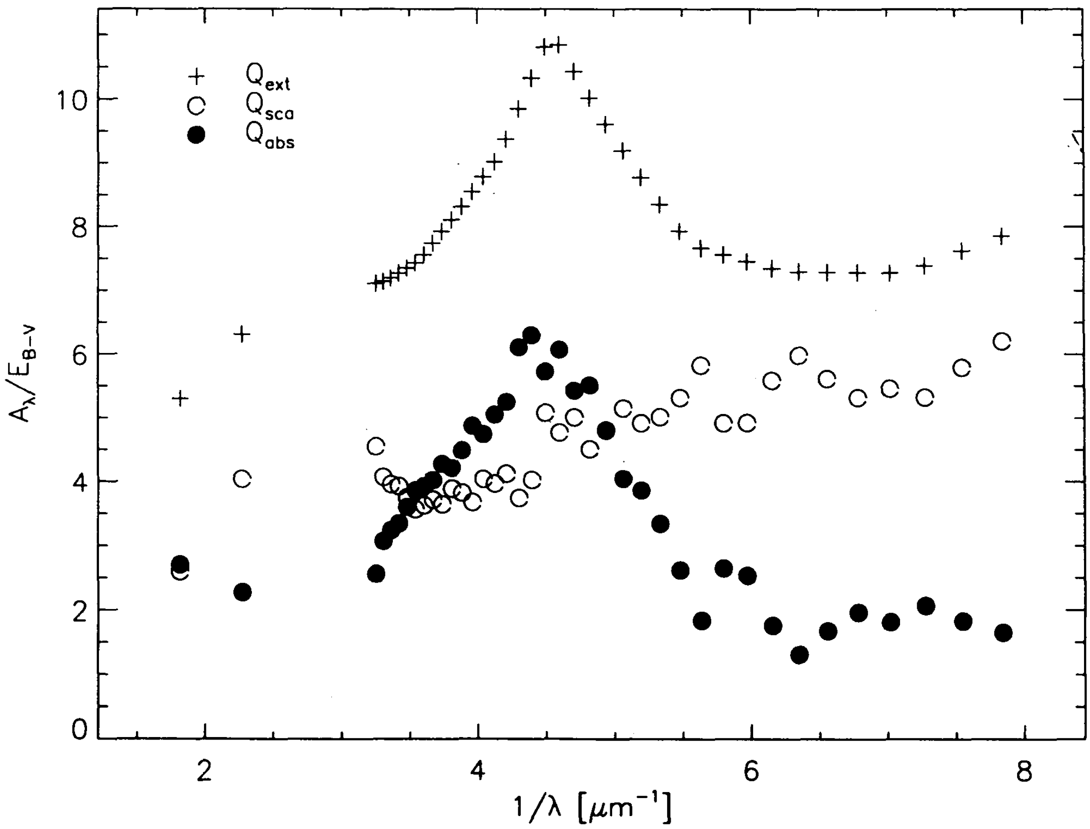


Calzetti et al., 1995, Fig. 2

Monte Carlo Simulation of optical intensity profile of reflection nebula consistent with scattering off dust shell with $\tau \sim 0.3$ around star.

Dust profile: inner low-density sphere with $r = 0.16\,\mathrm{pc}$, shell with gradually increasing density with $0.16\,\mathrm{pc} < r < 0.3\,\mathrm{pc}$, decrease outside.

Scattering Halos: IC 435, IV

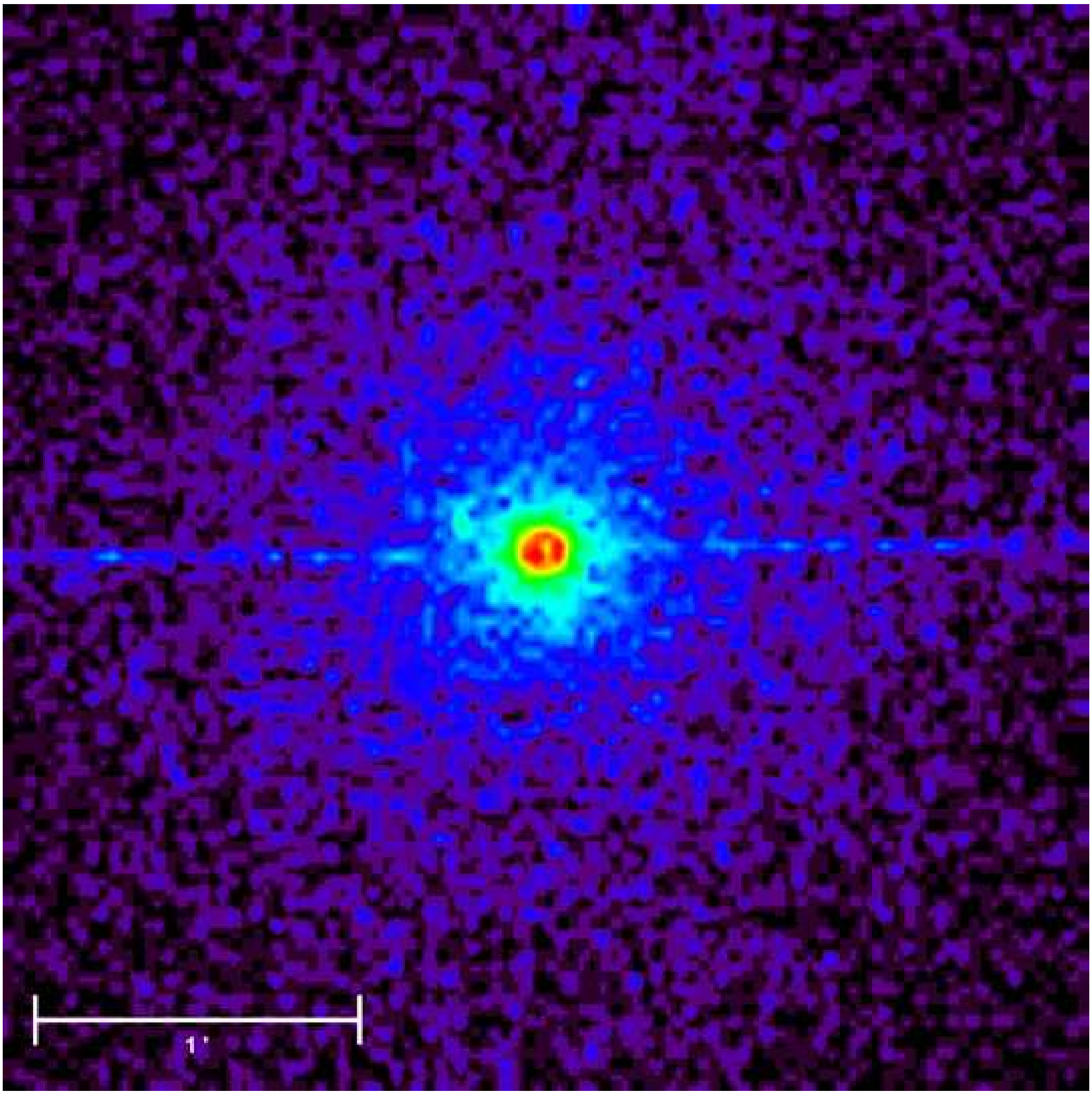


Calzetti et al., 1995, Fig. 5

Important result of the study of reflection nebulae:

2170 Å feature due to absorption, not scattering.

X-Ray Dust Scattering Halos



courtesy CXC

Scattering off dust also important in X-rays.

Allows to determine grain composition.

X-ray timing of halo also gives independent measure of distance to X-ray point source if scattering cloud is in foreground.

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Dust Models

Major dust models:

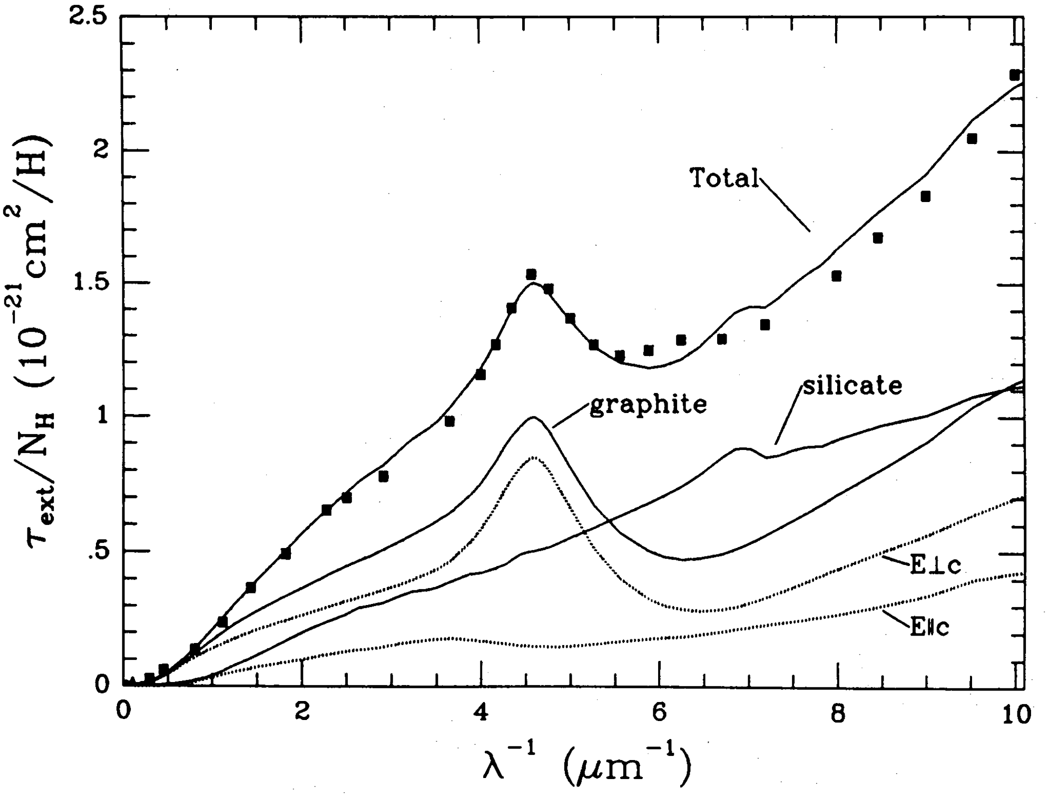
- MRN model
- Core-mantle models
- post-IRAS models

Models must take constraints on dust models into account:

- extinction curve (IR to UV)
- abundance deficiency of ISM gas phase
- (narrow) spectral features

See Witt, IAU Symp. 197, for a discussion of results.

Dust Models: MRN



Draine & Lee, 1984, Fig. 7

MRN Model (Mathis, Rumpl, Nordsieck, 1977): "mother of all dust models".

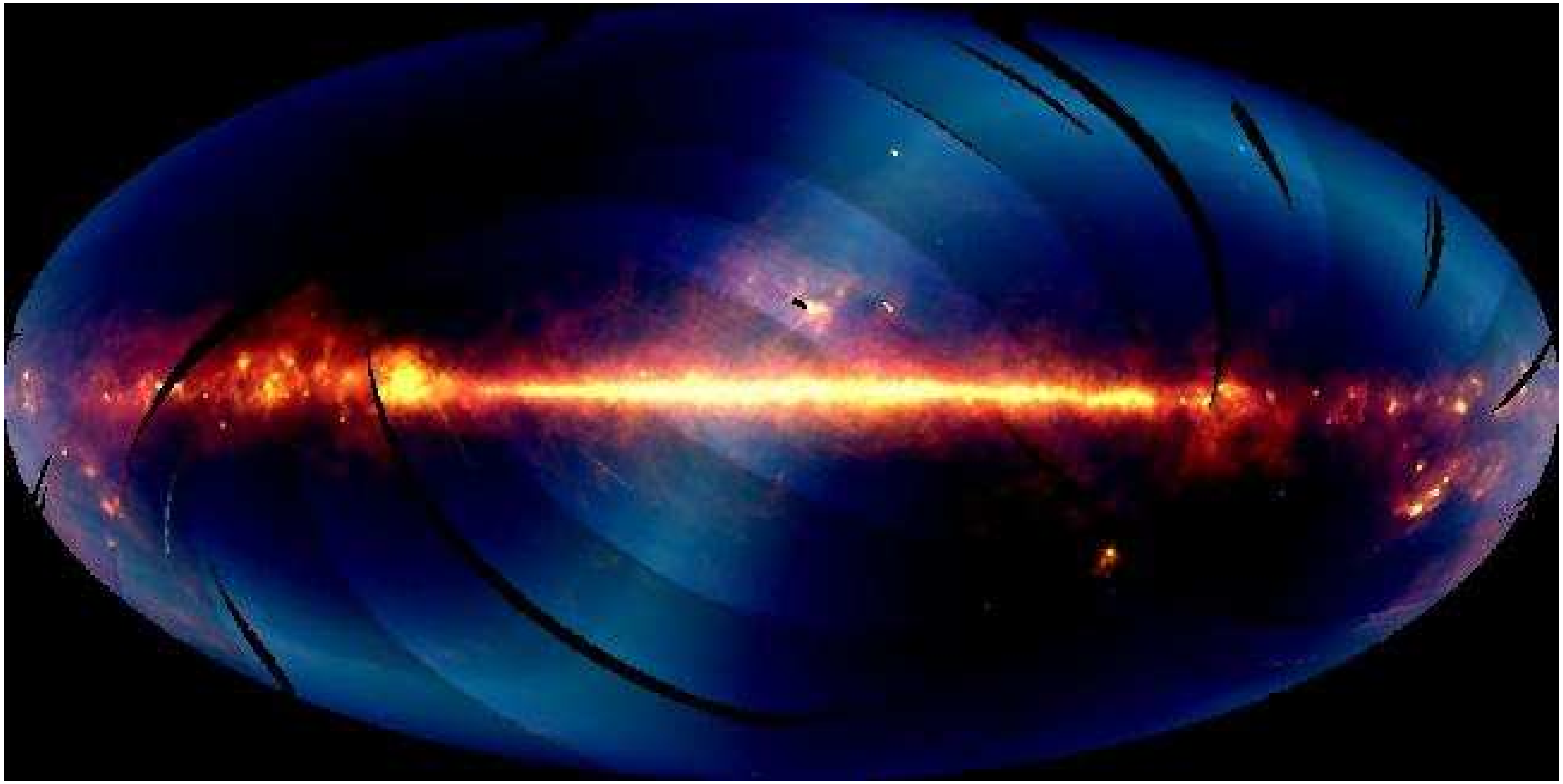
later upgrades: Draine & Lee (1984), Draine & Anderson (1985)

- Pure power-law distribution of grains, $n(a) \propto a^{-3.5}$
- No small grains ($<$ 5 nm), no very large grains ($>$ 250 nm).

Either:

- all C ends up as CO, remaining O-atmos make silicates and metal oxides.
- all O ends up in CO, remaining C forms carbonaceous components (graphite and other stuff. . .)

Dust Models: The IRAS Challenge, I



IRAS All Sky Map (blue: 12 micron, green: 60 micron, red: 100 micron)

Mainly thermal emission from small particles.

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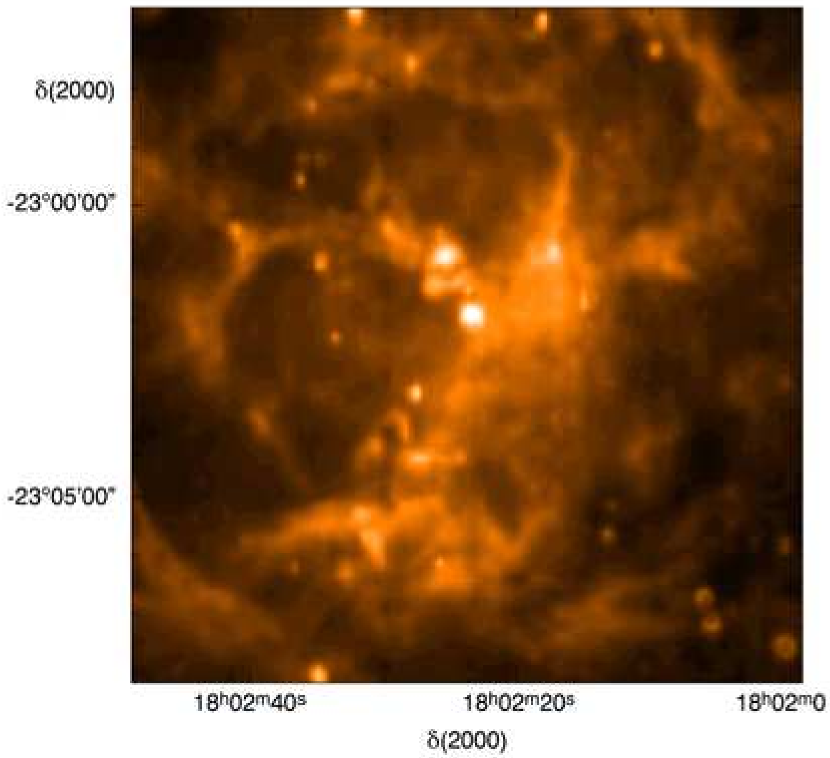
TRIFID NEBULA:
A DUSTY BIRTHPLACE OF STARS

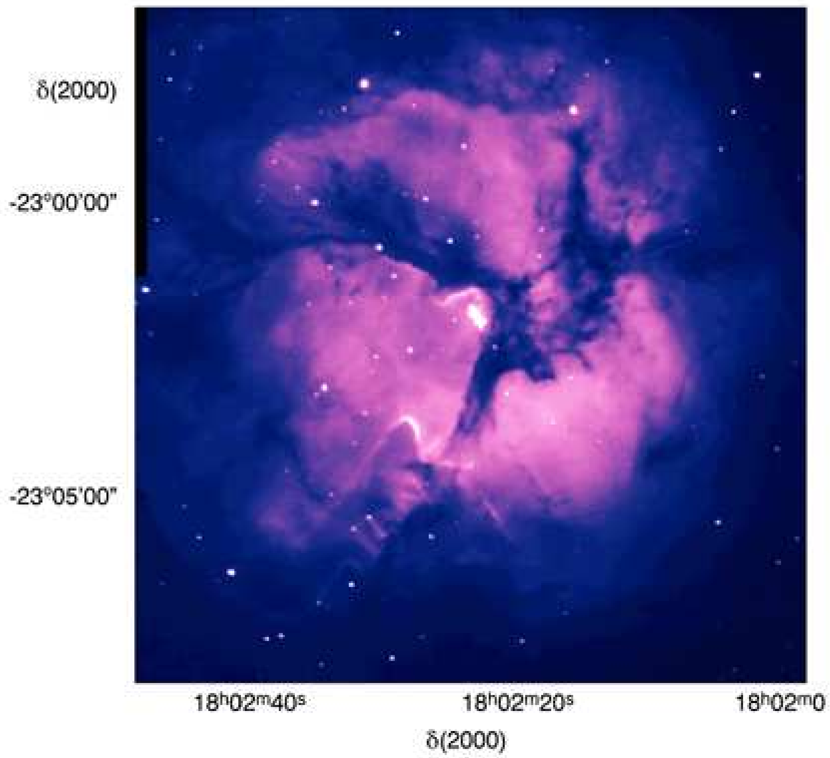
ISOCAM (6" pixel) Filter LW10



ISOCAM infrared image at 8-15 microns

Credit: ESA/ISO, ISOCAM and J. Cernicharo et al.

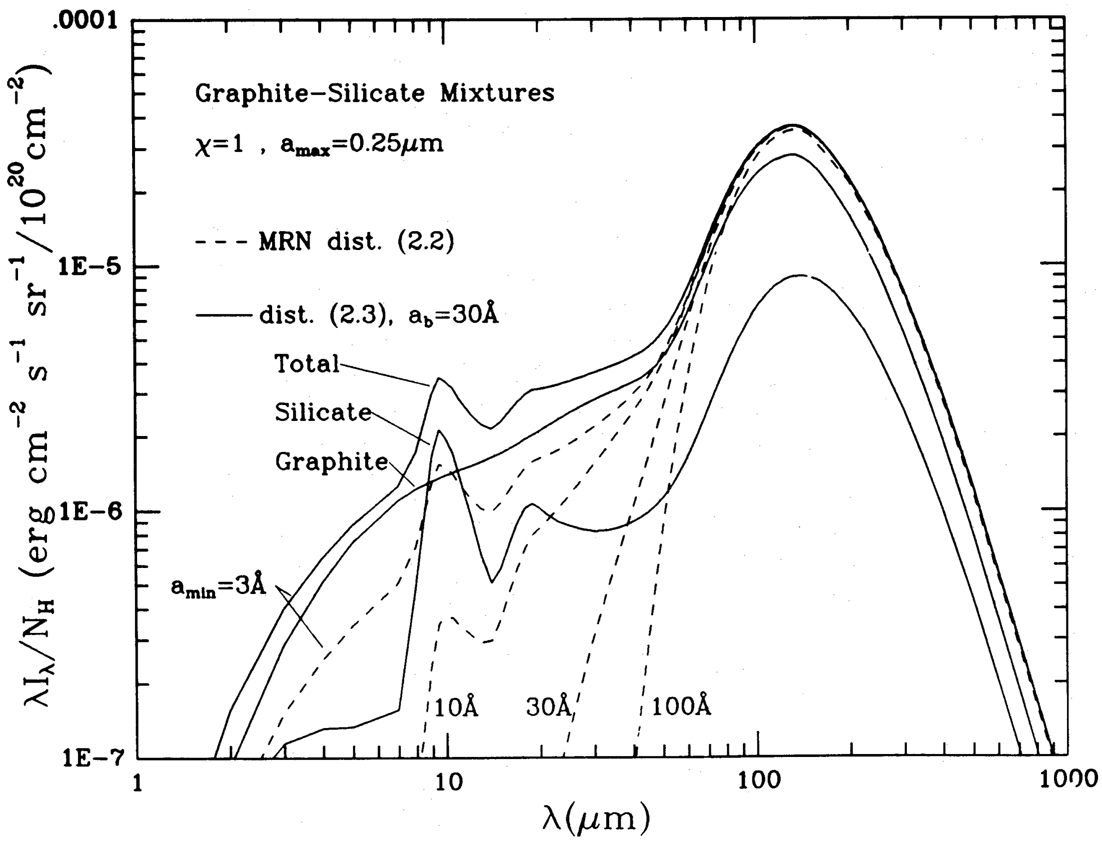
Hα Image taken with the IAC80 telescope



IAC8O visible-light image (H-alpha)

Credit: IAC, Observatorio del Teide, Tenerife

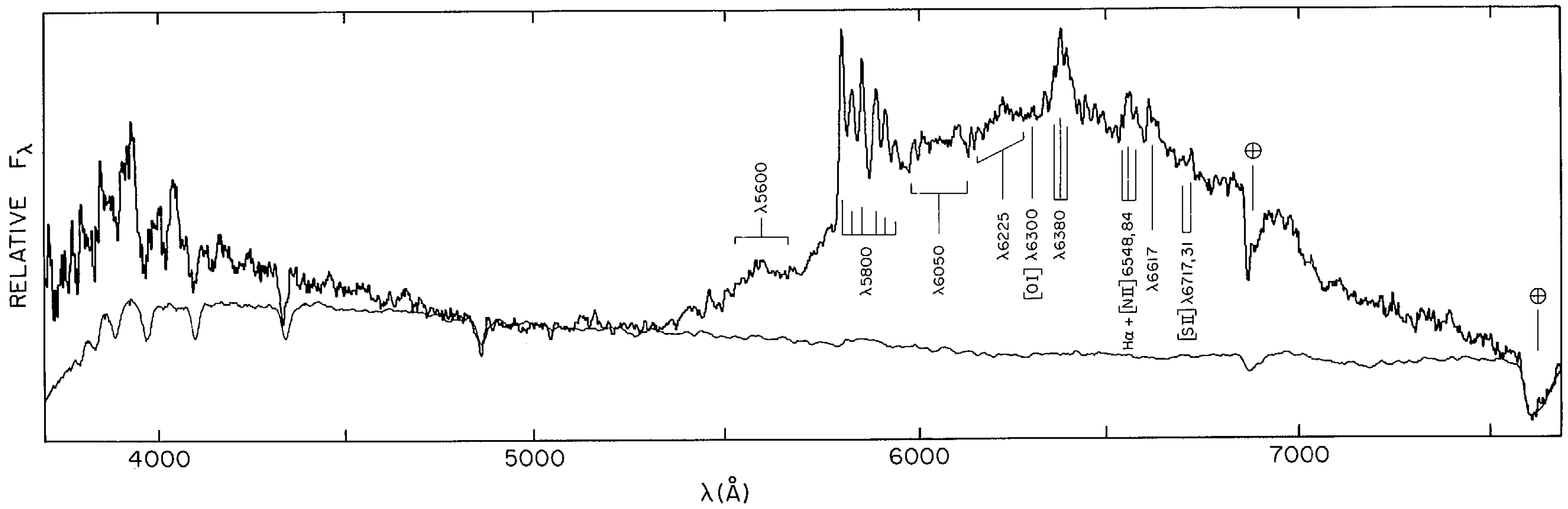
Dust Models: The IRAS Challenge, III



Draine & Anderson

Also thermal infrared emission necessary $\Longrightarrow$ add population of very small grains with $3\,\mathrm{nm} < r < 5\,\mathrm{nm}$ (i.e., between large molecules and small MRN grains).

Extended Red Emission, I



Schmidt, Cohen, Margon (1980)

Closely associated with dust: Extended Red Emission, seen first in the Red Rectangle around HD 44179, and now in many (but not all) reflection nebulae. Normally associated with H_2 emission. Most likely fluorescence from complex molecules

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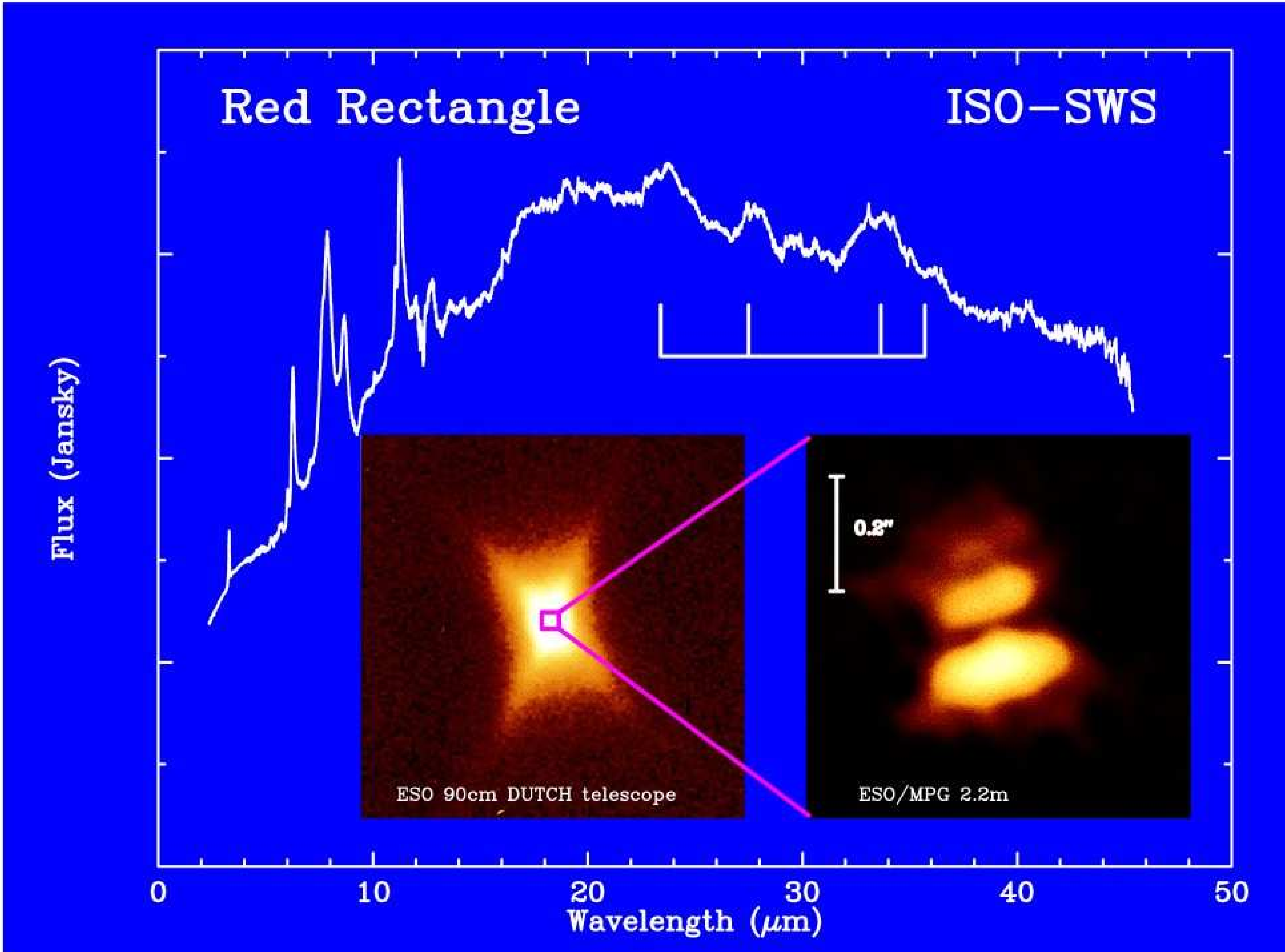
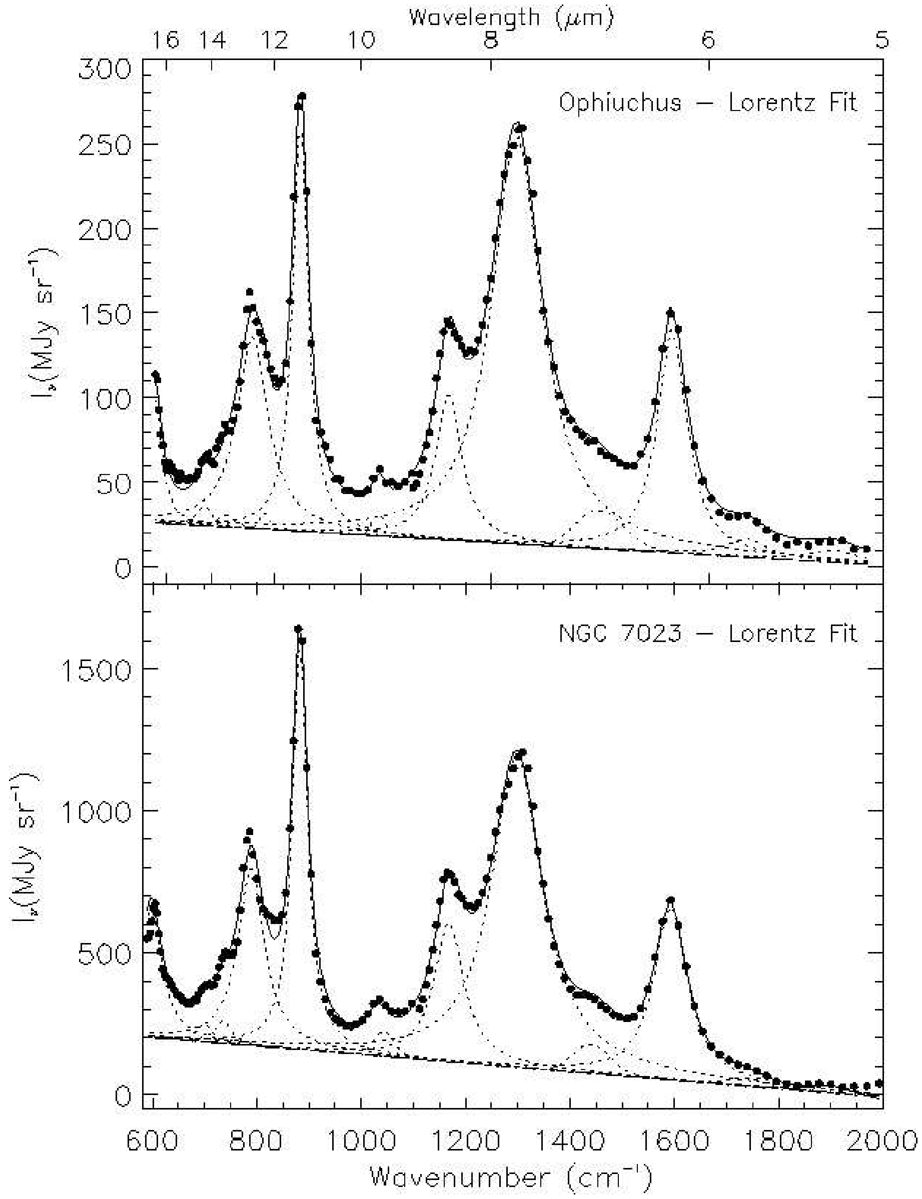

Red Rectangle
ISO−SWS
Flux (Jansky)
Wavelength (μm)
0
10
20
30
40
50
ESO 90cm DUTCH telescope
0.2"
ESO/MPG 2.2m

UIBs



(Boulanger et al.; 1998)

Unidentified emission structures seen at 3.3, 6.2, 7.7, 8.6, 11.3 μm seen in H II regions, YSOs, diffuse ISM, and even AGN: “unidentified infrared bands”

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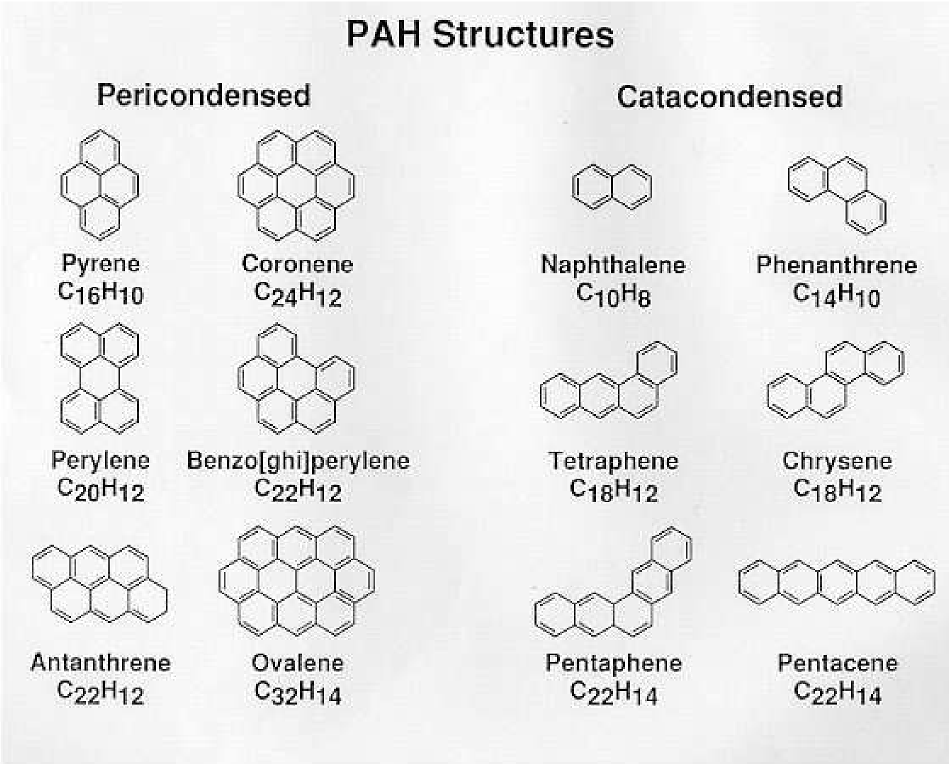
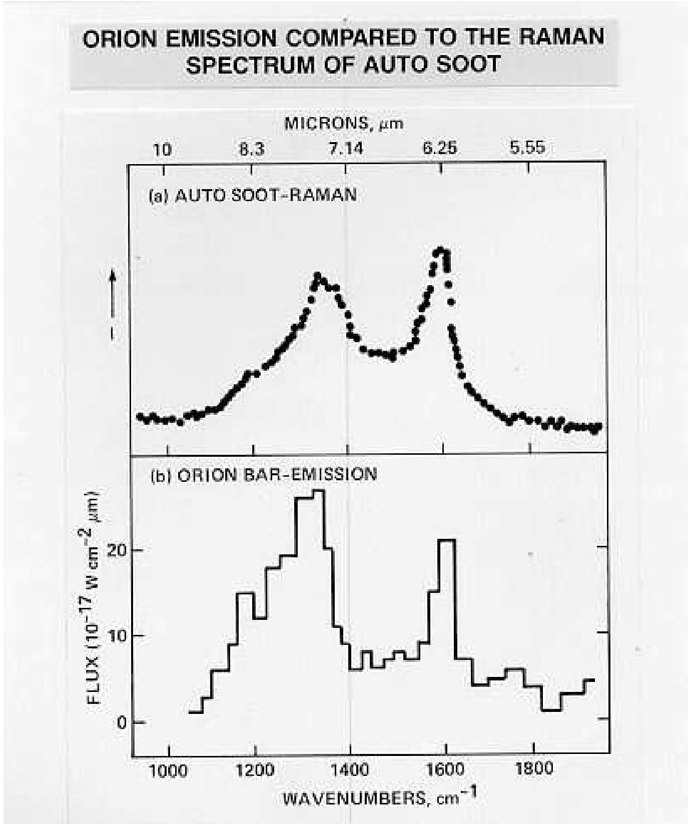
PAHs, I





UIB and ERE emission might be related to polycyclic aromatic hydrocarbons (PAHs), complex large carbonaceous molecules (UIB: related to C-C, C-H modes)

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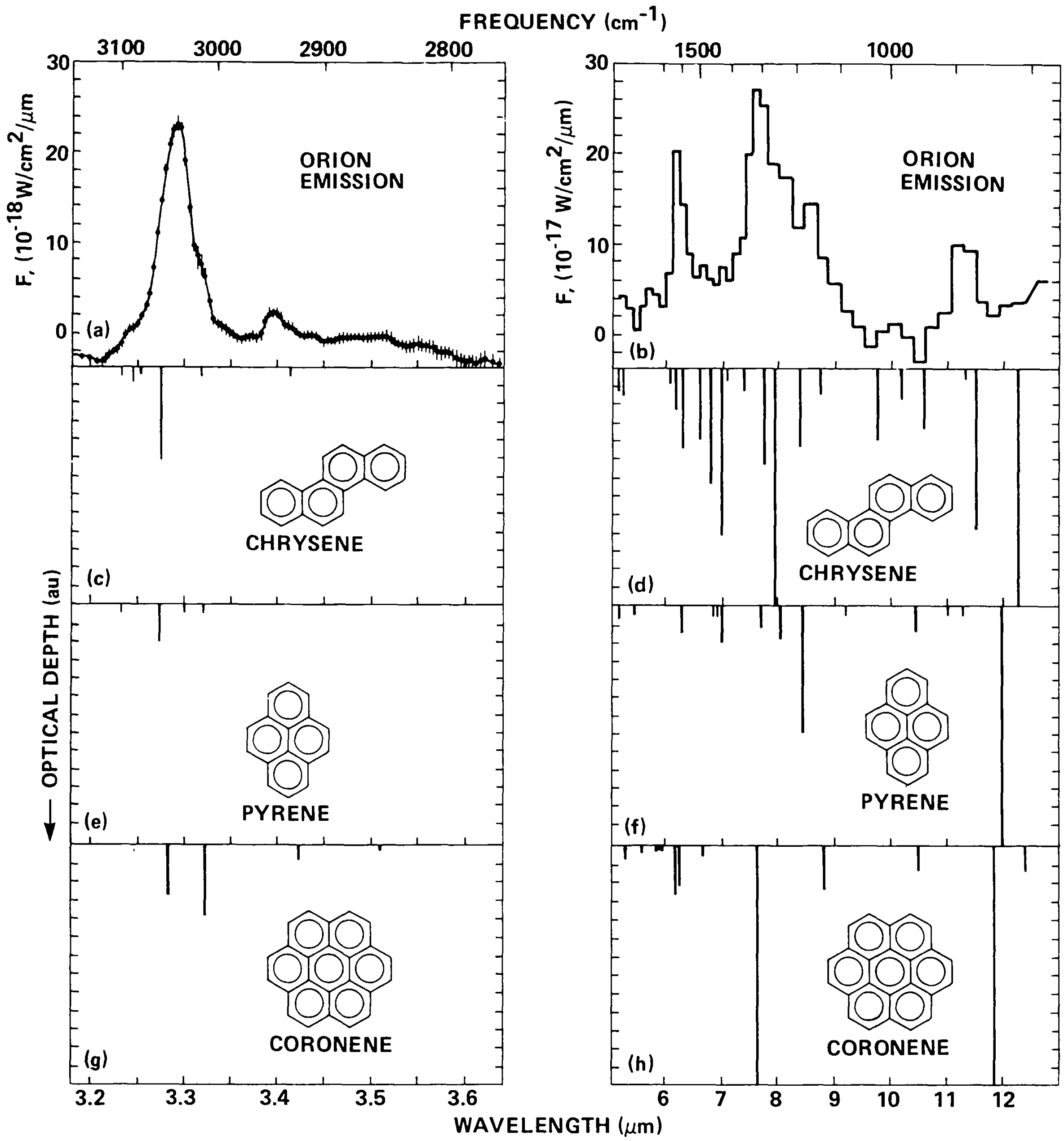
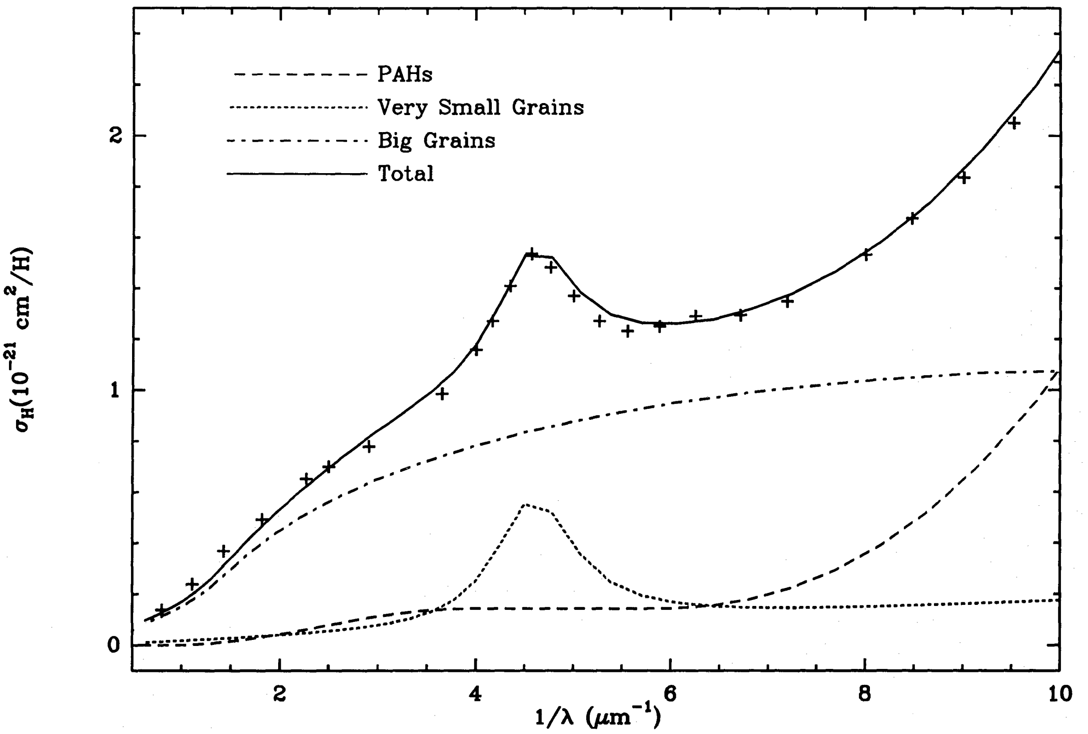
PAHs, II



Allamandola, Tielens, Barker (1989)

C-H stretch at 3.3 μm due to stretching in aromatic ring (IR molecular fluorescence due to UV photons).

PAHs, III



Dśert, Boulanger, Puget (1990)

Inclusion of PAHs in dust models can also account for extinction curve, need three distinct populations:

- big grains (15 nm to 110 nm),
- very small grains (1.2 nm to 15 nm)
- PAHs (<1.2 nm)

Also predicts UIB emission!

Problems with Désert et al. model is small size of large grains, might be inconsistent with X-ray halos... Possible solution: fluffy grains (Fogel & Leung, 1998)

Dust Formation

Where does dust come from?

Three potential sources:

1. Condensation out of the ISM
2. Condensation in cool stellar outflows
3. Condensation in protostars

ad 1) only possible in very dense molecular clouds: formation of clusters of 10...20 atoms as “condensation nuclei”; accretion of further molecules via collisions.

Due to small densities dust formation timescale very long (10^8 years), thus rather impossible.

Dust is mainly generated in stars and then ejected into the ISM.

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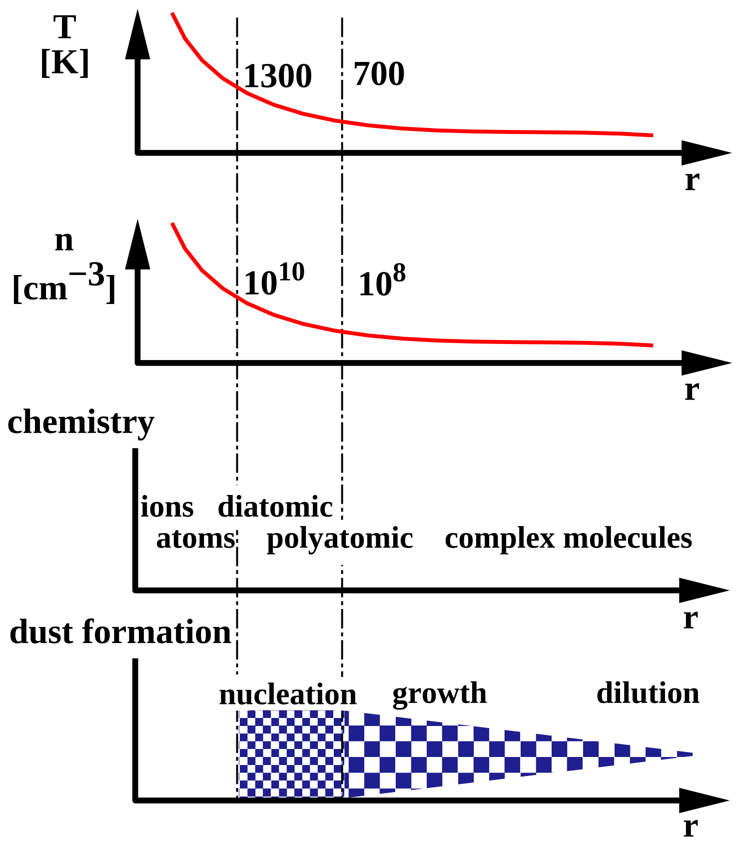
Dust Formation



(Sedlmayr & Krüger; 1997)

Dust formation in stars

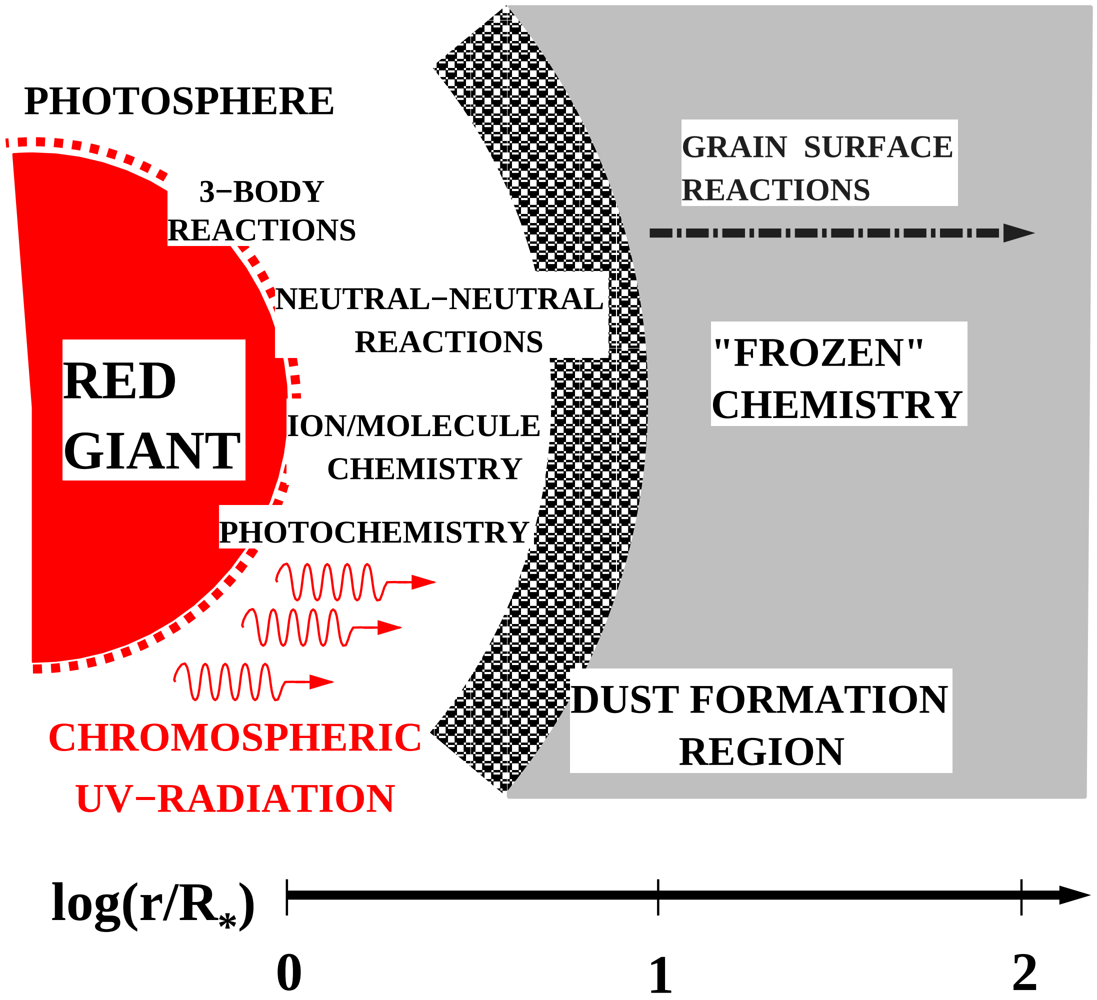
Stellar atmospheres have much higher density than GMCs (solar photosphere: $10^{17}\,\mathrm{cm}^{-3}$, late type giants: $\sim 10^{15}\,\mathrm{cm}^{-3}$, compared to $10^{6}\,\mathrm{cm}^{-3}$ in GMCs)

$\Longrightarrow$ much higher condensation probability.

General process:

1. formation of molecules
2. accretion of more material, formation of clusters
3. formation of macroscopic particles

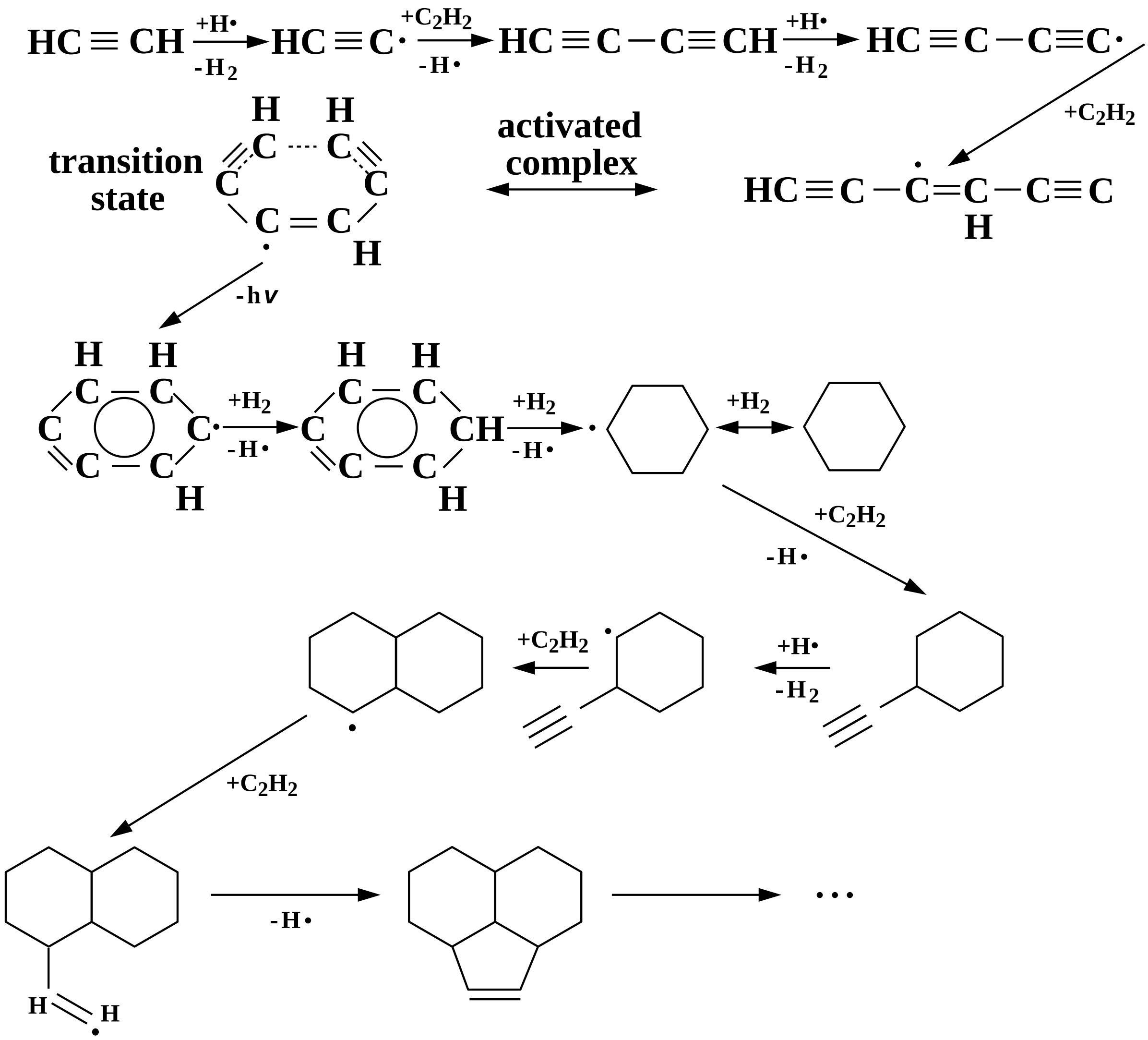
Dust Formation



(Sedlmayr & Krüger; 1997)

Complex nonstationary chemistry makes things very complicated. . .

Dust Formation



(Sedlmayr & Krüger; 1997)

Possible chemical reaction network for generation of PAHs in C-stars.

The Orion Nebula and Trapezium Cluster
(VLT ANTU + ISAAC)

ESO PR Photo 03a/01 (15 January 2001)

Star Formation, II

Overview of star formation

In general, star formation will occur in several stages:

1. Initial collapse of gas cloud
2. Formation of Protostar
3. Formation of Disk and Wind
4. “Birth of star”

This and the following heavily based on good summary by Kevin Volk, Calgary; see also Shu, Adams, Liziano, ARAA, 1987

Initial Collapse, I

Typical GMC density: several 100 atoms cm^{-3}.
To produce star need $\sim 1\,M_\odot$. This corresponds to radius of about 0.5 pc.

Therefore: reduce size of cloud by factor 10^7.

Questions:

- How to get rid of angular momentum?
- How to get rid of magnetic field?
- How to get rid of potential energy?

Binding energy of sphere:

$$V = -\frac{GM^2}{r} \sim 10^{41}\,\mathrm{erg} \tag{10.62}$$

for $M = 1\,\mathrm{M}_\odot$ and $r = 0.5\,\mathrm{pc}$.
This energy needs to be radiated away in very short time!

Initial Collapse, II

First process is initial collapse.

Cloud unstable to collapse if mass exceeds Jeans mass,

$$M_{\mathrm{J}} = \left(\frac{\pi k T}{\mu m_{\mathrm{H}} G}\right)^{1.5} \rho^{-0.5} \sim 18\,\mathrm{M}_{\odot}\, T^{1.5} n^{-0.5} \qquad (10.63)$$

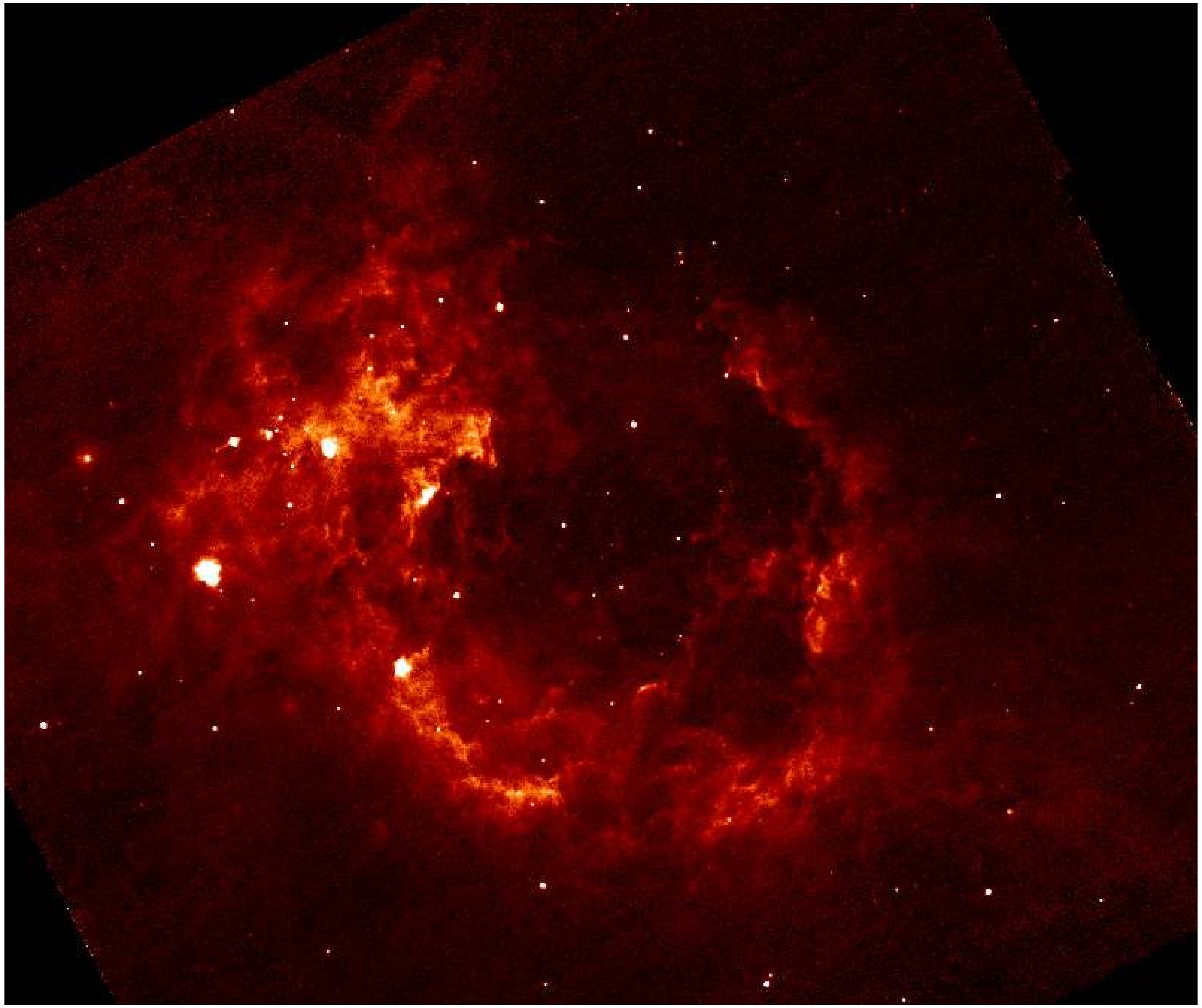
Fragments of GMC of this mass probably formed in shocks; either internal (turbulence) or external (SNRs?)

Mass of fragment strongly depends on magnetic fi eld (pressure $\propto B^2$ can stop collapse) $\Longrightarrow$ need to get B-fi eld out of cloud via ambipolar diffusion.

Ions in cloud coupled to B-fi eld, neutrals are not $\Longrightarrow$ neutrals only interact with ions (=B-fi eld) via collisions $\Longrightarrow$ if B-fi eld gradient: acceleration of ions $\Longrightarrow$ separation of speeds $\Longrightarrow$ ions forced out of cloud, B-fi eld follows $\Longrightarrow$ B-fi eld (mainly) diffuses out. Timescale: few million years; uncertainty very large.

also: does not work for more massive clouds

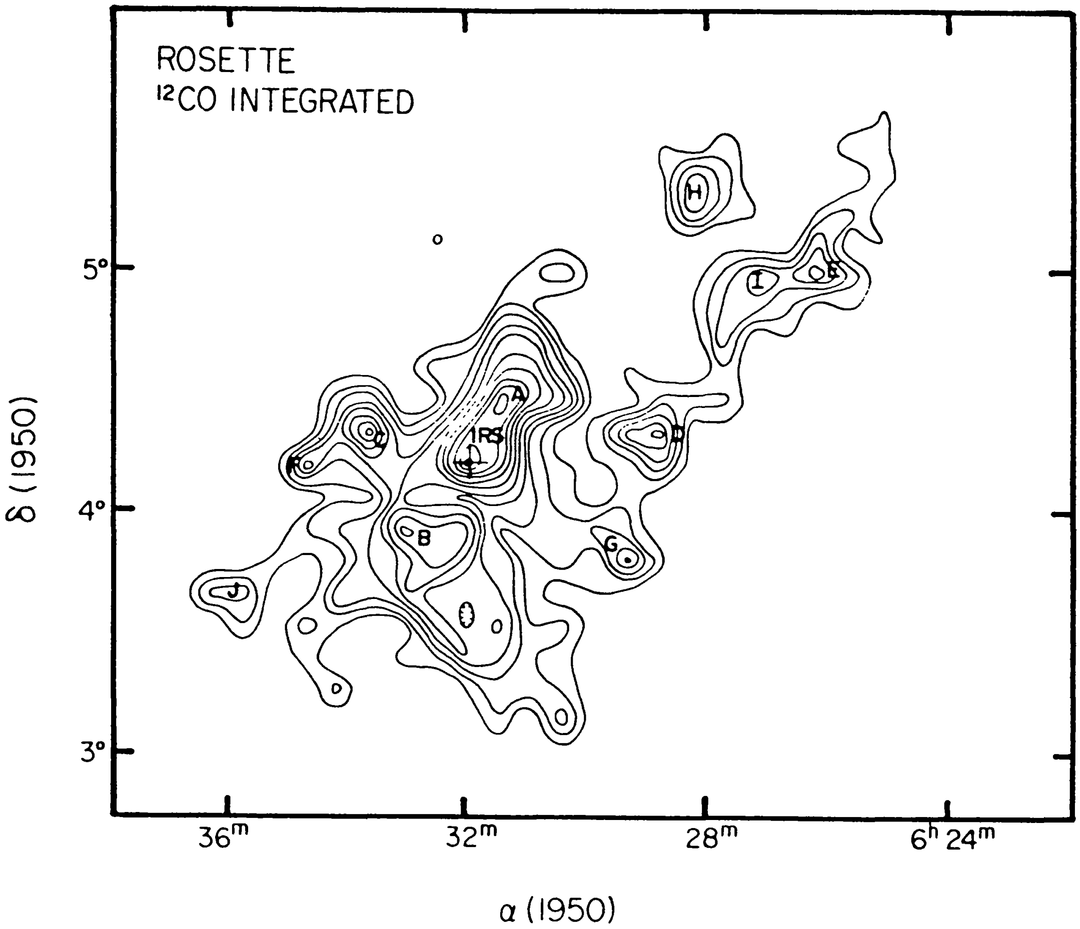
Initial Collapse, III



courtesy MSX Galactic Plane Survey; 8 micron

Example for clumpy star forming region: Rosette nebula

Initial Collapse, IV

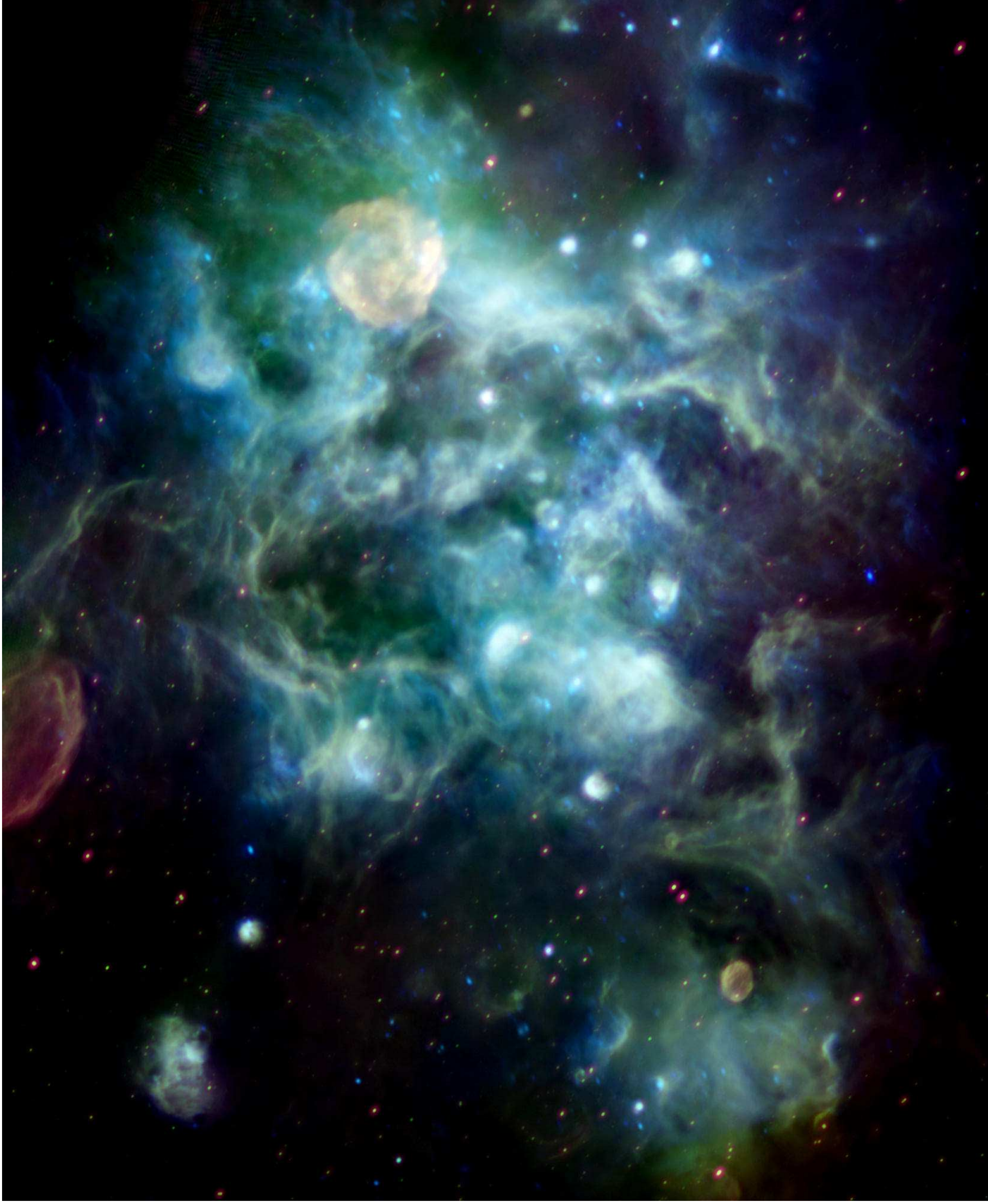


Shu et al.

Clumps in the Rosette nebula.

Mass inferred: a few solar masses, radii measured 0.1 pc.

Surrounding envelope: several 100 $M_{\odot}$.

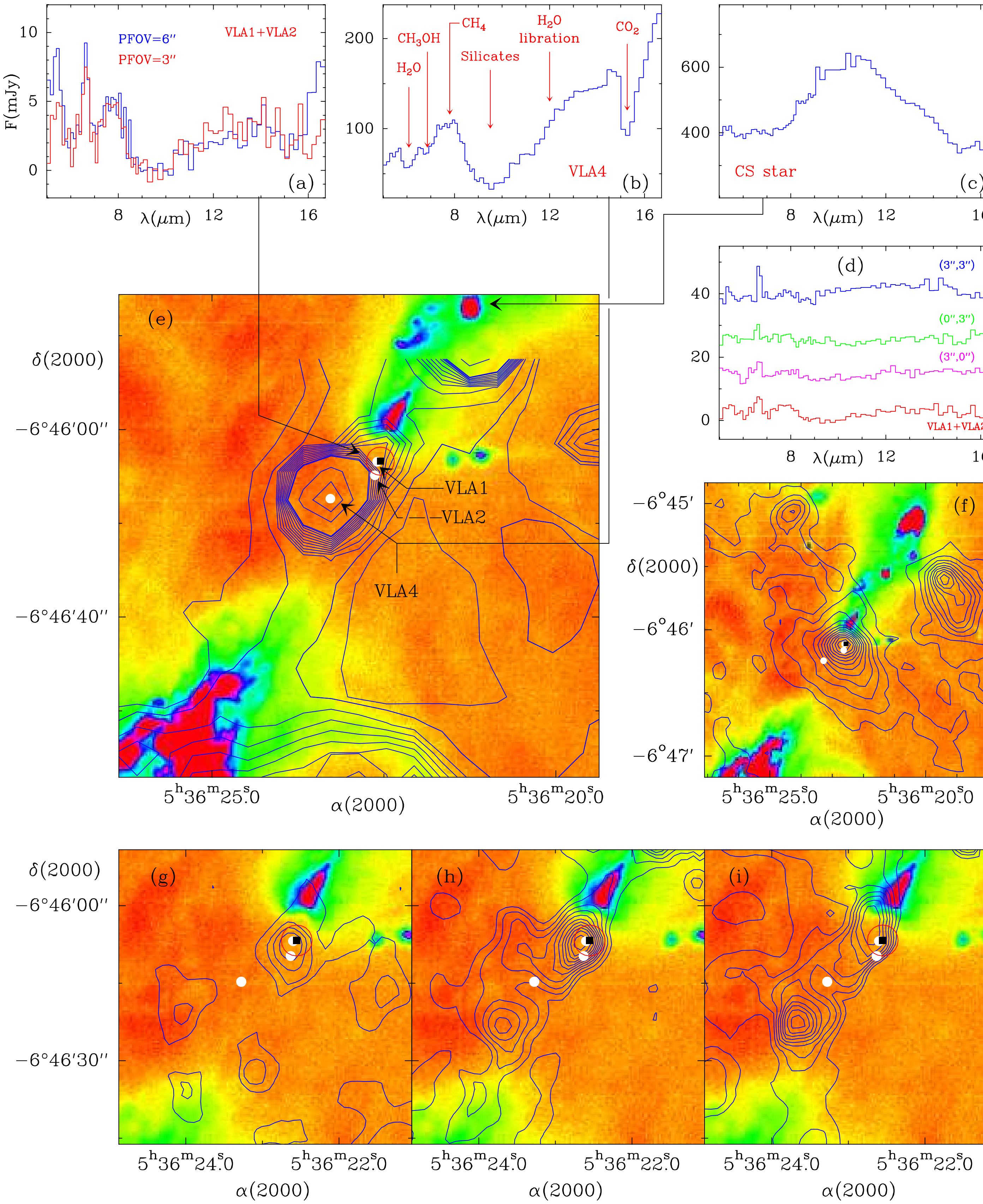


Formation of protostar, I

Once core collapses $\Longrightarrow$ formation of protostar.

Termination of infall once $\sim 0.3\,\mathrm{M}_\odot$ accreted (ignition of deuterium). Star remains fully convective until $0.5\,\mathrm{M}_\odot$ reached.

Core collapses first, then surrounding matter collapses onto core. Typical timescale $\sim 10^{-5}\,\mathrm{M}_\odot\,\mathrm{year}^{-1}$ for $T \sim 35\,\mathrm{K}$ and typical magnetic fields.



ISO spectra and images of earliest protostars VLA 1, VLA 4, and the Cohen-Schwartz star

Formation of Disk and Wind, I

Some net angular momentum of clump $\Longrightarrow$ Material rotates $\Longrightarrow$ disk forms around protostar (typical radius several 100 AU). Shortly later: outflow forms, either as bipolar outflow or as jets.

Origin of outflow unclear, probably related to some MHD instability, similar to active galactic nuclei.

General observational fact: all observed systems with disks have outflows.

Formation of Disk and Wind, II

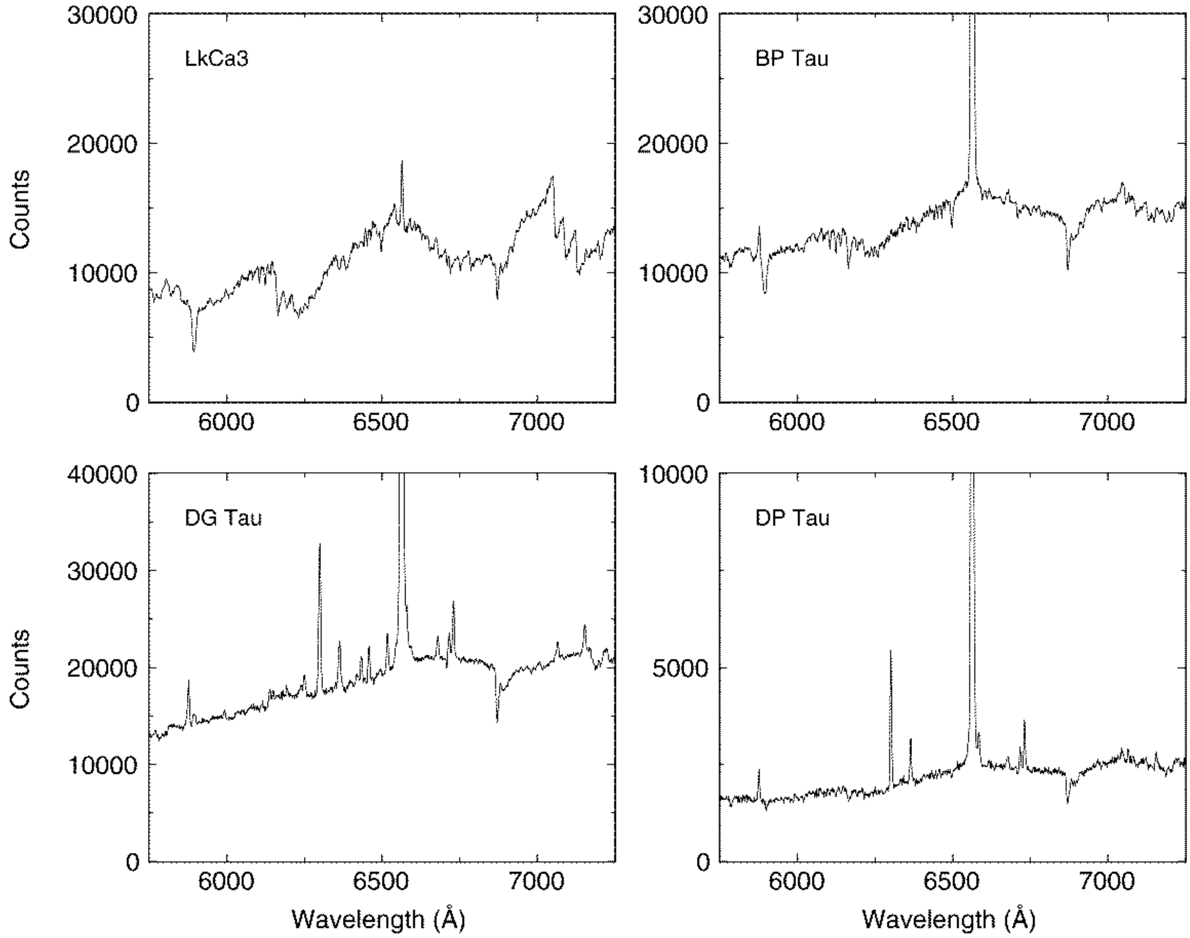
All stellar objects before reaching the main sequence are called Young Stellar Objects (YSOs). Most prominent examples: T Tauri stars and FU Orionis stars.

Definition of T Tau Star:

- Irregular variability, amplitude up to 3 mag
- Spectral type later than F5
- strong emission lines in Ca II H and K and hydrogen lines, presence of strong Li absorption at 6707 Å.
- low intrinsic luminosity
- association with nebulosity

in weak emission line T Tau stars, emission lines are (guess what) weaker, only 10% of all T Tau are classical “strong-emission line” T Taus.

Formation of Disk and Wind, III



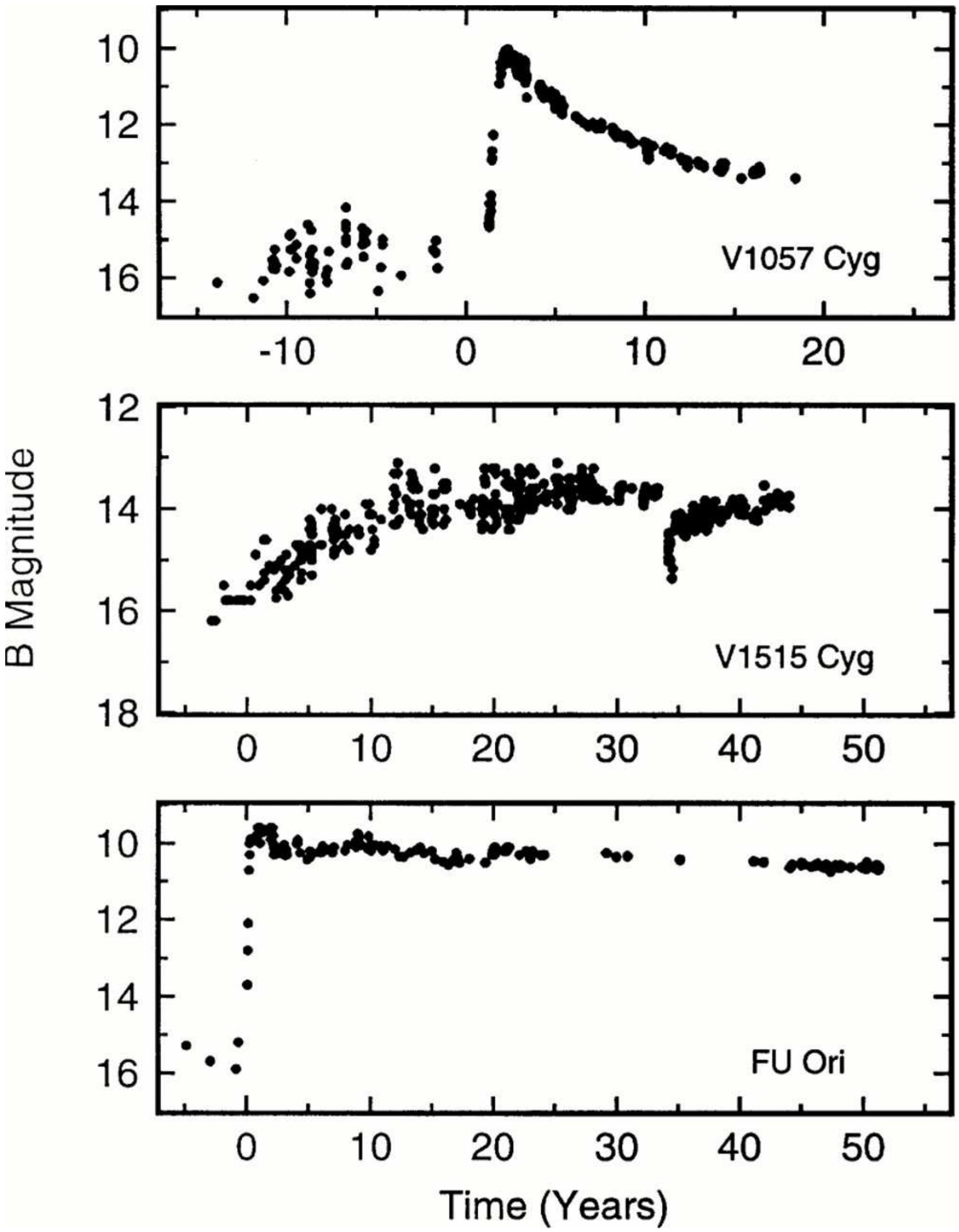
Kenyon et al. (1998)

Typical spectra clockwise:

- weak-line T Tau star (LkCa3),
- classical T Tau (BP Tau, DP Tau),
- to strong emission line T Tauri star DG Tau.

Emission line analysis gives in disk accretion rates of $\dot{M} \sim 10^{-7} \ldots 10^{-9}\,\mathrm{M}_\odot\,\mathrm{year}^{-1}$.

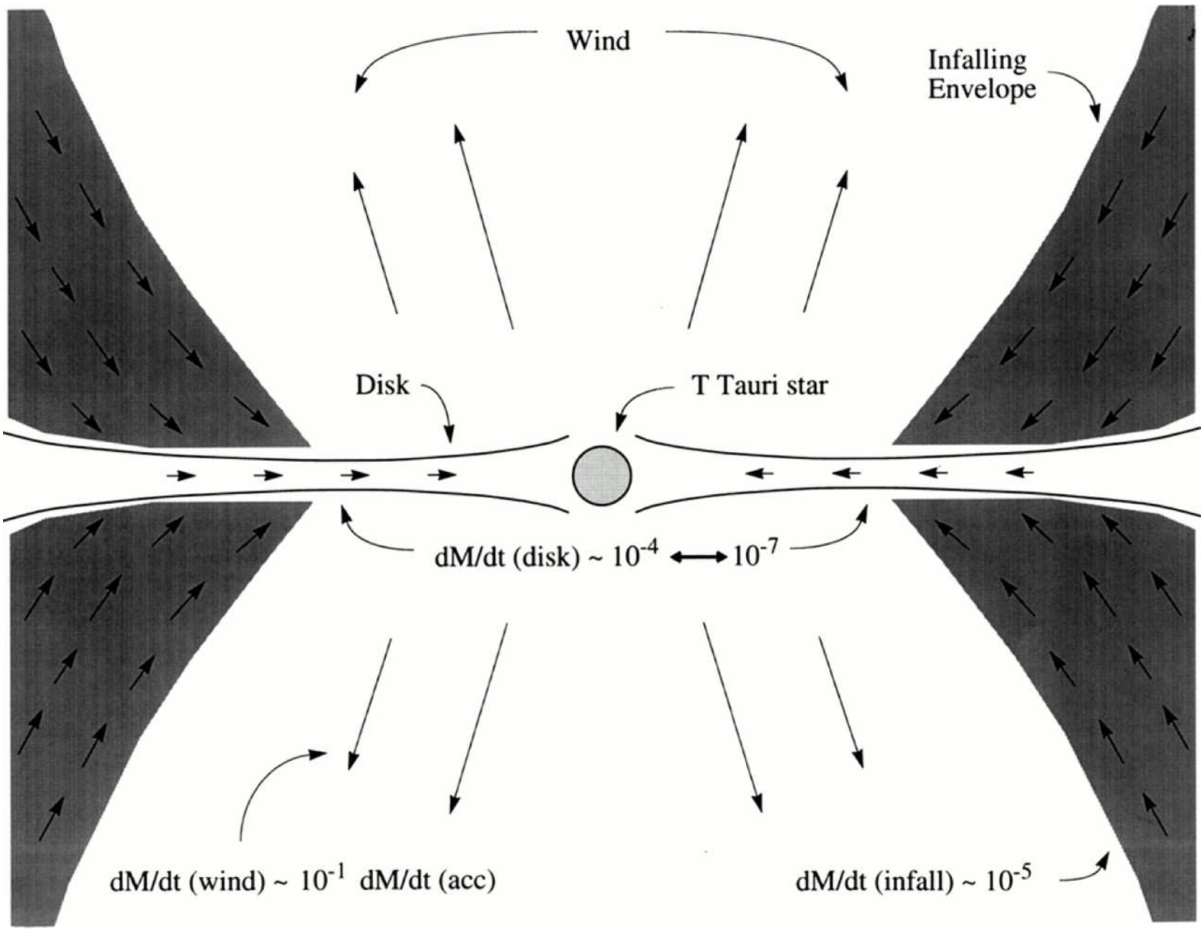
Formation of Disk and Wind, IV



Hartmann & Kenyon (1996)

Special objects: FU Ori Stars: very strong outbursts!

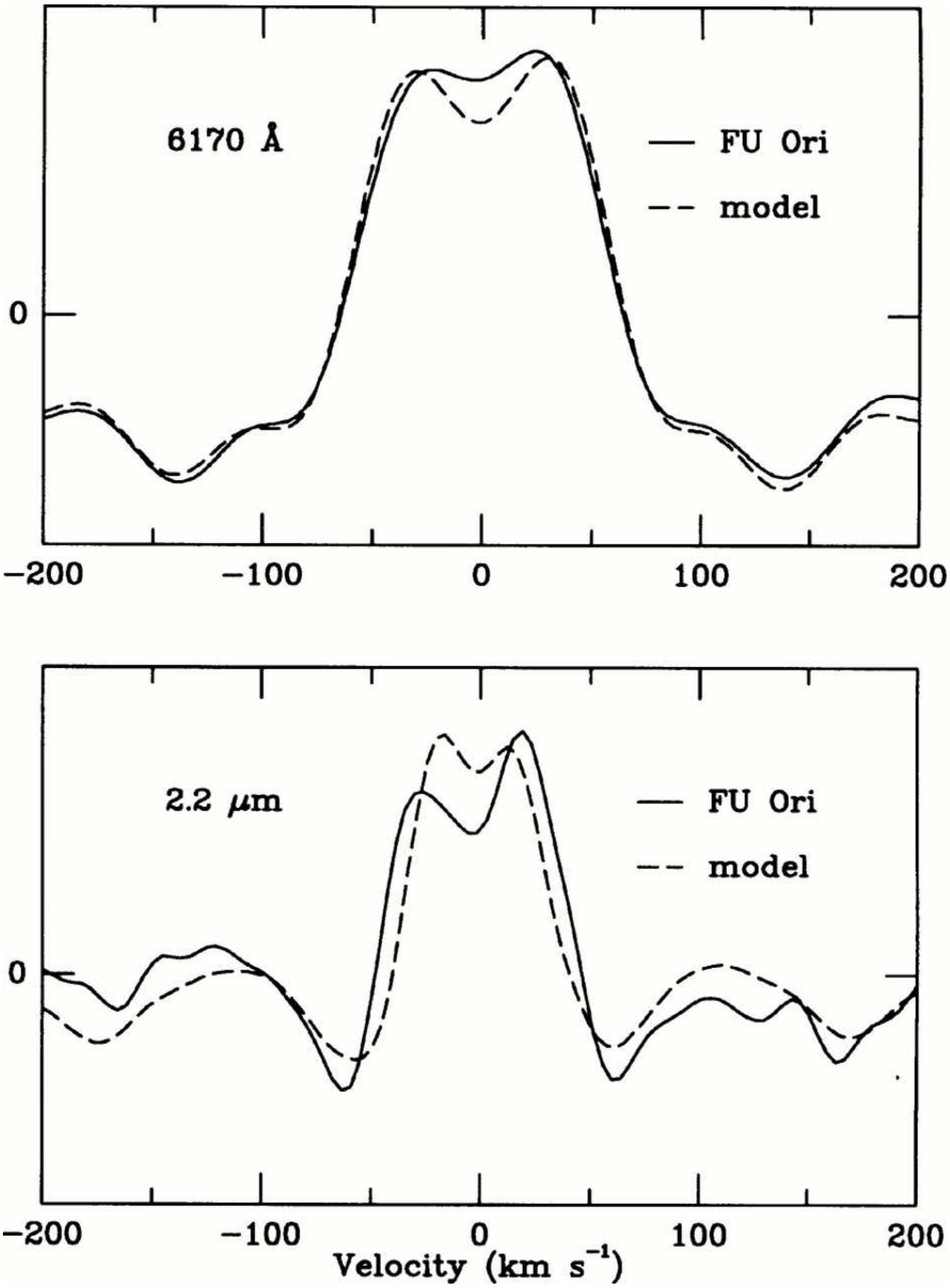
Formation of Disk and Wind, V



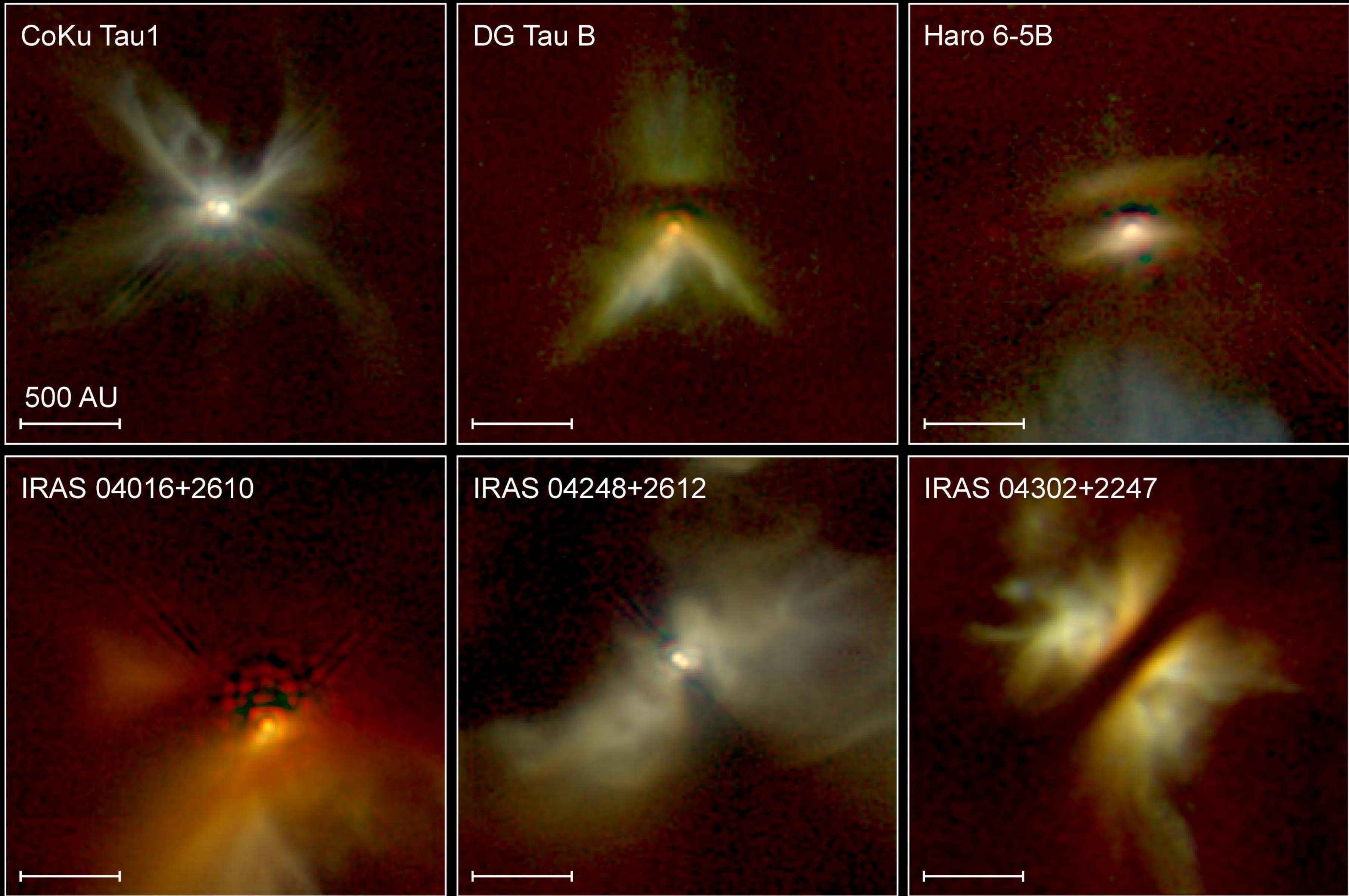
Hartmann & Kenyon (1996)

FU Ori Star outbursts caused by extreme increase of mass accretion rate.

Formation of Disk and Wind, VI



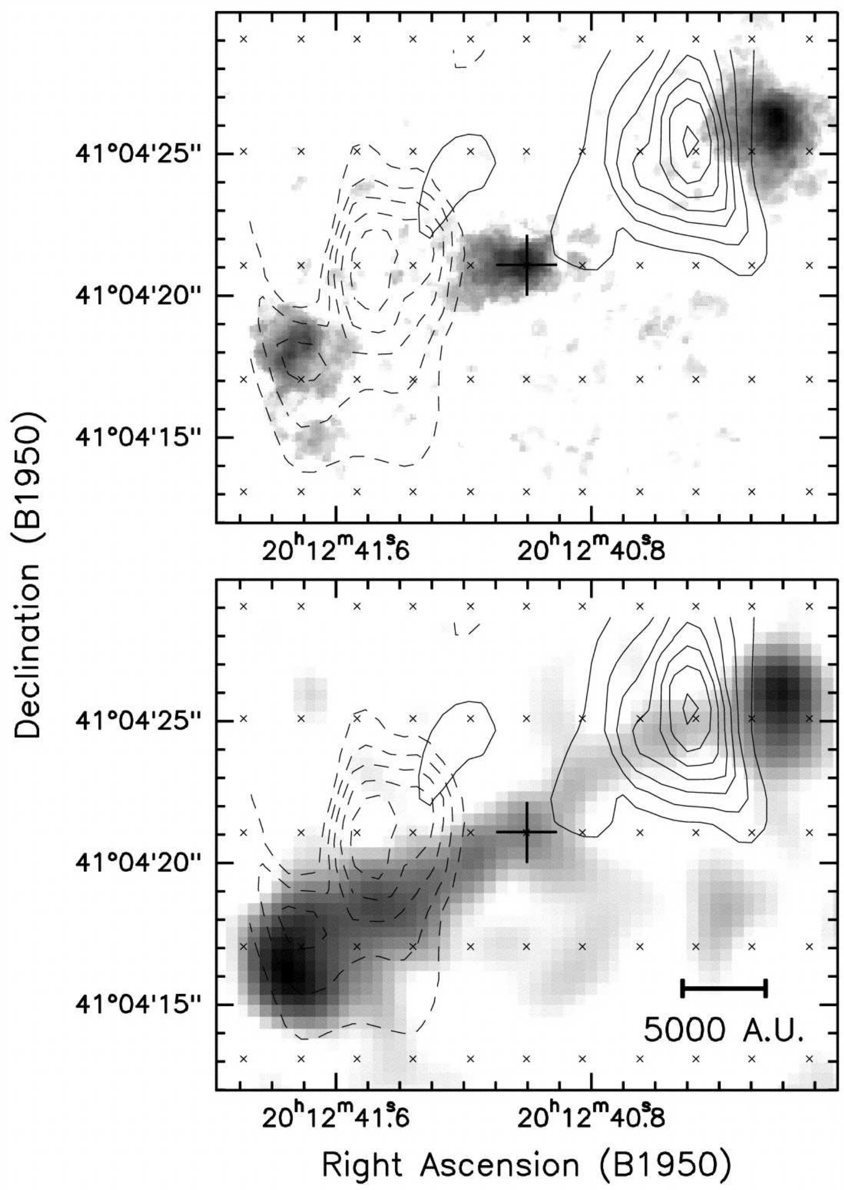
Spectral line profiles of FU Ori stars indicate presence of accretion disk in these systems.



Young Stellar Disks in Infrared

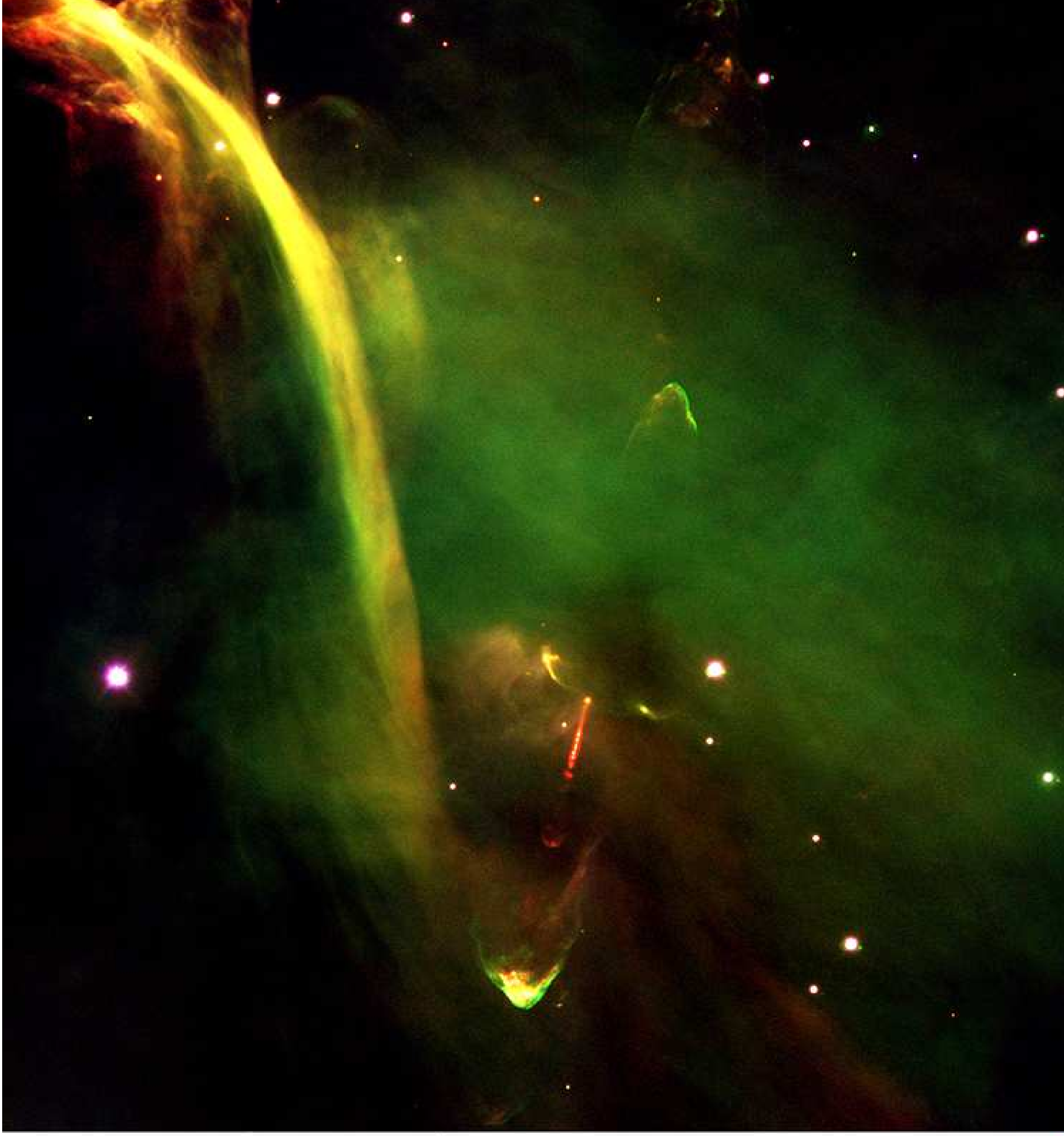
Hubble Space Telescope • NICMOS

Formation of Disk and Wind, VIII



Kawamura et al. (1999)

Molecular outflow around IRAS 20126+4106, contour lines: blueshifted (solid) and redshifted (dashed) CO emission, greyscale images: top: NH_3, bottom: SiO.



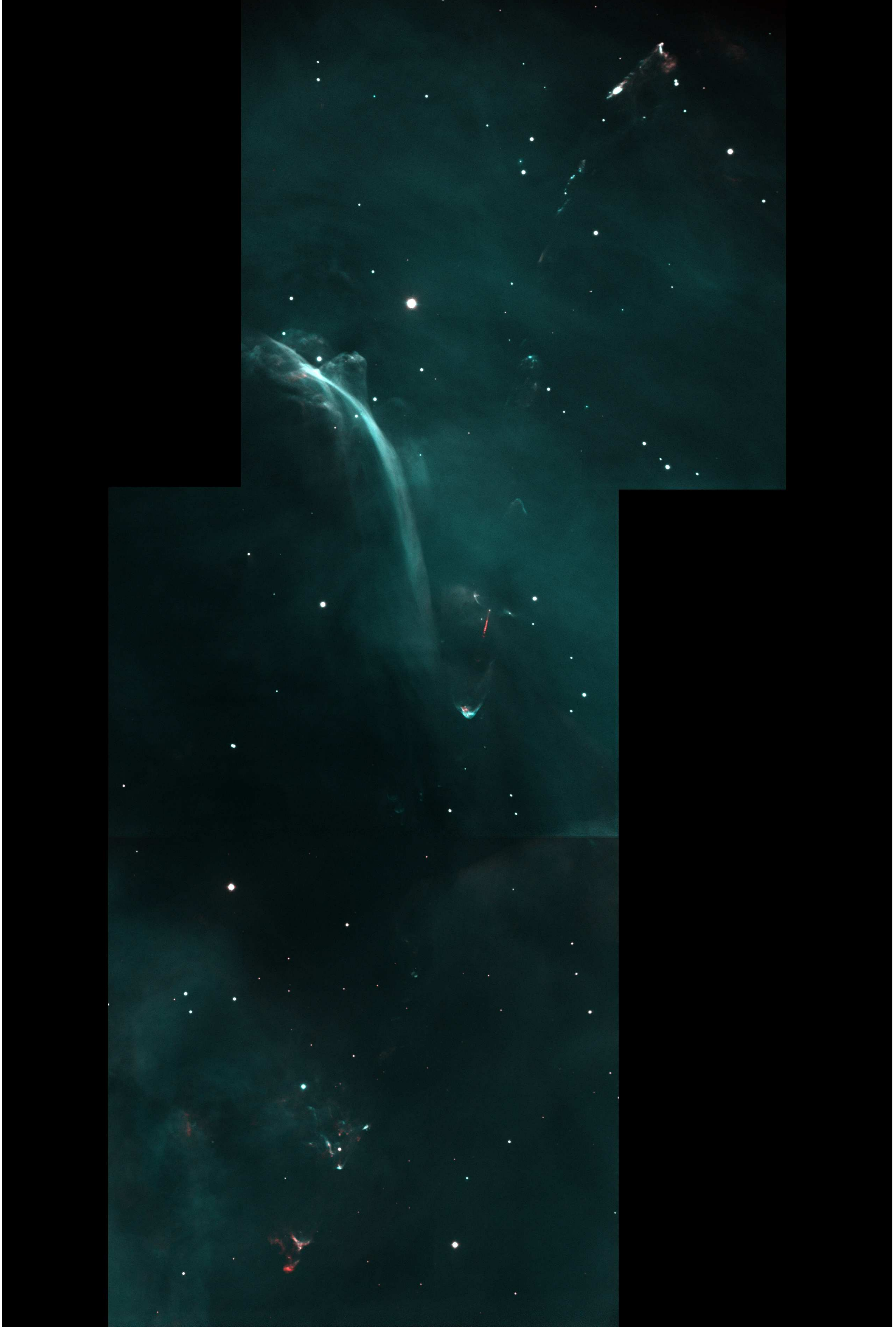
Protostar HH-34 in Orion (VLT KUEYEN + FORS2)

ESO PR Photo 40b/99 (17 November 1999)

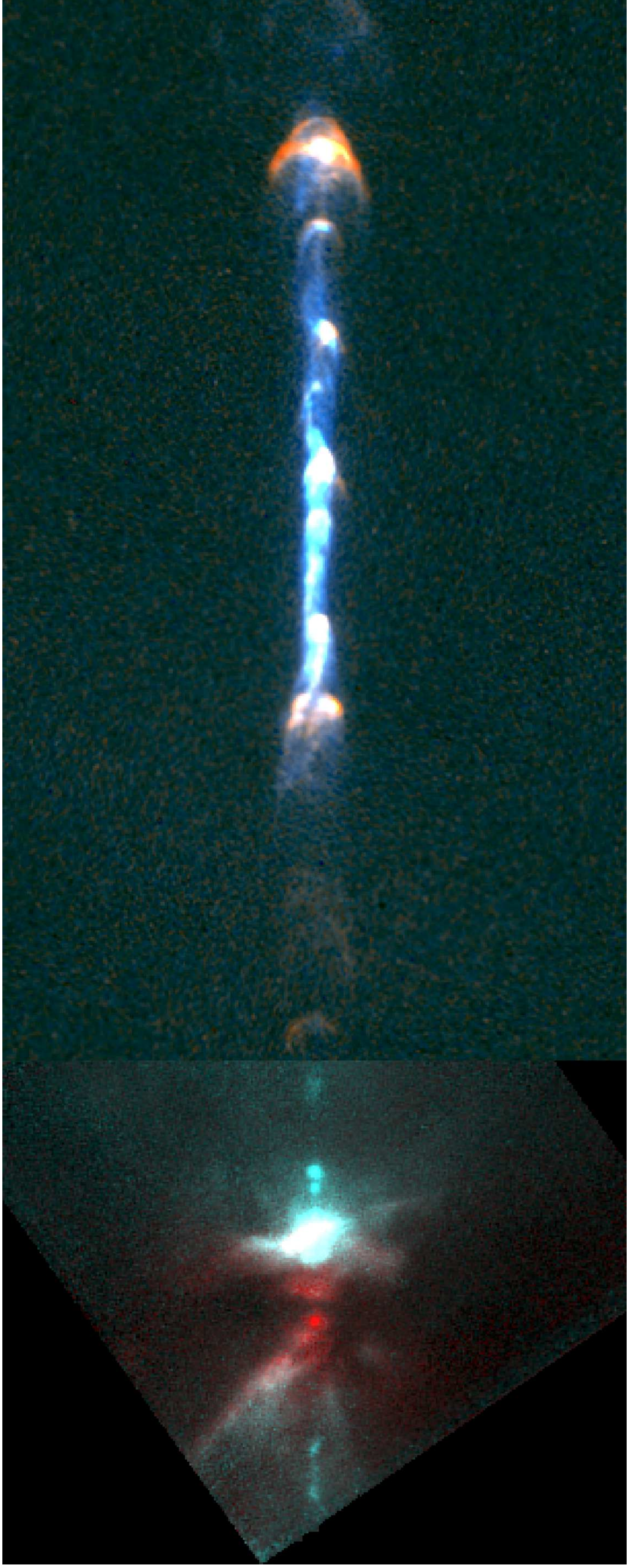
Herbig Haro Objects: Shocks from jets of YSOs

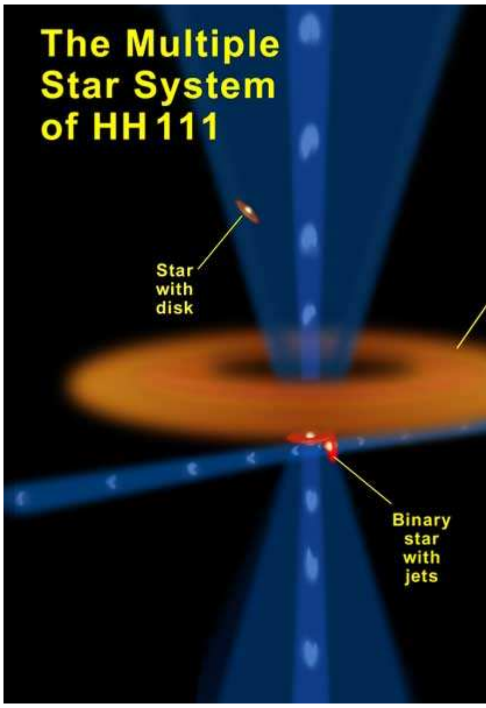
typical speeds: 70. . . 100 km/s; spectral lines shows shoc

excitation



HH34, full image (courtesy J. Bally)



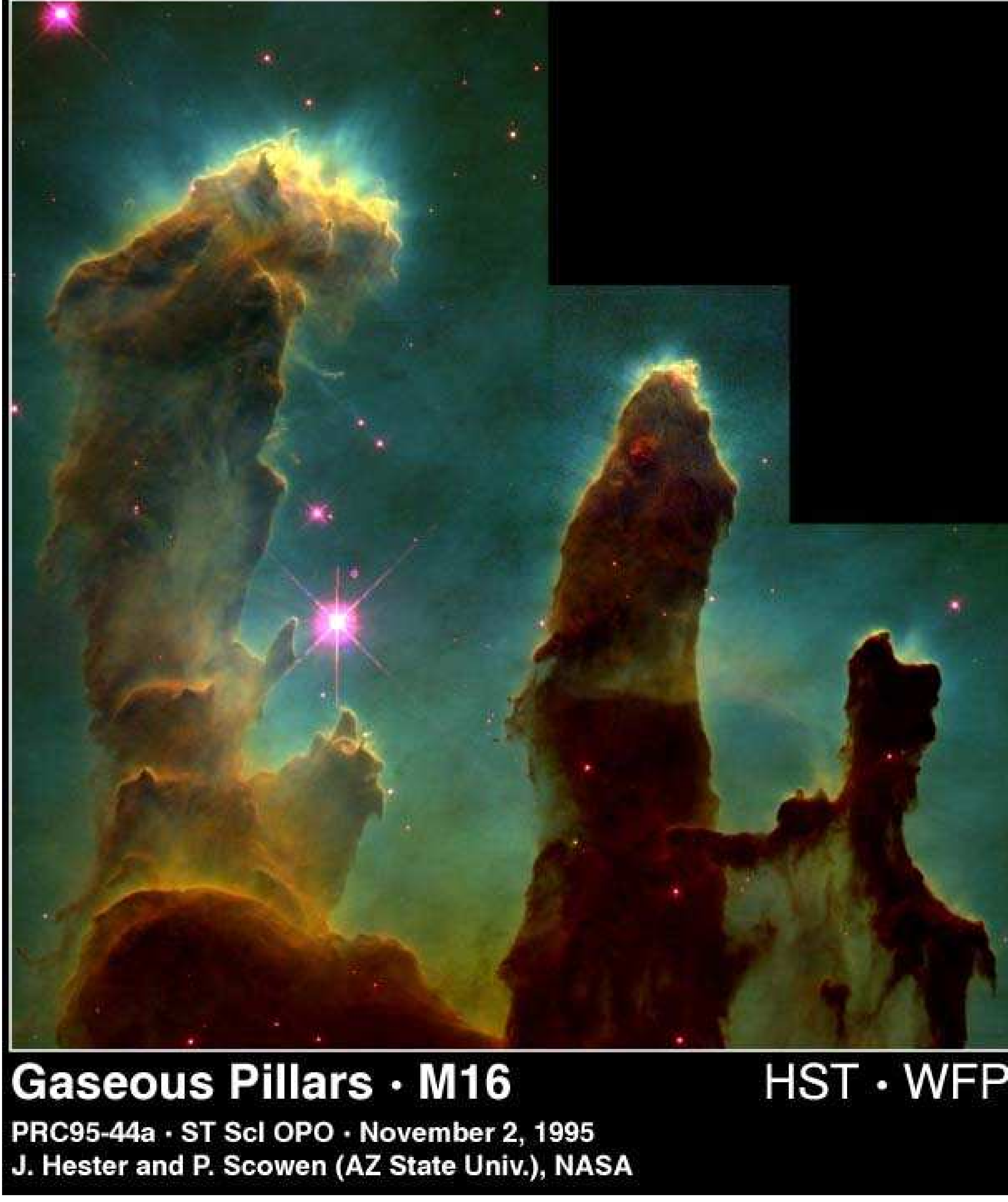


courtesy Bo Reipurt
Ka Chun Yu, J. Bally

Unveiling of Protostar

Outflow removes most surrounding material $\Longrightarrow$ Star becomes visible to outside observers.

After a few million years $\Longrightarrow$ evolution towards main sequence
(see class on stellar evolution for this).



Evaporating gaseous globules (EGGs): stars ionizing surrounding material away.

IR-View of "Pillars of Creation" at Centre of Eagle Nebula
(VLT ANTU + ISAAC)

ESO PR Photo 37b/01 (20 December 2001)

Protoplanetary Disks in the Orion Nebula
Hubble Space Telescope • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University)
STScI-PRC01-13

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