Circumstellar Medium II: Characterization from infrared and optical observations

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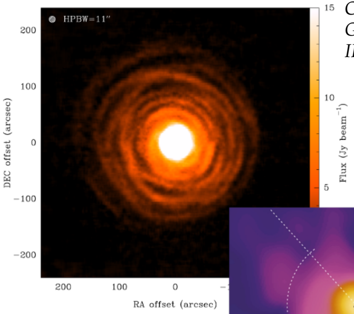
Outline

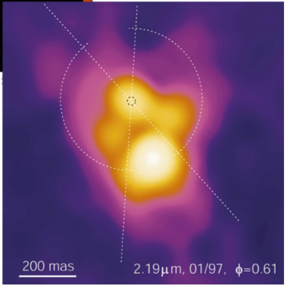
1. The circumstellar envelopes of evolved stars
   - Asymptotic Giant Branch (AGB) stars
   - (Proto-)Planetary Nebulae [(P)PNe]
   - The photodissociation region (PDR)
   - Why do we observe them in the IR and optical spectral ranges?
2. Infrared observations
   - Continuum emission
   - The dusty component of the CSEs
   - Molecular ro-vibrational spectra
   - Physical conditions
   - Gas kinematics derived from infrared spectra
   - Molecular abundances
   - Masing lines involving infrared pumping
3. Optical observations
   - Molecular electronic spectra

CSE of evolved stars[1]

- $P \simeq 100 - 2000$ days [2]
- $M_* \simeq 1 - 8\ \mathrm{M}_\odot$
- $R_* \sim 100 - 1000\ \mathrm{R}_\odot$ [1]
- $T_{\rm eff} \simeq 1500 - 3000$ K [3]
- High abundance of metals
- Formation of a circumstellar envelope (CSE) [4]:
  1. Matter ejection due to stellar pulsation,
  2. formation of dust ($r \sim 1 - 50\ \mathrm{R}_*$),
  3. radiation pressure over the dust grains,
  4. dust and gas acceleration ($v_\infty \simeq 5 - 30$ km s^{-1} [5, 3]).
- E.g.: IRC+10216, R Leo, IK Tau, Y CVn, VX Sgr, V Cyg, χ Cyg, W Aql,. . .



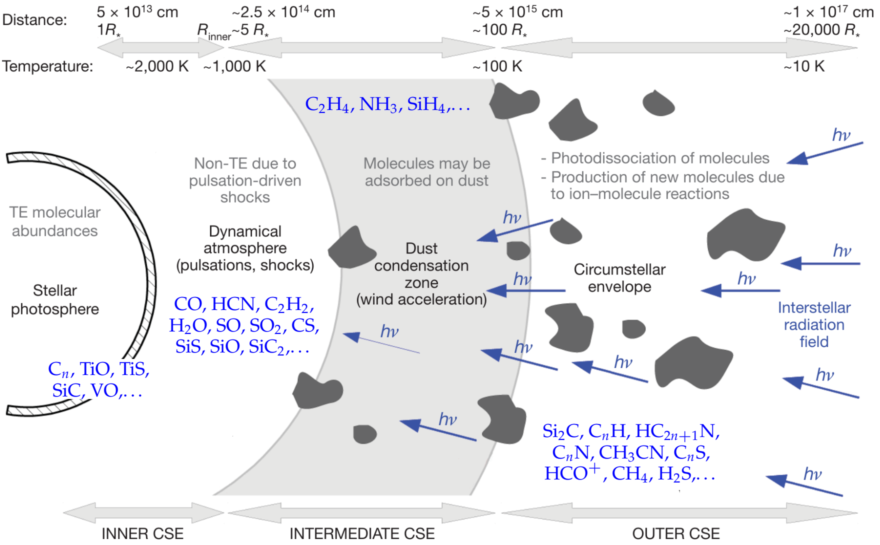
Observation of CO(2-1) at 230 GHz towards IRC+10216 [6]



Observation of the continuum at 2.19 μm with a spatial resolution ≃70−90 mas [7]

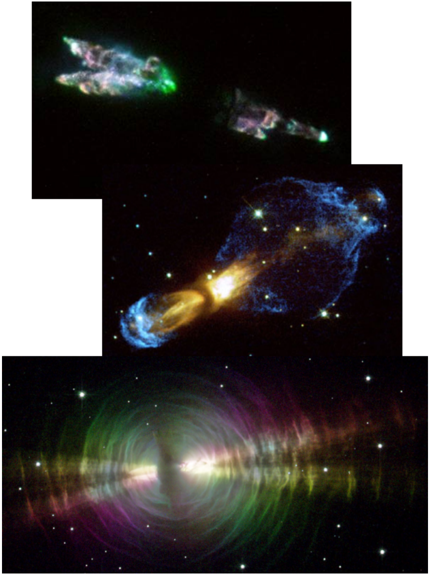
Images from IRC+10216, the archetypical C-rich AGB star

CSE of evolved stars[1] AGB stars

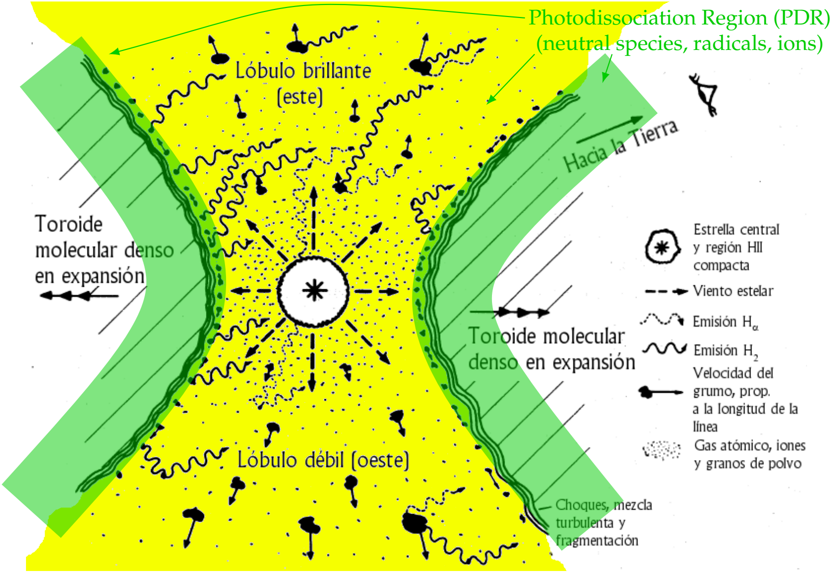


(Decin et al., 2010 [8])

- Next evolutive phase (transient) to the AGB stage.
- Most of the stellar envelope is ejected, unveiling the nucleus.
- $T_{\text{eff,nucleus}} \sim 10^4 - 10^5$ K.
- The UV radiatioin field emitted by the new white dwarf is quite strong.
- A new ultracompact HII region surrounds the central star.
- Eg.: CRL618, CRL2688, Calabash nebula

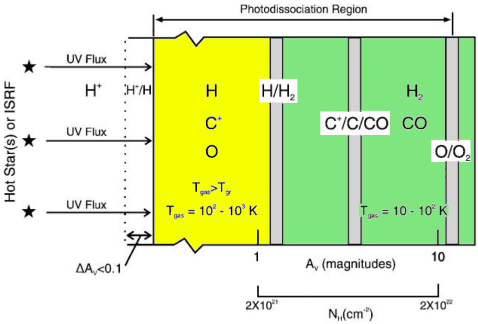


Images of CRL618, OH231.8+4.2, and CRL2688 (from top to bottom).

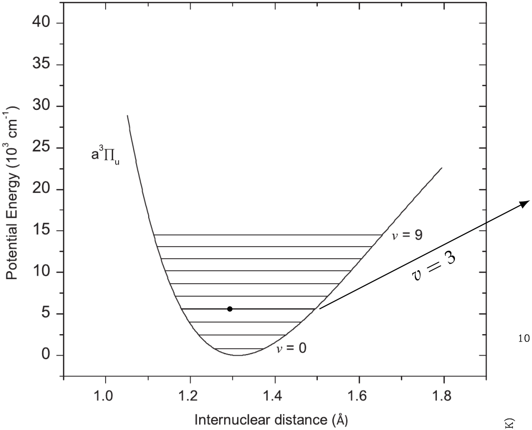


(Burton & Geballe, 1986 [9])

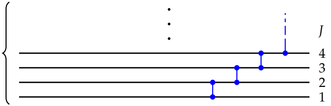
- Features:
  - $T_{K,gas} \sim 100 - 1000$ K,
  - $n_{gas} \sim 10^9 - 10^{13}$ m^{-3},
  - neutral gas with denser clumps prevail.
- Important reactions:
  - photoreactions,
  - reactions involving HI,
  - reactions involving vibrationally excited H_2,
  - endothermic reactions,
  - combustion (OI).
- Shielding is important (H_2, CO).
- HI, OI, OII, CI, CII,...
- H_2, H_3^+, C_nH, $C_{2n+1}N$, H_2O, OH, HCO^+, CH^+, H_3O^+, C_nH_2, $HC_{2n+1}N$, H_2CO,...

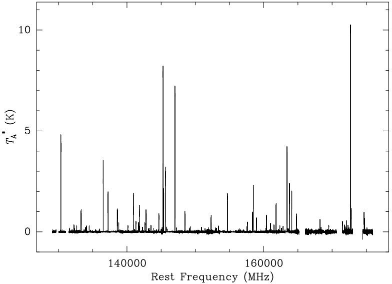


Structure of a photodissociation region (Hollenbach & Tielens, 1997 [10])



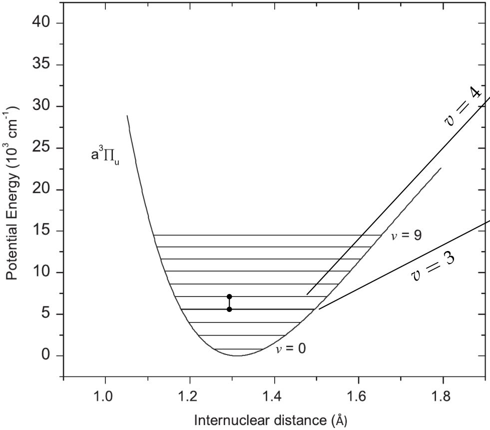
(Brooke et al., 2013 [11])

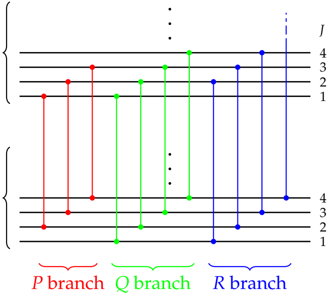




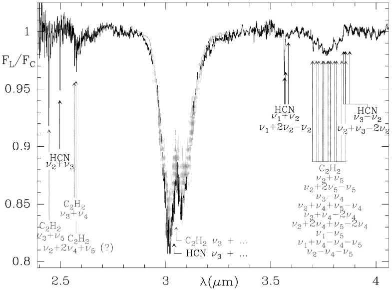
(Cernicharo et al., 2000 [12])

Why the optical and IR?



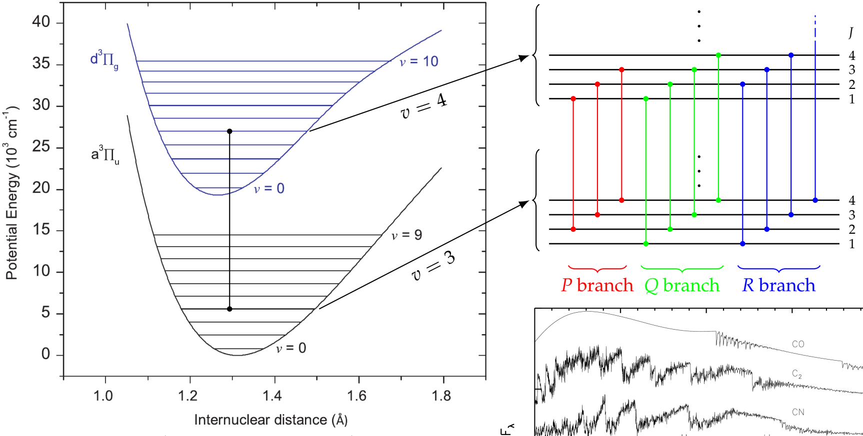


(Brooke et al., 2013 [11])

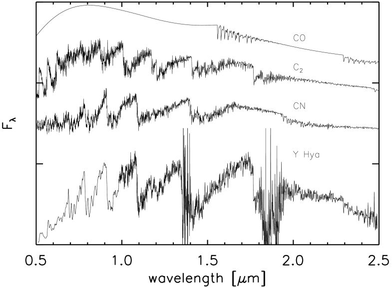


(Cernicharo et al., 1999 [13])

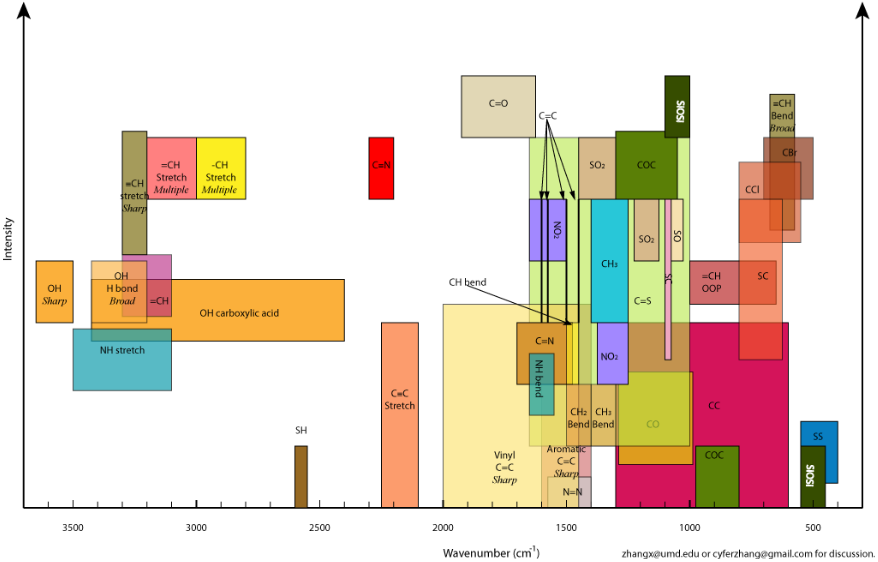
C_2 Swan system ($\lambda \simeq 5200$Å)

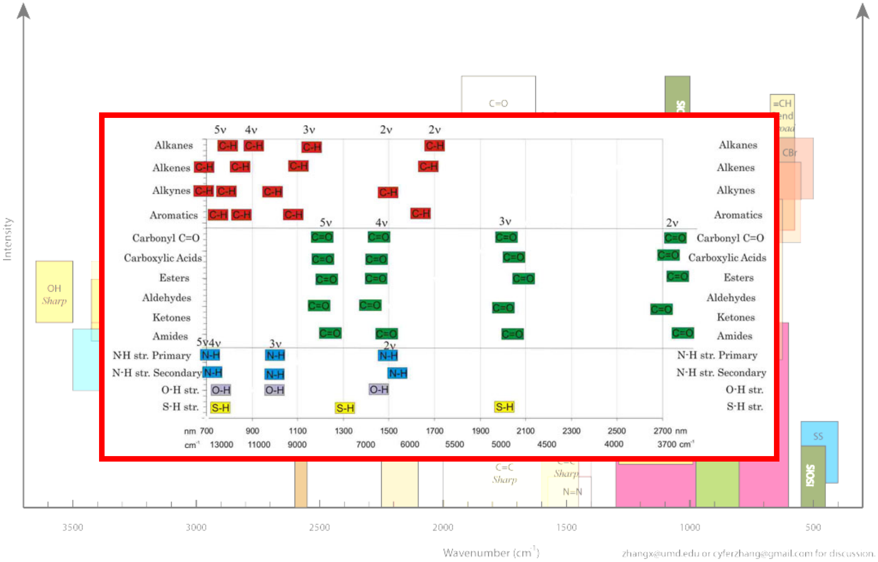


(Brooke et al., 2013 [11])



(Loidl et al., 2001 [14])


Intensity
OH
Sharp
=CH
stretch
Sharp
=CH
Stretch
Multiple
-CH
Stretch
Multiple
OH
H bond
Broad
=CH
OH carboxylic acid
NH stretch
SH
C≡N
C≡C
Stretch
C=O
C=C
CH bend
Vinyl
C=C
Sharp
NO2
C=N
NH bend
Aromatic
C=C
Sharp
N=N
SO2
COC
SiOSi
CH3
SO2
SO
SS
C=S
NO2
CH2
Bend
CH3
Bend
CO
CC
COC
=CH
OOP
SC
CCl
CBr
=CH
Bend
Broad
SS
SiOSi
3500
3000
2500
2000
1500
1000
500
Wavenumber (cm-1)
zhangx@umd.edu or cyferzhang@gmail.com for discussion.



Alkanes
Alkenes
Alkynes
Aromatics
Carbonyl C=O
Carboxylic Acids
Esters
Aldehydes
Ketones
Amides
N-H str. Primary
N-H str. Secondary
O-H str.
S-H str.
5v 4v 3v 2v
C-H
C=O
N-H
O-H
S-H
nm 700 900 1100 1300 1500 1700 1900 2100 2300 2500 2700 nm
cm-1 13000 11000 9000 7000 6000 5500 5000 4500 4000 3700 cm-1
Intensity
OH Sharp
C=O
C=C Sharp
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SS
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Wavenumber (cm-1)
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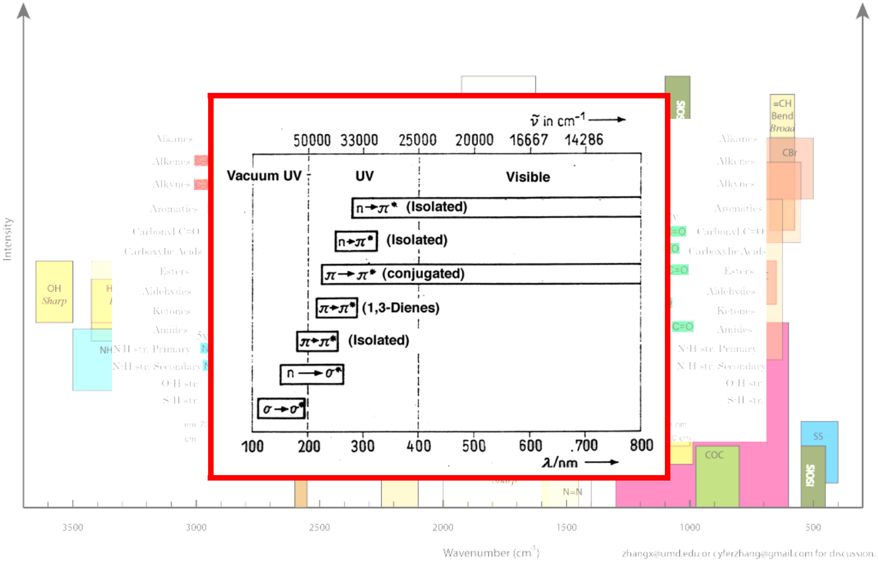
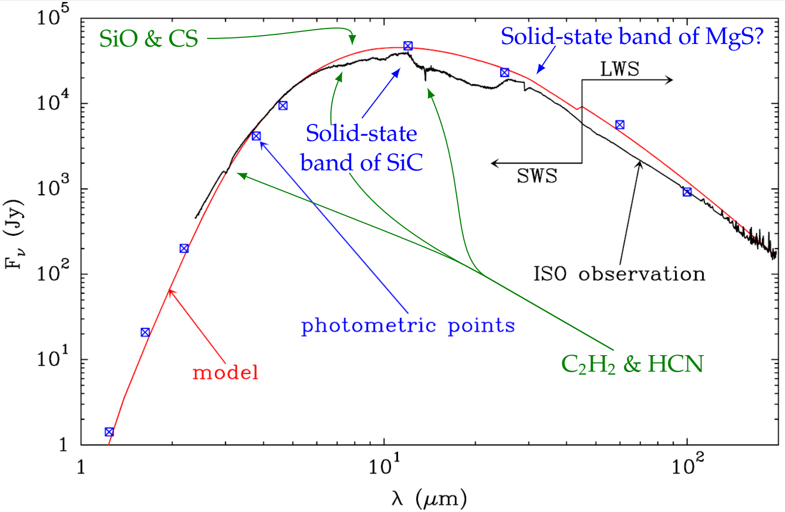
Why the optical and IR?

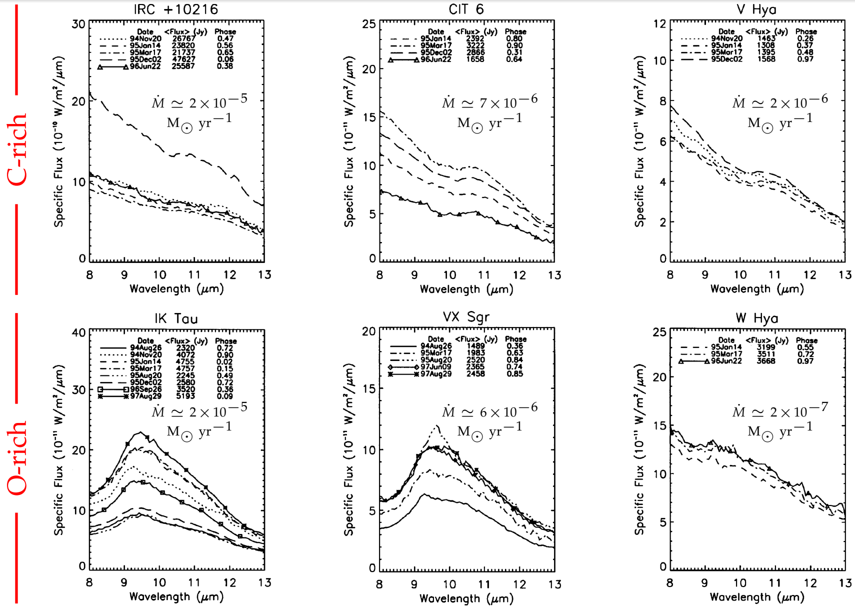




(Cernicharo et al., 1999 [13]; Agúndez et al., 2012 [15])

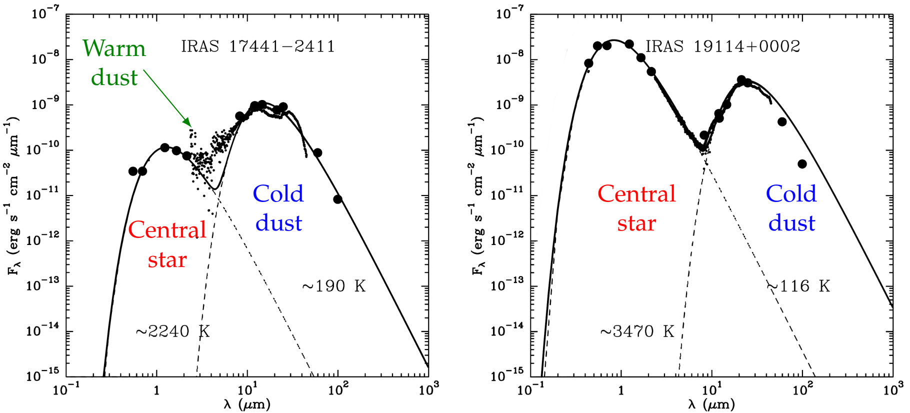
For an optically thin envelope $\Longrightarrow T_d(r) \propto r^{-2/(4+p)}, \quad \sigma_d^{abs}(\lambda) \propto \frac{\tilde{Q}_{abs}(\lambda)}{\lambda^p}$

Infrared observations Continuum emission: AGBs



(Monnier et al., 1998 [2]; Loup et al., 1993 [16]; Bujarrabal et al., 1994 [5]; Ramstedt et al., 2014 [3])

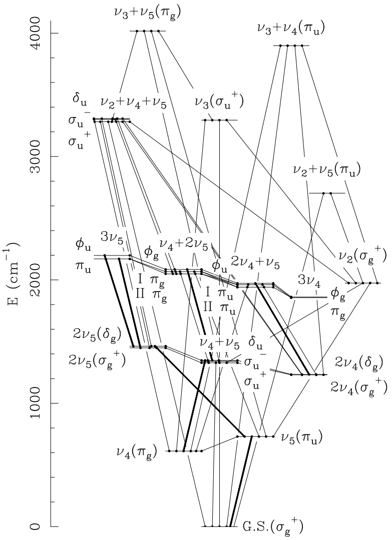
Continuum emission: PPNe



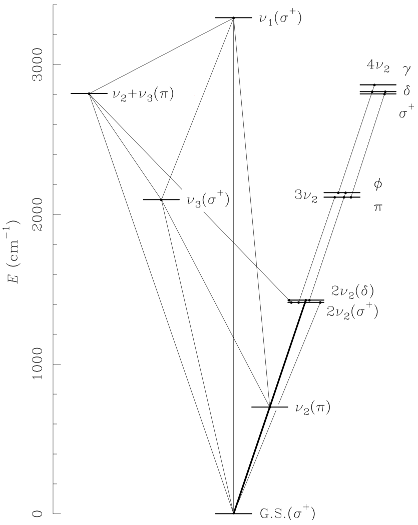
(Sánchez-Contreras et al., 2008 [17])

Observations of two PPNe composed of data from GSC2, 2MASS, MSX, IRAS, and ISO. The dashed curve is the fit to the observed data while the solid curve is the emission corrected from interstellar extinction. The continuum is composed of two contributions with different temperatures: the central star and the cold dust component.

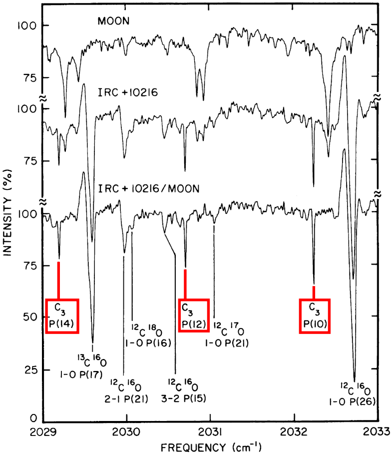
C_2H_2



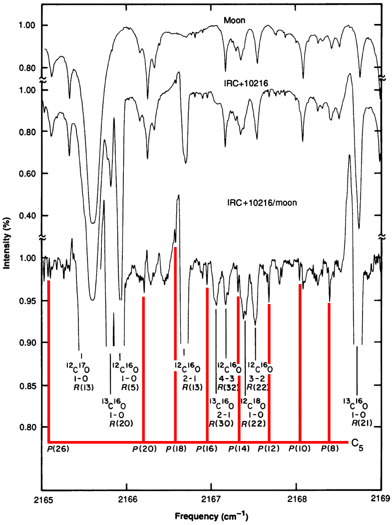
HCN



(Fonfría et al., 2008 [18])

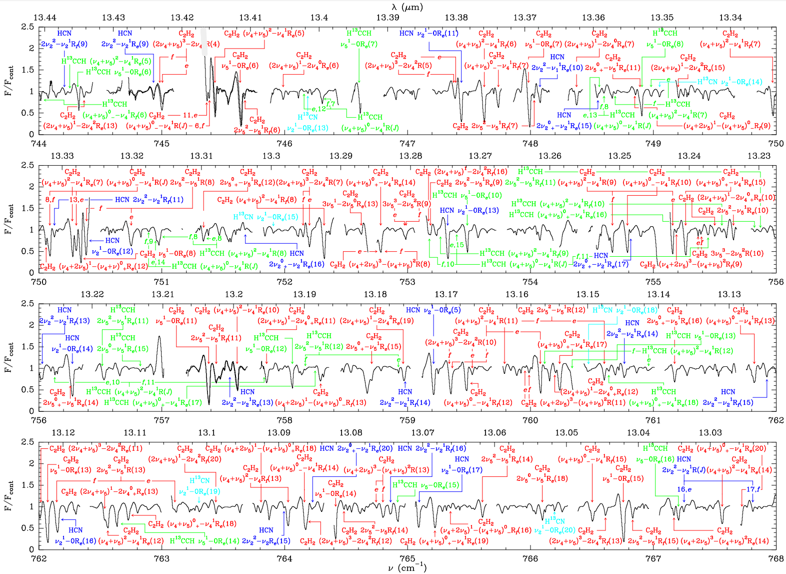


(Hinkle et al., 1988 [19])

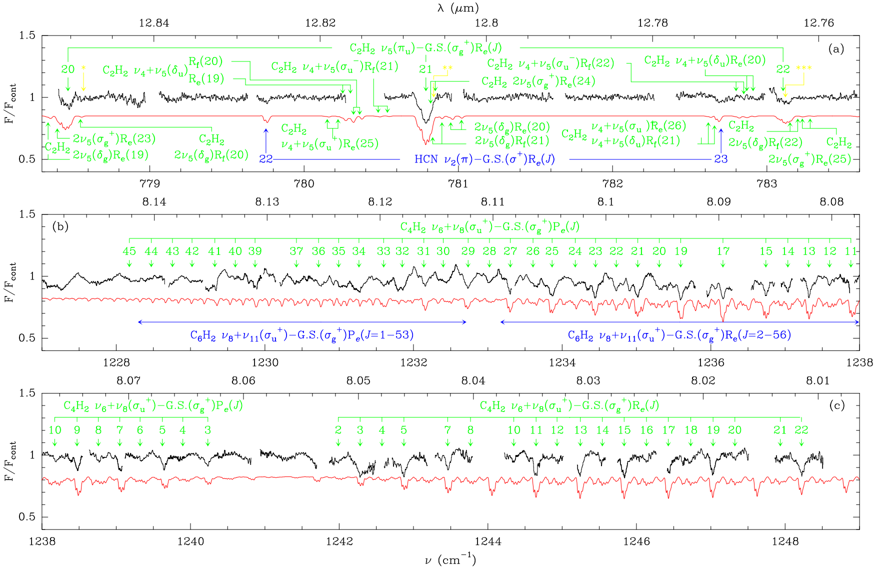


(Bernath et al., 1989 [20])

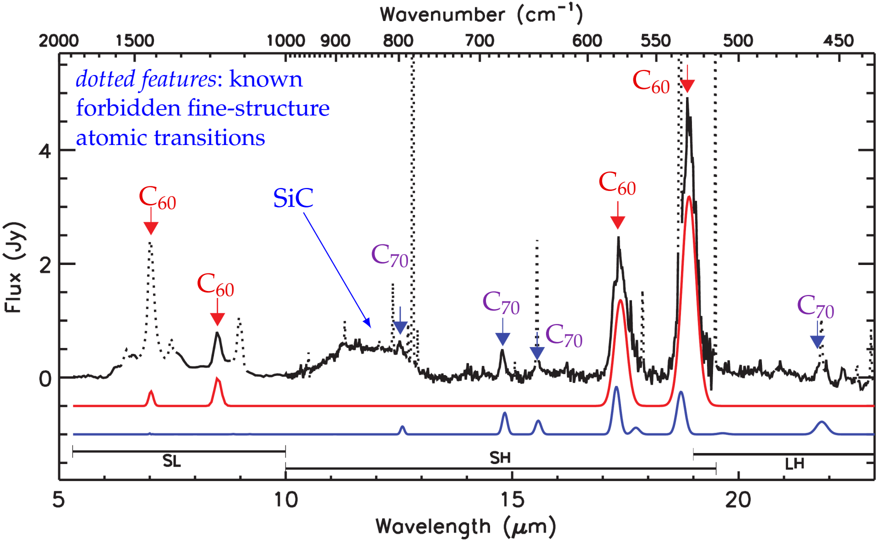
Infrared observations — Ro-vibrational spectra



(Fonfría et al., 2008 [18])



(Fonfría et al., 2011 [21])



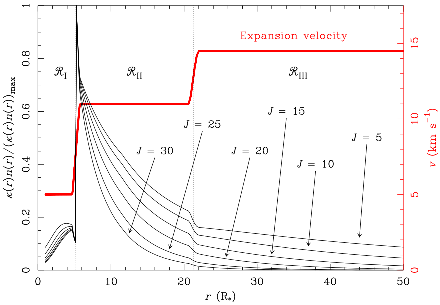
(Cami et al., 2010 [22])

- The opacity of each line depends on the excitation temperature

$$k_\nu \propto e^{-E_{\rm low}/k_{\rm B}T_{\rm exc}}\left(1-e^{-h\nu/k_{\rm B}T_{\rm exc}}\right)$$

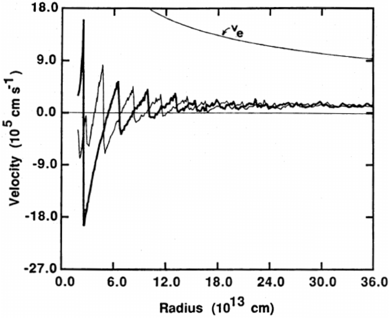
- Usually the opacity decreases with J mostly due to the Boltzmann factor:

$$e^{-E_{\rm low}/k_{\rm B}T_{\rm exc}} \simeq e^{-h\nu_i/k_{\rm B}T_{\rm exc}} \times e^{-hB_iJ(J+1)/k_{\rm B}T_{\rm exc}}$$



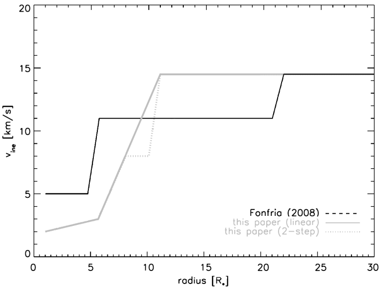
(Fonfría et al., 2008 [18])

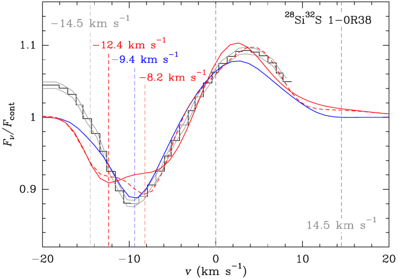
- The high excitation lines trace the inner layers of the CSE, where the excitation temperature is higher
- The low excitation lines mostly trace the middle and outer layers of the CSE
- The large number of ro-vibrational lines in a small spectral range allows us to analyze the whole CSE at the same time



(Bowen, 1988 [4])

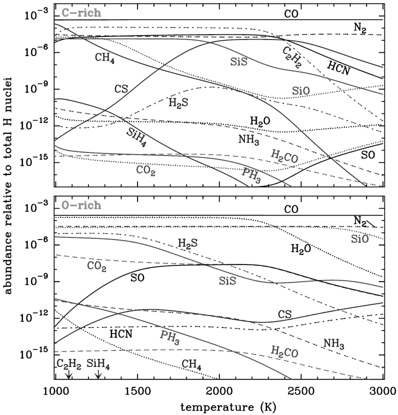
- The emission/absorption components of the line profiles are coupled to the gas expansion velocity field due to the Doppler effect
- We can derive this field with a good fit to the observed lines





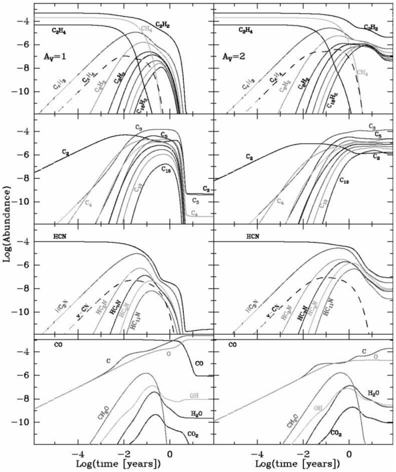
(Decin et al., 2015 [23]; Fonfría et al., 2015 [24])

Chemistry under TE



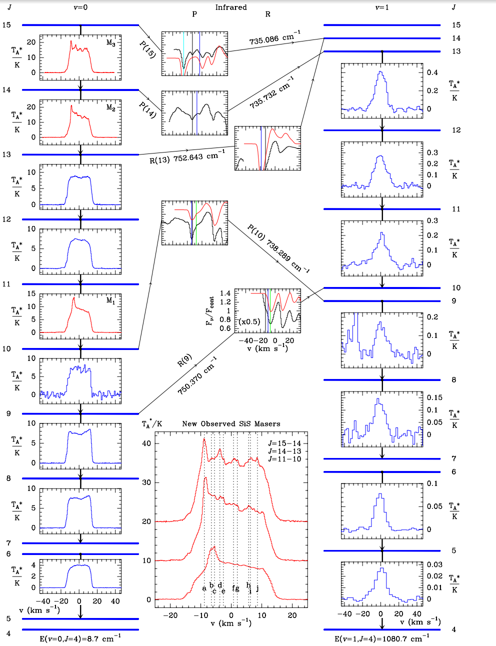
(Agúndez et al., 2010 [25])

Chemistry with UV radiation field



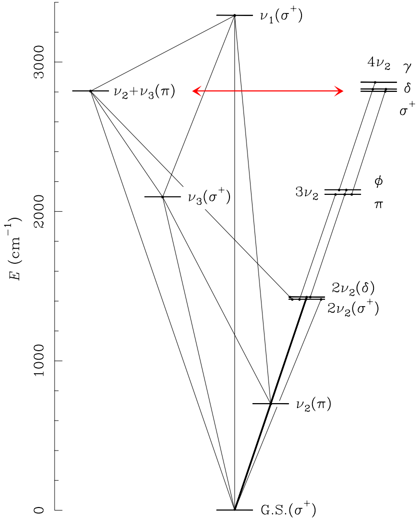
(Cernicharo et al., 2004 [26])

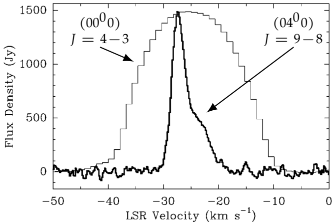
- Blendings between ro-vibrational lines of different molecules can produce masers in the mm range
  1. The exciting lines pump molecules of the ground vibrational state to rotational levels of an excited vibrational state
  2. These molecules decay to the ground vibrational state modifying the populations of the rotational levels
- If the exciting lines are strong enough, the population inversion happens
- Typical mechanism to explain the SiO and SiS masers

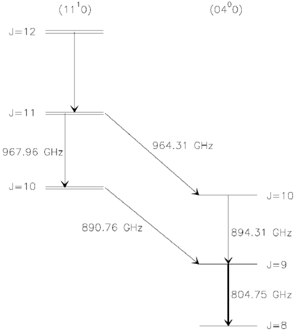


(Fonfría et al., 2006 [27])

Masers: resonances

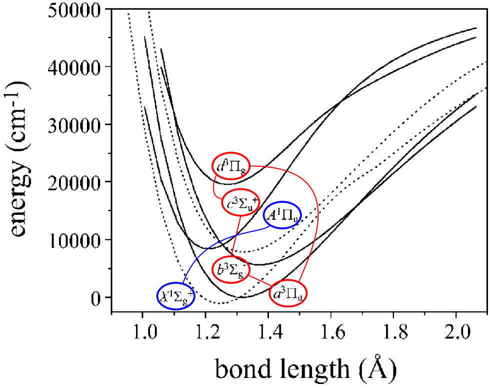






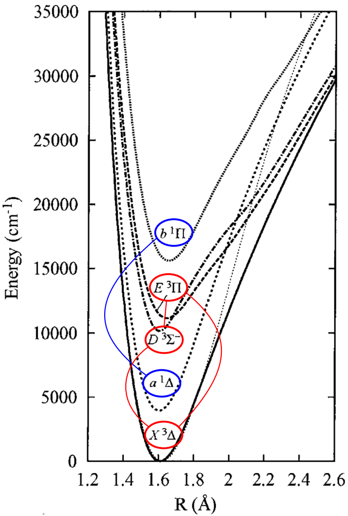
(Schilke et al., 2000 [28]; Schilke et al., 2003 [29])

C$_2$



(Kokkin et al., 2007 [30])

TiO



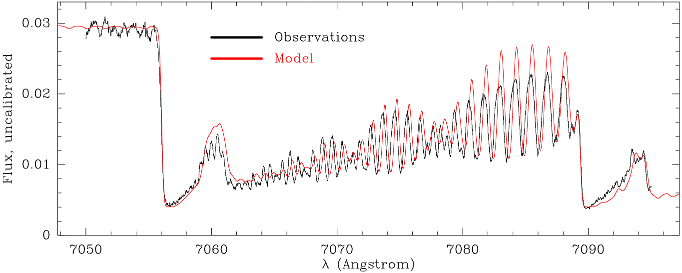
(Kobayashi et al., 2002 [31])

Allowed transitions if:

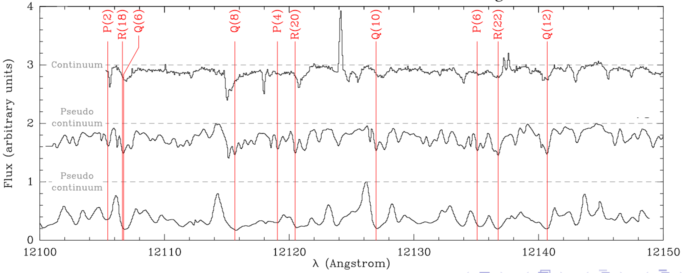
- There is no spin change
- $g \longleftrightarrow g$, $u \longleftrightarrow u$, $g \not\longleftrightarrow u$

Band strength decreases as $\Delta\Lambda$ increases

TiO $A^3\Phi_r - X^3\Delta_r$ system



C_2 Phillips system $(A^1\Pi_u - X^1\Sigma_g^+)$



References

[1] Vassiliadis & Wood, 1993, *ApJ*, 413, 641

[2] Monnier et al., 1998, *ApJ*, 502, 833

[3] Ramstedt & Olofsson, 2014, *A&A*, 566, A145

[4] Bowen, 1988, *ApJ*, 329, 299

[5] Bujarrabal et al., 1994, *A&A*, 285, 247

[6] Cernicharo et al., 2015, *A&A*, 575, A91

[7] Weigelt et al., 2002, *A&A*, 392, 131

[8] Decin et al., 2010, *A&A*, 518, L143

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[10] Hollenbach & Tielens, 1997, *An. Rev. Astron. Astroph.*, 35, 179

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[13] Cernicharo et al., 1999, *ApJ*, 526, L41

[14] Loidl et al., 2001, *A&A*, 371, 1065

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[16] Loup et al., 1993, *A&A Suppl. Series*, 99, 291

[17] Sánchez-Contreras et al., 2008, *ApJ Suppl. Series*, 179, 166

[18] Fonfría et al., 2008, *ApJ*, 673, 445

[19] Hinkle et al., 1988, *Science*, 241, 1319

[20] Bernath et al., 1989, *Science*, 244, 562

[21] Fonfría et al., 2011, *ApJ*, 728, 43

[22] Cami et al., 2010, *Science*, 329, 1180

[23] Decin et al., 2015, *A&A*, 574, A5

[24] Fonfría et al., 2015, *MNRAS*, 453, 439

[25] Agúndez et al., 2010, *ApJ*, 724, L133

[26] Cernicharo, 2004, *ApJ*, 608, L41

[27] Fonfría et al., 2006, *ApJ*, 646, L127

[28] Schilke et al., 2000, *ApJ*, 528, L37

[29] Schilke & Menten, 2003, *ApJ*, 583, 446

[30] Kokkin et al., 2007, *J. Chem. Phys.*, 126, 084302

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