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The Carbon-Bearing Material in the Outflows from Luminous Carbon-Rich Stars [and Discussion]

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The carbon-bearing material in the outflows from luminous carbon-rich stars

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Within the neighbourhood of the Sun, a number of highly evolved stars are carbon-rich in the sense that they have more carbon than oxygen so their outer atmospheres contain molecules such as CN, CH and C_2H_2. These stars are cool with atmospheric temperatures near 3000 K and they are also luminous, typically 10^4 times more powerful than the Sun. The outer envelopes of these stars are tenuously bound, and they all are losing mass at a very high rate, in some cases more than $10^{-5}\,M_\odot\ \mathrm{a}^{-1}$ (where $M_\odot$ denotes the mass of the Sun). These high luminosity carbon stars remain in this phase for a time, very approximately, near 10^5 years. They exhibit a large amount of carbon in their atmospheres because the products of the nuclear burning that occurs in the very centre of the star, including the synthesis of carbon, appear on the surface.

In the extended envelopes around these stars, there is a very active chemistry, and the gas is sufficiently cool that nucleation of solid dust grains occurs. These solid particles may grow to sizes as large as 1 μm although a more typical size is near 0.05 μm. We therefore can identify both relatively small carbon-bearing molecules (for example HC_7N) and much larger carbon-containing dust grains in the outflows. The amount of intermediate size particles or molecules, such as C_{60}, and their possible role in the circumstellar chemistry is not yet well understood. At least in the envelope of the well studied carbon star IRC+10216, there appears to be more carbon in CO and solid grains than in polycyclic aromatic hydrocarbons.

1. Introduction

As stars evolve, they expand into luminous, red giants (see, for example, Iben & Renzini 1983). When the red giant becomes sufficiently luminous, perhaps $L > 2000\,L_\odot$, where $L_\odot$ denotes the luminosity of the Sun, the mass loss rate becomes detectably large (more than $10^{-7}\,M_\odot\ \mathrm{a}^{-1}$). Indeed, mass loss rates approaching $10^{-4}\,M_\odot\ \mathrm{a}^{-1}$ are known (Jura 1991*b*).

Infrared and radio observations of the circumstellar envelope have been exploited very successfully. The most commonly studied molecule is CO; hundreds of nearby stars are known CO sources (Nyman *et al.* 1992). Additionally, over 50 different species have now been detected in various circumstellar envelopes (Olofsson 1992).

A star whose initial mass is between 1 and about $5\,M_\odot$ (an 'intermediate mass' star) is thought to evolve into a white dwarf of typically 0.6 to $1\,M_\odot$ (Weidemann & Koester 1983). As a result, main sequence stars can lose more than 50% of their initial mass. Since the Chandrasekhar limit for the maximum mass of a white dwarf is near $1.4\,M_\odot$, if this mass loss did not occur, there would be many more supernova and many fewer white dwarfs in the Milky Way than are observed.

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Both because the amount of mass that is lost is so substantial, and because there can be mixing of material from the very centre into outer layers of the star, the composition of the surface of a star losing a great deal of mass may reflect the large amount of nucleosynthesis that has occurred during the evolution of the star. Highly evolved mass-losing stars may display a number of distinctive elemental abundances. About half of the intermediate mass stars that lose mass very rapidly (that is $dM/dt > 2\times10^{-6}\,M_{\odot}\,\mathrm{a}^{-1}$) are carbon-rich (Jura & Kleinmann 1989). Therefore, carbon-rich environments are common.

In the atmosphere of a red giant star, the most stable molecule is CO. By standard thermodynamic arguments, most of the oxygen and carbon is contained within this molecule. If the star is oxygen-rich, then $[\mathrm{O}] > [\mathrm{C}]$ and the atmosphere contains molecules such as H_2O as well as CO. If the star is carbon-rich, then $[\mathrm{C}] > [\mathrm{O}]$ and the atmosphere contains large amounts of molecules such as CN and CH (Wallerstein 1973; Blanco 1989). Stars with $[\mathrm{C}] \approx [\mathrm{O}]$ are denoted as S-type; there are about a third as many S-type stars as there are carbon stars (Jura 1988). In the general galactic population carbon stars are very rare; however, as noted above, in the population of stars returning large amounts of mass to the interstellar medium, the carbon stars are common.

The carbon-rich stars losing a large amount of mass are a fascinating laboratory for studying carbon chemistry in space. Below, I describe what is known about these stars, and how we can hope to use them to understand the nature of celestial carbon-chemistry.

2. Circumstellar molecules

The best studied mass-losing carbon star is IRC+10216 which appears to be only 130 pc from the Sun; the closest of all these objects (see Jura 1991*b*). This star is probably losing mass at a rate, dM/dt, of about $2\times10^{-5}\,M_{\odot}\,\mathrm{a}^{-1}$ while the gas is flowing out at a speed, v_{∞}, of about 15 km s^{-1}. As a first approximation it seems that at least for many of these stars, we may assume a spherically symmetric mass loss. Consequently, we may write for the density, ρ, as a function of distance from the star, R, that

$$\rho = (dM/dt)/(4\pi v_{\infty} R^2). \tag{1}$$

The circumstellar chemistry is often subdivided into three main zones, which are determined by a comparison of the characteristic dynamic flow time, R/v_{∞}, with the chemical reaction times (Lafont *et al.* 1982; Omont 1987; Millar 1988). (i) In the region closest to the star (perhaps $R \approx 10^{14}$ cm), the density is sufficiently high that three-body chemical reactions occur in a time short compared to the dynamic time. In this régime, we expect the chemical abundances to approach thermodynamic equilibrium. (ii) Somewhat further away from the star ($10^{14}\ \mathrm{cm} < R < 10^{16}\ \mathrm{cm}$), there is a 'freeze-out' of the products of the three-body reactions (McCabe *et al.* 1979). In this region, two-body reactions dominate the active chemistry. (iii) Finally, far from the star ($R > 10^{16}$ cm), the density becomes sufficiently low that the only significant chemical processing is the photodestruction that results from absorption of ambient interstellar ultraviolet photons by the resulting molecules that flow from the central star.

For carbon-rich outflows, this scheme seems to predict, reasonably well, the observed abundances and spatial distributions of some of the most abundant circumstellar molecules such as CO and HCN (Olofsson *et al.* 1990; Cherchneff &

Barker 1992). Values of [HCN]/[H_2] as large as 10^{-4} are known (Jura 1991*a*), although this inferred ratio is very high compared with the value for most carbon stars (e.g. [HCN]/[H_2] $\approx 10^{-6}$ toward IRC+10216 according to Bieging *et al.* (1984)). Because the derived values of [HCN]/[H_2] are substantially lower than the estimated values for [CO]/[H_2] of 8×10^{-4} (Knapp & Morris 1985), it seems, as predicted by the models, that there is much more carbon contained within CO than within HCN. While detailed schemes to account for a number of other species in the outer envelope also have been successful (Glassgold *et al.* 1987; Nejad & Millar 1987), the formation of the larger species, such as HC_7N, is still unclear (see Jura & Kroto 1990).

It has not been possible to determine directly the carbon abundance ([C]/[H]) in the atmosphere of a carbon star losing a very large amount of mass (*ca.* $10^{-5}\,M_{\odot}\,a^{-1}$). However, such stars are thought to expel their envelopes and evolve into planetary nebulae in less than 10^5 years, and it is possible to measure directly the gas-phase abundances of carbon ([C]/[H]) and oxygen ([O]/[H]) in planetaries. Zuckerman & Aller (1986) report [C]/[O] abundances for 29 carbon-rich planetary nebulae, the likely evolutionary descendants of mass-losing carbon-rich stars. For these 29 planetaries, the average value of [C]/[O] is 2.3. Therefore, under the plausible assumption that while the star is a mass-losing red giant, essentially all the oxygen is contained within CO, there is still a lot of 'leftover' carbon, and it is quite possible that there is considerable additional carbon beyond what is found in CO or the solid dust grains.

One possible important reservoir of circumstellar carbon is C_2H_2. According to the theoretical models presented by Lafont *et al.* (1982), there may be 0.6 as much carbon being carried in C_2H_2 as there is in CO around IRC+10216. However, Keady & Hinkle (1988) have observed infrared line strengths to infer that [C_2H_2]/[H_2] = 5×10^{-5}. Therefore, according to their results, there is perhaps 0.1 as much carbon in C_2H_2 as in CO.

There is additional evidence that the abundance of C_2H_2 is relatively low in the outflow from IRC+10216. According to the standard models, we expect that in the outer envelope to IRC+10216, the C_2H_2 is photodissociated to produce C_2H (Glassgold *et al.* 1986). That is, the reaction

$$h\nu + C_2H_2 \rightarrow C_2H + H, \qquad (2)$$

should produce large concentrations of C_2H. Neither from infrared (Keady & Hinkle 1988) nor radio observations (Truong-Bach *et al.* 1987) does there seem to be as much C_2H as predicted by the photochemical models if C_2H_2 is abundant as 10^{-4} H_2. Because C_2H_2 might be a key molecule in the synthesis of larger molecules (Keller 1987), it is possible that there is relatively little C_2H_2 because it is consumed in the production of larger species.

3. Solid grains

Evidence for solid grains in the mass loss around carbon stars comes from (i) the infrared continuum emission which is far in excess of what is expected from the photosphere of the star. This excess radiation is thought to be the emission from relatively cool circumstellar dust grains. (ii) Many carbon-rich stars display strong emission near 11.3 μm thought to be the result of solid carbon (Papoular 1988). (iii) Some carbon stars exhibit reflection nebulosity which is the consequence of scattering by circumstellar dust grains (see, for example, Tamura *et al.* 1988). (iv) Often, a carbon star will display a net polarization because the circumstellar dust grains are distributed asymmetrically with the consequence of producing a net scattering.

While there is considerable uncertainty in the size distribution and composition of circumstellar dust grains, much of the evidence points towards some sort of amorphous carbon with a range of sizes up to *ca*. 1 μm although it seems that the grains can be successfully modelled with particles of radius 0.05 μm (Martin & Rogers 1987). Therefore, we anticipate that there are solid particles containing upwards of *ca*. 10^{11} atoms.

Jura (1986) has argued that for the carbon stars losing large amounts of mass on average, the mass of carbon in dust grains relative to the total amount of hydrogen is 4.5×10^{-3}, if the opacity at 60 μm is 150 $\text{cm}^2\ \text{g}^{-1}$. Because this dust to gas ratio is derived with the assumption that $[\text{CO}]/[\text{H}_2] = 8\times10^{-4}$, this result for the dust abundance implies that there is, on average, twice as much carbon contained within CO as there is contained within the solid grains. These data would therefore imply that for the stars losing a large amount of mass that $[\text{C}]/[\text{O}] = 1.3$. This result depends upon the infrared opacity of the circumstellar grains which is not well known. Nevertheless, if this model is correct and if, on average, [C]/[O] in the circumstellar envelopes of these stars in fact equals 2.3, then it appears that there should be some additional reservoir of carbon in the outflows from carbon rich stars besides CO and solid grains.

The nature of this other carrier of the carbon is unknown. It is possible that these other forms of carbon-bearing species are relatively fragile in the sense that they may survive the relatively cool and protected wind of the red giant and are then destroyed in the harsh environments of Planetary Nebulae that follow. Two arguments suggest that substantial erosion of carbon-bearing material occurs in carbon-rich planetary nebulae. (i) The [C]/[O] ratio in the ionized regions in carbon-rich planetary nebula averages 2.3, therefore there must be an appreciable source of gas-phase carbon beyond the photodestruction of the CO molecule. (ii) The inferred dust to gas ratio in the ionized regions of old, extended planetaries is between 10^{-3} and 10^{-4} (Pottasch *et al*. 1984), substantially less than the dust to gas ratio of 4.5×10^{-3} inferred for the red giant progenitors to these stars. Unless the analysis of the infrared data is substantially in error (see, for example, Huggins & Healy 1989), there has been substantial destruction of the carbon-bearing particles (grains, clusters, molecules) as the object evolved from being a red giant with an extended circumstellar envelope into a planetary nebula.

4. Intermediate size clusters

While we have direct observational evidence for small molecules and large grains, we have very little information about clusters in the outflows from carbon-rich stars. That is, we know very little about the particles with more than 10 atoms, but, say, fewer than 10^6 atoms in circumstellar regions (see Kroto & Jura 1992).

Infrared spectroscopy has revealed the presence of the ‘Unidentified features’ in carbon-rich planetary nebulae and other sources. There are particularly prominent features at 3.3, 6.2, 7.7, 8.6 and 11.3 μm (Sellgren 1990). These features are not detected in mass-losing carbon stars, but they are strong in ‘transition objects’ that are evolving from red giants to planetary nebulae such as the Egg Nebula, AFGL 2688 (Geballe *et al*. 1992), and the Red Rectangle (Geballe *et al*. 1989).

The infrared features are generally attributed to various vibrational modes of carbonaceous material, quite possibly PAHs (polycyclic aromatic hydrocarbons: Léger & Puget 1984; Allamandola *et al.* 1985) or HAC (hydrogenated amorphous carbon: Duley & Williams 1981). However, while the presence of the emission features provides evidence for organic compounds, it has not been possible to make specific identifications. Also, there are significant differences in the infrared spectral features in different carbon-rich objects. For example, the profile of the feature at 3.29 μm toward the Red Rectangle is quite different from that toward the carbon-rich planetary nebula NGC 7027 (Tokunaga *et al.* 1988).

It should also be noted that the PAH features appear to be primarily excited in regions where there is a substantial energy density of ultraviolet photons are present but where the hydrogen is neutral. That is, in the Orion Bar region, there is a strong anti-correlation between regions where the 3.3 μm feature is strong and where the Brackett α recombination line of ionized hydrogen is strong (Sellgren *et al.* 1990). Similarly, in the carbon-rich planetary nebulae, NGC 7027, the emission from the dust features appears to be more extended than the emission from the ionized gas (Aitken & Roche 1983; Woodward *et al.* 1989).

To date, neither PAH emission nor absorption has been detected in the circumstellar envelope around a cool carbon star; PAH emission has only been seen in carbon-rich environments where there is substantial energy density of ultraviolet radiation. This correlation could simply be an excitation effect; the carbon features are only excited by the presence of ultraviolet radiation. However, it could also be that carbon particles are eroded into PAHs in the environment where ultraviolet penetrates; either directly by the ultraviolet radiation or indirectly by shocks that accompany the radiation.

Here we place an upper limit to the amount of PAHs flowing out of the very well studied carbon star, IRC+10216 by placing limits on the strength of the PAH feature at 3.3 μm. Because the 3.3 μm feature is intrinsically quite broad, it is useful to consider relatively low resolution observations. Witteborn *et al.* (1980) have presented a spectrum with 2% resolution between 2.0 and 8.5 μm of IRC+10216. Treffers & Cohen (1974) and Merrill & Stein (1976) have presented similar data over much of the same spectral interval. Neither group detects any absorption at 3.28 μm at more than 5% of the continuum level. There is notable absorption at 3.1 μm, but this 'feature' is believed to be a blend of sharp molecular lines (Ridgway *et al.* 1978).

We can estimate the column density of material in a circumstellar shell, N_H, extending from radius R to infinite distance, from the expression:

$$N_H = (\mathrm{d}M/\mathrm{d}t)/(4\pi \mu R v_\infty), \tag{3}$$

where μ is the atomic weight of hydrogen. For IRC+10216, we adopt a distance of 130 pc (Jura 1991*b*), a mass loss rate of $2\times10^{-5}\,M_\odot\,\mathrm{a}^{-1}$ (Kwan & Linke 1982; Martin & Rogers 1987) with an outflow speed of 15 km s^{-1}. We also adopt an inner radius of 10^{15} cm from which the PAHs might be measured (see Keady *et al.* 1988). From these numbers we find that $N_H = 4.0\times10^{22}\ \mathrm{cm}^{-2}$. We adopt for the 3.28 μm PAH feature that $\sigma_{\text{C-H}} = 3.5\times10^{-20}\ \mathrm{cm}^{-2}$ (Léger *et al.* 1989) for each C–H bond in a PAH. The absence of a 3.3 μm feature at the 5% level therefore implies that $N_{\text{C-H}} < 1.4\times10^{18}\ \mathrm{cm}^{-2}$. Therefore, combining the two results, we may write that

$$N_{\text{C-H}}/N_{\mathrm{H}} < 3.5\times10^{-5}. \tag{4}$$

If we assume that about a third of all the carbon atoms within a PAH have an associated hydrogen atom, then we find that the amount of carbon within PAHs flowing out of IRC+10216 is less than about 10^{-4} of the hydrogen nuclei. Since $[\mathrm{CO}]/[\mathrm{H}_2]$ is about 8×10^{-4}, it seems that there is more carbon in CO and in grains than in PAHs flowing out of IRC+10216. Consequently, PAHs, by themselves, do not carry most of any 'excess' carbon, the carbon beyond that in CO and grains, in the outflow from IRC+10216.

Even though there may not be especially large abundances of PAHs flowing out of carbon stars such as IRC+10216, the possibility remains that the putative clusters of carbon particles flowing out of carbon-rich red giants may be related to a fascinating unsolved problem in astrophysics; the origin of the diffuse interstellar bands (Herbig 1975). These diffuse bands are found in absorption throughout the interstellar medium, but we do not know their carrier. Most carbon stars display such complex spectra that it is very difficult to search for the diffuse bands in their spectra. Pritchett & Grillmair (1984) reported that the diffuse band at 5780 Å† was particularly strong in the absorption spectrum of the carbon-rich planetary nebula NGC 7027. However, this object lies close to the galactic plane, and it is not certain whether the absorption features have a circumstellar or interstellar origin. Le Bertre & Lequeux (1992) argue that there is no evidence for an enhancement of the diffuse bands in the circumstellar matter around NGC 7027.

Le Bertre (1990) has found that the features at 4430, 5780 and 6284 Å are quite strong in the absorption spectrum of the A star companion to the mass-losing carbon star CS 776 (= IRC-20131). The diffuse band at 5797 Å is not present in the spectrum of this companion. Again, however, because the star lies in the galactic plane ($b = -0.81°$), much of the diffuse bands may be contributed by interstellar instead of circumstellar matter.

This difficulty for CS 776 can be assessed quantitatively. Le Bertre (1990) derives a mass loss rate from IRC-20131 of $4.5\times10^{-7}\,M_{\odot}\,\mathrm{a}^{-1}$. Scaled to the outflow velocity of the material of 26 km s^{-1} (Zuckerman & Dyck 1989) instead of the assumed value of 15 km s^{-1} and using Le Bertre's distance of 1.3 kpc instead of their estimate of 1.43 kpc, the re-computed mass loss rate from Claussen *et al.* (1987) is $6.6\times10^{-7}\,M_{\odot}\,\mathrm{a}^{-1}$ in reasonable agreement with the rate estimated by Le Bertre (1990). Because the separation of the A star companion from the carbon star CS 776 is 1.81″, the projected separation between the two stars is 3.6×10^{16} cm. Therefore, according to equation (3), the column density of circumstellar hydrogen between us and the A star companion to CS 776 is $1.5\times10^{19}\,\mathrm{cm}^{-2}$. However, the total extinction toward this companion is $A_V = 1.71$ mag (Le Bertre 1990) which, for a standard interstellar dust to gas ratio, corresponds to a hydrogen column density of $3\times10^{21}\,\mathrm{cm}^{-2}$ (Spitzer 1978). This column density is consistent with the expected concentration of interstellar matter within the plane of the Milky Way. Thus, towards the companion to CS 776, there appears to be about 100 times more interstellar than circumstellar matter. Therefore, unless the diffuse bands are extremely strong in the circumstellar matter around CS 776, it seems quite likely that the bulk of the diffuse bands in the spectrum result from interstellar matter.

The best evidence for a relation between carbon-particles and the diffuse interstellar bands comes from analysis of the Red Rectangle. The Red Rectangle is an usual mass-losing carbon star which is probably in transition into becoming a planetary nebula. Schmidt *et al.* (1980) using 6–20 Å resolution discovered intense optical emission bands longward of 5400 Å. With a higher spectral resolution of 1 Å,

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† 1 Å $= 10^{-10}$ m $= 10^{-1}$ nm.

Warren-Smith *et al.* (1991) resolved individual lines in this broad emission band. Sarre (1991) and Fossey (1990) have independently pointed out that the emission lines at 5799, 5855, 6380 and 6615 Å discovered in this high resolution spectrum of the Red Rectangle agree in wavelength very well with some of the strongest interstellar diffuse absorption bands that lie at 5797, 5850, 6376, 6379 and 6614 Å (Herbig 1975). It seems likely, therefore, that the carrier of at least some of the diffuse interstellar bands is being produced in the outflow from the Red Rectangle. In particular, Scarrott *et al.* (1992) have shown that the line profile of the bands both in emission and absorption can be reproduced by a complex molecules such as 'C_{60}-entity' (e.g. C_{60}^{+} or $C_{60}X$). Other complex carbon molecules such as PAHs and HAC have also been proposed to be the carrier of the broad bands in the Red Rectangle (d'Hendecourt *et al.* 1986; Wdowiak *et al.* 1989; Duley & Williams 1990).

Another possibility is that the diffuse bands are carried by PAHs. Recently, Salama & Allamandola (1992) have shown that $C_{16}H_{10}^{+}$ in an argon matrix has a strong absorption feature at 4435 Å, close to the strongest diffuse interstellar band at 4430 Å. However, in a neon matrix in which molecule-matrix interactions are expected to be less severe, the same absorption occurs at 4395 Å. Therefore, it is still uncertain whether gas-phase $C_{16}H_{10}^{+}$ exists in large enough quantities in the interstellar medium to produce the feature and whether this particular gas-phase ion absorbs at the precise wavelength to account for the diffuse interstellar band. Nevertheless, it is quite possible that any $C_{16}H_{10}$ in the circumstellar envelope around the Red Rectangle is ionized; Balm & Jura (1992) and Hall *et al.* (1992) have identified CH^{+} in the outflow from this star from the spectra of Waelkens *et al.* (1992).

With current instruments it is possible to make spatial maps of the emission from different species in the Red Rectangle. These maps might provide valuable clues to the origin of different spectroscopic features. For example, in the spectrum of the Red Rectangle, the emission features which correspond to the diffuse interstellar bands are concentrated in what appears to be two hollow cones oriented perpendicular to the plane of this bipolar system (Schmidt & Witt 1991). This hollow cone is similar to that proposed by Jura & Kroto (1990) to explain the observed (Nguyen-Q-Rieu *et al.* 1986) HC_7N emission (see around AFGL 2688, the 'Egg Nebula'), a very well studied carbon-rich object that appears to be in transition from a red giant to a planetary nebula.

5. Conclusions

Mass-losing carbon stars are major sources of carbon-rich material in the interstellar medium. In addition to small carbon-bearing molecules and large carbon grains, there may be a substantial amount of intermediate-size carbon clusters (C_{60}, PAHs, etc.) flowing out of these objects. At least towards IRC+10216, there appears to be more carbon in CO and in grains than in PAHs. A promising possibility is that the diffuse interstellar bands may be carried by carbon-rich clusters and that the identification of the carrier of the bands may also prove valuable insight into the nature of these intermediate-size carbon clusters in astrophysics.

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Discussion

A. S. Webster (*Royal Observatory, Edinburgh, U.K.*). There is now one carbon star known, and in the outflow from that star, the diffuse interstellar bands are known. So there is a binary companion between the spectra.

M. Jura. A problem arises, namely that the star lies right in the galactic plane, is eight-tenths of a degree from the plane, and the separation between the companion and the primary is little more than an arc-second, and the mass loss rate from that carbon star is not especially large (*ca.* $2 \times 10^{-7} M_{\odot}\ \mathrm{a}^{-1}$). When you work out the amount of material nominally for standard, of course the interstellar medium (ISM) fluctuates: there is *ca.* 100 times as much material between us and that secondary, as circumstellar matter. So I am not convinced. But there is so much more interstellar compared with circumstellar matter, that unless the circumstellar matter is good at carrying diffuse bands, which it might be, it is probably more of an anomaly in the local ISM.

A. S. Webster. It may or may not be, but the spectrum is peculiar. It doesn't look like a normal interstellar spectrum.

M. Jura. Even in the ISM there are fluctuations in the strengths of the interstellar bands with respect to each other. When you look at different stars, they are families of interstellar bands, that don't all arise the same way. Even in the ISM, I think there are families that come together, but the relative amount of each family varies from one line of site to another in the ISM. So that may be what is going on in this particular object. That is my suspicion, but I can't prove it one way or the other.

R. C. Haddon (*AT&T Bell Laboratories, U.S.A.*). What are the prospects for the killer experiment, which will once and for all answer this long standing question on C_{60} in space.

M. Jura. C_{60} in space would be identified if, for example, we could see two, three or four of the IR bands that Krätschmer showed earlier, or if we could see either an absorption or an emission in some direction. We have tried without success, but we'll keep trying, because we are getting smarter as we think about it, and why we have failed in the past. That would be a definite way. It could be that much of the C_{60} is ionized, and then the diffuse bands would be slightly shifted in wavelength. Another feature which I would hope to learn about from somebody, is what happens when C_{60} absorbs a UV photon, and is free, so that it's not colliding with the walls of the experiment? How is that energy going to be re-radiated? Maybe someone here knows the answer or is able to figure it out, and then the astronomers might be able to tell you. For example, in the IR spectrum of IRC+10216, you can look at the wavelengths at 7 μm, 8.5 μm and so on, and you don't see an absorption; but these are low f-value transitions, so the absence of C_{60} is not really definitive. If you can figure this out, may an electronic transition or transitions, can be measured or calculated.

E. Wasserman (*The Du Pont Company, U.S.A.*). In the case of the polyaromatic hydrocarbons, do you think they come from the larger small molecules, or more from monoatomic, diatomic and triatomic sources?

M. Jura. In some sense that must be true, because it all comes out from a stellar atmosphere, where the temperatures are so high that it is, at most, diatomic. So originally the stuff is very simple, when it gets further out, say a few stellar radii, you might get grains, and I don't know then whether you are knocking things apart to get PAHs, or where you never actually build it up sufficiently large to get a drain. I don't know the answer to that.