## Some Types of Carbon-Rich Star

<table>
<thead>
<tr>
<th>Type</th>
<th>C(N, late R)</th>
<th>C(J, early R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incidence</td>
<td>85%</td>
<td>15%</td>
</tr>
<tr>
<td>Chemistry</td>
<td>C/O &gt; 1; CN, C₂, s-pr. enhanced, often Tc.</td>
<td>C/O &gt; 1; CN, C₂, ¹³C isotopic species; not s-pr. enhanced, often Li-rich</td>
</tr>
<tr>
<td>L/L⊙</td>
<td>6 × 10³ to 7 × 10⁴</td>
<td>&lt; 10³ (some higher)</td>
</tr>
<tr>
<td>CSE</td>
<td>CO, dust</td>
<td>CO, dust</td>
</tr>
<tr>
<td>$\dot{M}(M_\odot, yr^{-1})$</td>
<td>10⁻⁷ to 10⁻⁵</td>
<td>$\sim$ 10⁻⁷</td>
</tr>
<tr>
<td>Evol. state</td>
<td>AGB</td>
<td>pre-AGB?</td>
</tr>
</tbody>
</table>

The Problem with J Stars

AGB models give C-rich, $^{13}$C-rich, Li-rich envelopes

- He-shell flashes and third dredge-up episodes
- Hot bottom burning at base of convective envelope: CNO cycle & $^7$Be $+ e^- \rightarrow ^7$Li $+ \nu_e + \gamma$
- High masses, $> 4M_\odot$

But:

- Evidence points to $M \lesssim 3M_\odot$ for J stars
- HBB converts C to $^{14}$N, ends C star phase
- There should be s-process enhancement: $^{13}$C($\alpha$, n)$^{16}$O

---

Hydrocarbons in Interstellar Dust

Outline

• Observables in the diffuse ISM
  – The absorption spectrum
  – The emission spectrum (Unidentified Infrared Bands)

• Organic chemistry & spectroscopy basics

• Constraints on the composition of the diffuse ISM

• The Unidentified Infrared Bands in various environments near stars
Observables in the diffuse ISM

Absorption in long sight lines (Pendleton & Allamandola 2002)

- Cyg OB2 No. 12 (B5 Ia^+, r = 1.7 ± 0.2 kpc, AV = 10.2)

- Galactic Center IRS 6E. Even the strongest feature, 3.4\(\mu\)m, is weak; max. optical depth is 0.2.

- Weakness of other features is significant
Unidentified Infrared Bands (Peeters et al. 2004)

In the diffuse ISM (Onaka 2004)
Organic chemistry & spectroscopy basics

In large molecules, chemical subgroups produce characteristic vibrational spectra, independent of the rest of the molecule. Large molecules vs. small

Types of vibration, each with its own frequency

- Stretch
- In-plane bend
- Out-of-plane bend
Some important subgroups

- Aliphatic groups: \( \text{CH}_3, \text{CH}_2 \) (form chains)
  e.g., pentane, \( \text{CH}_3 - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 - \text{CH}_3 \)

- Aromatic groups (based on benzene rings), e.g.:
• Classify aromatic rings according to number of adjacent CH groups

Example mode identifications (Pendleton & Allamandola 2002)

Bending mode identifications (out of plane) (Hony et al. 2001)
How the composition of the hydrocarbon molecules is constrained

Band strength ratios give relative numbers of different types of group or bond

- Measured band positions and strengths for various hydrocarbons
- Construct synthetic spectra for various mixtures
- Compare with observed spectrum
Another method: acquire spectra of various materials in the lab, accept those that match as candidate materials

Pendleton & Allamandola 2002

- Plasma processed carbon-rich materials work
- E. coli (doesn't work)
- Murchison meteorite hydrocarbon extract (works at 3.4 µm, but other parts of the spectrum don’t match)
- Other materials that failed have spectral features due to O, N components that are not present in the diffuse ISM
Conclusions

- Little O or N is present

- Ratio of CH stretch (3.4 µm) to deformation bands at 6.85 and 7.35 µm is consistent with maximum alkane chain lengths of about 4 mixed with aromatic groups

- The most successful laboratory analogs have clear aliphatic character and a comparably strong aromatic component.

- A molecule that is consistent with all observations

Likely structure of interstellar grains (Bakes, Bauschlicher, and Tielens 2004)
The Unidentified Infrared Bands (Peeters et al. 2004)

Generally recognized due to PAHs

Variations in spectrum from source to source

- Class A is like the diffuse ISM
- The CC modes vary in wavelength and correlate with each other more than the CH modes
Variations within individual sources: systematic change in Red Rectangle spectrum with distance from star; approaches diffuse ISM profile.
Radiation produced in cold environments: mechanism

- Grain absorbs single UV photon from star
- May eject an electron (10% probability)
- Or photon energy redistributed among many vibrational degrees of freedom, excites vibrational states
- Fluorescence when states decay

Implies

- Molecules are small, perhaps 50 to 100 C atoms
- Properties should depend on local radiation energy density
But many sources with different radiation fields have similar profiles

- Grain heating independent of radiation field
- Hotter stars have larger particles; same amount of energy per bond
- Particle size controlled by photodissociation; smallest stable size increases with stellar temperature

Conclusion: the UIR bands are a probe of physical conditions in interstellar and circumstellar space.
Ground truth: Titan (Bakes and Tielens 2004)

Lack of 3.4\(\mu m\) feature suggests ionized PAHs in haze in outer atmosphere

Importance of PAHs

- Diagnostic of interstellar conditions
- Among the cosmically most abundant molecules after \(H_2\) and CO
- PAHs with 15 to 500 carbon atoms contain 1 to 10% of all the carbon in the Galaxy.
- Significant in heating & cooling the ISM
- Significant in interstellar chemistry, e.g., catalytic formation of \(H_2\)
References


- E. L. O. Bakes, C. Bauschlicher, and A. Tielens, “Models of the Unidentified Infrared Emission Features”
- T. Onaka, “Unidentified Infrared Bands in the Diffuse Interstellar Medium”


Figure 6. Typical MIRS spectra of the Galactic plane. a) Area I ($l \sim -10^\circ$), b) Area II ($l \sim 50^\circ$), c) Area III ($l \sim 170^\circ$), and d) Area IV ($l \sim 230^\circ$). The zodiacal emission has been subtracted (see text).

Figure 6 shows typical MIRS spectra of the four areas. The zodiacal emission was estimated in the surrounding regions and has been subtracted. The spectra were averaged over regions of $8' \times 8'$ or $16' \times 16'$ for Areas I and II, or III and IV, respectively. The MIRS aperture size was $8' \times 8'$. The spectrum shape does not show appreciable variations within each area and the distribution of the UIR bands appears very similar to that of the IRAS 100 $\mu$m intensity also in the outer Galaxy. The spectra in Areas I and II seem to be similar to each other as suggested by Fig. 5. The Area I spectrum shows a slightly deeper valley around 10 $\mu$m than that of Area II, which can be attributed to larger silicate absorption. The presence of the emission in the 10 $\mu$m region is well demonstrated by the variation with the galactic latitude in Area II (Onaka et al. 1996), while that in the Area I spectrum is difficult to confirm partly due to the silicate absorption and partly to the uncertainty in the zodiacal emission subtraction. Note that Area I is located very close to the ecliptic plane. ISOPHOT-S spectra do not confirm the presence of the emission around 10 $\mu$m in the diffuse emission, but their uncertainties are compatible with the intensity level of the MIRS spectrum (Kahanpää et al. 2003). In the spectra of Areas I and II there seem to be faint features present around 5.5 and 7.0 $\mu$m, which may be weak companions of the UIR bands (e.g. Allamandola et al. 1989).
H-X STRETCHING FREQUENCIES

\[ \nu, \text{cm}^{-1} \]

\[ \lambda, \mu \text{m} \]

C-H STRETCH

N-H STRETCH

O-H STRETCH

FREE

COMPLEXED

BROAD

BROAD, UNSTRUCTURED

H$_2$O

ALCOHOLS

CH$_3$OH

CH$_3$-(CH$_2$)$_n$-OH

CARBOXYLIC ACIDS

\[ \text{H} - \text{C} - \text{H} \]

\[ = \text{C} - \text{H} \]

\[ \equiv \text{C} - \text{H} \]

\[ \text{NH}_3 \]

\[ \text{AMMONIA} \]

\[ \text{AMINES} \]

\[ \text{AMIDES} \]

\[ \text{O} - \text{C} - \text{N} - \text{H} \]
The basic structural and molecular character of carbonaceous, interstellar dust in the diffuse interstellar medium. The molecular details have been deduced from the spectroscopic constraints as discussed in §§ 5 and 6. The specific geometries of the aromatic plates and aliphatic components simply represent what is likely. The structure is somewhat splayed out to reveal the molecular structural details: we envision the actual structure somewhat more closed in. For the interconnected species (not the free-floating entities), the relative numbers of aromatic and aliphatic carbon-hydrogen bonds, as well as their subclassification within type, are all consistent with the observed spectrum described here. The latter includes the aliphatic —CH₃ to —CH₂— ratio, and the relative numbers of aromatic solo, duo, trio, and quartet hydrogens deduced from the interstellar IR emission bands as described in Hony et al. (2001). The approximate volume of this fragment is on the order of 10⁻¹⁹ cm³. Thus, a typical 0.1 μm DISM carbonaceous dust grain would contain approximately 10⁴ of these fragments. The encircled regions are expanded showing the different structural units. The carbon atom distribution of this fragment is summarized in Table 3.

Forth, Mennella et al. (1999) have suggested that the aliphatic component makes its way into the dense cloud, where it is destroyed by irradiation within the cloud. Once deep in the cloud, ice layers may further inhibit the formation of new CH bonds (Menella et al. 1999). Interestingly, these hydrocarbon grains may also be important in the conversion of H to H₂ (Pirronello et al. 1999). A thorough discussion of the life cycle of grains can be found in Jones, Tielens, & Hollenbach (1996) and Tielens (1998).

6.3. Other Carbonaceous Materials

Comparison of the DISM 3.4 um feature to that of the Murchison meteorite extract (Fig. 14a) indicates a remarkable similarity, and it has been suggested that an unaltered
The UIR Features after ISO

Figure 1. The ISO-SWS spectra of the planetary nebula NGC 7027 and the Photo-Dissociation region at the Orion Bar illustrate the richness and variety of the UIR spectrum. Also indicated are the aromatic mode identifications of the major UIR features.

A broad emission plateau of variable strength is present underneath the 6.2, 7.7 and 8.6 µm features. The onset of this emission plateau seems to be variable and falls longwards of ∼ 6 µm while it extends to ∼ 9 µm. The out-of-plane CH bending modes are present at 10.8, 11.0, 11.2, 12.0, 12.7, 13.2 and 14.5 µm and also sit on a broad emission plateau. At even longer wavelengths, a new feature has been reported at 16.4 µm (Moutou et al., 2000; Van Kerckhoven et al., 2000) as well as a weak emission plateau between 15 and 20 µm (Van Kerckhoven et al., 2000). It should be emphasized that not all sources show all these emission features at the same time and their peak position and relative strength vary as discussed below.
UIR Emission Features from Titan Haze