JOINT DISCUSSIONS

DIFFUSE INTERSTELLAR CLOUDS

DAVID L. LAMBERT
Department of Astronomy
The University of Texas
Austin, TX 78712, USA

S. R. FEDERMAN
Department of Physics and Astronomy
University of Toledo
Toledo, OH 43606, USA

Abstract: Diffuse clouds are interstellar objects through which starlight is not greatly extinguished. As a result, many studies rely on ultraviolet and visible measurements. The focus of this review is on spectroscopic work involving atomic and molecular lines. From these measurements, the physical and chemical makeup of the clouds is derived. Here we stress that technological advances have influenced our perception of diffuse clouds.

1.   Introduction

Even the casual explorer will discover that interstellar gas is far from uniformly distributed. The concept of 'interstellar clouds' was introduced long ago. Physical conditions within clouds differ so greatly that sub-classifications of interstellar clouds are necessary. This short review is devoted to diffuse clouds which may be defined as "regions of the interstellar gas in which the total continuous extinction by dust particles at visual wavelengths, A_V, is less than 2 magnitudes" (van Dishoeck 1990). Other major classes of interstellar clouds are the 'dense clouds', 'H II regions', and 'supernova remnants'. The clouds are separated by lower density intercloud gas that may be warm (T ~ 10^3-10^4 K) to hot (T ~ 10^6 K).

Individual isolated clouds with $A_V \lesssim 2$ across their maximum extent are, by definition, diffuse clouds. A portion of a cloud may resemble a diffuse cloud in physical and chemical properties, yet the contiguous regions forming the bulk of the cloud may be of a different type. Obvious examples of such partial diffuse clouds are:
  • the outer skin of a dense cloud that is penetrated by the general interstellar radiation field;
  • the interface between a H II region sustained by young hot stars and the remainder of their parental dense cloud. This interface dubbed "a photodissociation region" (Tielens and Hollenbach 1985) may resemble an isolated diffuse cloud.

Why study diffuse clouds? With only a slight exercise of poetic licence, we may note that studies of diffuse clouds offer insights into the formation of stars in dense clouds, the chemical evolution of the galaxies, and the origin of the Universe:
  • **Star formation**. An understanding of dense clouds and their ability to sustain star formation will require, in part, the specification of their physical and chemical conditions. It is supposed that observational studies of their simpler cousins - the diffuse clouds - will be helpful to understanding the dense clouds.
  • **Galactic chemical evolution**. The chemical composition of the entire (gas plus dust) diffuse cloud is not readily estimated from the atomic and ionic abundances of the gaseous component because the depletion of gas onto grains is a major but poorly understood determinant. A few opportunities exist, however, to obtain some data pertinent to galactic chemical evolution. In particular, the isotopic ratios D/H and $^{12}C/^{13}C$ have proven of interest to modellers of galactic chemical evolution.

65

• **The origin of the Universe**. The claim that diffuse clouds hold clues to the Universe's origin is, of course, based in part on the use of the CN molecule's rotational ladder as a thermometer of the cosmic microwave background. Even with the spectacular success of the COBE satellite, the CN molecule remains of cosmological interest. Since the Big Bang is most probably the only site for D synthesis and D is most reliably measured in the diffuse clouds, the D/H ratio is of cosmological interest.

2. An Historical Perspective

In the beginning, diffuse clouds were probed exclusively by photographic spectroscopy of bright stars behind the clouds. Analyses of a cloud's absorption lines led to several important discoveries, including the detection of the diatomic molecules CH, CH^+, and CN, and the severe depletion of Ca in the gaseous phase. With the advent of 21-cm H I observations, the physical conditions in the clouds were further characterized; for example, the H I spin temperature provided an estimate of the kinetic temperature ($T_{spin} \cong T_{kin} \simeq 100$ K). 21-cm observations also provided much information on the Galactic distribution of neutral H.

Expansion of observational characterization of diffuse clouds was provided by the *Copernicus* satellite (Spitzer 1978). Among many major highlights, we may mention: the demonstration that the H_2 molecule is prevalent in all but the most diffuse of clouds (interstellar H_2 was discovered by Carruthers 1970); the applications of the H_2 lowest (J = 0 and 1) rotational levels to measure the kinetic temperature of a cloud and of the high (J $\gtrsim$ 3) rotational levels to measure the local ultraviolet radiation field (Spitzer & Cochran 1973, Spitzer, Cochran, & Hirshfield 1974; Savage *et al.* 1977); the studies of the transition from atomic (H I) gas at a cloud's edge to molecular (H_2) gas in the interior with self-shielding of H_2 being the dominant factor in reducing the photodissociation rate (Federman, Glassgold, and Kwan 1979); the use of the populations of atomic fine structure levels (*e.g.*, C I $^3P_{0,1,2}$) to determine the pressures within clouds (Jenkins & Shaya 1979); measurements of column densities for many atoms in one or more stages of ionization led to estimated elemental abundances for the gas and to a characterization of the depletions of these elements into/onto the dust grains (see review by Jenkins 1987).

Analyses of *Copernicus* spectra in combination with optical spectroscopy suggested that a typical diffuse cloud has a kinetic temperature $T_{kin} \sim 70$ K, and a density $n_t(H I + 2H_2) \sim 100$ cm^{-3}. The cloud radius is $r \simeq 5$ pc, as inferred from n_t and the measured column densities, as well as from maps of interstellar extinction (Knude 1979) and from 21-cm observations of the angular radius (Crovisier *et al.* 1985). Turbulence within the cloud as estimated from the curve of growth for the uv absorption lines and from 21-cm line widths is typically $\xi \sim 3$ km s^{-1}.

3. The Revolutions of the 1980s and 1990s

Thanks to the introduction of sensitive detectors (Reticons, CCDs) in high resolution optical spectrographs, and to the development of millimeter and radio spectroscopy, the revolution begun by *Copernicus* continues using ground-based telescopes. Today, ultraviolet spectra from the *Hubble Space Telescope* (HST) are further expanding our knowledge of diffuse clouds.

3.1 CHEMISTRY OF DIFFUSE CLOUDS

The observer interested in cloud chemistry sets out to measure the column density of many neutral atoms, ions, and molecules and to compare the results with predictions from a network of chemical reactions operating at the estimated physical conditions (T,n). Most calculations assume that the network is run at a steady-state. Some calculations consider the transient effects of interstellar shocks. Observational tests may take two limiting forms: (i) comparison of observed and predicted column densities for a few species for an ensemble of clouds, and (ii) detailed comparisons of many atomic and molecular species for individual clouds. One may further distinguish two approaches to testing the proposed chemical reaction networks: (i) local tests in which two (or a few) species are compared and (ii) global tests in which the entire network is tested.

As examples of local tests, we comment on CH, C_2, and CN. Formation of CH is initiated by $C^+ + H_2 \rightarrow CH_2^+ + h\nu$, see Federman's (1982) reaction network. The adopted reactions rates are a mix of measured, theoretical, and estimated rates. Note, in particular, that the rate for $C^+ + H_2 \rightarrow CH_2^+$ is quite uncertain and usually set by the observed CH abundance! Examination of the network shows that the (volume) density n(CH) is approximately proportional to $n(H_2)$, or $N(CH) \propto N(H_2)$ where N denotes a column density, *i.e.*, an observable quantity. Danks, Federman, and Lambert (1984) compared observations and predictions where N(CH) was derived from observations of CH at 4300 Å and $N(H_2)$ was taken from *Copernicus* observations of H_2 (Bohlin *et al.* 1978). Predictions for model clouds of high ($n_t = 2500$ cm^{-3}, T = 30 K) and low density ($n_t = 150$ cm^{-3}, T = 55 K) bracket the observed linear relation between N(CH) and $N(H_2)$. The observed scaling of CH with H_2 suggests that synthesis of CH is well understood in diffuse clouds. A reaction scheme for CH synthesis in atomic H may be identified (Bates & Spitzer 1951; Solomon & Klemperer 1972), but too little CH is produced and, moreover, the scheme predicts $N(CH) \propto N(H\ I)$, but the observed CH-H I relation is a scatter diagram (Federman 1982). Diffuse cloud chemistry of CN was investigated by Federman, Danks, and Lambert (1984, FDL) who suggested that observations supported a relation $N(CN) \propto N(H_2)^3$ and proposed that CN is produced from CH by $CH + N \rightarrow CN + H$ and primarily from C_2 by $C_2 + N \rightarrow CN + C$ and destroyed by photodissociation. For the thicker diffuse clouds and the dense clouds, direct estimates of H_2 column densities are unavailable. In such cases, Federman and Lambert (1988) and van Dishoeck and Black (1989) use CH as a surrogate for H_2 and compare observations and predictions through plots of $N(C_2)$ vs N(CH) and N(CN) vs N(CH). With the photodissociation rate used by Black and Dalgarno (1977), FDL (see also Federman and Lambert 1988) showed that the observed CN abundance was then predicted correctly using the observed abundances of C_2 and CH. The great strength of these tests is that they are largely immune to uncertainties in those parts of the theoretical network controlling the abundance of C_2 and CH.

In contrast to the above studies are the comprehensive analyses of clouds along individual lines of sight. Papers by van Dishoeck and Black (1986, 1989) are *the* standard in this latter field. It is patently impossible to give here anything but the flavor of vDB's calculations. A cloud is taken to consist of homogeneous plane-parallel layers in hydrostatic equilibrium and subjected to an external pressure. The radiation field inside the cloud is calculated in some detail and, in particular, the self-shielding of H_2 and CO is evaluated. Except for the formation of H_2, the dust grains are not considered to contribute directly to the formation of molecules. The grains, of course, influence the chemistry through their control of the uv radiation field and the selective depletion of atoms in the gas. The chemical reaction network is assumed to have attained equilibrium. In cases considered to date a single cloud is assumed to dominate the line of sight.

Physical conditions (*i.e.*, n_t,T) within the cloud are constrained by several observed column densities: N(low J,H_2) and N(low J,C_2) $\rightarrow$ T; N(high J,C_2) and the fine structure populations of C, C^+, and O $\rightarrow$ f(n_H,T). The high J (≥ 3) levels of H_2 are assumed to be populated by fluorescence and, hence, N(high J,H_2) provides an estimate of the intensity (I_{uv}) of the ultraviolet radiation field. (If these levels are populated through shocks or by the formation of H_2 on the grains, I_{uv} will be overestimated.) The observed H_2/H ratio measures the ratio $n_H y_f / I_{uv}$ where y_f is the efficiency of H_2 formation on grains. The model clouds have warm exteriors (T ~ 100-200 K) and cool denser interiors (T ~ 30 K). Note that thermal equilibrium was not a requirement of the models and, in fact, the known heating sources are inadequate to maintain the exterior layers at the above temperatures - see van Dishoeck (1990). Prescriptions for model construction are completed by specifying a set of parameters, such as the depletions of the elements onto the grains, the rate of ionization by cosmic rays, the values of key uncertain chemical reaction rates, *etc.*

The following comparison of observed (Ob) and predicted (Pr) column densities is for the line of sight to ζ Per - see van Dishoeck (1990, Table 2) for discussion of the selected model and the sensitivities of the predictions to physical conditions and assumptions. When the observational and model uncertainties are considered, N(Ob) $\cong$ N(Pr) for all but CO, CH^+, CN, and NH.

	C	C$^+$	CH	C$_2$	OH	CO	CH$^+$	CN	NH
Ob	3.3,15	3.0,17	2.0,13	1.9,13	4.2,13	6.1,14	3.5,12	3.0,12	9.0,11
Pr	3.1,15	3.8,17	2.1,13	1.0,13	5.0,13	7.1,13	2.6,11	4.8,11	2.4,10

CO and CN: Photodissociation controls the destruction of both molecules. Thanks to recent work, the photodissociation cross-sections appear to be well known, but the rates in diffuse clouds depend, of course, also on the incident uv radiation field (at $\lambda \lesssim 1000$ Å) and the extinction properties of the grains. Note that vDB's (theoretical) photodissociation rate for CN is greater than that adopted by Federman and Lambert (1988) who obtained agreement between the observed and predicted N(CN). Quite probably, the large discrepancy between N(Ob) and N(Pr) for CO and CN is due to an overestimate of I_{uv} which may have resulted from the assumption that the high-J levels of H$_2$ are populated entirely by fluorescence.

NH: The observed N(NH) is provided by Meyer and Roth (1991) who obtained the first detections of NH in diffuse clouds. Meyer and Roth offered two ideas for increasing the predicted N(NH). First, they noted that the initiating reaction for N chemistry (N$^+$ + H$_2$ → NH$^+$ + H) was probably underestimated by vDB. Second, they proposed that NH may be formed primarily on grains, either directly as NH or indirectly as NH$_3$. Although hydride formation on grains is likely to operate with similar efficiencies for NH, CH, and OH (Crutcher and Watson 1976), the expected contributions from grains to CH and OH formation are negligible relative to the contributions from gas-phase chemistry. Examination of NH in an ensemble of clouds may reveal clues to the importance of the dust grains. It may be noted that with the observed amount of NH, about 30% of the observed CN can be formed via a sequence beginning with C$^+$ + NH → CN$^+$ + H.

CH$^+$: The observed N(CH$^+$) for ζ Per (and other clouds) greatly exceeds the predicted values for cool atomic (H) and for cool molecular (H$_2$) gas. Elitzur and Watson (1978) proposed that CH$^+$ was formed by the endothermic reaction C$^+$ + H$_2$ → CH$^+$ + H - 0.4 eV in gas heated (T ~ 2000 K) by the passage of a shock front. Another endothermic reaction, O + H$_2$ → OH + H - 0.4 eV, leads to OH production. However, as noted in the above Table, adequate OH is produced in cool molecular gas and, hence, shocks that account for CH$^+$ apparently produce excess OH. This difficulty was alleviated with the introduction of magnetohydrodynamic shocks (Draine and Katz 1986). Then, in the postshock gas, the ions drift relative to the neutrals and the endothermicity of C$^+$ + H$_2$ can be overcome at a lower temperature. The neutral-neutral reaction leading to OH is suppressed. Unfortunately, several problems remain: (i) the predicted velocity shifts between CH$^+$ and species formed in the cold compressed post-shock (and preshock) gas are not observed consistently; (ii) extant calculations of CH$^+$ synthesis in MHD shocks are unable to account for the high N(CH$^+$) (~ few x 10^{13} cm^{-2}) observed along some lines of sight; (iii) the MHD calculations require n(H$_2$)/n(H) ~ 1 in the low density preshock gas for efficient CH$^+$ production, but such a concentration of H$_2$ requires a high extinction and, hence, a large cloud which should be betrayed by strong lines of Na D, *etc.*

Although theoretical exploration of shocks has not yet been exhausted, it appears timely to investigate other scenarios. Photodissociation regions (Tielens and Hollenbach 1985) offer a likely site for CH$^+$ formation. White (1984) proposed that CH$^+$ near the Pleiades was formed as molecular gas flowing through the cluster was heated and dissociated; this involves a PDR as part of a diffuse cloud. Other observed tracers of warm gas in a PDR or elsewhere must be considered with CH$^+$; *e.g.*, OH and the high J levels of H$_2$ (Lambert and Danks 1986). It is high time that we understood the chemistry of CH$^+$, a readily oberved radical that is almost ubiquitous in diffuse clouds.

In summary, understanding of the chemistry within diffuse clouds progressed remarkably in the 1980s. As illustrated above, striking problems remain. For some of these problems, their solution may be found among the microscopic processes controlling the chemistry, *e.g.*, a new experiment or a quantum calculation may show an adopted rate constant to be in error, additional observations may suggest that the ultraviolet extinction by the dust grains is not what is now assumed, and so on. Before a complete

quantitative accounting is achieved for all species, one may suppose that the present simple cloud models must be made more realistic: plane-parallel or spherical models in steady state and illuminated uniformly from the outside are easily handled, but nature's clouds are surely more complex. The challenge to the interstellar chemist in the 1990s is to formulate observational constraints that may allow the construction of more realistic models.

3.2   HIGH-RESOLUTION SPECTROSCOPY

Since the diffuse clouds are cold and not highly turbulent, high spectral resolution is needed to resolve the line profiles of a cloud's absorption and emission lines. Resolved lines are routinely provided at millimeter/radio wavelengths, but interpretation is then possibly compromised by the finite beam width of the telescopes. At optical and ultraviolet wavelengths where the clouds are probed by absorption line spectroscopy, the beam width defined by the angular diameter of the background star is exquisitely narrow, but the spectral resolution is too often an order of magnitude or more less than that required to resolve the interstellar lines. The principal advantages of spectra providing resolved line profiles were succinctly stated by Hobbs and Welty (1991) who discuss observations of the Na D_1 line at a resolution of 0.6 km s^{-1}: "First, a nearly full enumeration of the various kinematically distinct parcels of gas along the observed light path is realized, within the unavoidable limits set by any negligible differences between the radial velocities of spatially separate gas clouds and by the minimum column density which corresponds to the threshold for detection of the line. Second, accurate measurements can be made of the widths of the resolved line components, and hence of upper limits on the temperature and on the internal mass motions of each distinct cloud." The realization that a line seen on low resolution spectra is formed in "kinematically distinct parcels of gas" necessarily affects the conversion of equivalent width to column density, but the errors presently incurred in analysis of low resolution spectra are largely irrelevant to the intercomparison of observed and predicted column densities of atoms and molecules because (i) the observations can often be based on weak lines and (ii) the predicted column densities contain much greater uncertainties. The principal novelty offered by the identification of "kinematically distinct parcels of gas" comes from the comparison of profiles provided by the distinct "parcels" and especially by comparisons of profiles for lines sensitive to different physical conditions, *e.g.*, CH and CH$^+$, or C I ($^3P_0$) and C I ($^3P_2$). Brief remarks on recent papers must suffice to illustrate these advantages of high resolution spectroscopy (HRS).

The Na D lines. HRS of the Na D lines was pioneered by Hobbs (1969). Blades, Wynne-Jones, and Wayte (1980) resolved the hyperfine structure components in clouds in front of δ and α Cyg. Hobbs and Welty (1991) have used the Tull (1972) spectrograph at the McDonald Observatory's 107-inch telescope to observe the Na D_1 line at a resolution of 0.6 km s^{-1}. Observations of six bright stars showed at least 43 distinct "parcels" with many clear detections of the two hfs components from a single cloud. Upper limits to a cloud's kinetic temperature and turbulent velocity were obtained directly from linewidths corrected for the instrumental profile: limits of T $\leq$ 400 K and ξ < 0.5 km s^{-1} are common with the most stringent limits being T < 100 K and ξ < 0.24 km s^{-1}. Not all the clouds are cold with subsonic turbulence. Six of the 43 clouds have widths requiring T > 2500 K if ξ = 0 km s^{-1} or ξ > 1.0 km s^{-1} if the cloud is very cold. By observing lines of species differing in mass, it may be possible to resolve the thermal and turbulent contributions to the linewidth; for example, observations of CH 4300 Å and Na D or Na D and K I 7699 Å. Of course, many components seen in Na D will not provide detectable lines in the other species. Pursuit of this work is highly desirable because all other estimates of the kinetic temperature are indirect and based on excitation temperatures.

CH and CH$^+$ toward ξ Per. Interstellar lines in the spectrum of ξ Per were an early target for the GHRS (Cardelli *et al.* 1991; Savage *et al.* 1991; Smith *et al.* 1991). Prior to the HST observations the CH 4300 and CH$^+$ 4232 Å lines were observed with the Tull spectrograph at a resolution of 0.8 km s^{-1} (Crane, Lambert, and Sheffer, 1991) - see Lambert, Sheffer, and Crane (1990; also Crane, Hegyi, and Lambert 1991) for discussion of similar observations of ζ Oph. Figure 1 shows the ξ Per profiles. The profiles were analyzed using a three-cloud model. For CH each component was represented by two identical sub-components separated by 1.0 km s^{-1}, which is the splitting of the Λ-type doublet for this transition.

Our observations of ζ Oph clearly resolved the Λ-type doublet. In the case of ξ Per, the individual lines, here presumed to come from a single cloud, are broader and the Λ-type doubling is not resolved. The doublet structure in the core of the CH line arises from the presence of two clouds. By inspection of Figure 1, one can see that the CH and also the CH^+ line has a broad component to the red of the two narrower lines. The following table summarizes the heliocentric radial velocities (v in km s^{-1}), the relative column densities (N), and the widths (FWHM-corrected, Δv in km s^{-1}) of the three components:

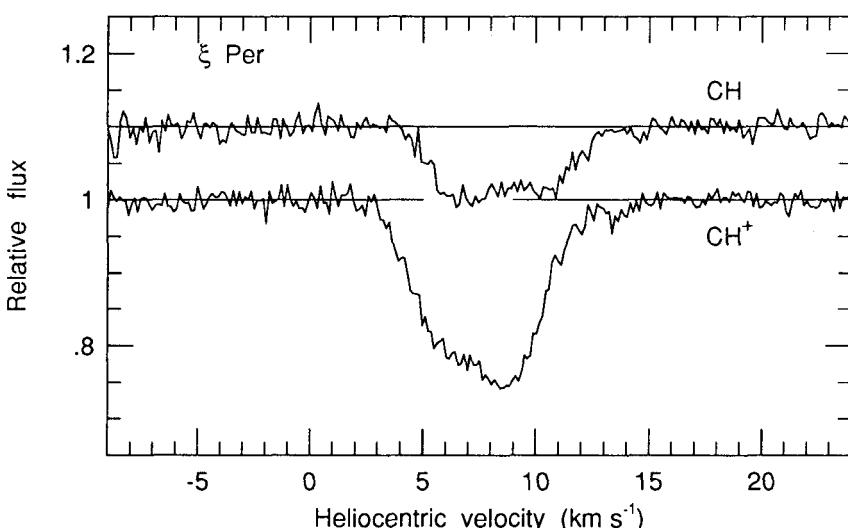|	CH				CH^+	
v	Δv	N		v	Δv	N
7.3	2.3	1.00		6.2	3.4	1.00
10.7	2.4	0.85		9.3	3.3	1.22
13.3	11.0	0.54		12.3	6.0	0.21

Figure 1. Observed line profiles of CH 4300 Å and CH^+ 4232 Å lines in the spectrum of ξ Per at a resolution of 0.6 km s^{-1}.

Existence of the three components was seen first in optical atomic lines: Na D (Hobbs 1969), K I 7699 Å (Hobbs 1974), and Ca II K (Marschall and Hobbs 1972); the broad CH and CH^+ component is probably to be identified with the 'atomic' component at v = +16 km s^{-1}. A weak Ca II K and Na D component at +25 km s^{-1} has no molecular counterpart.

Broad (Δv ≳ 10 km s^{-1}) components of CH and CH^+ lines are common (Crane et al. 1991), but the Na D_1 profiles (Hobbs and Welty 1991) do not show the equivalent component; the corresponding b-value for Na D_1 is b > 4.5 km s^{-1}, if the width of the CH/CH^+ component is entirely thermal, and, the lower limit approaches b > 6.0 km s^{-1} if turbulence is dominant. Hobbs and Welty (1991) give b = 2.6 and 1.9 km s^{-1} as the two largest b-values in their sample of 43 components. This shocking (!) difference deserves further study.

We comment next on some of the ultraviolet line profiles that show cloud-to-cloud differences for ξ Per. Of especial interest as a diagnostic of physical conditions are the C I lines from the ground state $^3P_0$ and the excited fine structure states $^3P_1$ and $^3P_2$. The GHRS spectra clearly show that the $^3P_2$ atoms contribute only to the +7 km s^{-1} component, the $^3P_1$ atoms to the +7 and +10 km s^{-1} components, and

the $^3P_0$ atoms to the three (+7, +10, and +13 km s^{-1}) components. Since the velocity differences between the components are comparable to the instrumental resolution, the estimation of relative column densities for the blended components is necessarily less certain than for the CH/CH$^+$ lines. Nonetheless, the differences between the C I ^3P profiles clearly show that the +7 km s^{-1} (and the +10 km s^{-1}) component is of much higher gas pressure than that at +13 km s^{-1} - see Smith *et al.* (1991) for further discussion.

Strong uv lines of Fe II, O I, and other species betray the presence of components that may be too tenuous to detect in optical lines. For ξ Per such lines show absorption over the range -5 to +25 km s^{-1}, a range broader than that (+5 to +15 km s^{-1}) of most optical and other uv lines sampling the diffuse clouds. Of particular interest is the +25 km s^{-1} gas, also seen at Ca II K and Ti II (Stokes 1976) in the optical. Savage *et al.* show that the gas phase abundances are solar for this component, but the usual severe depletions prevail in the lower velocity (diffuse) gas: "Evidently in the lower column density medium the heavily depleted elements are returned to the gas phase by a process that has converted dust into gas with nearly complete conversion in the +25 km s^{-1} component and partial conversion in the -5 km s^{-1} component". Note the implicit assumption: the gas in question did once contain grains. In the diffuse clouds (+5 to +15 km s^{-1}), the depletions are more severe in the higher pressure +7 km s^{-1} components than in the +10 and +13 km s^{-1} components. The ξ Per line of sight also contains 'ionized' gas betrayed by Al III, S III, Si IV, and C IV lines extending over the range -20 to +20 km s^{-1} (Savage *et al.* 1991).

Where is this gas that is almost free of grains? How are the grains destroyed? By examining other lines of sight, including those traversing a H II region, it may be possible to answer these questions. Then, it may be possible to examine other more fundamental questions: at what rate are grains formed in circumstellar envelopes destroyed in the interstellar medium? Is this rate so rapid that grains must also be formed in the interstellar medium? If ξ Per is typical, it is only a small fraction of interstellar gas that has been rid of grains.

Our discussion has been biased toward what we know best, interstellar spectroscopy, but because of the advances made within the past decade in far infrared and gamma-ray astronomy, we close with recent findings in these fields. Interstellar dust grains preferentially absorb short-wavelength radiation from the Galactic distribution of stars and re-emit the energy at far infrared wavelengths. This emission from dust in diffuse clouds near O and B stars has been detected by IRAS. For instance, the cloud in front of the Pleiades shows enhanced emission in the directions to the brightest stars (Castelaz, Sellgren, and Werner 1987); moreover, hot spots caused by enhanced emission at 60 micrometers (relative to 100 micrometers) seen toward other B stars (Van Buren 1989; Federman, Strom, and Good 1991). This emission is associated with the infrared cirrus discovered by Low *et al.* (1984). Boulander and Perault (1988) have studied the association between infrared cirrus and diffuse clouds. The COS-B satellite has provided the most complete picture of diffuse gamma-ray emission. For energies between 50 MeV and 5 GeV, the emission arises through interactions between cosmic rays and interstellar matter (Bloemen 1989). Bloemen describes the information extracted from the data, including the important conversion factor relating CO to H$_2$.

"Judicious omissions and hazardous generalities" was how Bowra (1967), the classical scholar and Oxford wit, described the ingredients of reviews he was requested to write. We hope that despite the omissions and generalities to which we plead guilty, this review will appeal to a few now presently engaged in other activities to turn to investigate problems of the diffuse clouds.

References

Bates, D. R., and Spitzer, L., Jr. 1951, *Ap. J.*, **113**, 441.
Black, J. H., and Dalgarno, A. 1977, *Ap. J. Suppl.*, **34**, 405.
Blades, J. C., Wynne-Jones, I., and Wayte, R. 1980, *M.N.R.A.S.*, **193**, 849.

Bloemen, H. 1989, *An. Rev. Astron. Astrophys.*, **27**, 469.

Bohlin, R. C., Savage, B. D., and Drake, J. F. 1978, *Ap. J.*, **224**, 132.

Boulanger, F., and Perault, M. 1988, *Ap. J.*, **330**, 964.

Bowra, C. M. 1967, *Memories 1898-1939*, (Cambridge: Harvard Univ. Press).

Cardelli, J. A., Savage, B. D., Bruhweiler, F. C., Smith, A. M., Ebbets, D. C., Sembach, K. R., and Sofia, U. J. 1991, *Ap. J. (Letters)*, **377**, L57.

Carruthers, G. R. 1970, *Ap. J. (Letters)*, **161**, L81.

Castelaz, M. W., Sellgren, K., and Werner, M. W. 1987, *Ap. J.*, **313**, 853.

Crane, P., Hegyi, D. J., and Lambert, D. L. 1991, *Ap. J.*, **378**, 181.

Crane, P., Lambert, D. L., and Sheffer, Y. 1991, in preparation.

Crovisier, J., Dickey, J. M., and Kases, I. 1985, *Astr. & Astrophys.*, **146**, 233.

Crutcher, R. M., and Watson, W. D. 1976, *Ap. J.*, **209**, 778.

Danks, A. C., Federman, S. R., and Lambert, D. L. 1984, *Astr. & Astrophys.*, **130**, 62.

Draine, B. T., and Katz, N. 1986, *Ap. J.*, **310**, 392.

Elitzur, M., and Watson, W. D. 1978, *Ap. J. (Letters)*, **221**, L141.

Federman, S. R., 1982, *Ap. J.*, **257**, 125.

Federman, S. R., and Lambert, D. L. 1988, *Ap. J.*, **328**, 777.

Federman, S. R., Danks, A. C., and Lambert, D. L. 1984, *Ap. J.*, **287**, 219.

Federman, S. R., Glassgold, A. E., and Kwan, J. 1979, *Ap. J.*, **227**, 466.

Federman, S. R., Strom, C. J., and Good, J. C. 1991, *A.J.*, **102**, 1393.

Hobbs, L. M. 1969, *Ap. J.*, **157**, 135 and 165.

Hobbs, L. M. 1974, *Ap. J.*, **188**, L67.

Hobbs, L. M., and Welty, D. E. 1991, *Ap. J.*, **368**, 426.

Jenkins, E. B. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach and H. A. Thronson, Jr. (Dordrecht: Reidel), p. 533.

Jenkins, E. B., and Shaya, E. J. 1979, *Ap. J.*, **231**, 55.

Knude, J. 1979, *Astr. & Astrophys. Suppl.*, **38**, 407.

Lambert, D. L., and Danks, A. C. 1986, *Ap. J.*, **303**, 401.

Lambert, D. L., Sheffer, Y., and Crane, P. 1990, *Ap. J. (Letters)*, **359**, L19.

Low, *et al.* 1984, *Ap. J. (Letters)*, **278**, L19.

Marschall, L. A., and Hobbs, L. M. 1972, *Ap. J.*, **173**, 43.

Meyer, D. M., and Roth, K. C. 1991, *Ap. J. (Letters)*, **376**, L49.

Savage, B. D, Bohlin, R. C., Drake, J. F., and Budrich, W. 1977, *Ap. J.*, **216**, 291.

Savage, B. D., Cardelli, J. A., Bruhweiler, F. C., Smith, A. M., Ebbets, D. C., and Sembach, K. R. 1991, *Ap. J. (Letters)*, **377**, L53.

Smith, A. M., Bruhweiler, F. C., Lambert, D. L., Savage, B. D., Cardelli, J. A., Ebbets, D. C., Lyu, C.-H., and Sheffer, Y. 1991, *Ap. J. (Letters)*, **377**, L61.

Solomon, P. M., and Klemperer, W. 1972, *Ap. J.*, **178**, 389.

Spitzer, L., Jr. 1978, *Physical Processes in the Interstellar Medium*, (New York: Wiley).

Spitzer, L., Jr., and Cochran, W. D. 1973, *Ap. J. (Letters)*, **186**, L23.

Spitzer, L., Jr., Cochran, W. D., and Hirshfeld, A. 1974, *Ap. J. Suppl.*, **28**, 373.

Stokes, G. M. 1978, *Ap. J. Suppl.*, **36**, 115.

Tielens, A. G. G. M., and Hollenbach, D. J. 1985, *Ap. J.*, **291**, 722.

Tull, R. G., in *Proc. ESO/CERN Conf. on Aux. Instrumetation for Large Telescopes*, (Geneva: ESO), p. 259.

Van Buren, D. 1989, *Ap. J.*, **338**, 147.

van Dishoeck, E. F. 1990, in *The Evolution of the Interstellar Medium*, ASP Conf. Series Vol. 12, p. 207.

van Dishoeck, E. F., and Black, J. 1986, *Ap. J. Suppl.*, **62**, 109.

van Dishoeck, E. F., and Black, J. 1989, *Ap. J.*, **340**, 273.

White, R. E. 1984, *Ap. J.*, **284**, 695.