RADIO AND MILLIMETER OBSERVATIONS OF CIRCUMSTELLAR ENVELOPES

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ABSTRACT. Circumstellar chemistry has been confined largely to analysis of a few dozen molecules in the envelope of one carbon-rich star, IRC+10216. A new generation of large millimeter wavelength telescopes promises to broaden the data base to include many other stars and additional molecules. Carbon-monoxide emission has already been detected from approximately 130 stars and many of these are prime candidates for chemical studies. The detection of HCN emission in a few oxygen-rich stars was quite unexpected and indicates that nonequilibrium chemical processes are important in at least some circumstellar envelopes. New millimeter wavelength interferometers can measure the spatial distribution of various molecules for comparison with predictions of models for photodissociation, freeze-out on grains, self-shielding, and nonspherical outflow.

1. INTRODUCTION

Asymptotic giant branch (AGB) stars are rich sources of molecular line emission. The AGB stars are surrounded by extensive envelopes of dust grains and molecular gas which is flowing outward into interstellar space. In the most extreme stars, the mass loss rate, $\dot{M}$, is approximately 10^{-4} $M_\odot$ per year. Rapid mass loss on the AGB affects the ultimate fate of intermediate-mass stars (main-sequence masses between 1.4 and approximately 7 $M_\odot$) which, apparently, die as white dwarfs rather than as supernovae.

AGB stars contribute the majority of the total mass returned by stars to the interstellar medium. Taking 1.6 $M_\odot$ as the average main-sequence mass of a white dwarf progenitor star and 0.6 $M_\odot$ as the average mass of a white dwarf, then, with a white dwarf birth rate of one per year, the total galactic $\dot{M}$ due to AGB stars is approximately 1 $M_\odot$ per year. Supernova probably return only one-tenth as much mass to the galaxy each year, on the average. AGB stars and their descendents, the planetary nebulae, contribute most of the nitrogen and carbon synthesized inside stars and returned to space. Supernovae contribute the oxygen and heavier elements.

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An advantage to investigating chemistry in the envelope around an AGB star, as compared with the interstellar medium or a meteorite, is the relatively simple history of the former environment. This eliminates one of the many free parameters that enter into models of interstellar molecular clouds. Another advantage of circumstellar envelopes is a clear division into both oxygen-rich (O/C > 1) and carbon-rich (C/O > 1) environments. Then we are able to investigate chemistry as a function of the very important C/O ratio.

2. MOLECULES AND LINE SHAPES

In the best-studied, carbon-rich circumstellar cloud (IRC+10216), 21 molecules have been identified in the microwave region of the spectrum as of December 1985. The complete list is given by Olofsson (1985) and it includes mostly linear carbon-containing molecules. Typically, molecules in IRC+10216 that contain carbon are approximately 100 times more abundant, relative to H_2, than they are in the interstellar medium. The two rings identified in astrophysical sources, SiC_2 and C_3H_2, are both found in IRC+10216. Three molecules that do not contain carbon, SiS, SiO and NH_3, are included among the 21. Of these, SiS and SiO appear to be less abundant than one would expect based on chemical equilibrium calculations for the stellar photosphere and NH_3 appears to be overabundant.

In oxygen-rich circumstellar envelopes, eight molecules in total have been detected. Five (CO, H_2S, SO, HCN, and SO_2) are seen in "quasi-thermal" emission (see Figs. 1 and 2), two in strong maser emission (H_2O and OH) and one (SiO) in both quasi-thermal and maser emission. In the following discussion we largely ignore the maser emission which is considered in detail in the contribution by Dr. Walmsley at this conference.

Unlike microwave molecular lines from the interstellar medium, circumstellar envelopes display only a few basic profile shapes. These are shown in Figures 1 and 2. Circumstellar line formation is described in the reviews by Morris (1985) and by Olofsson (1985) and references therein.

There are very few observational exceptions to these four basic line shapes. In IRC+10216, the $J = 1 \rightarrow 0$ transition in SiS has two narrow spikes at the extreme profile velocities and is, no doubt, in maser emission (Rieu et al. 1984; Sahai et al. 1984). In V Hya, a narrow feature appeared in the $J = 1 \rightarrow 0$ CO profile in June 1985 that was not present in June 1976 (see Fig. 3). Probably, this represents the first example of a CO maser seen in either a circumstellar or interstellar environment. In § 5 we discuss kinematic processes that sometimes cause nonstandard circumstellar line profiles.

3. CIRCUMSTELLAR CARBON MONOXIDE

In this and the following section we concentrate on circumstellar CO and HCN since observations of other molecules are either very sparse

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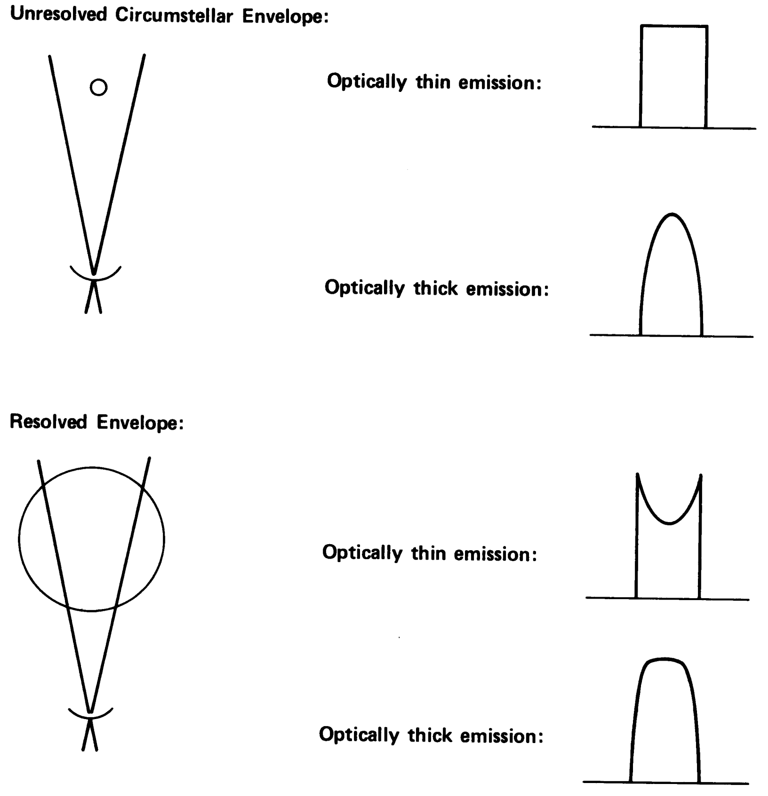

Figure 1: Theoretical millimeter wavelength line profiles: the profile shape is determined primarily by two parameters, the optical depth of the line, τ, and the ratio of the angular size of the emitting region, R, to the beam size of the telescope, B.

or else are rather dated (e.g., SiO, Morris *et al.* 1979) with no recent reports.

As of December 1985, CO has been detected in approximately 130 circumstellar envelopes, mainly in cool AGB stars, but also in a few supergiants and planetary nebulae (see Zuckerman and Dyck 1986b and references therein). In each case, the emission is either $J = 1 \rightarrow 0$ or $J = 2 \rightarrow 1$ or both. About 60% have enhanced carbon abundances (i.e., $C/O \gtrsim 1$). This percentage agrees well with the percentage of planetary nebulae with $C/O \gtrsim 1$ as deduced from optical and infrared spectra (Zuckerman and Aller 1986).

It is not possible to deduce whether a star is C-rich or O-rich from CO data alone, although the ratio of integrated CO intensity to total stellar flux received at the Earth is somewhat larger, on average, for the C-rich stars (e.g., Zuckerman and Dyck 1986a). This is probably due in part to a larger $f = [CO]/[H_2]$ in the C-rich envelopes as described below.

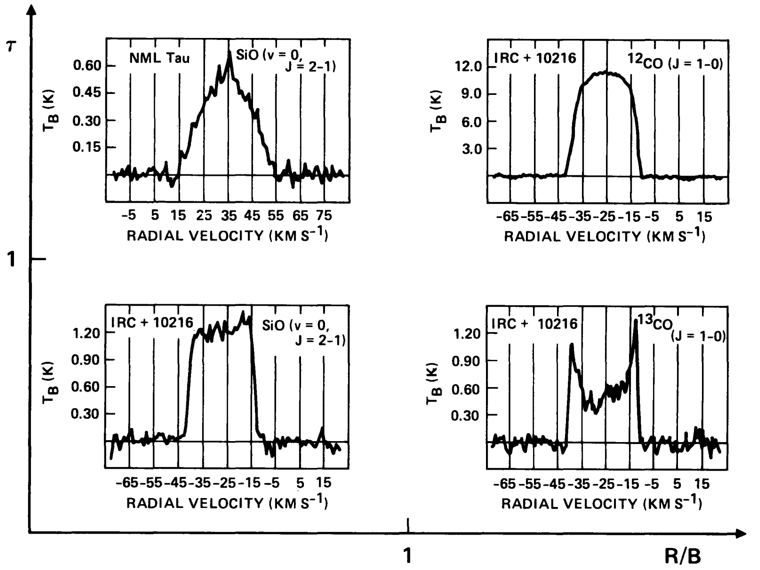

Figure 2: Actual profiles (from Olofsson 1985) illustrating the various situations depicted in Fig. 1. The quantities τ, R, and B are defined in the caption to Fig. 1.

In oxygen-rich stars f is related to C/H and, in carbon-rich stars, f is related to O/H. If one assumes solar abundances for C/H and O/H and that CO is fully associated as suggested by theory, then we would have $f_{max} \sim 9 \times 10^{-4}$ and 1.6×10^{-3} for O-rich and C-rich AGB stars, respectively. If one deduces $\dot{M}_{CO}$ for a given star from CO observations (e.g., Knapp and Morris 1985) and uses f_{max}, then one obtains a lower limit to $\dot{M}_{H_2}$. More generally, $f < f_{max}$ is assumed (e.g., Knapp and Morris 1985; Zuckerman and Dyck 1986a) and CO data are used to deduce $\dot{M}_{H_2}$, which is a quantity of great interest in studies of AGB stars.

However, as this is a symposium on chemistry, we actually want to measure f which may be written as $\dot{M}_{CO}/\dot{M}_{H_2}$. $\dot{M}_{CO}$ may be determined from microwave CO observations, but not trivially, since one needs to know the excitation mechanism and worry about processes such as molecular self-shielding (Morris and Jura 1983). $\dot{M}_{H_2}$ is even more difficult to determine and there are three general techniques:

1) Use of CO mapping data in conjunction with a model for collisional excitation (Kwan and Linke 1982). This technique has been applied only to IRC+10216 but, with the new generation of large millimeter wave telescopes and interferometers, data should become available for numerous other stars.

2) Assumption that radiation pressure on dust grains drives the mass loss such that $\dot{M}_{H_2} V_\infty = L_{IR}/C$. Here V_∞ is the terminal outflow velocity as deduced from the CO profile and L_{IR} is the "infrared

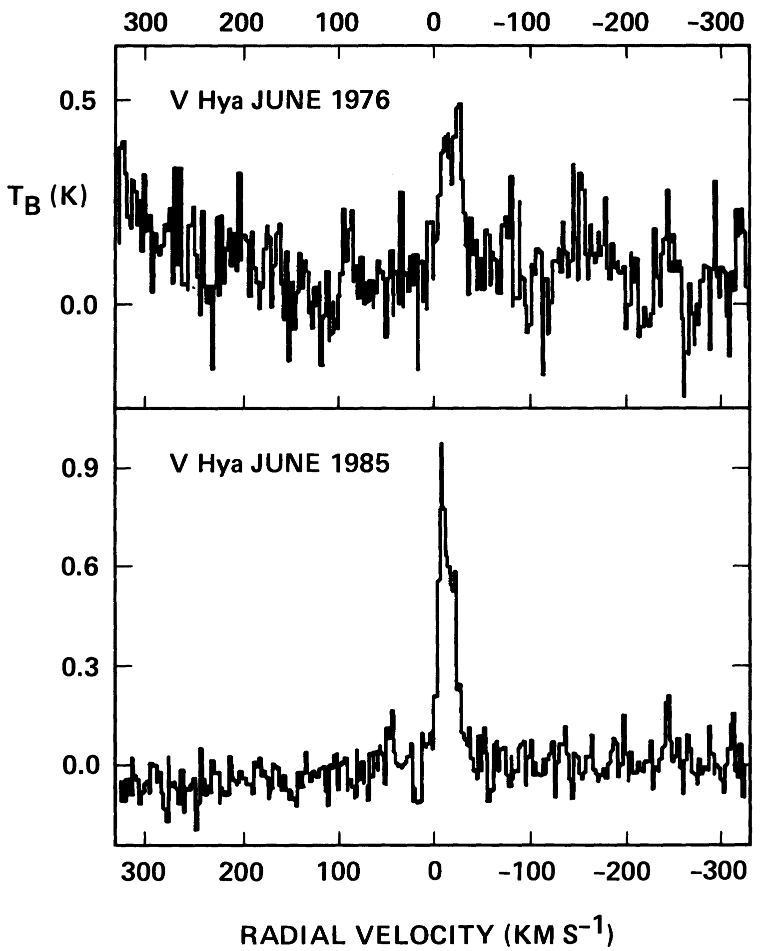

Figure 3: Carbon monoxide spectra of the classical N-type carbon star V Hya from Zuckerman and Dyck (1986b). The abscissa, V_{LSR}, is radial velocity with respect to the local standard of rest. The ordinate is brightness temperature. The narrow spike at $V_{LSR} \sim -10$ km s^{-1} (near the red edge of the 1985 spectrum) was clearly not present in 1976 and may represent the first example of a CO maser seen in either a circumstellar or interstellar environment.

excess" measured at mid-infrared wavelengths. This excess is that seen above an extrapolation of a blackbody flux distribution fitted to the optical and near-infrared portion of the stellar spectrum. L_{IR} is often not easy to determine.

3) Use of broadband far-infrared or submillimeter fluxes (e.g., Sopka et al. 1985) and an assumed value for the quantity $M_{H_2}/M_{dust\ grains}$. This method suffers from uncertain dust opacities at far-infrared wavelengths which enter into the determination of M_{dust} and the fact that M_{H_2}/M_{dust} is not likely to be the same for all stars.

4. CIRCUMSTELLAR HCN

As of December 1985, HCN J = 1 → 0 emission has been detected from approximately 30 circumstellar envelopes, mainly in surveys by Olofsson et al. (1982) and by Zuckerman and Dyck (1986b). Most of the 30 objects are carbon-rich but three are oxygen-rich (Deguchi et al. 1986; Jewell et al. 1986), two are S-type (C/O ~ 1), and one is the planetary nebula NGC 7027 (Olofsson et al. 1982). Because CO emission is excited in a given envelope over a much larger radial distance from the central star than is HCN emission, one expects that, in general, the observed brightness temperature of the CO should exceed that of HCN. Surprisingly, there are two carbon-rich stars, AFGL 2233 and IRC+10401, where HCN appears to be brighter than CO (Zuckerman and Dyck 1986b). (Such a situation is unheard of in interstellar clouds.) The reason is, at present, uncertain but may be related to the fact that the HCN excitation may be primarily radiative rather than collisional and the J = 1 → 0 HCN transition even may be inverted. Measurement of HCN and CO source sizes in these stars with an interferometer should clarify the situation.

A number of C-rich stars with large outflow velocities (V_∞ up to approximately 35 km/s) have been found to lie within a few degrees of the galactic plane (Zuckerman et al. 1986a). These include both AFGL 2233 and IRC+10401. If radiation pressure on dust grains drives the mass loss, then stars with large V_∞ also should have large bolometric luminosities and masses (Jura 1984; Iben and Renzini 1983). This is consistent with the location of these stars near the galactic plane. Therefore, by using V_∞ and galactic latitude as discriminants, it should be possible, in the future, to study circumstellar chemistry as a function of the initial main-sequence mass of the underlying star.

Table 1 lists HCN abundances in some circumstellar and interstellar environments. The large HCN abundances deduced for some oxygen-rich envelopes cannot be understood as due to freeze-out of photospheric abundances in the circumstellar environment if the theoretical calculations of Tsuji (1973) and Vardya (1966) are correct. The HCN must then be produced by some secondary process (e.g.,

Table 1. HCN Abundances

	[HCN]/[H_2]
Interstellar medium	2×10^{-8}
Carbon-rich stellar envelopes	$\gtrsim$ few $\times 10^{-6}$
Oxygen-rich stellar envelopes: theory (Tsuji 1973; Vardya 1966)	$\lesssim 10^{-10}$
A few oxygen-rich stellar envelopes (NML Tau, OH 231.8+4.2, IRC+10420)	$\gtrsim 10^{-8}$

ion-molecule reactions, shocks, photochemistry) occurring in the circumstellar shell. Again, an interferometric measurement of the distribution of the HCN emission in these shells may provide an important clue as to the processes at work. We note in passing that, whatever secondary process is responsible, it is also likely to be at work in many interstellar clouds. Since we know that the three circumstellar environments in question are O-rich, it follows that HCN may be produced at the observed levels in interstellar clouds even in an oxygen-rich gas phase environment. This is, therefore, an argument, although certainly not a completely compelling one, against the idea that the gas phase component of dense interstellar clouds is carbon-rich.

5. KINEMATIC COMPONENTS

A very few evolved objects appear to show two kinematic components (Fig. 4). In Figure 5 we sketch a simple model that might explain such a profile. Here the bipolar nebulosities are envisaged to be expanding more rapidly than the denser obscuring disk closer to the central star. The disk has been observed directly in the infrared in two, young, bipolar planetary nebulae, NGC 6302 (Lester and Dinerstein 1984) and NGC 2346 (Gatley and Zuckerman 1986).

An example of a different type of profile with two kinematic components is shown in Figure 1 in Masson et al. (1985). Weak high-velocity emission "wings" appear on CO profiles of the planetary nebula NGC 7027. Similar high-velocity emission appears in HC_3N profiles of AFGL 2688 (the "Egg Nebula") obtained with the 45-m Nobeyama antenna (Zuckerman et al. 1986b). Masson et al. argue that the high-velocity gas in NGC 7027 has been shocked by the expansion of the H II region into the surrounding neutral cloud. Since there is no known H II region at AFGL 2688, this explanation may leave something to be desired. An alternative mechanism for producing shocked gas could involve the collision of a high-velocity wind from the central star with the slower wind that was ejected while NGC 7027 and AFGL 2688 were still red giants (e.g., Beckwith et al. 1984 and references therein). Alternatively, at least in AFGL 2688, the weak wings rather might be due to nonspherical kinematics of the type described in the preceding paragraph. Interferometric observations of AFGL 2688 should clarify the picture. If shocked gas is involved, then the large telescopes now coming into operation should enable us to study its chemistry.

6. FUTURE PROSPECTS

The new generation of large millimeter wavelength antennae operating at high frequencies with sensitive receivers is ideally suited to a study of small objects such as circumstellar envelopes. Therefore, a literal explosion of new data in this field is inevitable.

The very new 30-m IRAM telescope has already detected SO_2 and SO in oxygen-rich envelopes and HCN, surprisingly, also has been detected

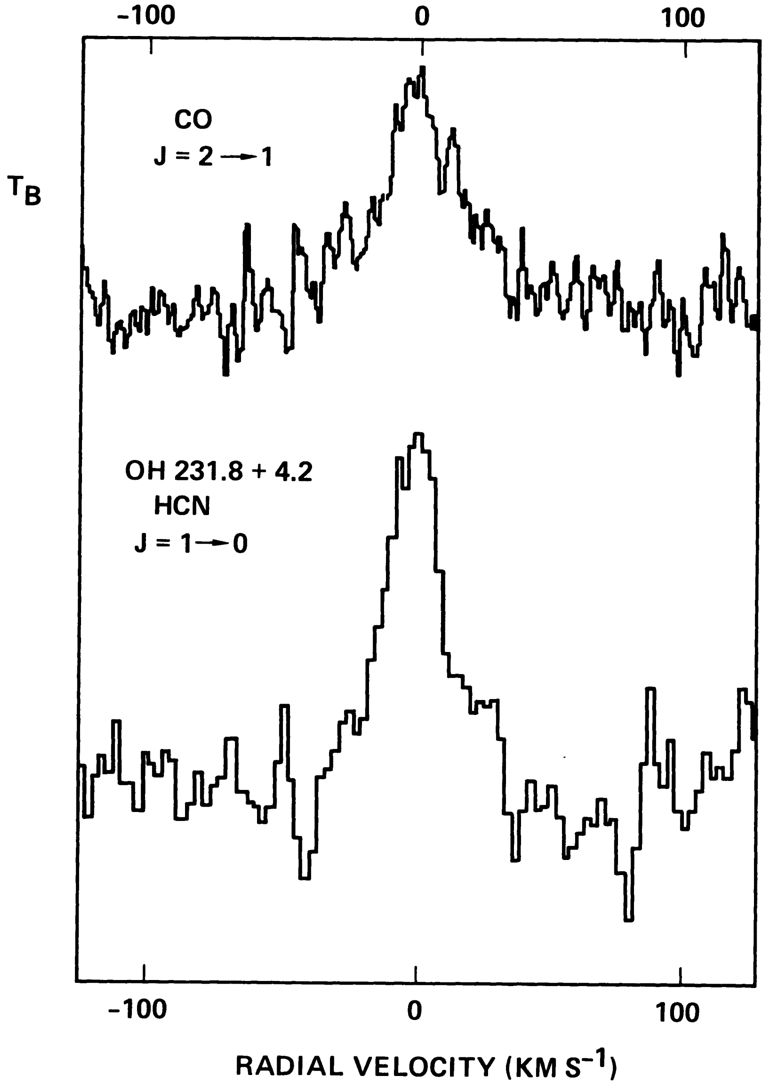

Figure 4: HCN (Deguchi *et al*. 1986) and CO (Jewell *et al*. 1986) spectra of a late M-type (oxygen-rich), bipolar AGB star. Two kinematic components may be seen in each spectrum. The broader one has a somewhat smaller width than the OH maser emission profile from this star. The units on the ordinate are not important and are not shown.

in this type of circumstellar environment with the 14-m University of Massachusetts and 12-m NRAO telescopes. There is, therefore, some hope that the chemistry of O-rich envelopes will prove to be sufficiently rich to challenge theorists.

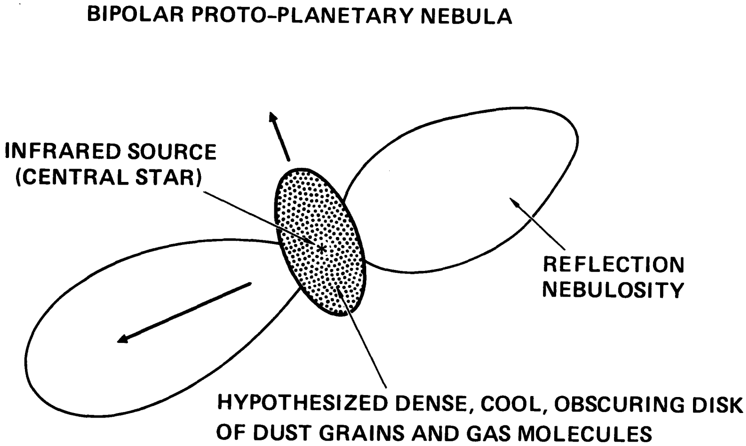

Figure 5: Standard model for the type of bipolar geometry that might explain the two-component profile shown in Fig. 4. Fully 50% of planetary nebulae with known morphologies are bipolar (Zuckerman and Aller 1986).

High-frequency antennae built by the UK and USA on Mauna Kea, Hawaii, should enable investigation of the submillimeter transitions of neutral carbon in circumstellar gas. Perhaps molecular ions, such as HCO^+, will be detected soon also. The very recent detection of vibrationally-excited HCN emission in IRC+10216 by Ziurys and Turner reported at this meeting (and Ap. J., in press) is of special interest for those of us who study circumstellar molecules since their excitation is likely to be due, in most cases, to near infrared radiation which populates the vibrational levels. Future observations of excited vibrational levels of HCN and other molecules should enhance substantially our understanding of the conditions in the expanding envelopes.

Telescopes in the northern hemisphere have been limited to observations of stars north of declination -42°. The new telescopes in Hawaii should reach to about -60° and soon we might have SEST, a large millimeter wavelength telescope in the southern hemisphere.

Finally, increased sensitivity may enable us to detect molecules in the vicinity of classes of stars (e.g., the R CrB and RV Tau types) that never have been seen by radio astronomers. Chemistry in the carbon-rich, hydrogen-poor gas surrounding the R CrB stars might be especially interesting.

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DISCUSSION

LANGER: I don't agree with your argument that the large abundance of HCN in oxygen rich stars implies that C/O is less than 1 in interstellar clouds because you are comparing environments with very different chemistries. The suggestion that C/O > 1 in ISC applies only to the gas phase abundances and there is the possibility that more O is locked up in grains or exists as a frozen H_2O mantle. The failure to detect $^{18}O^{16}O$ in 2 ISC implies that O_2 is much smaller than model predictions. Until O_2 or H_2O are detected in ISC (and not in a hot shock region as the H_2O observations in Orion), there is no evidence supporting C/O < 1; on the other hand, the large CI abundance is consistent

with C/O > 1 even though other (untested) hypotheses may be viable.
ZUCKERMAN: The dominant chemistry in the circumstellar envelope is determined by three body reactions at high densities in and near the stellar photosphere. This chemistry produces very little HCN in environments where O/C > 1. Therefore, in oxygen-rich stars with detectable HCN lines some other, secondary, chemical process must be responsible for the large HCN abundances. Almost, any process, that one can imagine (e.g. ion-molecule reactions, photo dissociation, shocks, etc.), must also be taking place, more or less, in interstellar clouds. Therefore, until we understand how the HCN is produced in the oxygen-rich circumstellar gas, it is certainly premature to say that a similar process is definitely not important in an oxygen-rich interstellar cloud.

OMONT: I would like to mention that we have also detected the transition J = 1-0 in the (0, 2, 0) state of HCN.

SAHAI: The comparison of HCN to H_2 abundance in circumstellar envelopes and IS clouds is not valid because there is little doubt that the neutral-neutral reactions dominate circumstellar chemistry, whereas in IS chemistry ion-molecule abundances are important.
ZUCKERMAN: I do not agree, please see my response to the comment by Dr. Langer.

GREENBERG: The O to C ratio in interstellat dust is certainly > 1 (independent of any currently acceptable grain model) so that it is impossible for the C to O ratio in the gas (in all forms) to be greater than unity if the overall cosmic abundance ratio is already less than unity.

TURNER: We (Ziurys and Turner 1986, Ap.J. (Lett.) 300, L19) see clearly a wing on one side of the HCN (J = 3-2) profile in IRC+10216. Are such wings (deviations from a parabolic lineshape) as unusual as Dr. Zuckerman implied?

PIRRONELLO: What is the present ideas of the mean kinetic energy of particles in carbon stars?
ZUCKERMAN: These winds are blowing out with a mean velocity of about 20 km/s. I can compute the kinetic energy as well as you can. However, if you go towards the planetary nebulae stage, it is known to have larger wind velocities than the red giants, and then the things get complicated as in planetary nebulae, the wind velocity has a large dispersion.

SHAPIRO: Is it agreed by the experts that the general ("cosmic") abundance of oxygen exceeds that of carbon - notwithstanding local fluctuations of the O/C ratio?
ZUCKERMAN: Main sequence stars are oxygen-rich (O/C > 1) as is the ionized gas in H II regions such as the Orion Nebula.