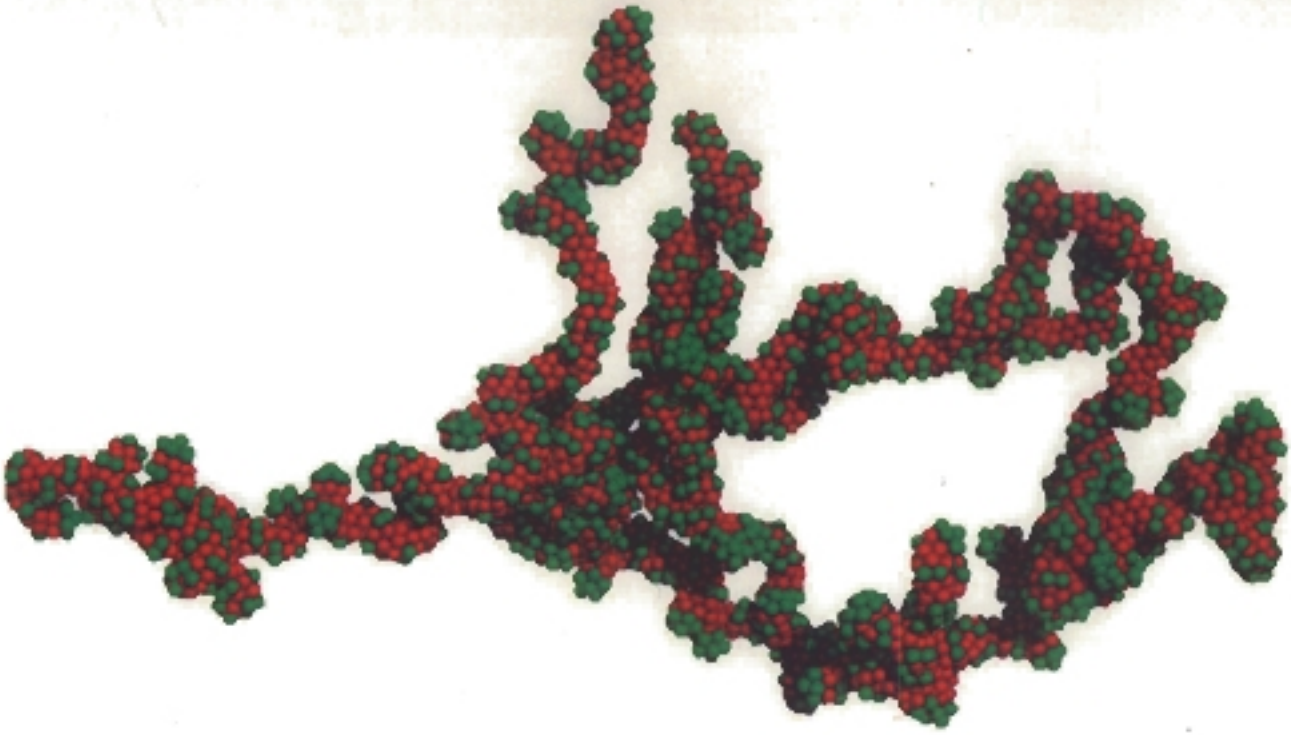


Solids in the Universe

Optical Photoluminescence from Interstellar Nanoparticles

Fermi Lab Colloquium, 21 April, 2004

Adolf N. Witt

The University of Toledo

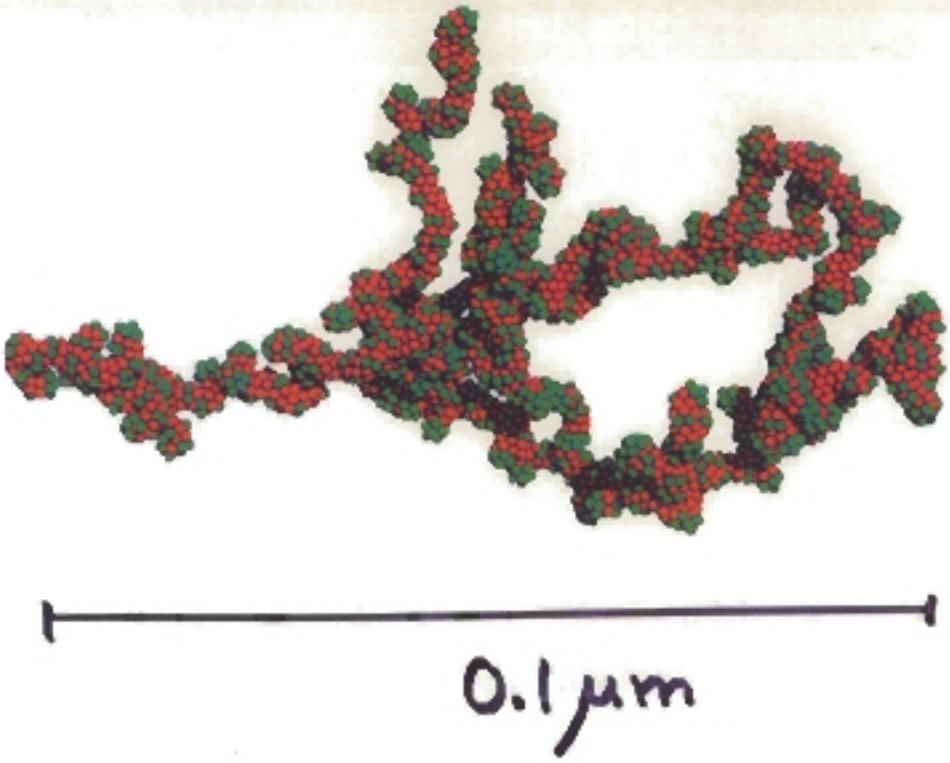
Outline

- Introduction: Interstellar Grains & Nanoparticles

- Observations of Interstellar Photoluminescence
  - Extended Red Emission
  - Blue Luminescence

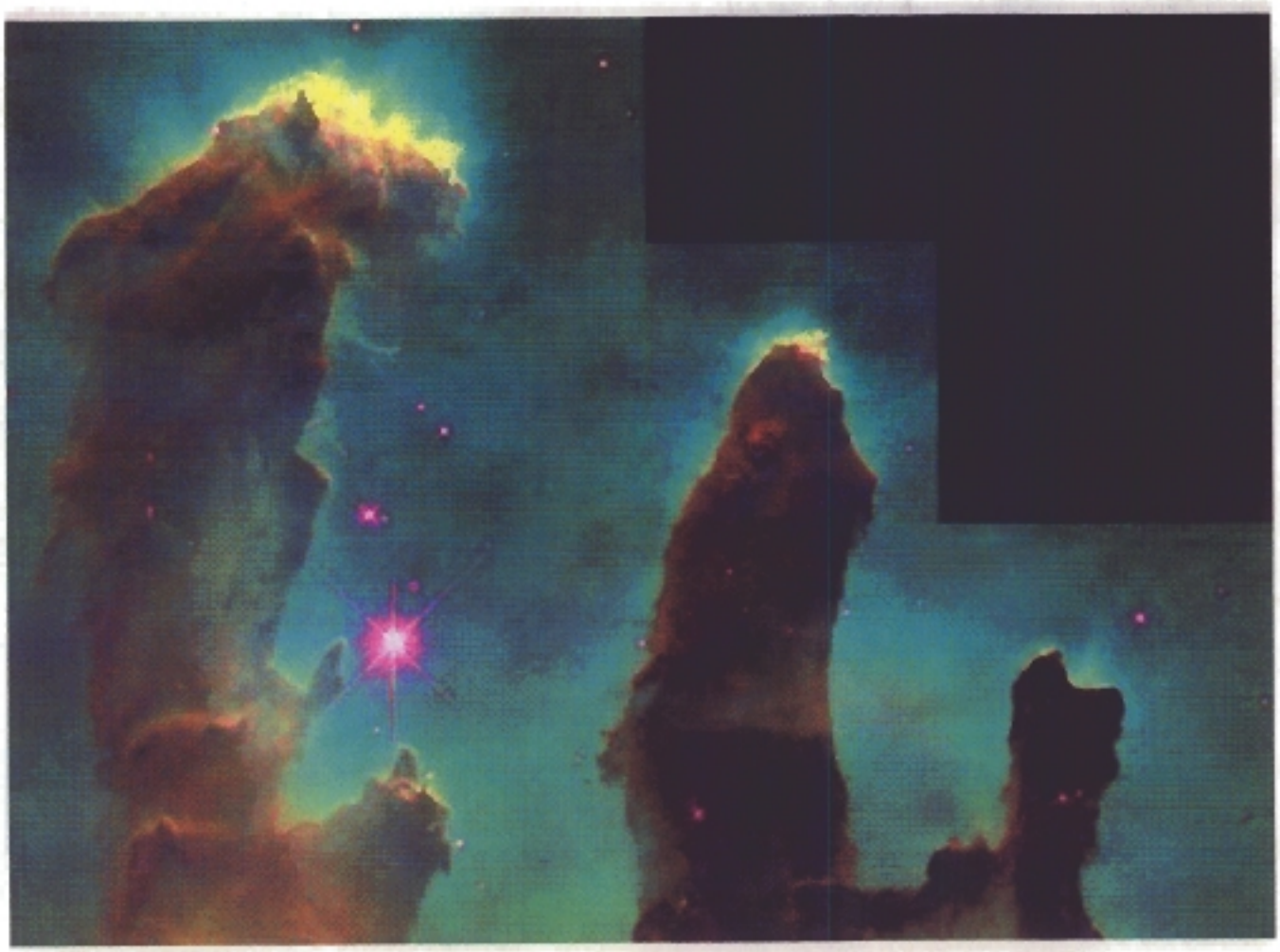
  Possible Sources: Silicon Nanoparticles and PAHs

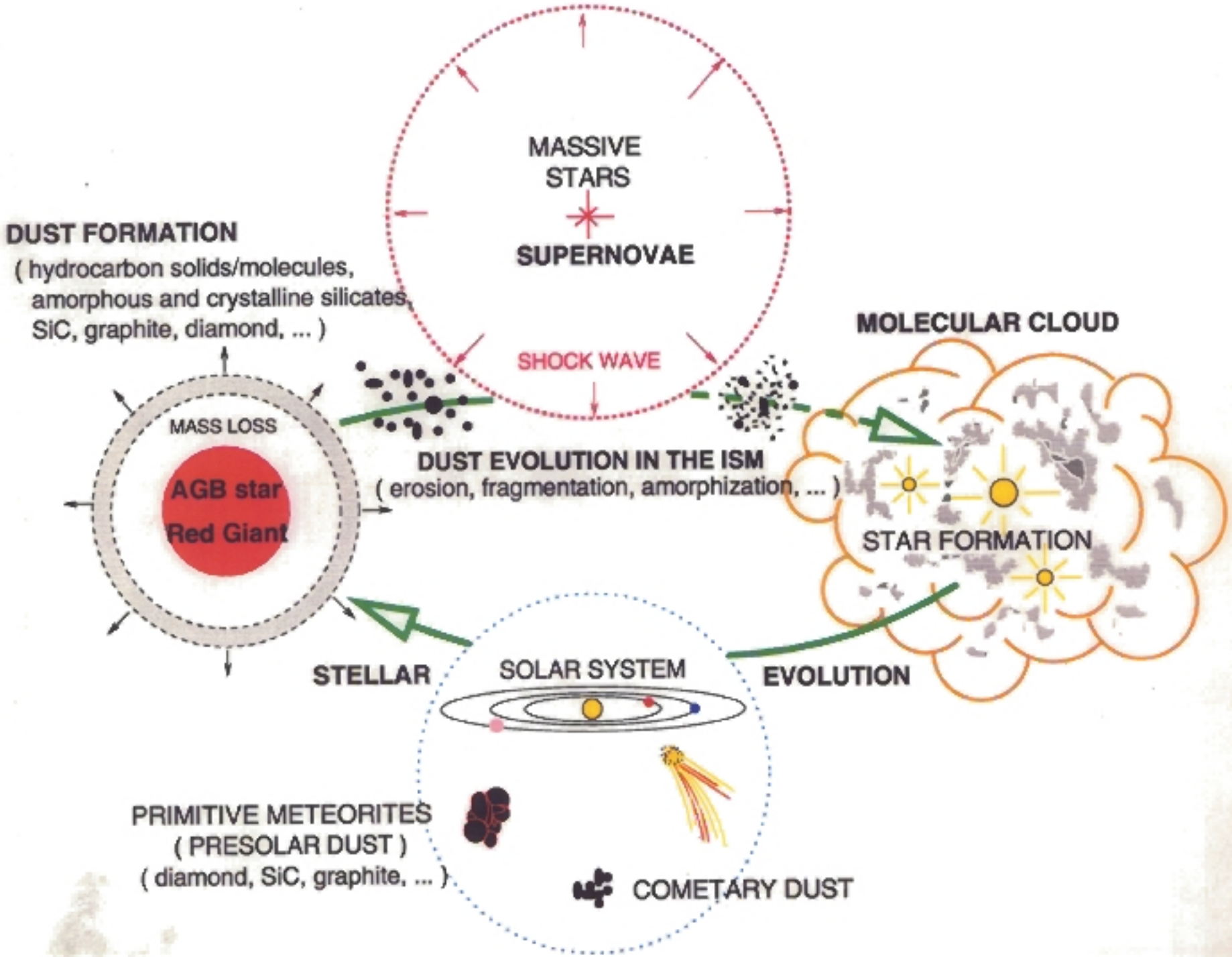
  Conclusions

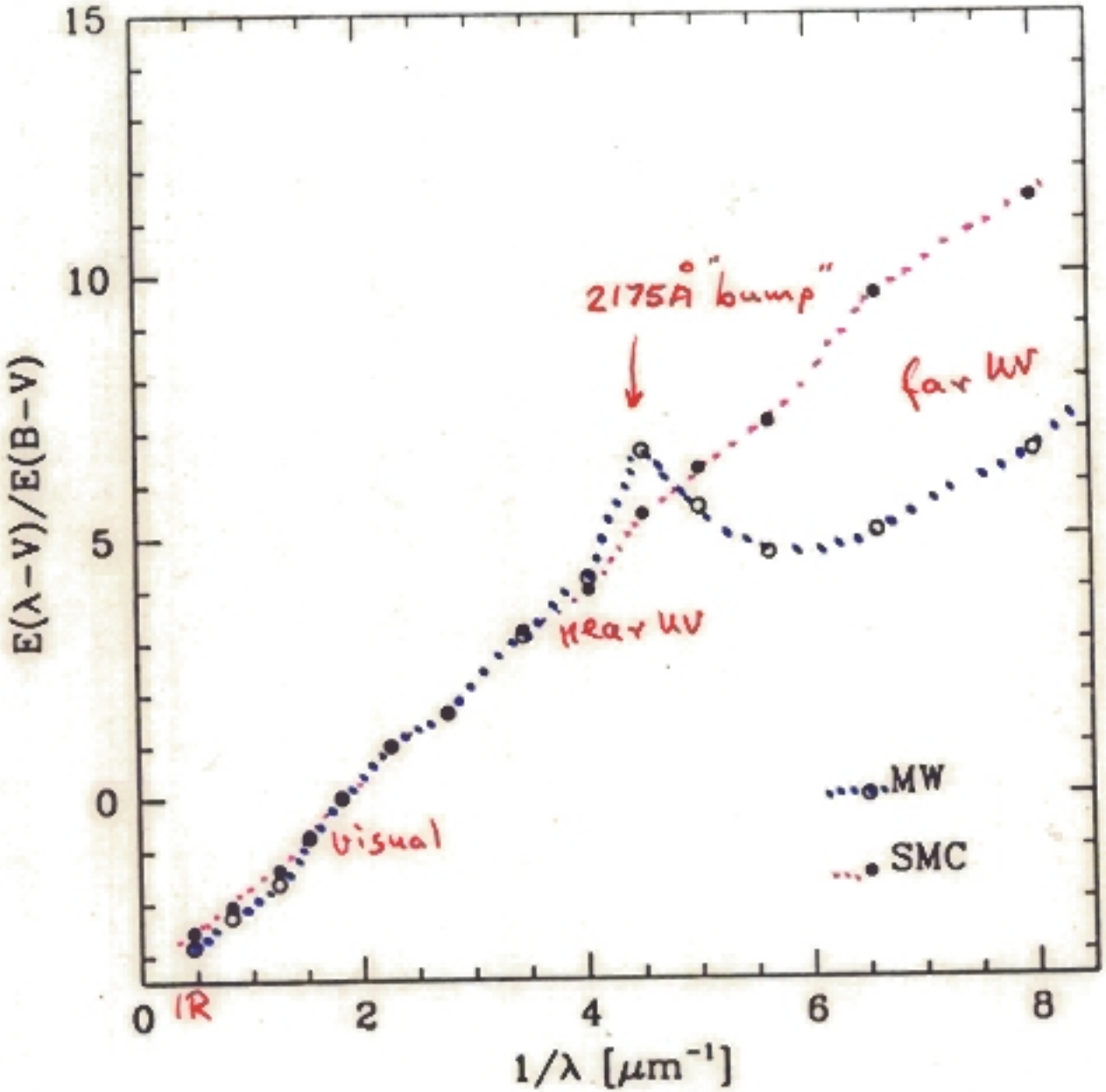

0.1 μm

Why are nanoparticles important?

- Their collective UV/optical absorption cross section is comparable to that of classical interstellar grains in the ISM.
- They are most likely the structural building blocks of larger, composite grains.
- They are important sources of photoelectrons, thus contributing to the heating of the ISM.
- Their large surface/volume ratio makes them the dominant reservoir of solid surfaces in the ISM, enabling the formation of molecular hydrogen and other molecular reactions.

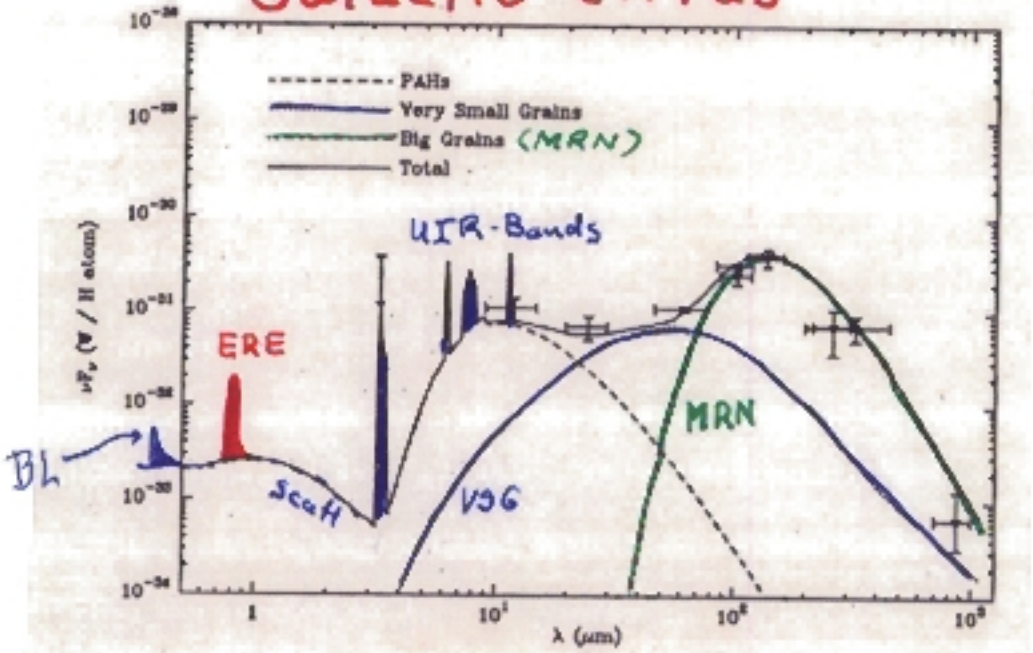



MASSIVE
STARS
SUPERNOVAE
SHOCK WAVE
DUST FORMATION
(hydrocarbon solids/molecules,
amorphous and crystalline silicates,
SiC, graphite, diamond, ...)
MOLECULAR CLOUD
MASS LOSS
AGB star
Red Giant
DUST EVOLUTION IN THE ISM
(erosion, fragmentation, amorphization, ...)
STAR FORMATION
STELLAR
SOLAR SYSTEM
EVOLUTION
PRIMITIVE METEORITES
(PRESOLAR DUST)
(diamond, SiC, graphite, ...)
COMETARY DUST



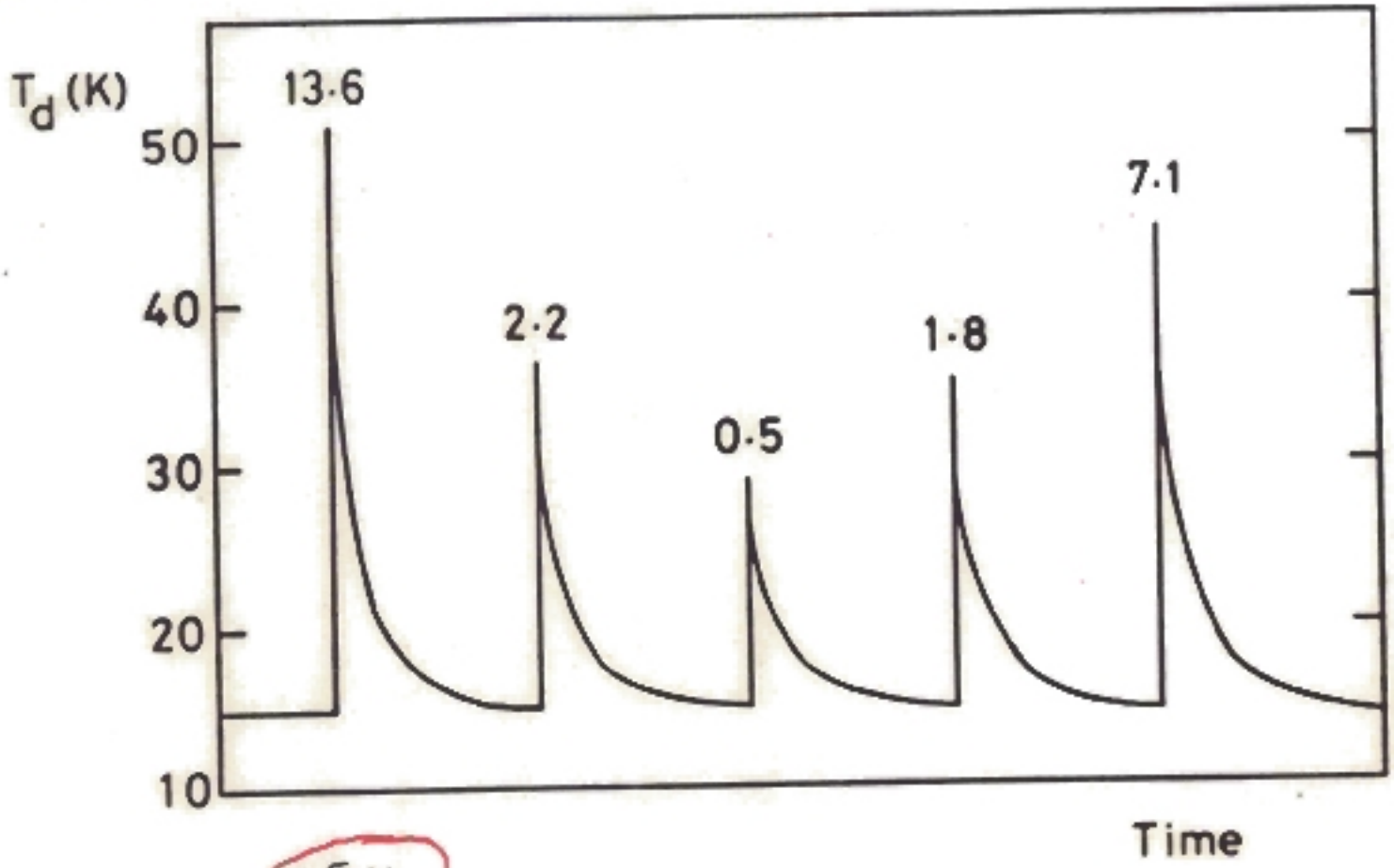
Wavelength dependance of interstellar extinction

Galactic Cirrus



ERE results from electronic recombination.

BL most likely due to fluorescence by PAHs

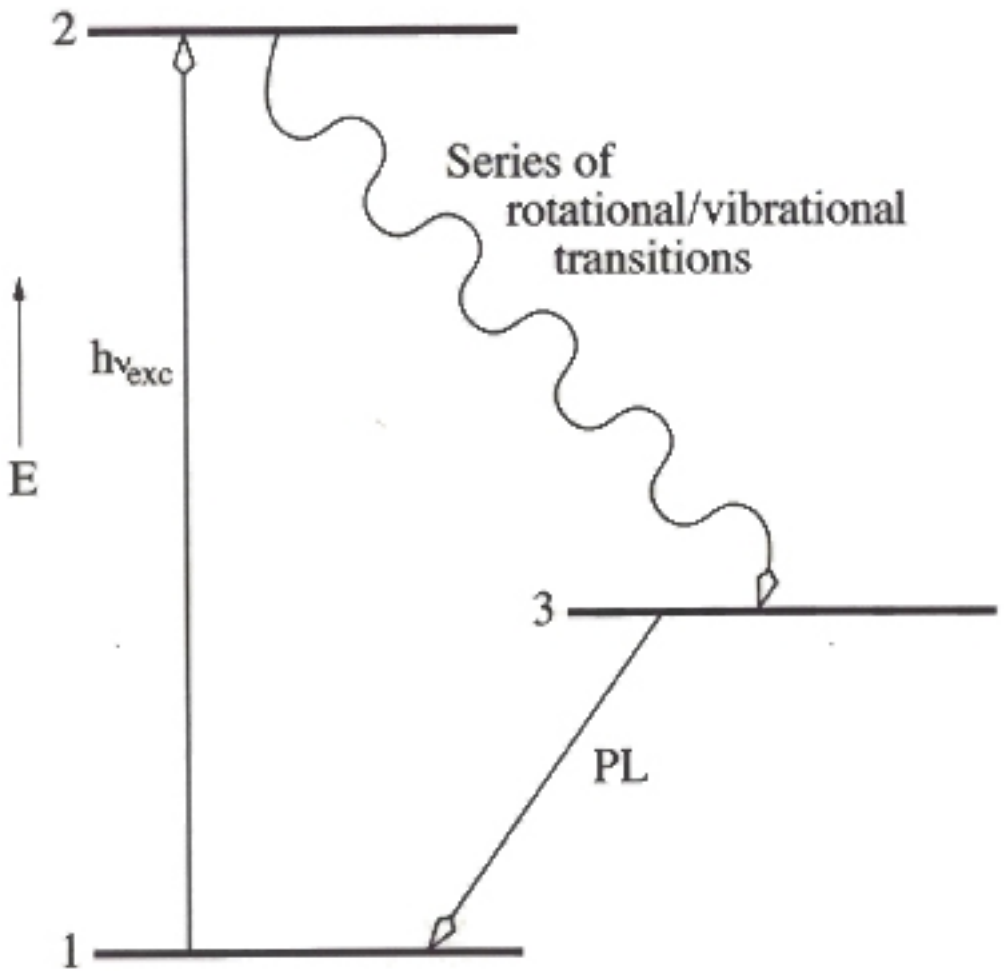


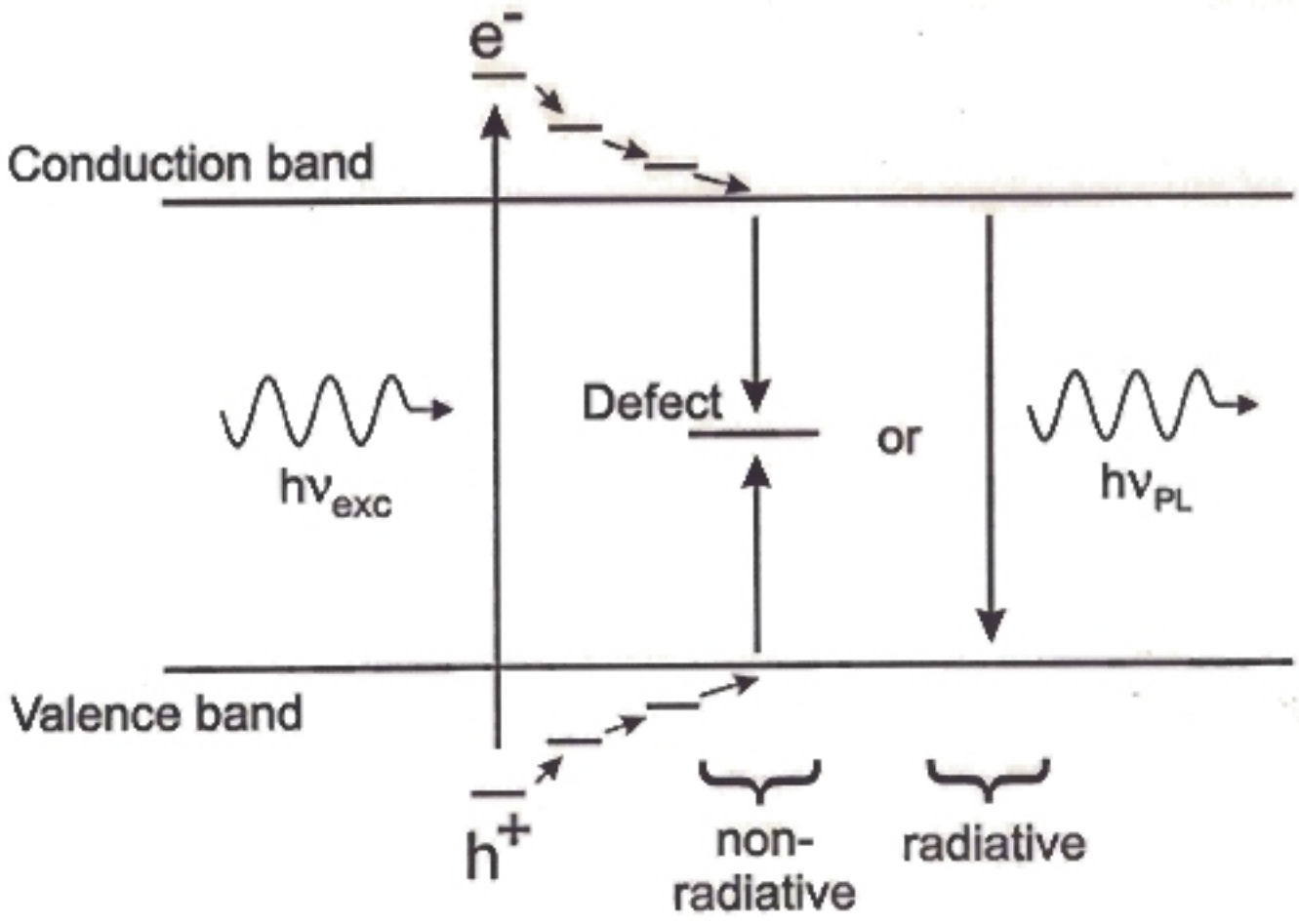
= 5μm

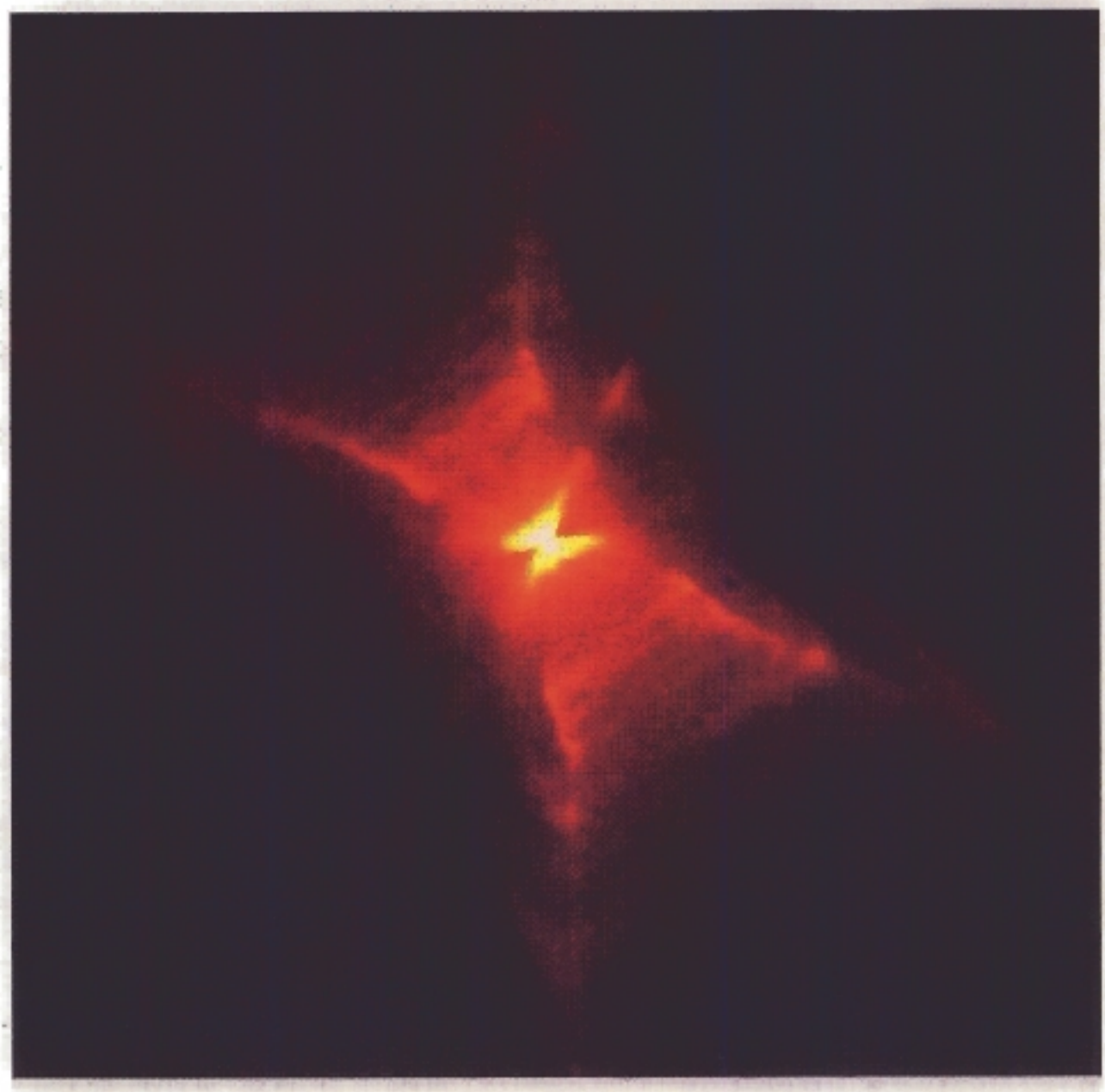
Figure 6.1 A schematic representation of temperature fluctuations in a small grain (radius $a = 0.005\,\mu m$) produced by periodic absorption of individual photons. Each temperature spike is labelled by the photon energy in electon volts, and the time interval between spikes is one hour. (Adapted from Aannestad and Kenyon 1979.)

Diffuse IR emission at few μm wavelengths requires temperatures up to 1200 K ⇒ grain sizes ≪ 10 nm!

Photoluminescence




e-
Conduction band
Defect
or
hνexc
hνPL
Valence band
h+
non-
radiative
radiative



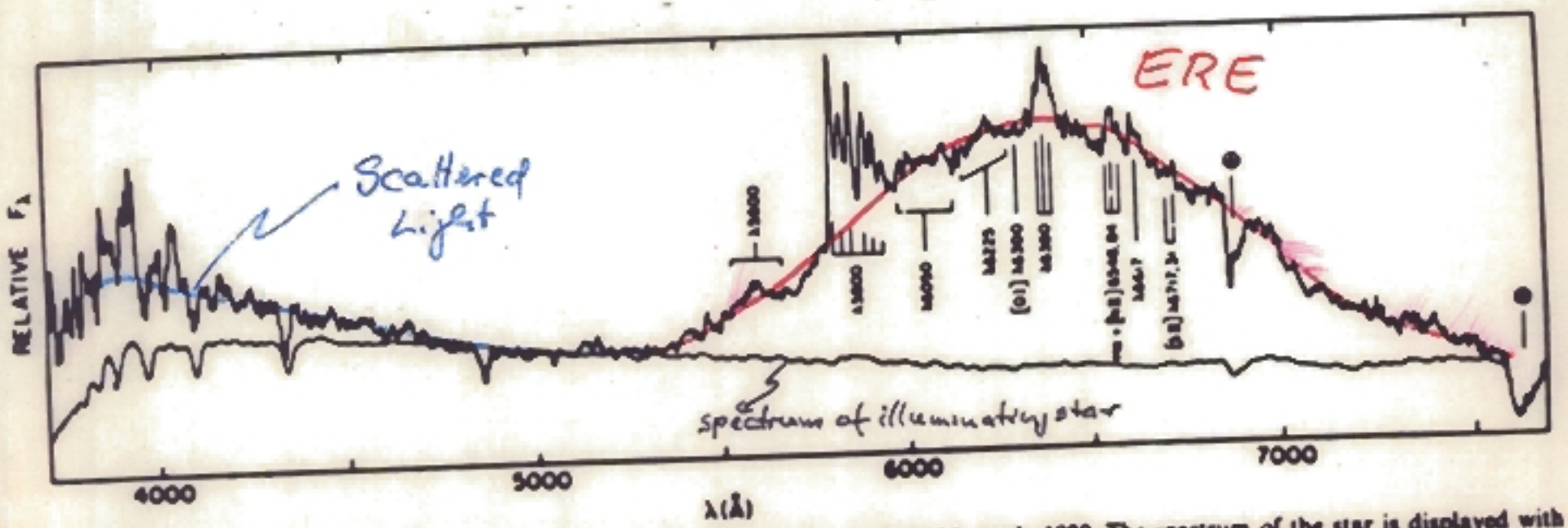
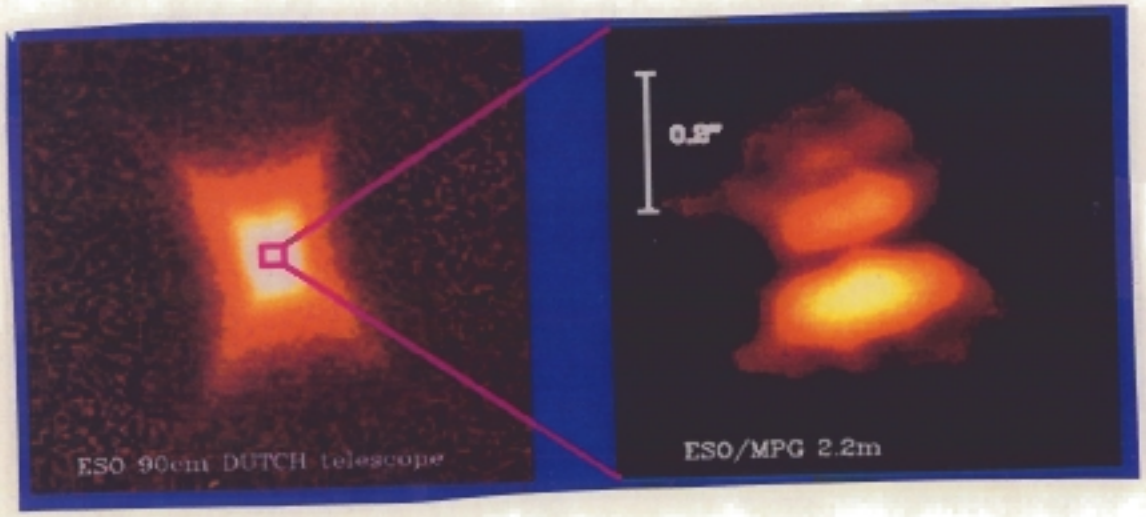


Fig. 1. Spectra of the nebula (upper line) and of the star HD 44179, obtained by Schmidt et al., 1980. The spectrum of the star is displayed with a certain reduction factor (≈1300) to allow direct comparison. The aperture of the diaphragm is 2"8 and the observation of the nebula was made 10" north from the star



ERE: Defining Observational Characteristics

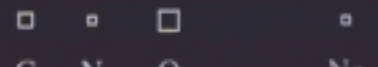
- Broad, unstructured emission band in 540 – 950 nm range
- Peak wavelength is variable: 610 – 880 nm
- Intensity consistent with UV-powered photoluminescence process
- Quantum efficiency >> 10%
- Observed widely throughout MW Galaxies and other galaxies
- Presence of dust and UV illumination necessary but not sufficient
- Not associated with larger grains: absence of scattering in PNe
- Peak wavelength and quantum yield strongly affected by density and hardness of local UV radiation field: → Photoprocessing

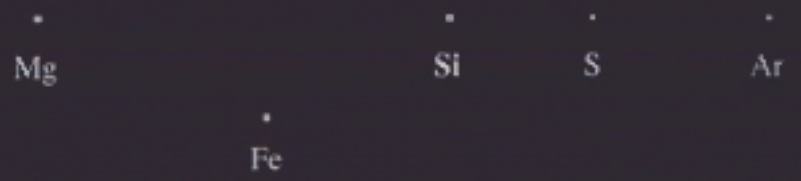
Constraints on ERE carrier candidates

- Cosmically abundant, photoluminescent material (C, Si)
- Ability to survive under a wide range of interstellar and circumstellar conditions
- Ability to shift ERE peak from 600 nm to >900 nm
- High intrinsic PL efficiency (>>10%)
- Photo-excitation mainly by far-UV photons (<150 nm)
- Ability to luminesce and luminescence spectrum must be controllable through photo-processing

The Astronomer's Periodic Table

(Ben McCall)

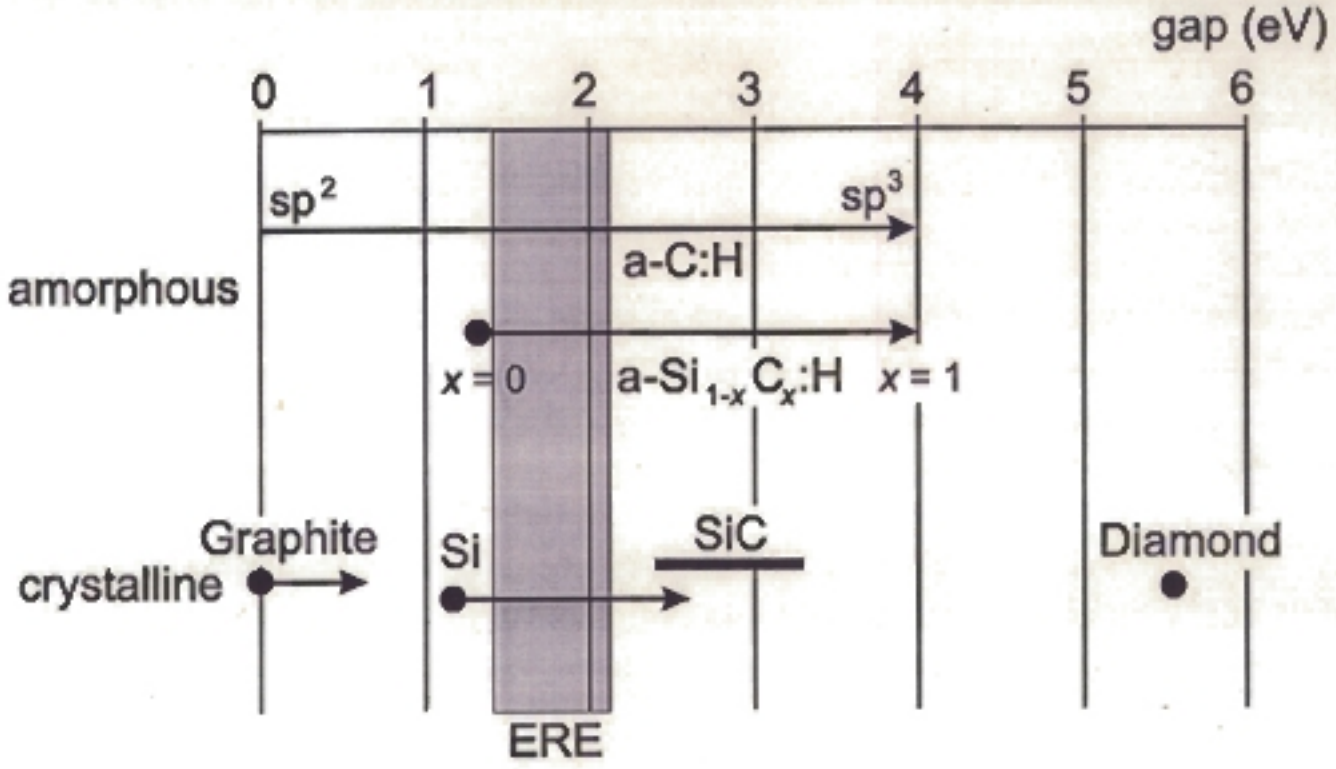




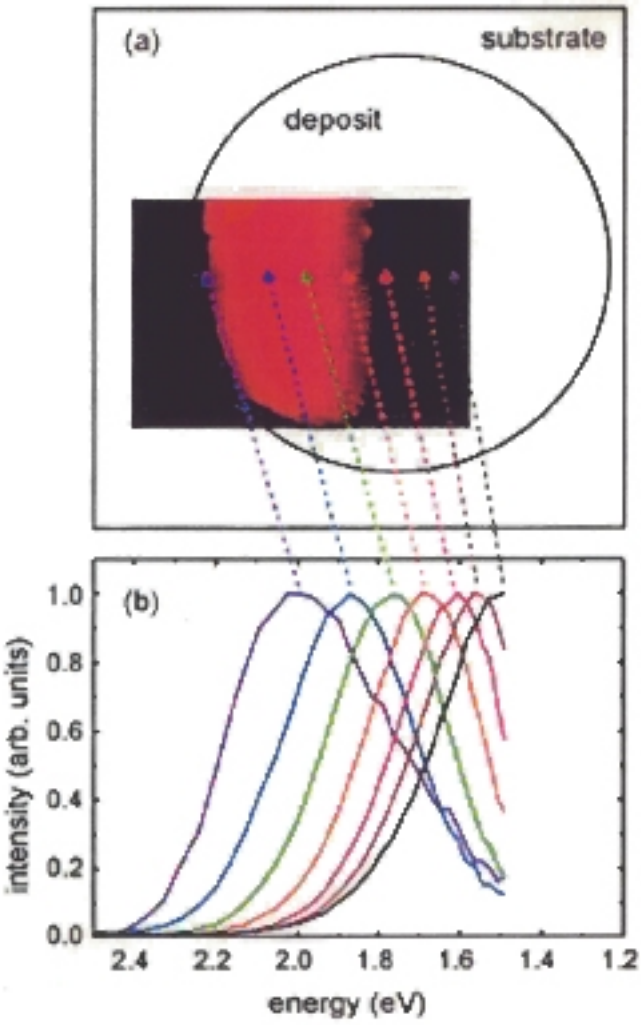
Courtesy Ben Mc Call

Identification of the ERE carrier

- No current "unified" dust model predicts or explains ERE.
- Numerous proposals: HAC, PAHs, QCC, C60, Carbon nanotubes, biological particles, organic hydrocarbon clusters, thermoluminescence in irradiated silicates, silicon nanoparticles, …..
- No single proposal satisfies ALL astrophysical constraints.
- Most promise: silicon nanoparticles, with oxygen, carbon, or iron passivation of dangling surface bonds.

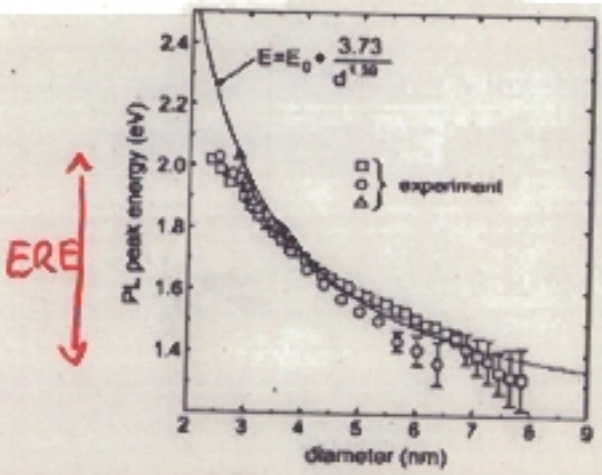

gap (eV)
0
1
2
3
4
5
6
sp2
sp3
amorphous
a-C:H
x = 0
a-Si1-xCx:H
x = 1
Graphite
crystalline
Si
SiC
Diamond
ERE

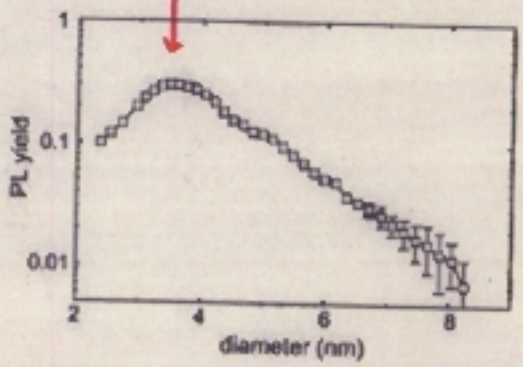
Silicon Nanoparticles, experimental data

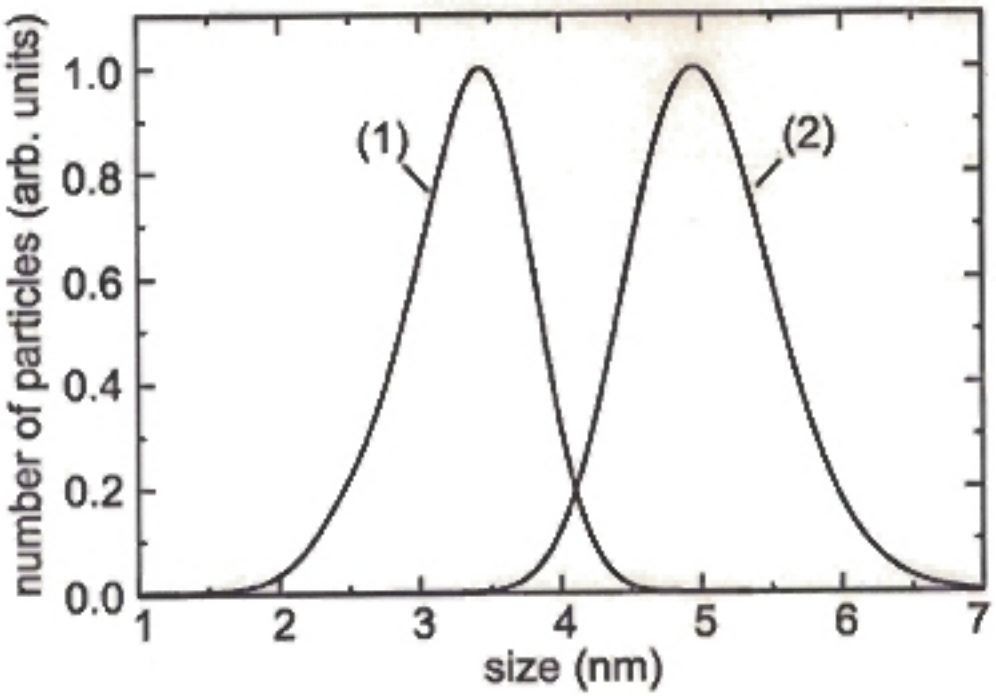


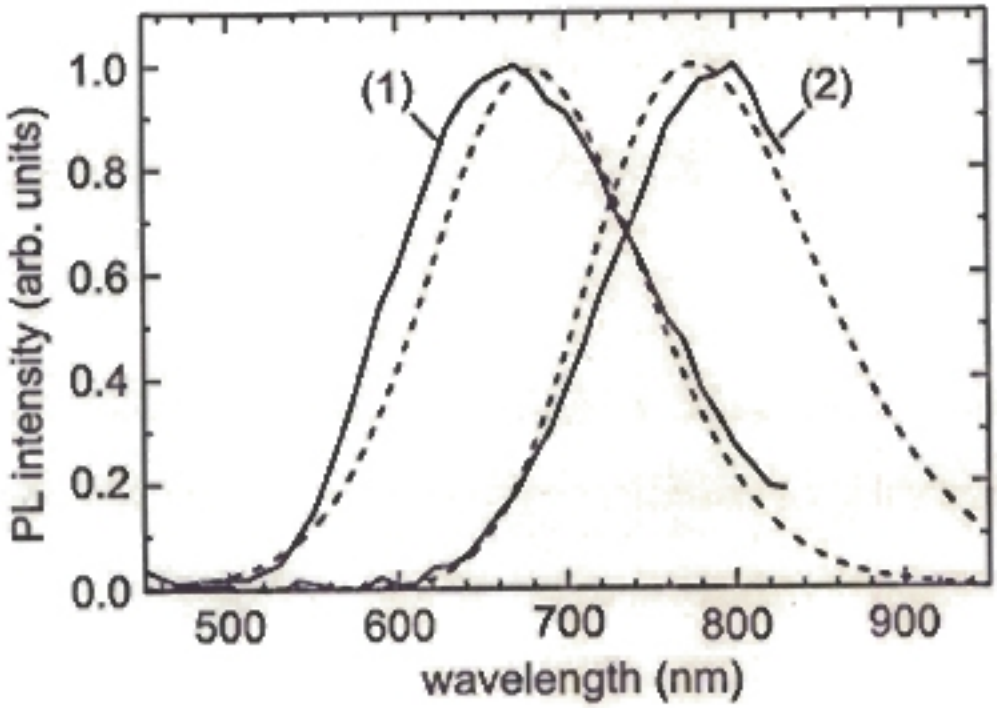
max yield for 3.5 nm Ø
≙ 680 nm wavelength

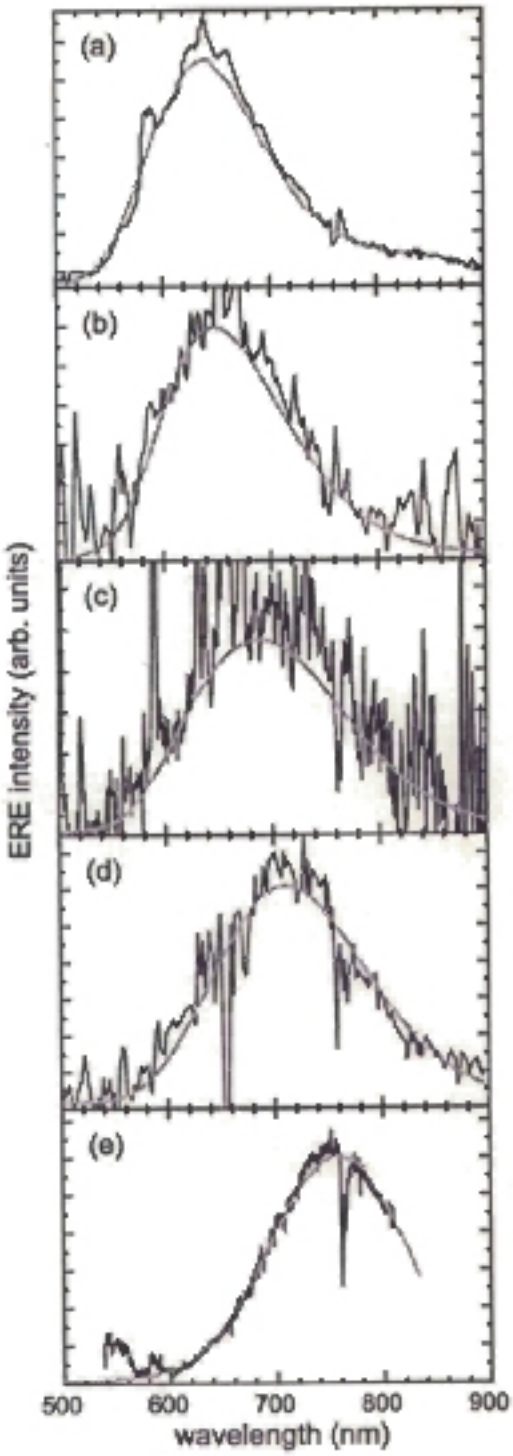
ERE

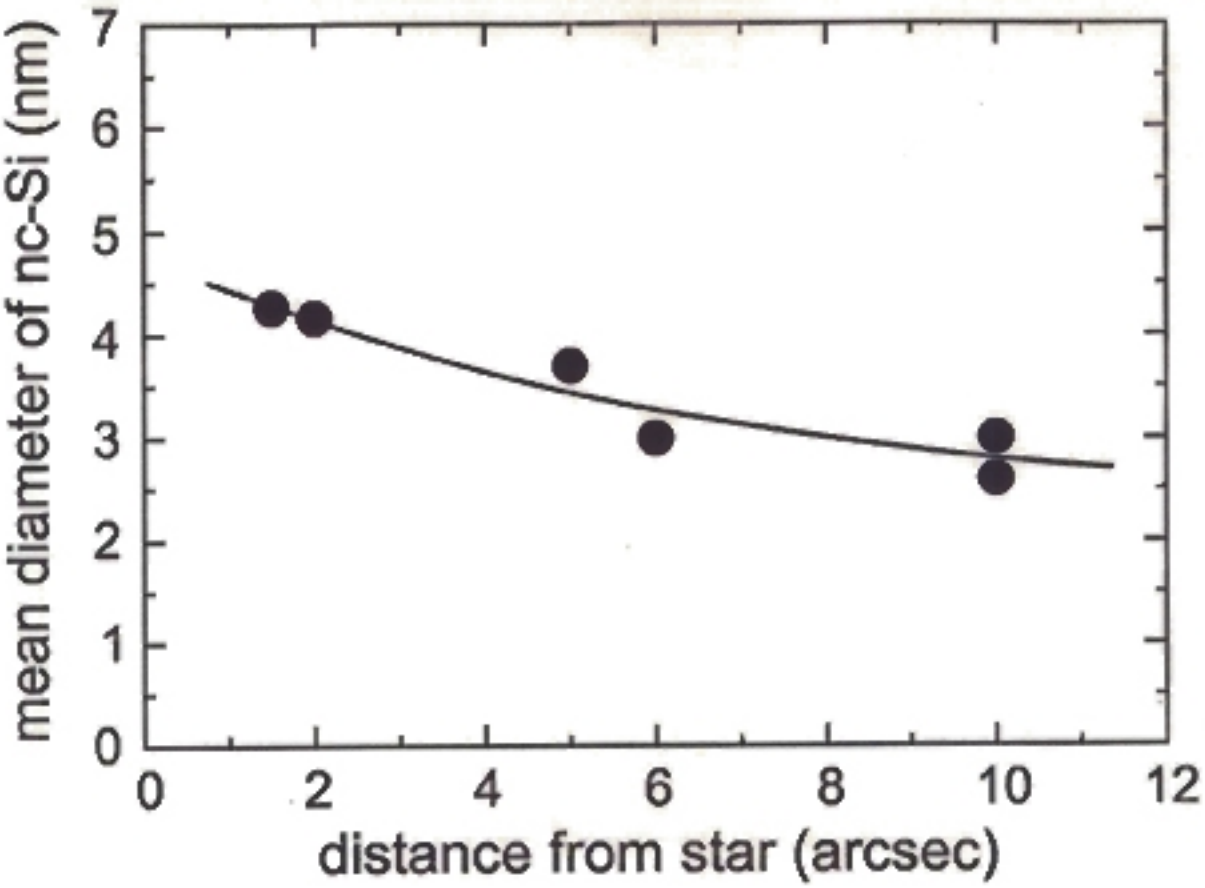





number of particles (arb. units)
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
size (nm)
(1)
(2)

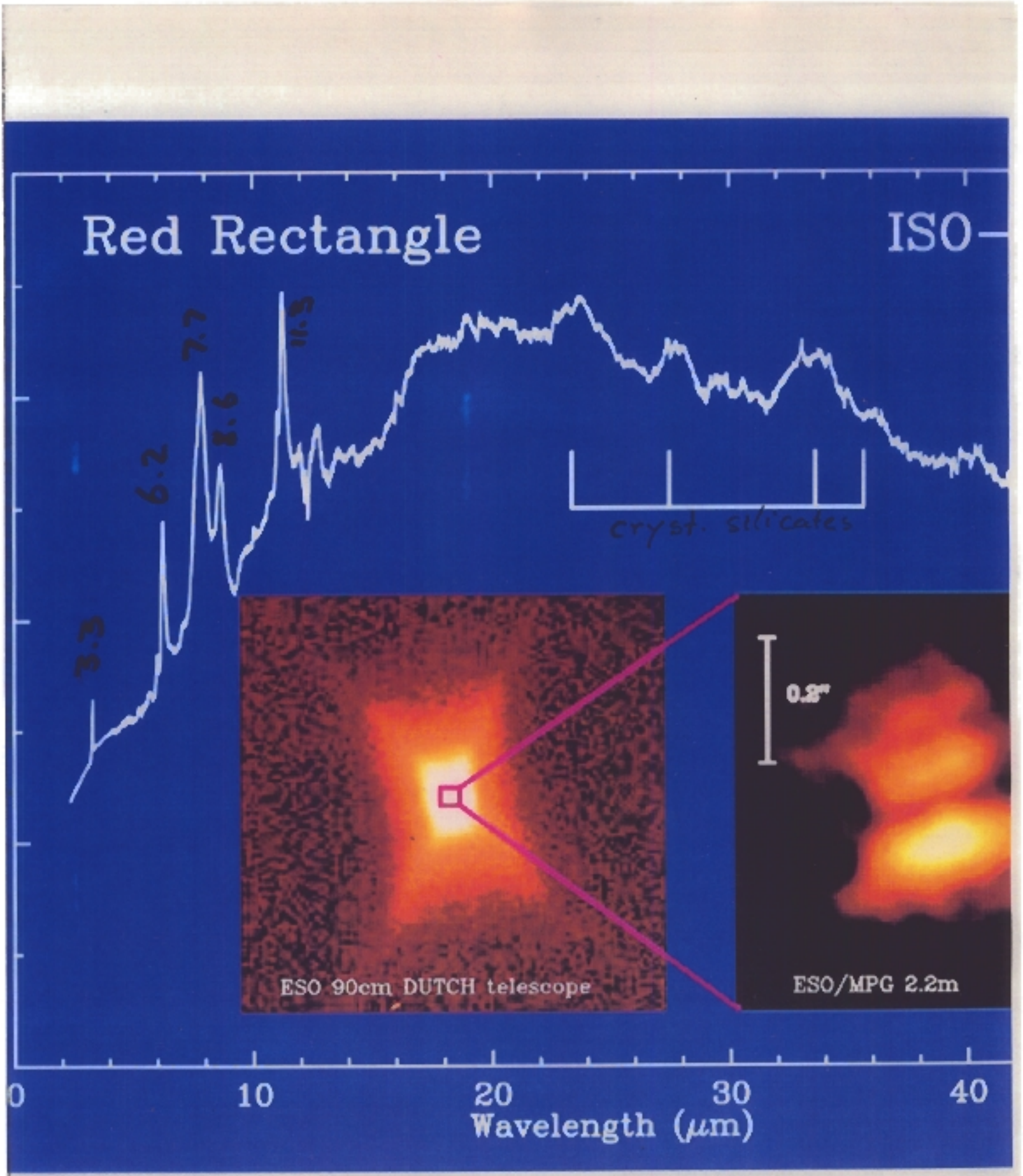

PL intensity (arb. units)
1.0
0.8
0.6
0.4
0.2
0.0
500
600
700
800
900
wavelength (nm)
(1)
(2)

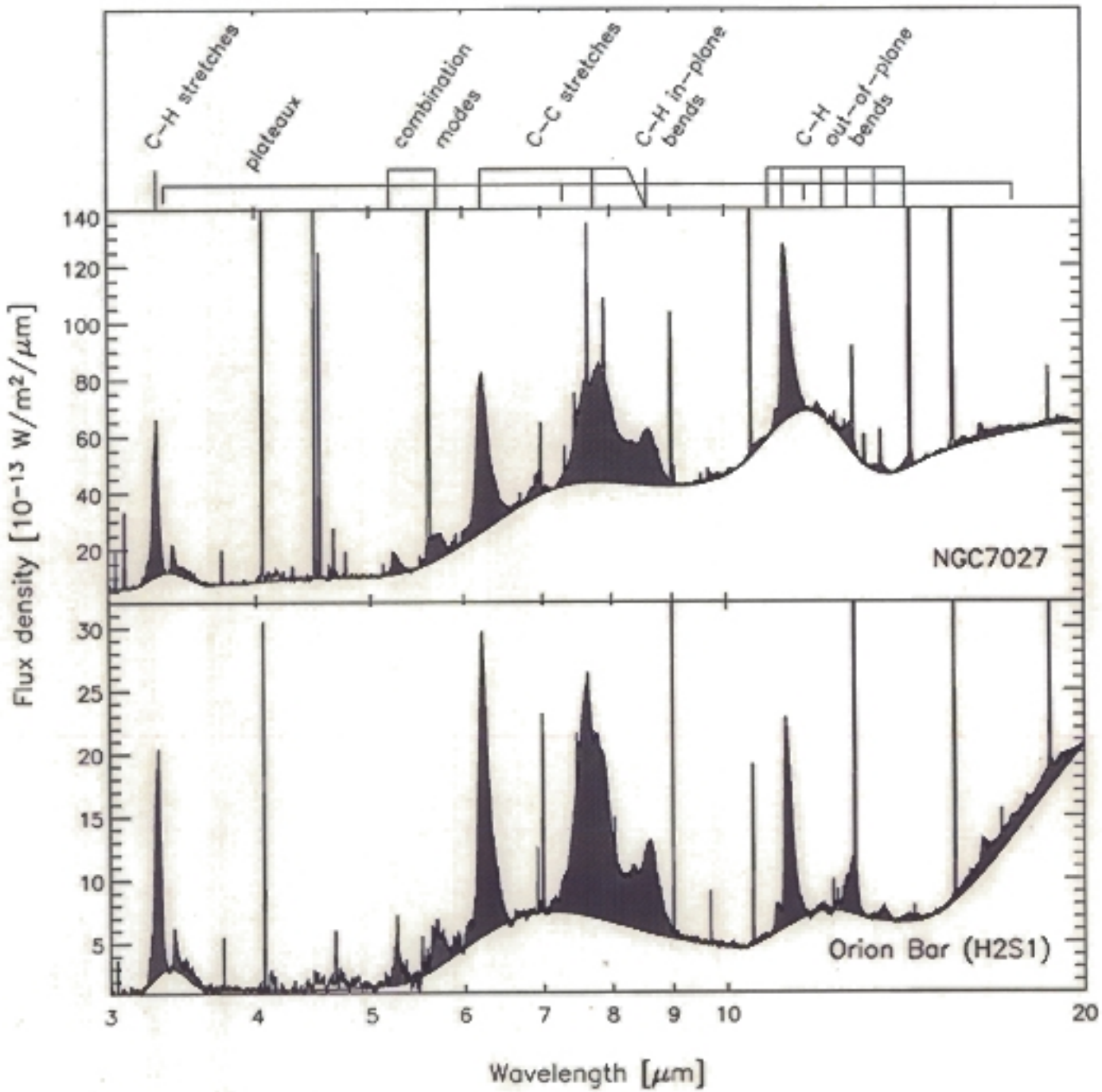

(a)
(b)
(c)
(d)
(e)
ERE intensity (arb. units)
500
600
700
800
900
wavelength (nm)

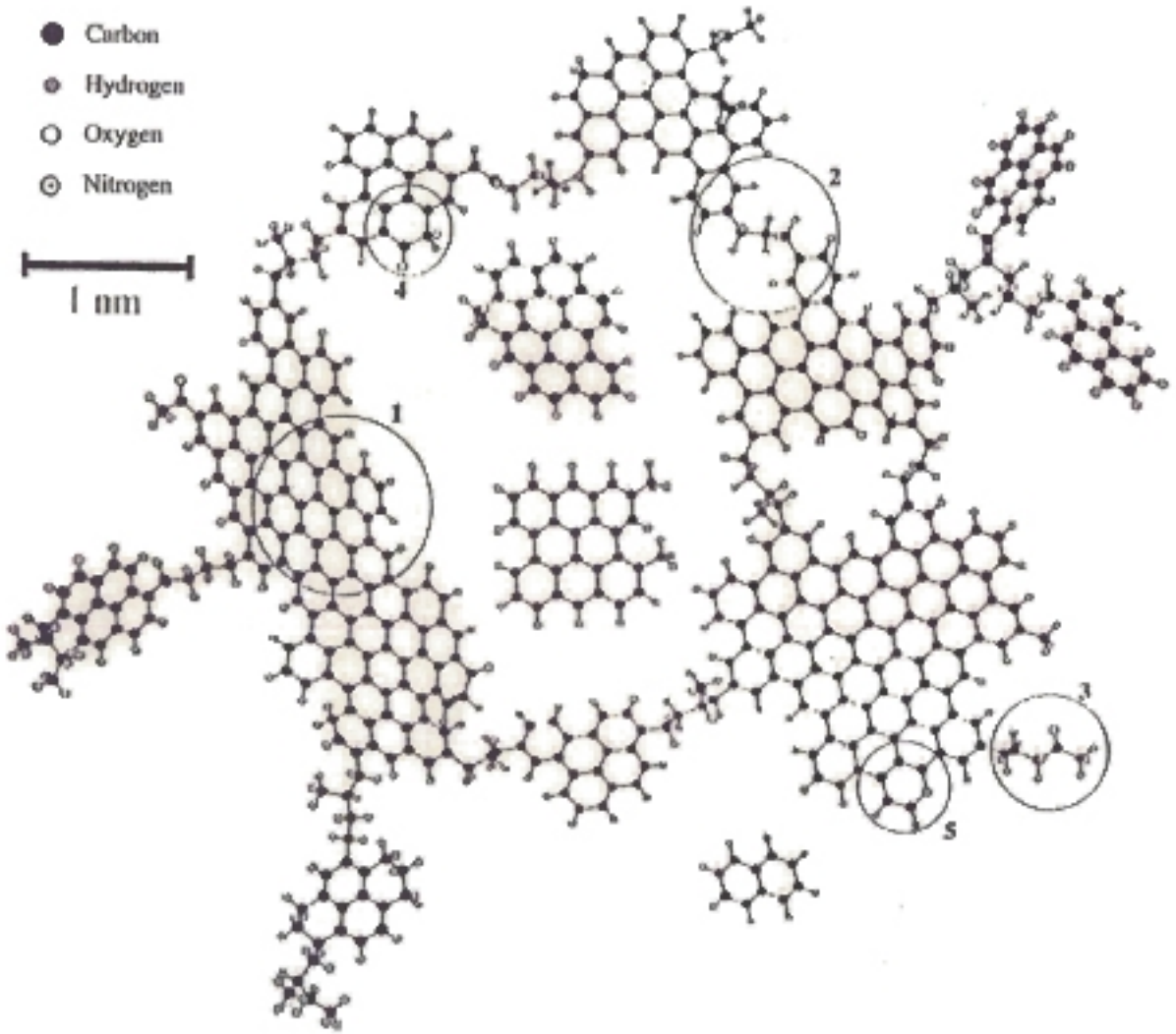

mean diameter of nc-Si (nm)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
distance from star (arcsec)

Conclusions

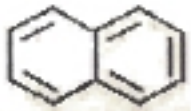
- ERE is a well-characterized property of dust existing in a wide range of astrophysical environments.
- The ERE carrier is a major component of interstellar dust and contributes ~20% of UV/opt. absorption.
- The identification of the ERE carrier remains a challenge for laboratory astrophysics and dust theory.


Red Rectangle
ISO
3.3
6.2
7.7
8.6
11.3
cryst. silicates
ESO 90cm DUTCH telescope
0.2"
ESO/MPG 2.2m
0
10
20
30
40
Wavelength (μm)

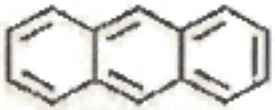

C–H stretches
plateaux
combination modes
C–C stretches
C–H in-plane bends
C–H out-of-plane bends
NGC7027
Orion Bar (H2S1)
Flux density [10⁻¹³ W/m²/μm]
Wavelength [μm]


Carbon
Hydrogen
Oxygen
Nitrogen
1 nm
1
2
3
4
5

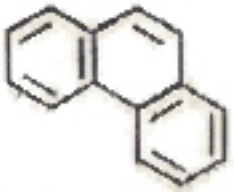
Catacondensed



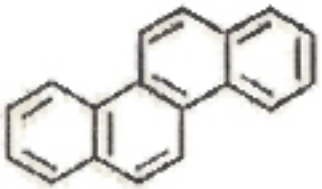
Naphthalene
$C_{10}H_8$



Anthracene
$C_{14}H_{10}$

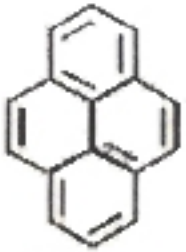


Phenanthrene
$C_{14}H_{10}$



Chrysene
$C_{18}H_{12}$

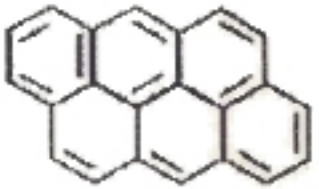
Pericondensed



Pyrene
$C_{16}H_{10}$

Coronene
$C_{24}H_{12}$

Perylene
$C_{20}H_{12}$



Antanthrene
$C_{22}H_{12}$

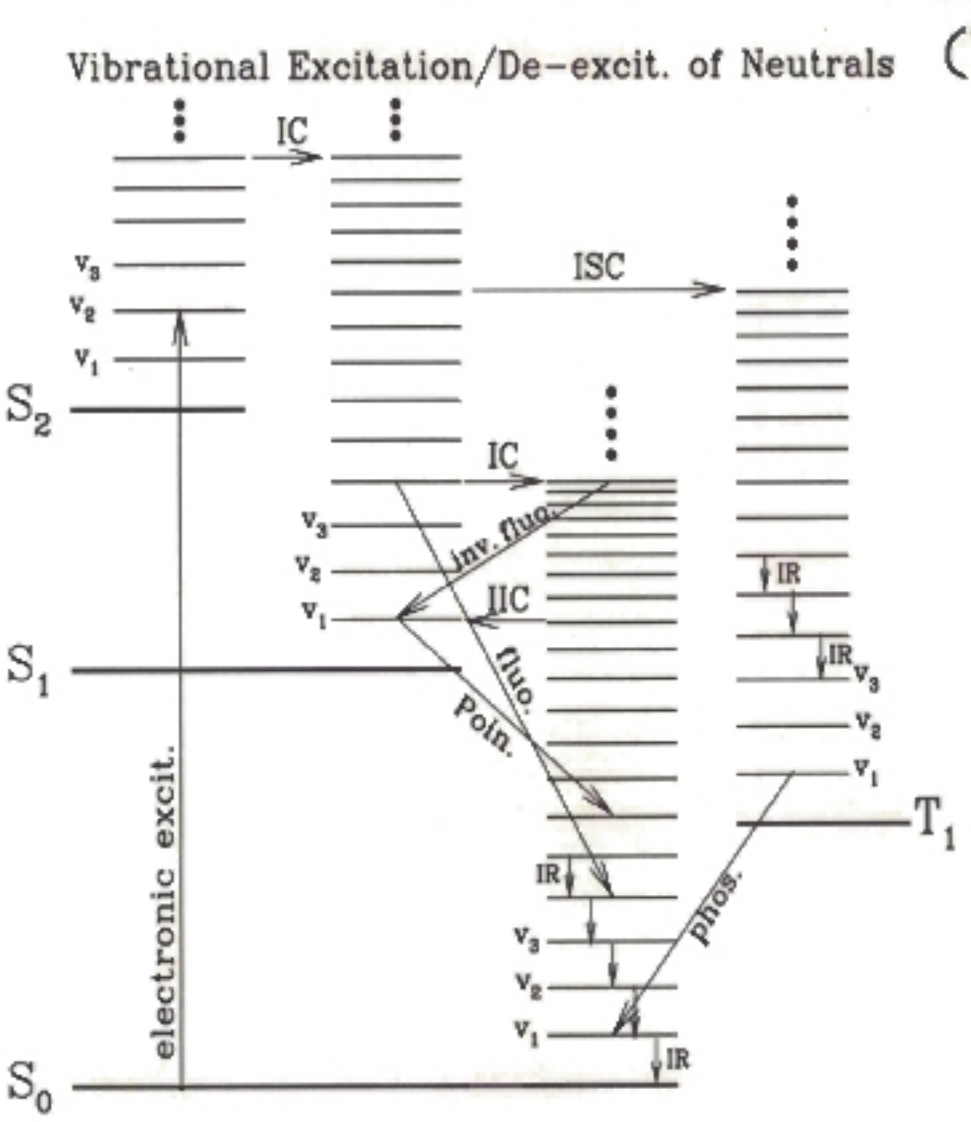
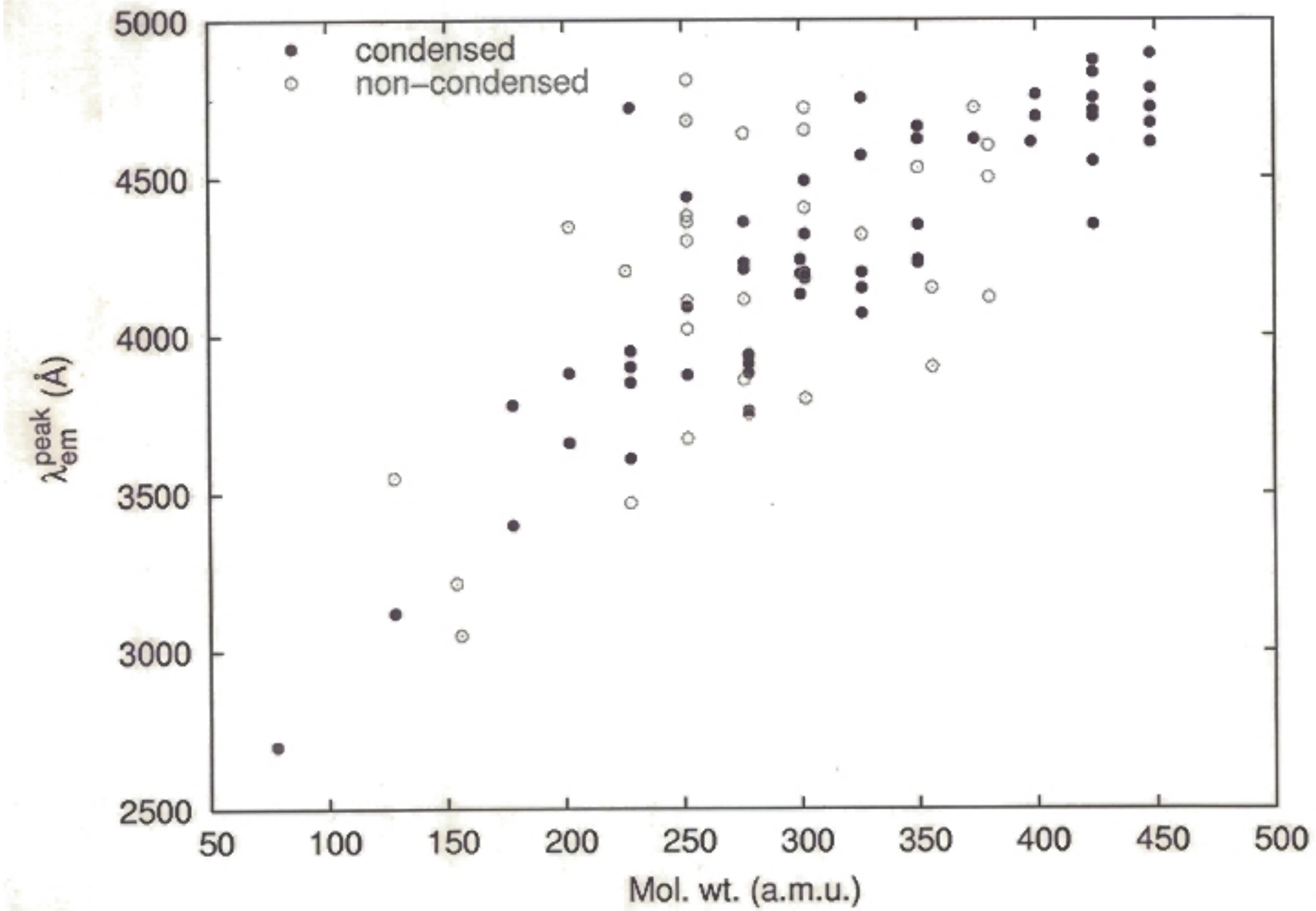
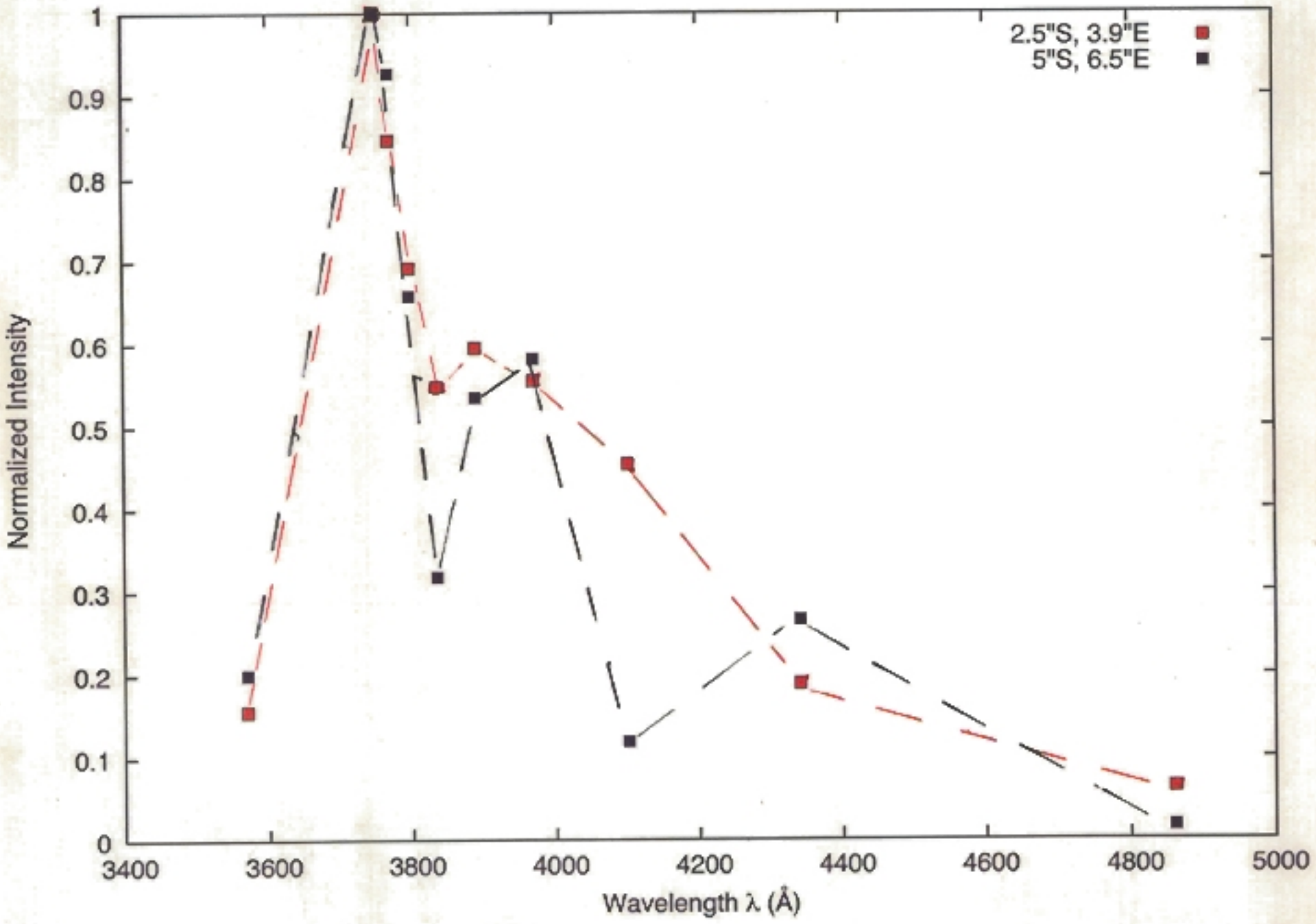


Figure 1. Step ladder model of a large neutral molecule. The schematic energy levels involve an electronic part (singlets S_0, S_1, S_2 ... and triplets T_1, T_2 ...) and a vibrational part (v_1, v_2, v_3...). Upon absorption of an UV/visible photon, the molecule makes an electronic transition from the ground state S_0 to an upper state S_n, followed by (1) radiationless internal vibrational redistribution, (2) radiationless electronic transitions (internal conversion [IC] and intersystem crossing [ISC]), (3) radiative electronic transitions (fluorescence and phosphorescence), (4) radiative inverse electronic transitions (inverse fluorescence, and Poincaré fluorescence resulted from the inverse internal conversion [IIC]), and (5) IR vibrational transitions.


condensed
non–condensed
5000
4500
4000
3500
3000
2500
50
100
150
200
250
300
350
400
450
500
λ_{em}^{peak} (Å)
Mol. wt. (a.m.u.)


2.5"S, 3.9"E
5"S, 6.5"E
Normalized Intensity
Wavelength λ (Å)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
3400
3600
3800
4000
4200
4400
4600
4800
5000

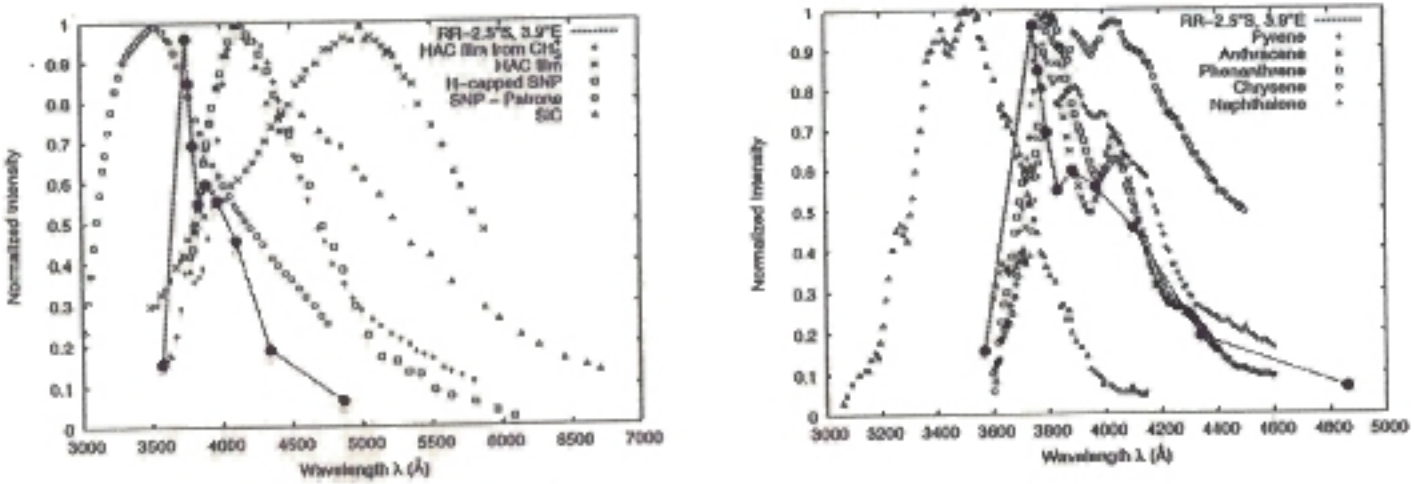
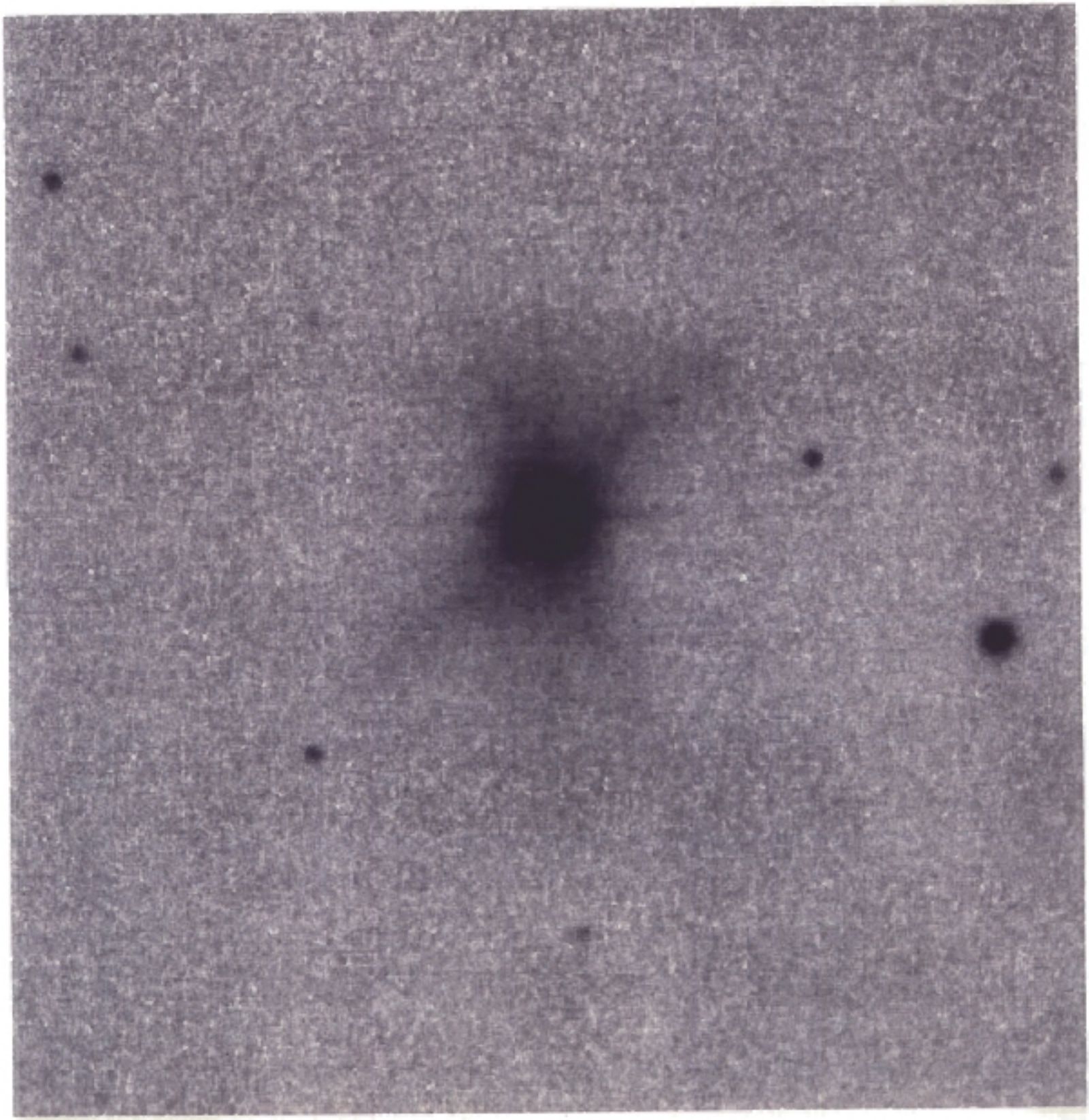


Fig. 4.— The UV/blue fluorescence spectra of the RR nebula compared to PAH and solid-state fluorescents. (a), comparison with some solid-state candidates and (b), comparison with small neutral PAHs. The intensities are normalized for easy comparison of the spectra with existing laboratory fluorescence spectra. The dashed lines representing the RR fluorescence spectrum are drawn to guide the eye (measurements exist only at specific wavelengths indicated by solid circles).

Red Rectangle at blue wavelengths, 380nm – 480nm
David Malin, AAT



 1999, MNRAS 303, 446

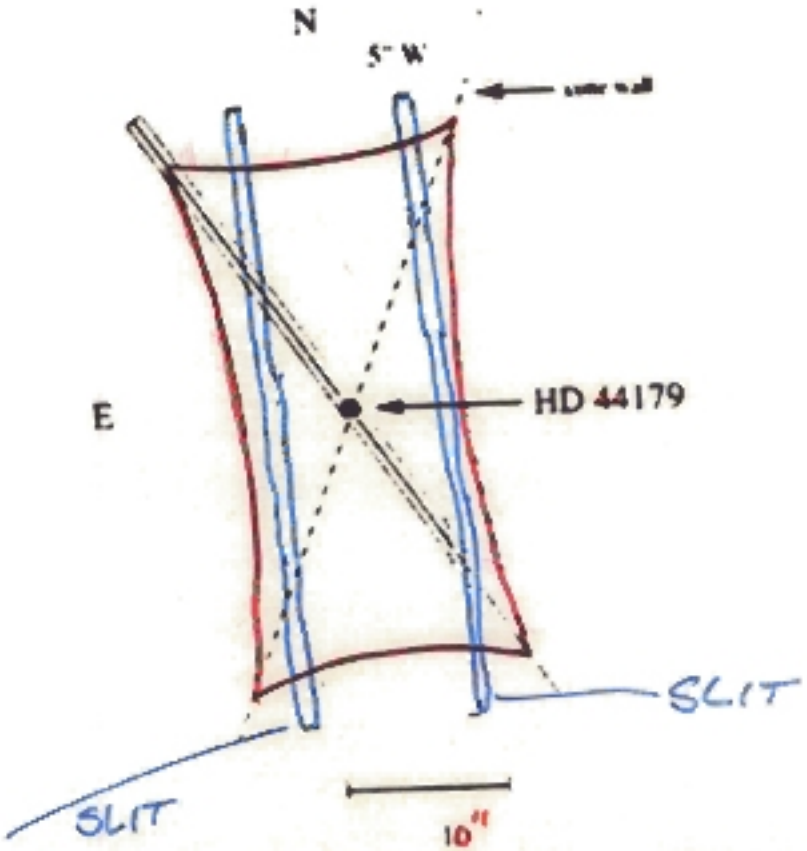


Figure 2. A sketch of the geometry of the Red Rectangle showing some of the adopted slit positions 5 arcsec east, 5 arcsec west (PA = 5°) and along the north-east–south-west whisker (PA = 43°). See Table 1 for full details of slit alignments.

KERR et al. 1999
MNRAS 303, 446

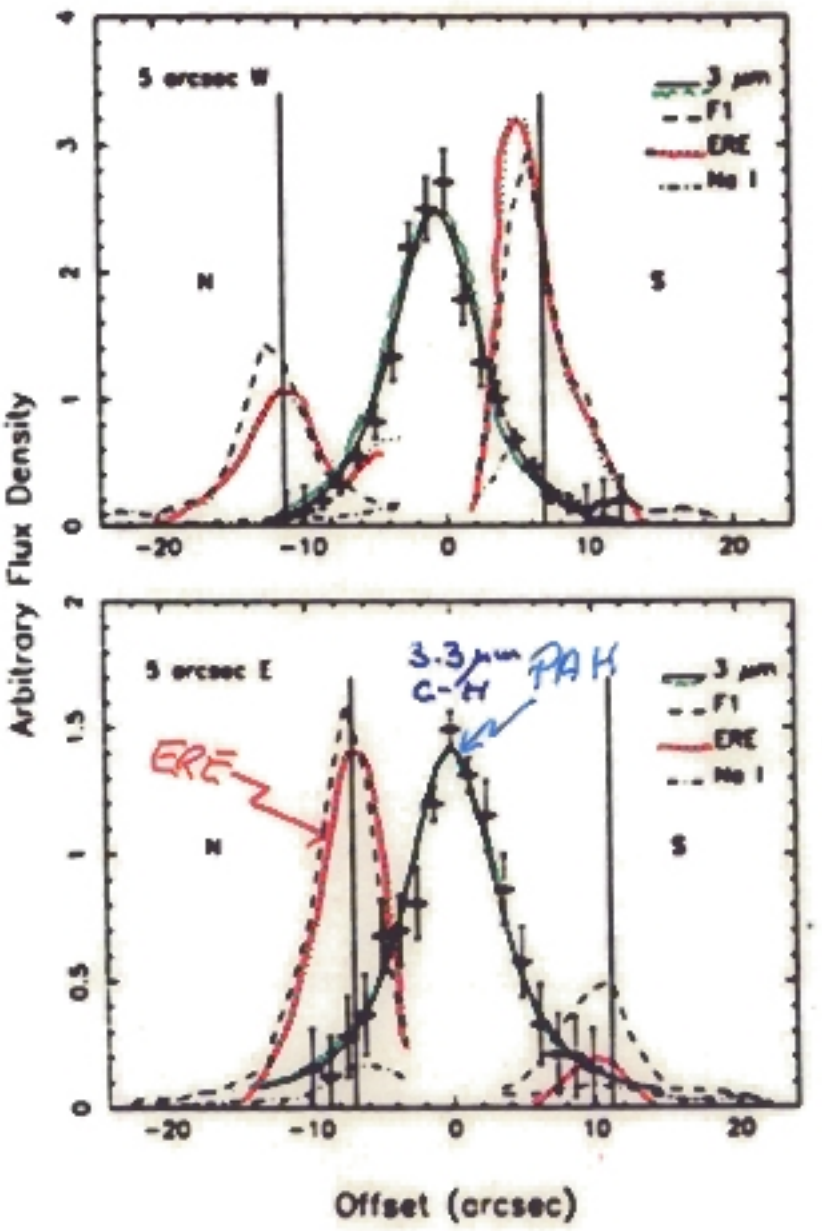
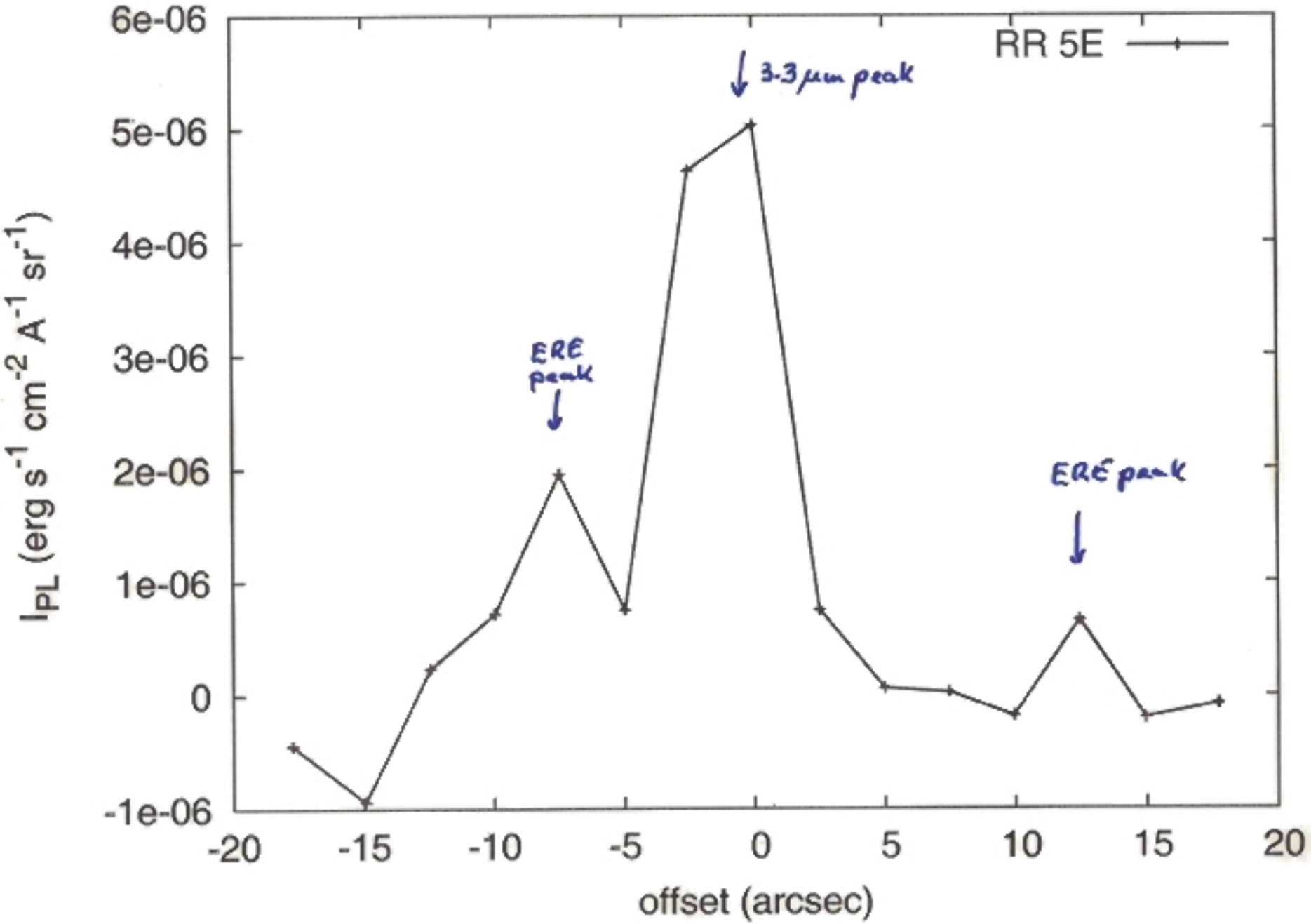


Figure 8. Comparison between the intensity distribution of the 3.3-μm band (this work) and the ERE, F1 (5800 Å) and Na I emission recorded by Schmidt & Witt (1991).


RR 5E
3.3 μm peak
ERE peak
ERE peak
6e-06
5e-06
4e-06
3e-06
2e-06
1e-06
0
-1e-06
-20
-15
-10
-5
0
5
10
15
20
offset (arcsec)
I_PL (erg s^-1 cm^-2 A^-1 sr^-1)

Conclusions: Blue Luminescence

- Blue luminescence (BL) detected in RR
- Peak ~ 378 nm; FWHM ~ 30 nm. (T* ~ 10,000 K)
- BL strongly correlated with UIR band emission.
- Spectral match with gas-phase fluorescence spectra of three- and four ringed condensed PAHs.
  - Ionization discontinuity of small PAHs in RR central star spectrum confirms presence of three- and four-ringed PAHs.
- BL does not match expectations for small SNP and HAC nanoparticles.

Summary

- Interstellar dust is the dominant form of solid matter in the Universe.
- About 35% of absorption cross section of interstellar dust is due to nanoparticles.
- Nanoparticles are the likely building blocks of larger composite dust particles.
- Photoluminescence of interstellar nanoparticles yields information on their sizes and composition:
- Extended Red Emission: Photoluminescence from semiconductor nanoparticles in quantum confinement regime. (Silicon nanoparticles)
- Blue Luminescence: Fluorescence from 3- and 4-ring PAHs.
- Study of interstellar nanoparticles provides opportunities for investigating interactions of nanoparticles with single photons under strong isolation conditions.

Principal Collaborators

Karl Gordon, Steward Observatory, Univ. of Areizona

Tracy Smith, SSI-Columbus

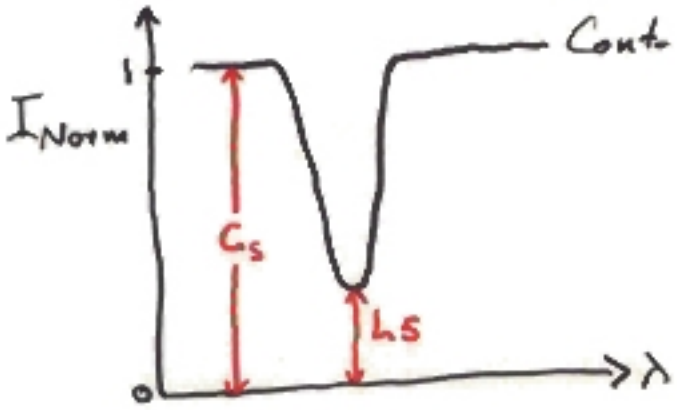
Uma Vijh, University of Toledo

Donald York, University of Chicago

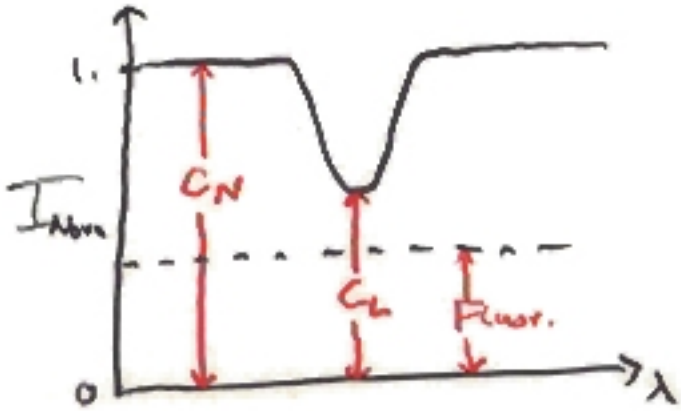
Line-Depth Technique for Detection of Blue Fluorescence

(applied to Reflection Nebulae)

Absorption line in Stellar Spectrum



Same line in Nebular Spectrum + Fluorescence



$$\frac{I^N_{Fluor}}{I^N_{cont}} = \frac{Fluor}{C_N - Fluor} = \frac{R_S}{R_N} - 1$$

where $R_S = \frac{C_S - L_S}{C_S}$; $R_N = \frac{C_N - L_N}{C_N}$