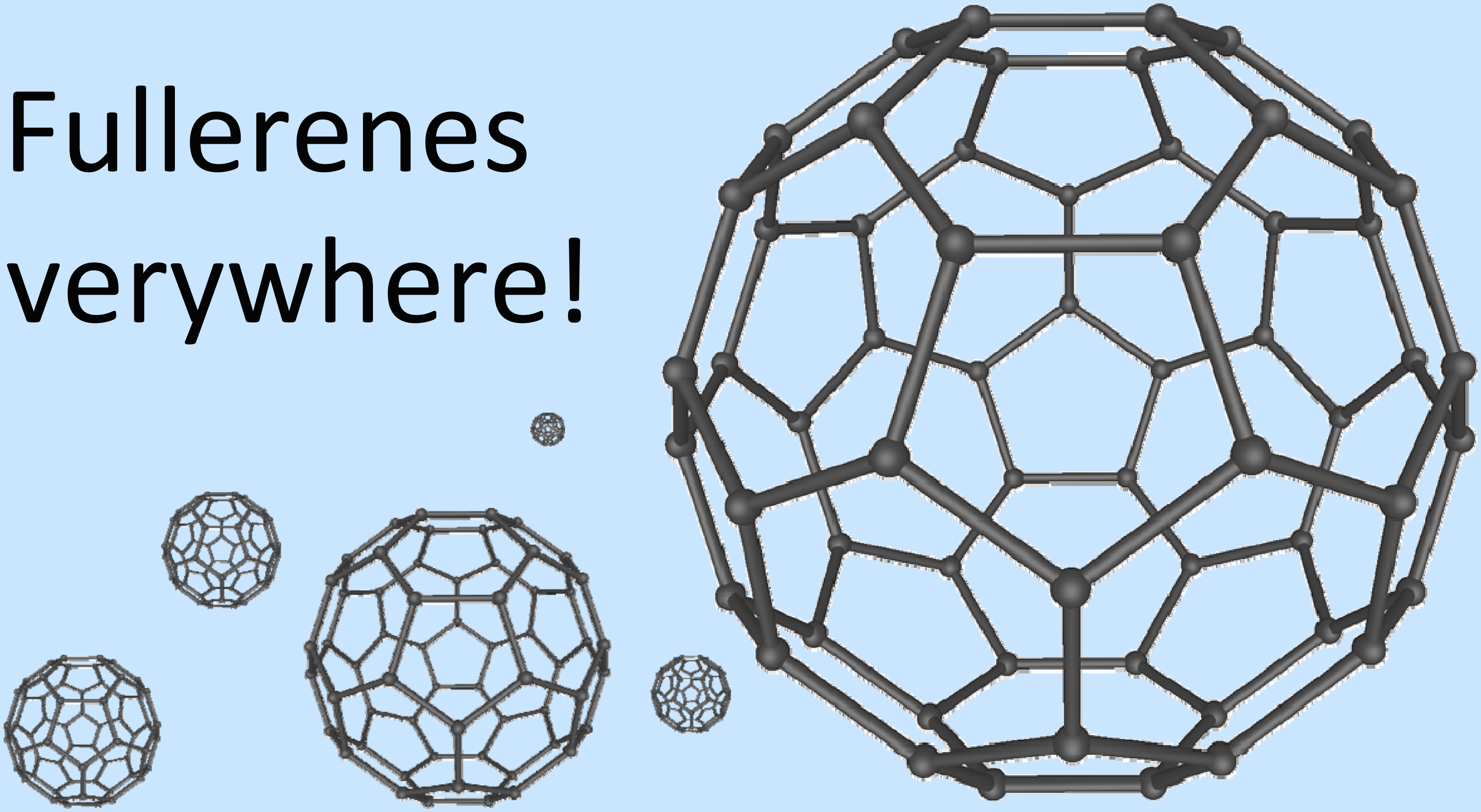
Fullerenes everywhere!



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Outline

- Knowing fullerene: a brief history
- Fullerene and other carbon compounds in space
- fullerene in stars
  - The first detection: planetary nebula Tc1, a hydrogen-poor environment?
  - Spitzer spectra of four fullerene-containing planetary nebulae
  - The first detection of fullerene in an extragalactic star, and the C_{60} mass estimate
  - Discussion, possible evolutionary paths

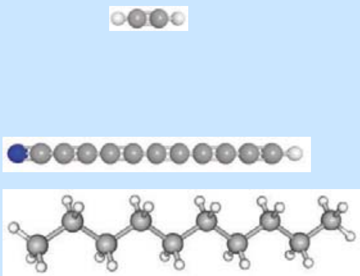
PN: planetary nebula CRD: carbon-rich dust ORD: oxygen-rich dust MCD: mixed-chemistry dust (amorphous: aliphatic)
PAH: polycyclic aromatic hydrocarbons HAC: hydrogenated amorphous carbon

Fullerenes: a brief history

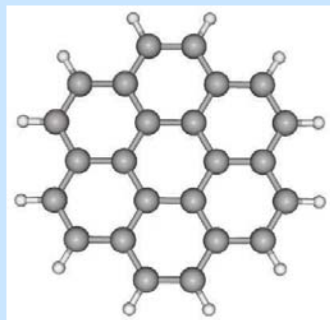
- The most common fullerene is C_{60} (buckyball), a cage-like carbon molecules of 60 atoms, spherical, very important in medicine and solid state science for their special shape, solidity, and inner vacuum, of the approximate size of a DNA step
- Fullerenes have been predicted since the 70s (Osawa+ 1970)
- Sept 1985: C_{60} created in laboratory, named Buckminsterfullerene (for famous dome architect), Kroto+ 1985 (Nobel prize, 1996)
- 1992: fullerene found on Earth in carbon-rich shungite (Buseck+)
- 2003: fullerene in meteorites (Harris+)
- 2009: possible fullerene signature in ISM (C_{60}+ bands), Misawa+
- 2010: possible fullerenes in reflection nebula NGC 7023, Sellgreen+
- 2010: C_{60}, C_{70} in Tc1 (Galactic PN), Cami et al., first firm detection of C_{60} in space
- 2010: C_{60}, C_{70} in 3 additional Galactic and an SMC PN (García-Hernandez+), first extragalactic detection
- Fullerene was searched for (but not found) in C-rich AGB and post-AGB stars, and in RCrB stars

carbon in space

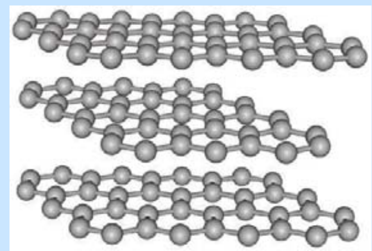
Eherenfreund & Foing 2010



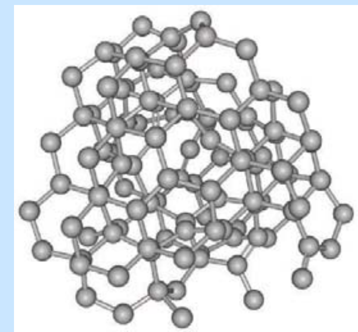
Carbon chains
ubiquitous



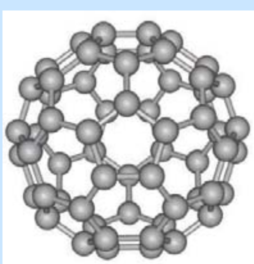
Polycyclic Aromatic Hydrocarbons (PAH)
ubiquitous



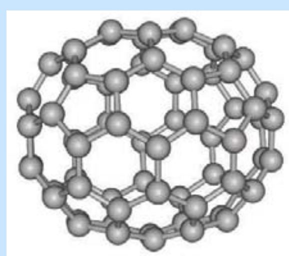
Graphite
meteorites



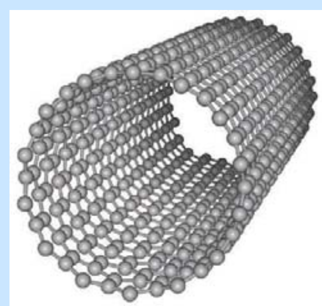
Amorphous Carbon
most of ISM/CSM carbon dust



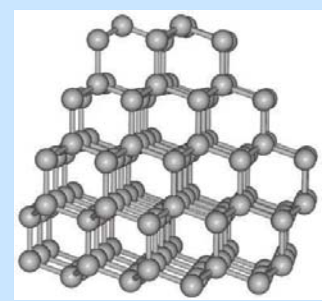
C_{60}
planetary nebulae



C_{70}
planetary nebulae



Carbon nanotubes
not observed



Nanodiamond
meteorites

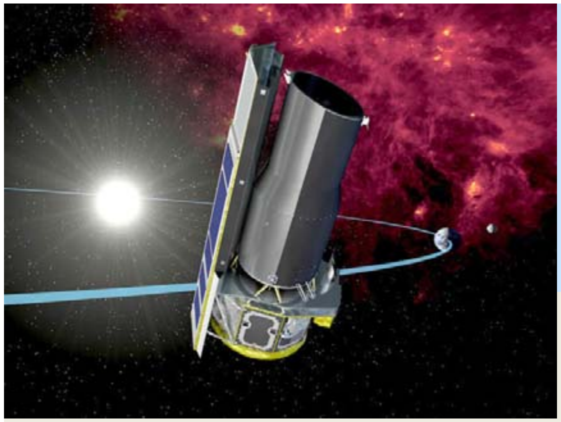
Detection of fullerenes in planetary nebula Tc1

- Spitzer/IRS spectrum shows prominent C_{60} emission bands (7.0, 8.5, 17.4, and 18.9 mm) and weak features of C_{70} atop a dust continuum (amorphous carbon type) and typical nebular emission lines. No PAHs nor other molecules are present.
- No cations, anions (fullerene is in neutral state), suggesting molecular carriers attached to solid material rather than gas.
- Tc1 is a young, low-excitation Galactic PN, with a double shell structure, the central star still enshrouded by a dense nebular core, and a fainter extended shell. The Spitzer aperture matches the dense nebular core size.
- Cami et al. state that Tc1 is a final helium-shell flash PN (Iben+ 1983), whose inner nebular core is hydrogen depleted, and it corresponds to a second PN ejection that stripped away all the available stellar hydrogen. This seems to agree with the fact that fullerenes, on Earth, can be synthesized by vaporizing graphite in a hydrogen-poor atmosphere.

PAHs: polycyclic aromatic hydrocarbons

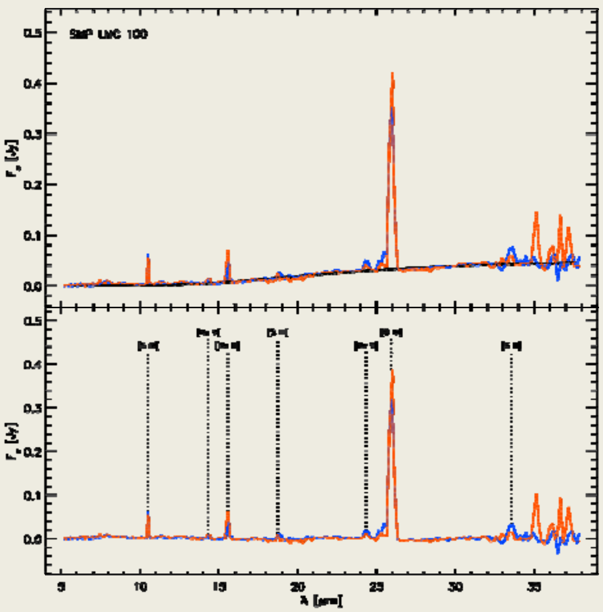
Our program

- When Cami+'s paper was still in prep., without knowing of the C_{60} detection we were looking for fullerenes in a sample of ~240 PNe
- Our team built a complete and homogeneous database of Spitzer/IRS ~5-38 mm PN spectra
  - GO 3633 (PI: Bobrowsky), Galactic bulge (Perea-Calderon+ 2009), 40 PNe
  - GO 20443 (PI: Stanghellini), Galactic disk (Stanghellini+ in prep.), 157 PNe
  - GO 50261 (PI: Stanghellini): SMC and LMC (Stanghellini+ 2007; Shaw+ 2010), 41 PNe

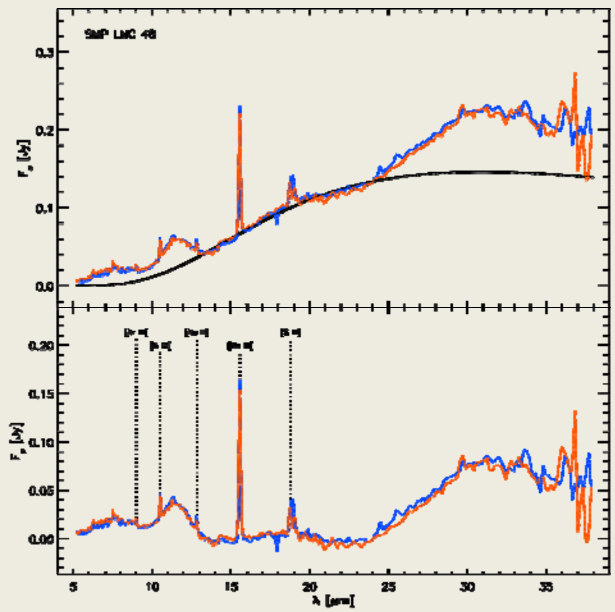


IRS/Spitzer spectra, MC PNe

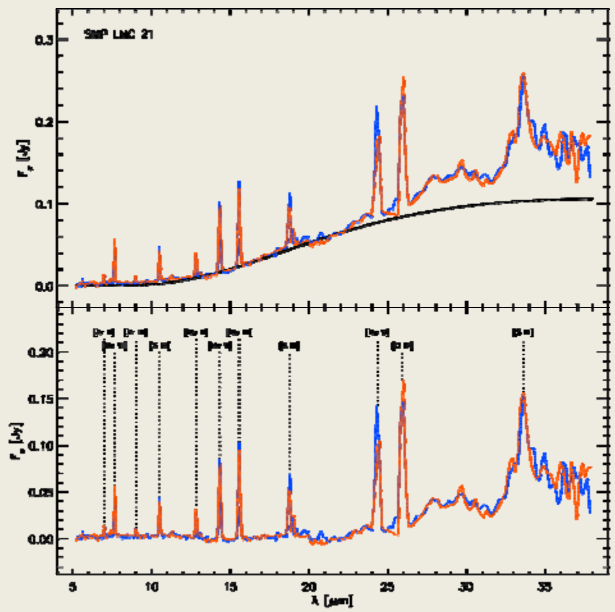
F



CRD



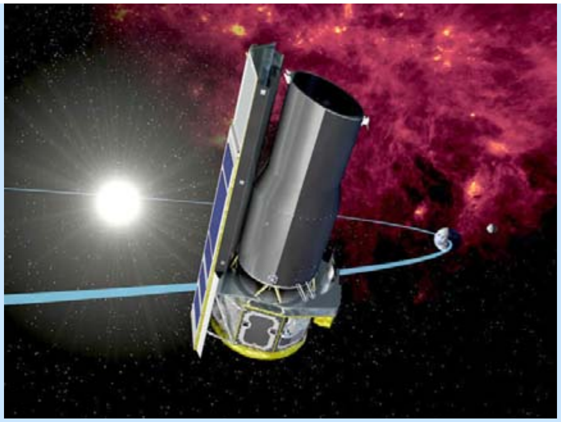
ORD



About half of the spectra are dominated by <u>emission lines with very low dust continuum</u> (featureless=F)

Many show solid state features compatible with <u>carbon-rich dust</u> (CRD) grains such as SiC, PAHs, ...

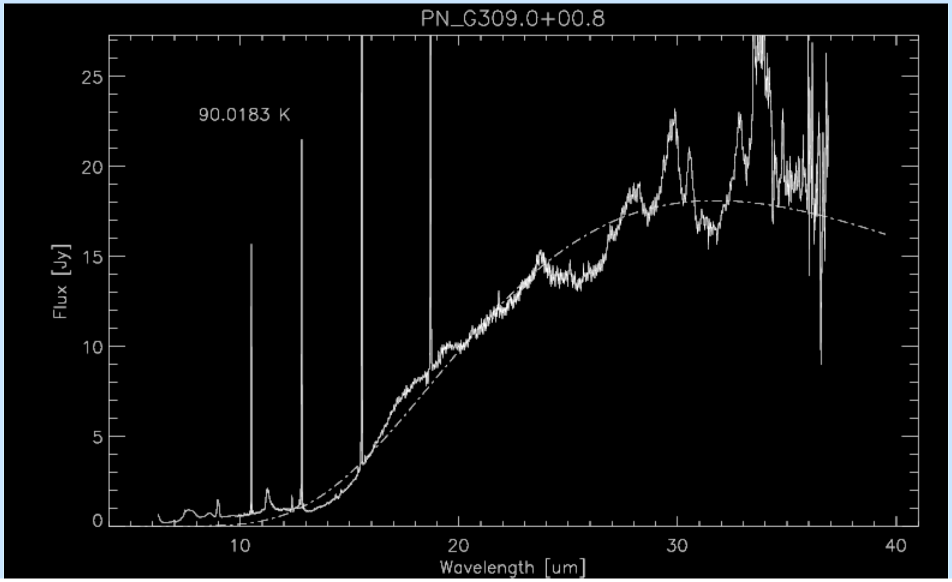
A few present <u>oxygen-rich dust</u> (ORD) grains, such as silicates (crystalline or amorphous)



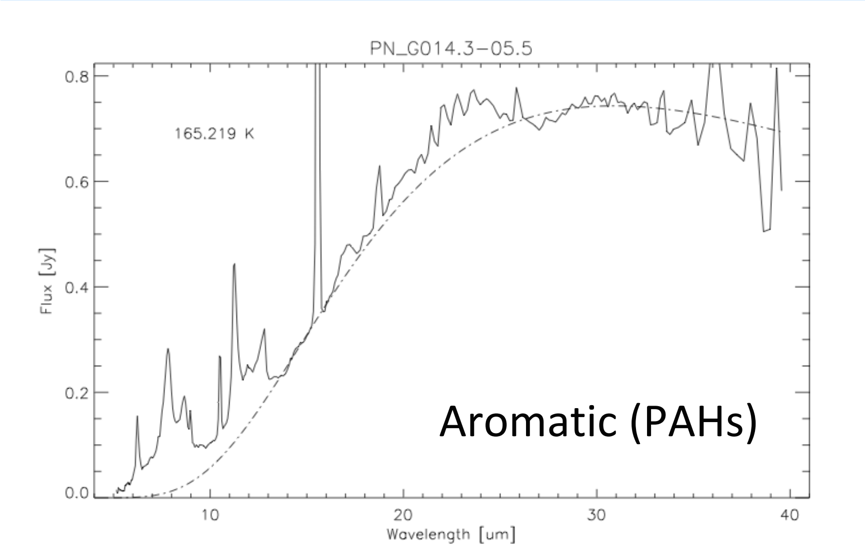
IRS Spitzer Spectra, compact, Galactic disk PNe

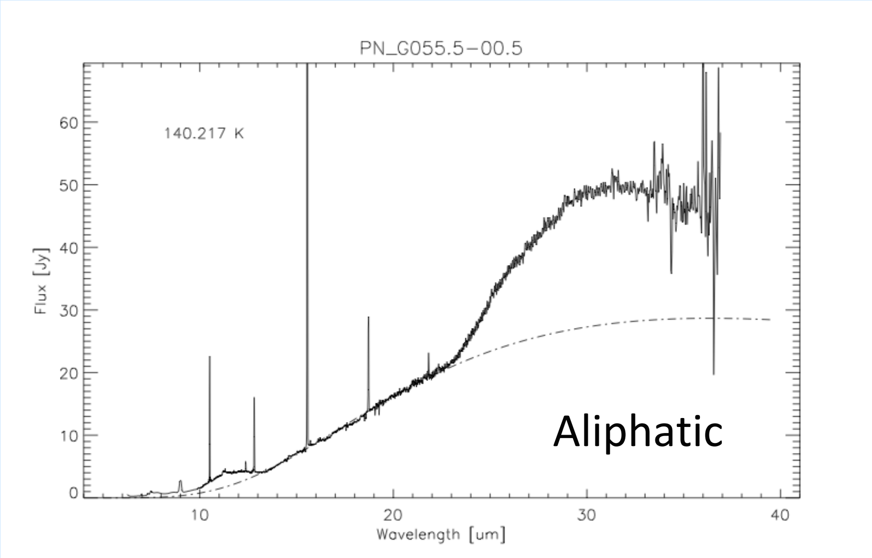
157 PNe with radius < 4”; pure Galactic disk population, excluding bulge (within 10° of GC, q ≤ 10 ”, $F_{5GHz} \leq 0.1$ Jy) and halo (Type III with |z|≥ 800 pc) PNe- the sample includes all Galactic disk PNe with these restrictions, excluding a handful of PNe already in the Spitzer/IRS archive, to the limiting magnitude observable with Spitzer

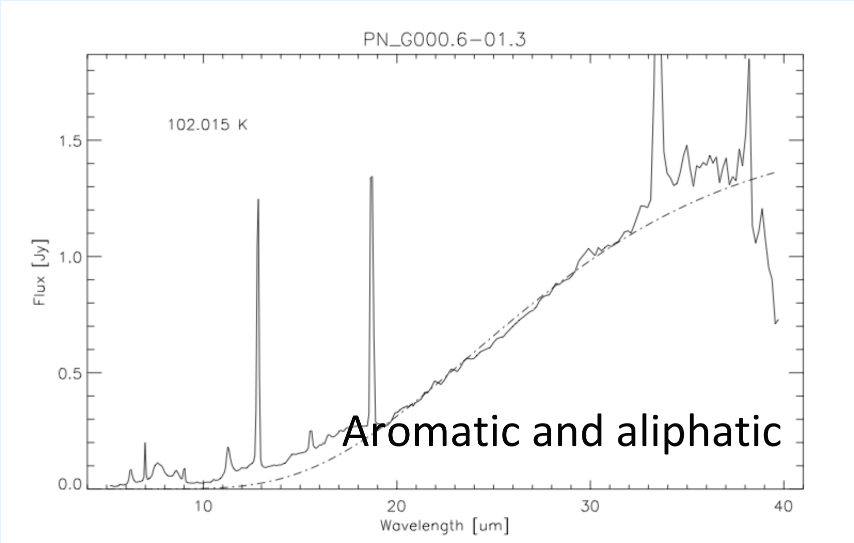
We found featureless (F), oxygen-rich (ORD), carbon-rich (CRD),
<u>and mixed-chemistry </u>(MCD) dust types (not seen in MC PNe)



Types of CRD PNe

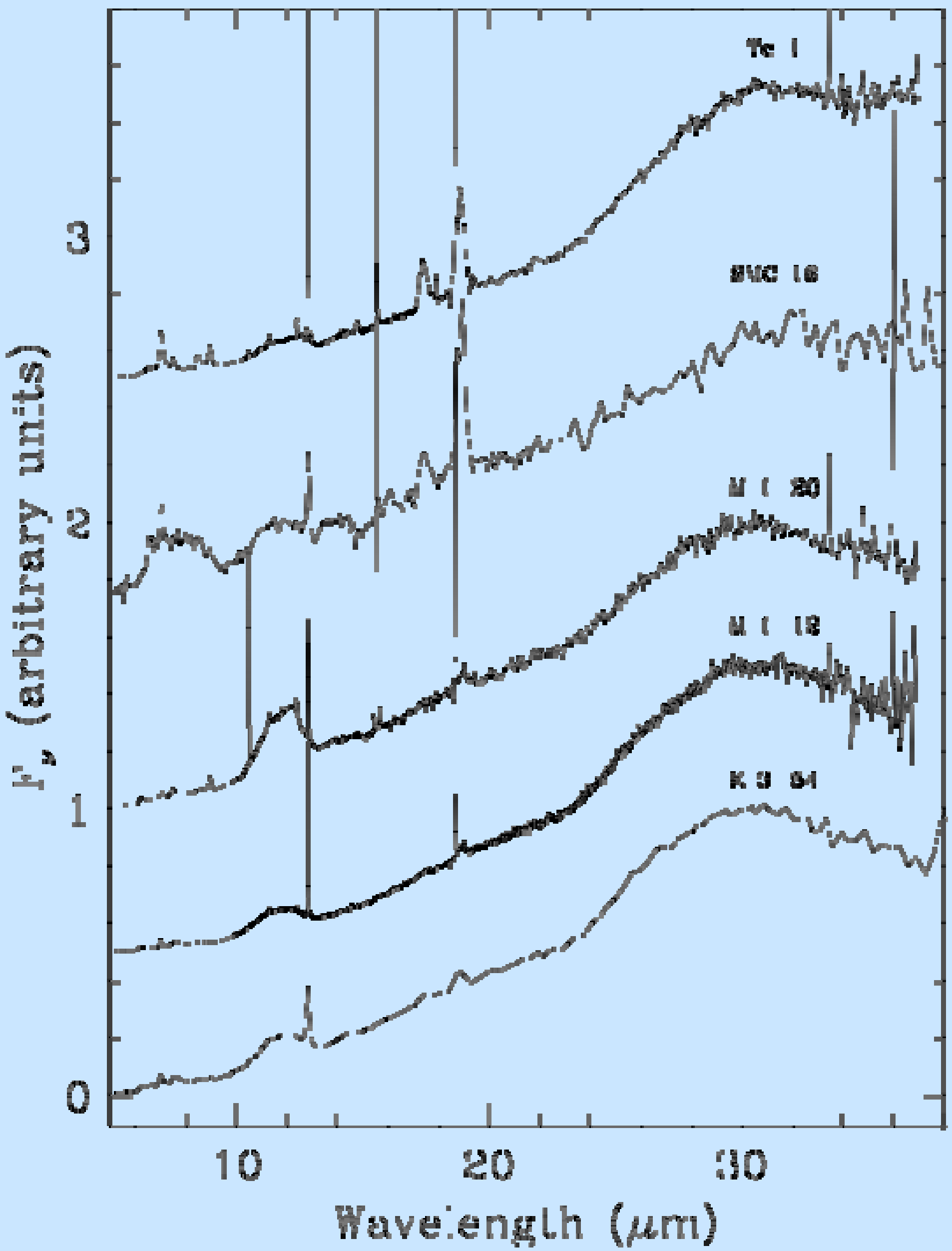






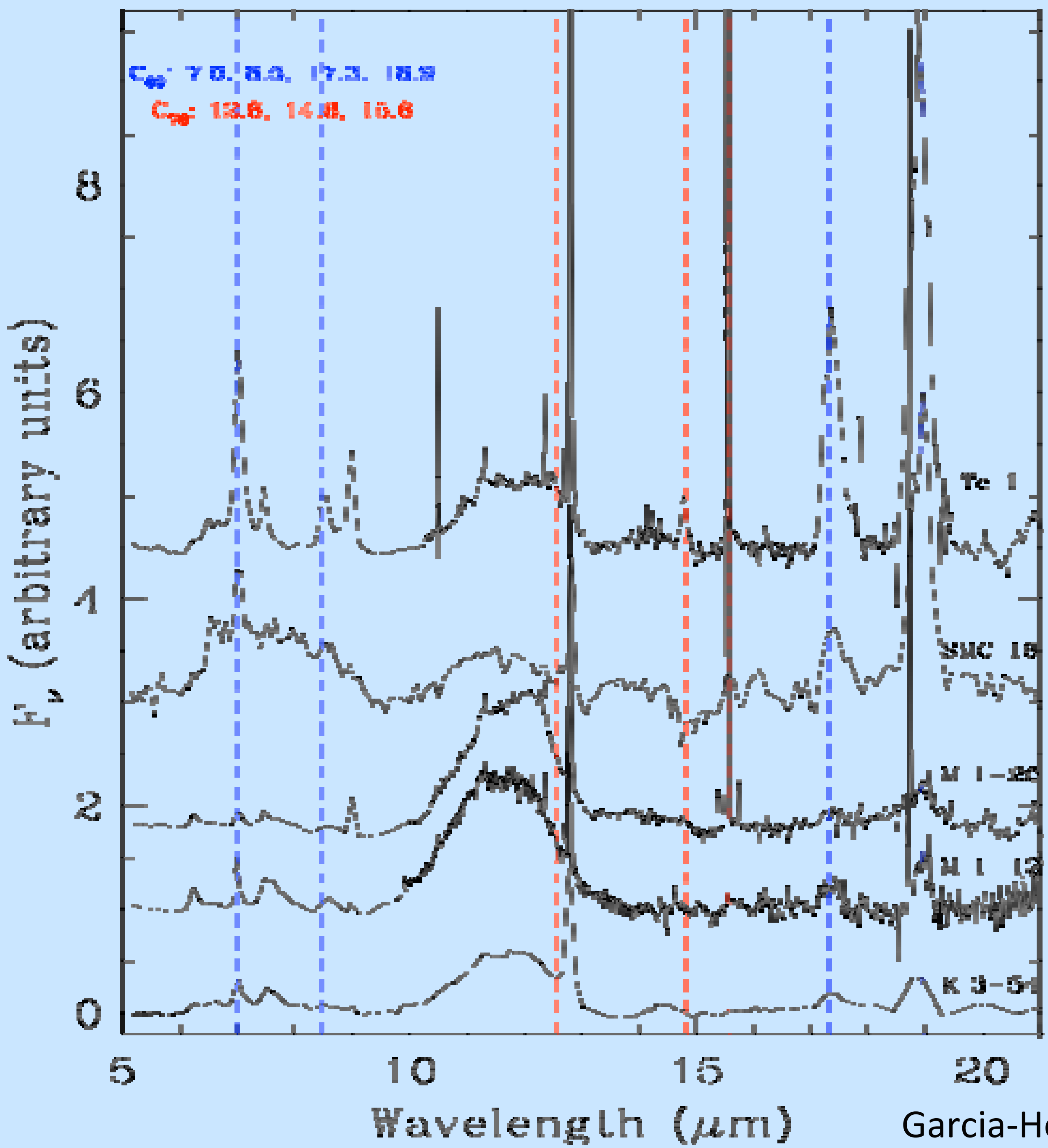
CRD: carbon-rich dust
PAHs: polycyclic aromatic hydrocarbons

We found fullerenes in 3 Galactic and 1 SMC PNe



- Plotted here the fullerene containing PNe including Tc1
- ~2% of PNe studies contains fullerenes
- all low-excitation PNe with similar spectra, energy distribution, dust type (CRD)
- Amorphous silicate dust bump λ~11.5 (SiC)
- Unidentified bump at λ~30 (MgS?) (Speck+ 2009; Hony+ 2002) HACs?
- M1-20, M1-12, K3-54 , and SMC 16 all have low-mass progenitors (Stanghellini+ 2007, 2010)
- Note: all (except Tc1) are compact (diameter<4")

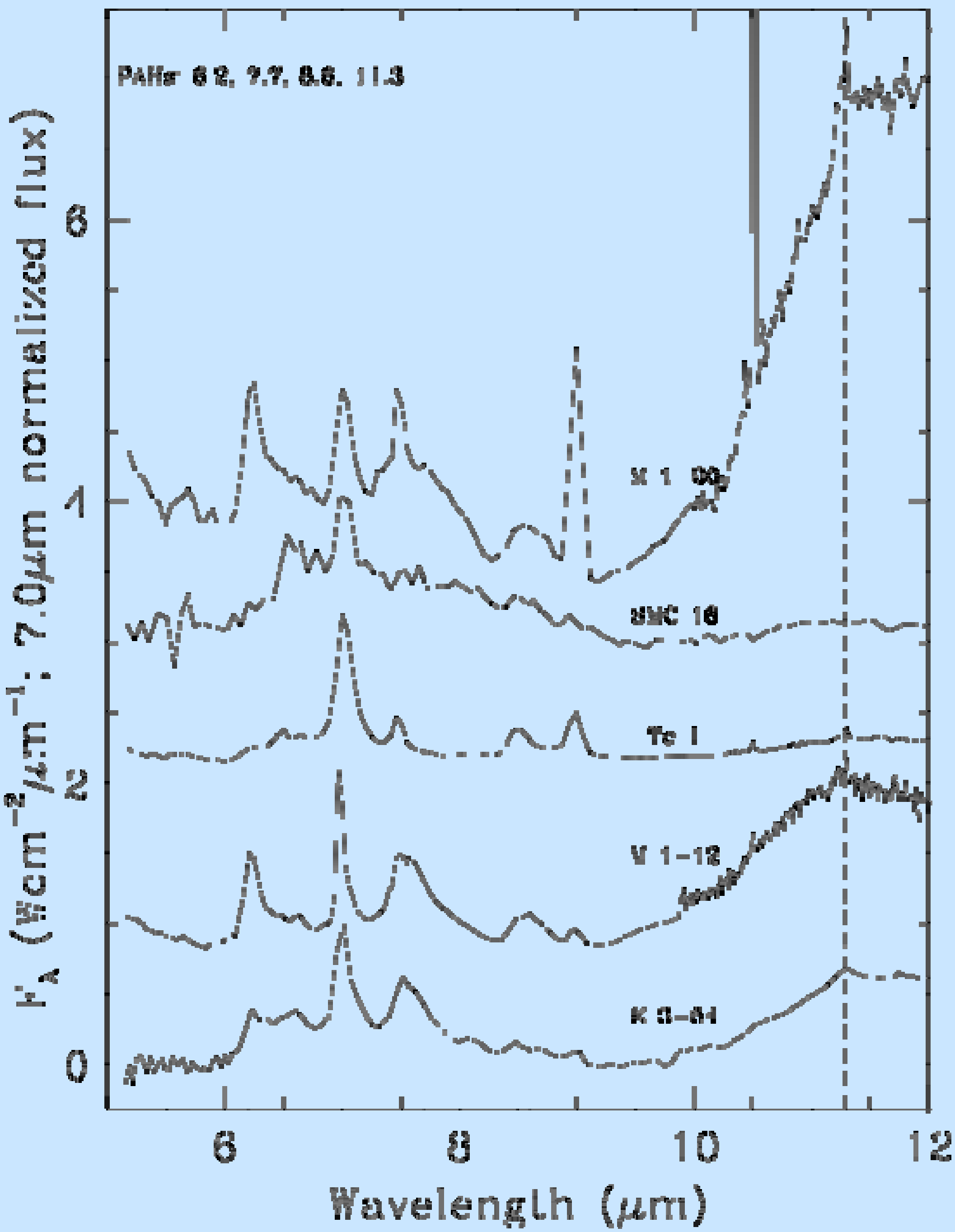
CRD: carbon-rich dust; HAC: hydrogenated amorphous carbon



Continuum-subtracted spectra to show detailed fullerene band emission

C_{60} present in 5 PNe (all bands)

Garcia-Hernandez+ 2010 ApJL in press



While all targets show a typical aliphatic carbon spectrum, very accurate continuum subtraction reveals that they all have weak PAHs fetaures (thus they are all aliphatic/aromatic CRD PNe). There is co-existance of fullerene+PAH (i.e., Hydrogen).

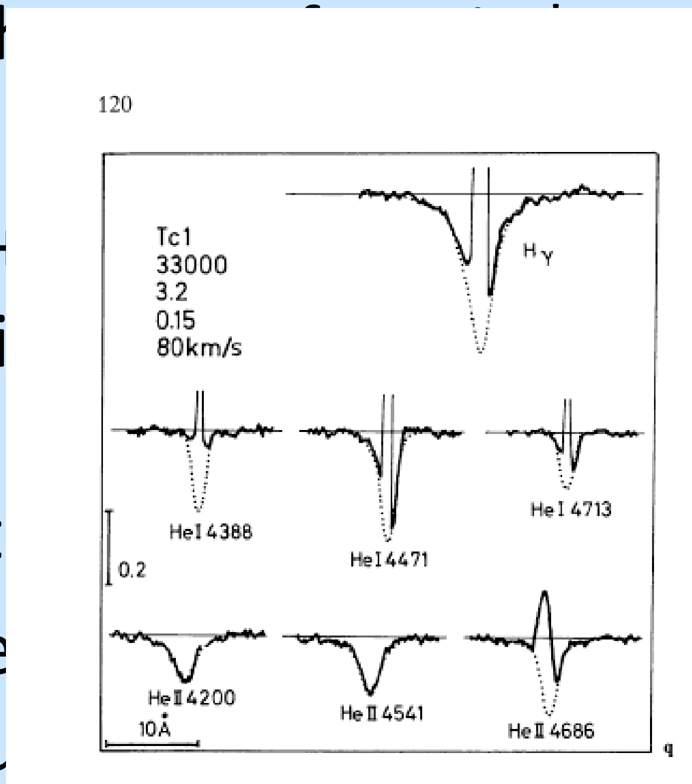
There is no evidence that these PNe are hydrogen-poor.

So what about Tc1?

CRD: carbon-rich dust amorphous=aliphatic

PAH: polycyclic aromatic hydrocarbons

The missing hydrogen in Tc1



- Indeed, th * hydrogen-poor
- Cami et a ntral star's (Mendez- nebular core's(Wi , showing evidence nd a typical H-rich central st
- This syste en through the final heliu 1983), which depletes the inner part of the system of any hydrogen remained after the standard PN ejection.

Formation of fullerenes

- All PNe where fullerene has been found are normally H-rich (no final helium-shell flash). Note that they span metallicity (SMC) and mass ranges, but their MIR spectra are surprisingly similar.
- To explain co-existence of fullerenes and PAH one has to invoke photochemical processing of solid, very small hydrogenated amorphous carbon (HACs, Scott+ 1996, 1997); broad λ~30 μm emission found in all these PNe could be associated with HACs (Ghisko+ 2001)
- Carbon compounds transform from aliphatic to aromatic when UV radiation increases, from the AGB to the final PN stages; in C-rich, low-excitation PNe this translation is slow, and only in a very small fraction of transition objects we can observe all products of it (fullerenes, PAHs, HACs).
- Higher progenitor mass PNe might evolve too fast from the AGB to the PN stages, and observations of fullerenes in these might be impossible; furthermore, it looks like all high-mass progenitors produce PNe that are ORD rather than CRD
- We conclude that fullerene formation may be facilitated when the hydrogen has been removed from the surface of carbonaceous grains. The de-hydrogenation of the grains is not a consequence of a H-poor environment, rather the photochemical processing of HACs.
- C60 is a hardy molecule: it might survive past the destruction of PAHs and HACs. This is what we might be observing in Tc1 (note SMC 16, so similar to Tc1 but with just hints of the PAHs)

CRD: carbon-rich dust ORD: oxygen-rich dust PAH: polycyclic aromatic hydrocarbons
HAC: hydrogenated amorphous carbon

Absolute probe!

- SMC 16 is an absolute probe of fullerene, since we know its distance
  - d_{SMC} ~ 61 kpc (Hilditch 2005)
  - total number of C_{60} molecules ~ 9 x 10^{47}
  - $M(C_{60})$ = 5.44 x 10^{-7} $M_{\odot}$
  - M(H) = 0.09 $M_{\odot}$ (Shaw+2006)
  - M(C) ~ 1.72 x 10^{-4} $M_{\odot}$ (Stanghellini+ 2009)

=>

C_{60} represents ~0.32% of the total carbon in SMC 16

summary

- We detected fullerenes in 4 stellar objects (PNe) in the Galactic disk and the SMC
- All these, as well as previously fullerene-detected Tc1, are C-rich, and normally H-rich low-excitation PNe showing amorphous carbon dust
- We estimate the C_{60} mass in SMC 16 to be ~0.2 Earth masses
- We tentatively interpret the fullerene formation in the presence of hydrogen as through an evolutionary phase that includes the progressive evaporation of H-rich carbonaceous molecules attached to very small grains
- More lab experiments on this type of fullerene formation are needed, as well as detailed observations of the target PNe