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The Transition from Diffuse to Dense Clouds*

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Abstract

Optical and ultraviolet spectroscopy have shown that diffuse interstellar clouds can have a wide range of properties, with especially large variations in the nature of the UV extinction curve and the abundances of molecular species. More subtle variations are found in the properties of the diffuse interstellar bands, and there have been suggestions that elemental depletions from the gas phase into solid dust particles also vary significantly. It is the purpose of this paper to review studies of the relatively diffuse interstellar clouds where these variations occur, and to explore the possible relationship between dust properties, as indicated by UV extinction, and other cloud characteristics. The focus is on relatively dense diffuse clouds, which may be viewed as transitional or intermediate between ordinary diffuse clouds and dark clouds, because in principle the greatest amount of information is available for the intermediate clouds, and because they serve as indicators of processes that may occur in the denser molecular clouds. The paper begins with a brief review of some results from the literature on transitional or intermediate clouds, and then provides a summary of some recent results on one particular cloud, in front of the star BD+31°643, in the small open cluster IC348, which is part of the Perseus II complex of dark clouds and OB associations. The paper concludes with some tentative speculations about the possible status of the transitional clouds, along with a brief mention of the impact of upcoming instrumental developments on research in this area.

1. Introduction

While we cannot directly probe dark clouds using optical or ultraviolet observing techniques, the benefits of these methods are such that it can be useful to apply them to less dense clouds and use these regions as indicators of dark-cloud processes. These benefits include the ability to sample the abundances of various species in their ground state (via absorption lines) instead of some excited level (via emission lines); the accessibility of atomic as well as molecular species that are not observable through radio or infrared techniques; the ability to measure abundances and conditions in infinitesimally narrow beams along the sightlines to background stars; and the availability of information on the properties of dust in the observed material, since dust is largely invisible at radio wavelengths and provides information in the optical and the UV that cannot be duplicated by IR observations.

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The ideal situation from the observational point of view is one in which the same line of sight can be observed in optical, ultraviolet, infrared, and radio wavelengths, for then it is possible to combine the various types of information unique to each methodology and create the broadest possible picture of the observed material. This paper will review current studies of such regions, and will describe some results recently obtained on one particular cloud.

The clouds to which multi-spectral observations can be applied are intermediate in properties between the diffuse clouds (which typically have densities of 10 to 100 cm^{-3} and temperatures in the range from 50 to 100 K) and truly dark clouds (which would have densities in excess of 10^3 cm^{-3} and temperatures below 50 K). The intermediate clouds will have densities of several hundred cm^{-3} and temperatures of perhaps 30 to 50 K, and, in order to be observable in all the different wavebands, will have total line-of-sight visible extinctions of order 3 to 5 magnitudes (and there is reason for optimism that considerably darker sightlines can soon be probed in the optical, through the use of new 8- to 10-m class telescopes). But such clouds are probably not going to be observable in the ultraviolet in the foreseeable future—the capability of the Hubble Space Telescope (HST) for observing UV absorption lines in dark clouds will be discussed later in this paper.

The intermediate clouds that are the subject of this paper are interesting because they can truly represent intermediate conditions and processes between those that dominate in diffuse clouds and those that are effective in dark clouds. For example, it is found that in clouds with total extinction A_V in the range 2 to 4 magnitudes, significant chemical processing can occur, leading to a substantial molecular content (e.g. Jannuzi *et al.* 1988; van Dishoeck and Black 1986). Such clouds have been dubbed 'translucent' clouds by Jannuzi *et al.* (1988), but in this paper we will tend to refer to them as 'intermediate' clouds.

One of the questions of interest in probing the chemical and physical conditions is the relative importance of competing excitation processes. For example, shock-induced chemical reactions have been invoked by some authors as a means of explaining the high abundances of certain species (such as CH^+) that require activation energy for their formation, but there are competing scenarios in which excitation due to ultraviolet radiation provides the necessary energy. By exploring clouds known to represent a range of UV radiation field intensities, it may be possible to distinguish between these mechanisms. Another question of interest involves the competition between gas-phase and surface reactions in cloud chemistry. Whereas in diffuse clouds it is clear that gas-phase reactions dominate (except for molecular hydrogen), in dark clouds it appears possible that formation on dust grain surfaces is a viable formation mechanism. It may be possible to address this question by examining the intermediate clouds, searching for species (such as NH and NaH, both of which have optical transitions) which can only form on grains because there are no feasible gas-phase reactions which produce them.

The next section will provide a review of work that has been done on the intermediate clouds. The following section will then describe some recent work on one particular cloud, and the final section will summarise current results from this area of research and make some comments on future directions.

2. Results of Previous Studies

(2a) General Studies of Intermediate Clouds

The limited range of species that could be observed before the advent of ultraviolet absorption-line studies in the 1970s prevented much work from being done in probing detailed processes such as cloud chemistry or depletions onto dust grains. Some hints of these processes were derived from optical data; for example, the presence of large quantities of the diatomic molecules CH, CN, and CH^+ stimulated intensive studies of gas-phase chemistry in interstellar clouds (see the review by Black and van Dishoeck 1991) and produced some indication of the existence of elemental depletions (e.g. Routly and Spitzer 1952). But only when it became possible to observe many lines of a number of different atomic and molecular species (including the dominant molecules H_2 and CO) did a large amount of attention begin to be paid to the diffuse interstellar medium. Ironically, the revolution in UV technology has also stimulated a resurgence of optical absorption-line work, much of it directed toward the relatively dark and dense clouds that are the subject of this paper.

A number of authors have carried out comprehensive analyses of relatively dense diffuse clouds. These include Crutcher (1985), who undertook a study of the notoriously peculiar line of sight through parts of the Taurus cloud to the star HD29647 [see Snow and Seab (1980) and Goebel (1983) for reports on the UV and IR extinction properties of this line of sight]; Crutcher and Chu (1985), who carried out a similar study of HD147889, a star deeply embedded within the ρ Oph cloud, a region known for its unusual extinction properties, thought to be linked to the presence of enlarged grains (Carrasco *et al.* 1973); and a number of other studies of specific lines of sight (Hobbs *et al.* 1983; van Dishoeck and de Zeeuw 1984; Gredel and Munch 1986; Cardelli and Wallerstein 1986, 1988; Federman and Lambert 1988; Jannuzi *et al.* 1988; van Dishoeck and Black 1989).

At about the same time (the 1970s) when ultraviolet spectroscopy of interstellar absorption lines became possible, advances in the sensitivity of millimetre-wave receivers began to allow the detection of CO emission from diffuse clouds. A few authors began to exploit this, observing both ^{12}CO and ^{13}CO in some of the same clouds that were being observed by optical or UV absorption techniques (e.g. Knapp and Jura 1976; Dickman *et al.* 1983). This set the stage for comprehensive studies which combined the radio data with the optical and UV absorption measures, and several authors began to carry out such analyses. These include several of the studies cited above. In these studies, radio CO data have been combined with optical measurements of atomic and molecular absorption lines, the CO emission measures providing information on the size, morphology, and kinematics of a cloud, and the optical data yielding information on distance to the cloud, as well as column densities for several useful ions and a few diatomic molecules. Perhaps the most informative molecular species accessible through optical absorption measures is diatomic carbon (C_2), whose rotational populations provide diagnostics of kinetic temperature, density, and radiation field intensity (van Dishoeck and Black 1982), although, as we will see, there is substantial interest in others such as CN and CH.

(2b) A Diversity of Cloud Types

Probably the first indication of the enormous variety in conditions from cloud to cloud came with the first survey of ultraviolet interstellar extinction curves by Bless and Savage (1972), using data from OAO-2. This survey, and others since (see Mathis 1990; Massa *et al.* 1984; and the series of papers by Fitzpatrick and Massa 1986, 1988, 1990) have all shown that the UV extinction curve, particularly the rise toward the shortest observable wavelengths, can vary by a large factor from one cloud to another. The classical extremes of this behaviour are represented by ζ Ophiuchi on one hand, with its very steep far-UV extinction rise; and σ Scorpii on the other, with its very low, flat far-UV rise. Another contrast between the two types of curves is that the width of the 2175 Å extinction bump tends to be greater in the clouds having the ζ Oph-like far-UV rise. Despite these large contrasts, it was shown by Fitzpatrick and Massa (1986, 1988) and by Cardelli *et al.* (1989) that all observed extinction curves can be fitted accurately by varying only a few parameters, suggesting that the same components are present in all clouds, but perhaps in varying mixtures.

Even though it has been nearly 20 years since the existence of a wide range of dust properties was established, only recently have researchers begun systematically to seek possible relationships between the extinction properties of clouds and other characteristics. For example, Snow and Jenkins (1980), using ultraviolet spectroscopic data from the Copernicus mission, sought to determine depletions in the ρ Ophiuchi cloud, a region that exemplifies the σ Sco type of extinction curve (and in which, not coincidentally, resides σ Sco itself). The results of the Snow and Jenkins study showed that the relative depletions of the elements studied are nearly invariant from star to star within the cloud, and are very similar to the depletion pattern found for other clouds, even those of the ζ Oph type (e.g. Morton 1974, 1975; Snow 1975, 1976). There was a hint that the *total* extinction levels in the ρ Oph cloud, as opposed to the pattern of relative depletions from element to element, was enhanced in comparison to other clouds, but this was ameliorated to some extent by the subsequent revision of the estimated H I column density to the star ρ Oph (Shull and VanSteenberg 1985), which brought the overall level of depletion for the ρ Oph sightline closer to the norm.

A detailed analysis of depletions toward σ Sco, based on Copernicus data, has recently been completed (Allen *et al.* 1990). This study, which used line profile analysis in order to take velocity structure into account in the column density determinations, showed not only that the overall depletion pattern for the integrated sightline is similar to that for other reddened stars, but also that the depletions in separate velocity components in the σ Sco line of sight appear to be constant.

There is evidence that depletions do increase with increasing cloud density, as is implied by the results for the ρ Oph cloud just mentioned. For example, Joseph *et al.* (1986) found a tendency for stars having strong CN absorption to have greater depletions of refractory elements than did stars with weak or no CN. Since CN is often cited as an indicator of cloud density (e.g. Federman *et al.* 1984), a correspondence of depletions with CN can be intepreted as indicating that depletions vary with cloud density.

Another method for estimating depletions in dense regions, as opposed to more diffuse lines of sight, is to compare the abundances of neutral atomic species. Along a given sightline, most elements are singly ionised, even in the denser portions. But lines of neutral atoms are seen, and these must arise in the regions having the highest density. Thus relative elemental depletions inferred from the neutral species are indicators of depletions within the dense cloud core. In a survey of depletions derived from neutral atoms, Snow (1984) found cases where the presumed cloud core depletions were clearly greater than those along the integrated line of sight, as indicated by the abundances of ionised species, thus lending support to the idea that grain growth in dense regions leads to enhanced depletions.

General studies of depletions, based on ionised species and thus representing the mean diffuse interstellar medium, have reaffirmed the apparent invariance of the depletion pattern (see Joseph 1988), which probably has important consequences for understanding the origin of the depletions. Unfortunately, however, the most important species in connection with grain composition (i.e. carbon and oxygen) have not been accurately measured as yet in a significant sample of clouds, and the implications of invariant depletions of the minor species that have been well measured so far are unclear.

Molecular abundances do appear to vary strongly from cloud to cloud, and there are indications of a link between these abundances and the extinction-curve variations described above. Copernicus measurements of molecular hydrogen column densities (Savage *et al.* 1977) showed, for example, that the relative abundance of H_2 is much lower in the ρ Oph cloud stars than in other sightlines having the ζ Oph type of extinction curve. Since H_2 is thought to form predominantly on dust grains (Hollenbach and Salpeter 1970, 1971; see also the review by Shull and Beckwith 1982), it was suggested that the deficiency of H_2 in the ρ Oph cloud is due to enlarged grains there, which offer less surface area per unit of mass than in ζ Oph-like clouds (Snow 1983).

Other molecules are also deficient in clouds of the ρ Oph type, however, so there may be a link between UV extinction and gas-phase chemistry. From present information it is difficult to say what the link is. One difficulty is that many factors affect chemistry rates, including not only the available grain surface area, which governs H_2 and hence indirectly controls the species which devolve from H_2, but also the UV radiation field and the cloud density. Variations in CN abundances have been attributed to density differences from cloud to cloud (e.g. Crutcher, personal communication 1986; Joseph *et al.* 1986), but in at least some cases it appears more likely that the radiation field is the dominant factor (Snow *et al.* 1992; see comments in the next section). Since the low far-UV extinction that is usually attributed to the absence of small grains (e.g. Mathis *et al.* 1977; Draine and Lee 1984; Mathis 1990) is also responsible for allowing a high UV radiation field intensity to penetrate a cloud, it is very difficult to disentangle the effects of large grains from those of a high radiation intensity.

This issue was addressed by Cardelli (1988), who surveyed molecular abundances as a function of R, the ratio of total to selective extinction, and found that there is a strong tendency for the species H_2 and CH to decrease in abundance (relative to the total extinction) with increasing R. It had been shown previously that R and the far-UV extinction rise were closely correlated (Cardelli *et al.* 1988), so the implication was that molecular abundances decrease systematically from clouds of the ζ Oph type to those of the σ Sco type. Cardelli attributed this to a combination of loss of grain surface area and enhanced radiation intensity.

A more subtle effect was uncovered by Joseph *et al.* (1989), who compared molecular and atomic abundances with UV extinction properties of a sample of sightlines. Instead of the far-UV rise, they considered the strength of the 2175 Å bump, and found that stars in their sample tended to fall into one or the other of two categories: those having a strong UV bump, which had low CN abundances and detectable Fe I absorption at 3860 Å; and those having a weak UV bump, which had strong CN but little or no Fe I. In the terminology of the present study, the former group tend to be the σ Sco-type clouds, while the latter tend to be the ζ Oph-like regions. Perhaps the most striking aspect of the Joseph *et al.* study, apart from showing that CN, like H_2 and CH, tends to be deficient in the clouds with σ Sco-type extinction, is the behaviour of Fe I. One can speculate that the weakness or absence of Fe I in the ζ Oph-type clouds is due to either a lower degree of ionisation, since these clouds are better shielded from UV radiation, or a higher degree of depletion in the densest regions of the clouds, where lines of neutral atoms arise. The recent paper by Cardelli *et al.* (1991) shows that Ca I behaves in similar fashion, decreasing in abundance as the CN abundance increases. Cardelli *et al.* argued, through ionisation balance considerations, that the decrease in Ca I abundance is due to increasing calcium depletion with depth in the observed clouds.

Evidence that depletions of certain elements may be enhanced in dense clouds has been found by Joseph *et al.* (1986), who, using data from the IUE, found that the Mn/Fe ratio tended to become smaller for clouds having high CN abundances. This suggested that manganese is more depleted relative to iron in the ζ Oph-type clouds, but the effect only began to appear for rather heavily reddened lines of sight, too highly obscured to have been observed with Copernicus, unfortunately. Again, it is lamentable that accurate and complete depletion data are not available for the elements that count the most in grain composition.

The Joseph *et al.* work suggested that there may be a threshold among diffuse clouds, below which the depletions fit the 'standard' pattern, which is quite invariant, and above which some elements begin to show enhanced depletions. It is as if there is a cloud density or total extinction threshold above which selective deposition of certain species onto grains begins to occur. Interestingly, this threshold for depletions appears to occur near the point where the $3 \cdot 1\ \mu$m water ice absorption feature becomes detectable (e.g. Harris *et al.* 1978; Goebel 1983). It will be of interest to pursue this further, to see whether the presence or absence of the water ice feature correlates with depletions or with the nature of the UV extinction curve.

One additional interstellar parameter has been found to be connected to the type of UV extinction exhibited by a cloud: the unidentified diffuse interstellar bands. It has been known for some time that the bands tend to be weaker relative to the colour excess E(B–V) in dense clouds than in the more diffuse interstellar medium (Wampler 1966; Snow and Cohen 1974), but recently, since the advent of electronic detectors capable of producing accurate band profiles, more subtle effects have been found. Thanks mostly to work by Krelowski and collaborators (e.g. Krelowski and Walker 1987; Krelowski and Westerlund 1988; Sneden *et al.* 1992; Krelowski *et al.* 1992), it has been discovered that the *relative* band strengths are a strong function of the UV extinction curve. The clearest example is the ratio of the prominent bands at 5780 Å and 5797 Å; the central depth of the 5780 Å feature is greater in clouds having σ Sco-type UV extinction, while the 5797 Å band is deeper in clouds having ζ Oph-like extinction. The origin of the diffuse bands is as yet unknown, despite nearly 60 years of effort to identify them (see the reviews by Krelowski 1988; Smith *et al.* 1977; Herbig 1975), so it is not at all clear how their behaviour as a function of UV extinction curve will help in understanding the chemical and physical processes in interstellar clouds. Perhaps the best hope is that the reverse will be true: that the correlation with UV extinction, molecular abundances, and/or depletions will assist in the ultimate identification of the band carriers.

Before leaving this review section, it is worth while to emphasise that clouds do not all fall neatly into one or the other of the two types that have been discussed. There are clouds intermediate in properties between the ζ Oph types and the σ Sco types, and there may well be some that have contradictory properties, such as a steep far-UV rise but the wrong ratio of diffuse bands or an unexpected abundance of one molecule or another. One very unfortunate aspect of the current data availability is that little work has been done as yet to compile large samples of sightlines where all of the parameters have been measured; instead we find little overlap between the stars in one study and those in another. Until a more concerted effort is made to collect complete data on a significant number of stars, it will be difficult to further explore the tantalising trends that have been unearthed.

3. A Case Study: BD+31°643

As already mentioned, the ρ Ophiuchi cloud has been widely studied for clues to the interaction between interstellar gas and dust. This is an ideal cloud for such studies in many ways: it is associated with a rich molecular cloud containing many embedded infrared sources (e.g. Myers *et al.* 1978; Harris *et al.* 1978); it is characterised by enlarged dust grains (Carrasco *et al.* 1973); and it has a number of bright, early-type stars embedded at moderate optical depths, providing several good probes for use in absorption-line studies. The ρ Oph cloud is the prototypical σ Sco-like region, and by itself heavily dominates all conclusions about such regions, such as those reviewed in the previous section. It would be nice to find other such regions, so as to provide a basis for comparison and generalisation.

The small open cluster IC348 lies in the Perseus II dark cloud complex, and is part of the Perseus OB2 association (Lynds 1969). The cluster lies just to the south of o Per, a star that has been well studied for interstellar lines (Chaffee 1974; Chaffee and Lutz 1977; Snow 1975, 1976). Although the terminology was not in use in the 1970s when these studies were carried out, it is clear from the results (the nature of the UV extinction curve, the strong molecular lines, and the diffuse band ratios) that the o Per line of sight is a ζ Oph-type of region. But a study of optical extinction properties of interstellar material associated with IC348 shows evidence for dust grain enlargement (Strom *et al.* 1974), indicating that this material may be more akin to the σ Sco-like clouds. Thus here we seem to have a situation where both σ Sco and ζ Oph types of cloud material coexist within the same cloud complex.

Until now, no follow-up work has been done on interstellar material in IC348, largely because the brightest star in the cluster, BD+31°643, is an eighth-magnitude mid-B star, a difficult subject for high-resolution spectroscopy with high signal-to-noise ratios. Recently we have succeeded in obtaining good data on a few wavelength regions, using the Canada–France–Hawaii Telescope (CFHT). The regions successfully observed included coverage of the following lines: Na I D lines, the H and K lines of Ca II, Ca I at 4226 Å, Fe I at 3860 Å, and the molecular features of CN (3874 Å), CH (4300 Å) and CH^+ (3958 and 4232 Å), as well as the diffuse interstellar bands at 5780, 5797 and 6613 Å. The detailed results of the analysis of these data will be presented elsewhere (Snow *et al.* 1992). A brief summary is given here.

The star itself (also known as HDE281159) has $V = 8{\cdot}53$, spectral type B5V, and colour excess E(B–V) = 0·88 (sources are summarised by Strom *et al.* 1974). The star is also listed as a double star (2730AB in the Aitkin Double Star Catalog), which has led us to reconsider the photometry, as discussed below. Previous interstellar line work has been very limited, consisting mostly of measurements of the Na I and Ca II lines by Cohen (1973), using photographic spectra. Considerable information is available on radio-emitting species, however, as a result of several studies of the Perseus II region. From these studies, which often included radio maps, we can derive estimates of the H I, CO, CH, and OH column densities toward BD+31°643 (e.g. Sancisi 1974; Sancisi *et al.* 1974; Willson 1981; Lang and Willson 1978; Kutner *et al.* 1980). The results are summarised in Table 1, where comparisons with the o Per line of sight are given.

Table 1. Comparison of *o* Persei and BD+31°643

Quantity	o Persei	BD+31°643
A_V	0·96	2·78
E(B–V)	0·32	0·88
N(H I)^A	$7{\cdot}4\times10^{20}$ cm^{-2}	($2{\cdot}8\times10^{21}$ cm^{-2})
$N(H_2)^A$	$4{\cdot}1\times10^{20}$ cm^{-2}	($5{\cdot}5\times10^{20}$ cm^{-2})
Total H^A	$1{\cdot}6\times10^{21}$ cm^{-2}	($3{\cdot}9\times10^{21}$ cm^{-2})
Molecular fraction^B	0·53	(0·28)
N(CN)	$3{\cdot}3\times10^{12}$ cm^{-2}	$<1{\cdot}1\times10^{12}$ cm^{-2}
N(CH)	$3{\cdot}4\times10^{13}$ cm^{-2}	$5{\cdot}3\times10^{13}$ cm^{-2}
N(OH)	$1{\cdot}3\times10^{14}$ cm^{-2}	$1{\cdot}5\times10^{14}$ cm^{-2}
$N(CH^+)$	$4{\cdot}8\times10^{12}$ cm^{-2}	$8{\cdot}3\times10^{13}$ cm^{-2}
Ca depletion	−3·02 dex	−3·56 dex

^{A} Values in parentheses are not directly measured, but inferred from indirect indicators, as explained in the text.
^{B} The molecular fraction of hydrogen nuclei in the form of H_2 molecules.

The total gas column density toward BD+31°643 could not be measured directly, since we had data for neither Lyman-α nor H_2, but an estimate could be made, based on the radio H I data (Sancisi 1974) and on our CH results, using the well-established correlation between CH and H_2 (Danks *et al.* 1984; Mattila 1985). We find a total hydrogen column density of $3{\cdot}4\times10^{21}$ cm^{-2}, with the fraction of hydrogen nuclei in molecular form estimated to be $f = 0{\cdot}28$. [For *o* Per and ζ Oph, *f* is about 0·5, whereas for the ρ Oph cloud stars *f* averages around 0·2 (Snow 1983).]

Combining the estimated hydrogen column density with our results on Ca II leads to the conclusion that calcium is slightly more depleted toward BD+31°643 than toward *o* Per. Since it appears very likely, based on extinction maps (Lynds 1969; Strom *et al.* 1974) that IC348 is a denser region than the sightline toward *o* Per, this suggests that enhanced cloud density is linked to enhanced depletions in this region.

It is possible to estimate, or at least place limits on, depletions in the dense cores of diffuse clouds by comparing the column densities of neutral atomic species. Since these are trace ionisation stages, they tend to be significant only in regions with high density, so it is only in the cloud cores that we would expect to find such species as Ca I, Fe I, and other neutral atoms that have ground-state transitions in the optical. Using Na I as a comparison species, since sodium is usually little depleted (e.g. Morton 1974), our upper limits on Fe I and Ca I provide lower limits on the depletions of these species in the densest portion of the line of sight to BD+31°643. We find that iron in this region is at least as heavily depleted (relative to sodium) as it is in the corresponding region in the *o* Per line of sight, and that calcium is at least twice as depleted. While not very quantitative, these results tend to confirm the conclusion that within IC348 depletions are enhanced relative to surrounding, less dense clouds.

Perhaps the most interesting results from our optical absorption-line study of BD+31°643 are the molecular abundances, also summarised in Table 1. We find that CH is more abundant than in the *o* Per line of sight, by an amount (about 40%) consistent with the greater extinction, but that the CN and CH^+ abundances are very anomalous, relative to those toward *o* Per. For BD+31°643, CN was not detected, with an upper limit of only about one third of the observed column density toward *o* Per, while the CH^+ column density toward BD+31°643, one of the largest yet observed (Allen and Snow 1992), is more than 10 times greater than that toward *o* Per.

The low CN abundance in IC348 is almost certainly not a density effect, in view of the evidence already cited that this is a high-density region, relative to the *o* Per sightline. Thus earlier suggestions (Crutcher 1985; Joseph *et al.* 1986) that CN is a clear-cut density indicator must now be regarded as oversimplified. It is more likely in this case that an enhanced UV radiation field is responsible for the low CN abundance; it is probable that BD+31°643 is embedded directly in the observed interstellar cloud, whereas *o* Per lies behind it by some distance (Sancisi 1974; see also the remarks about CO excitation in IC348 by Kutner *et al.* 1980).

The high CH^+ abundance has two possible explanations. Since this molecular ion requires for its formation an activation energy of 0·4 eV, it cannot form readily in a cool, quiescent gas, and has posed a problem for interstellar chemistry theory (see the recent review by Gredel *et al.* 1992). The most widely cited mechanism for forming CH^+ is interstellar shocks, which can heat the gas sufficiently (Elitzur and Watson 1978). But more recently it has been suggested that another mechanism, formation of CH^+ through reactions of C^+ with vibrationally excited H_2, can be responsible (Stecher and Williams 1974; Jones *et al.* 1986). Vibrationally excited H_2 is produced in regions of high UV radiation intensity, so it is possible that the high abundance of CH^+ toward BD+31°643 is due to the inferred strong UV radiation field. This suspicion is supported by the velocity data: there is no discernable shift in velocity between CH^+ and other species in our study, and, perhaps more telling, the velocity dispersion for CH^+, derived from our curve-of-growth analysis (using the two CH^+ lines at 4232 and 3958 Å), is the same low value (1·5 km s^{-1}) as found for Na I. This is strongly suggestive that the CH^+ arises in the same region as the other species observed, and is not subject to either a velocity shift or a wider velocity dispersion, as might be expected if it were formed in a shock.

Finally, we discuss the properties of the dust in IC348. As noted earlier, optical and infrared photometry imply that the grains within the cluster are enlarged (Strom *et al.* 1974), but it is noteworthy that R, the ratio of total to selective extinction, does not reach values as high as in the ρ Oph cloud. The UV extinction curve, derived by us from IUE data (see Snow *et al.* 1992), shows a nearly normal curve, i.e. one that is close to the galactic average (Savage and Mathis 1979). Thus, from the optical/IR photometry, and from the UV extinction curve, it is not clear whether the cloud is closer to the σ Sco type, as might have been expected, or the ζ Oph type. The far-UV extinction rise is certainly steeper than that for the σ Sco cloud, so we might tend to designate this as more likely a ζ Oph-type region. But the ratio of diffuse band absorption depths at 5780 and 5797 Å, with λ5780 being deeper, clearly fits the σ Sco stereotype better. Thus the interstellar material in IC348 may represent a region that is intermediate between (or a mixture of) the two types of clouds outlined in the previous section of this review. That this region might represent a mixture of the two cloud types is not surprising, in view of its close proximity to o Per, which, as we have seen, is very much a ζ Oph-like cloud.

We find a possible anomaly in the colour excess of 0·88 that is quoted for BD+31°643, in that the relative gas column densities for this star and o Per would suggest a lower total extinction toward BD+31°643 than is implied by the photometry. The extinction study by Strom *et al.* (1974) implies that BD+31°643 has roughly three times more total extinction than o Per, implying that the former has about three times the total gas column density. But the CH and OH column densities for BD+31°643, based on radio emission-line data, are only about 50% greater than for o Per. Furthermore, the map of extinction for the region presented by McCuskey (1938) shows only about a half-magnitude difference in A_V between the positions of the two stars (it is very difficult to be certain of this, because the resolution of McCuskey's map is comparable with the separation between the two stars). The possibility exists, therefore, that the extinction toward BD+31°643 is not as great as implied by the photometry of Strom *et al.* (1974). If this is the case, then the estimated total gas column density given in Table 1 would have to be reduced, perhaps by as much as a factor of two. This would not alter the main conclusions presented here, but it would decrease the inferred calcium depletion to the point where it was only marginally greater than that toward o Per.

If the total extinction is indeed less than that derived by Strom *et al.* (1974), a possible explanation may lie in the fact that BD+31°643 is a binary, as seen in the Aitkin Double Star Catalog (it is actually a triple system, but the third component is well enough separated not to have affected the photometry).

If the companion is a late-type star, it is very possible that it has affected the measurement of B–V, thus resulting in a spurious derivation of total extinction. This point is explored quantitatively in Snow *et al.* (1992).

4. Possible Evolution of the Two Cloud Types

We have seen that there is a range of cloud properties, with the extremes represented by the ζ Ophiuchi and σ Scorpii sightlines. The flavour of our discussion has been in terms of a real dichotomy, with little mention of clouds that might lie between the two extremes, but the case of BD+31°643 shows that such intermediate cases exist. For the moment, however, it is helpful to consider the extremes only, as we attempt to understand how the contrasts in ultraviolet extinction, chemical processing, and possibly depletions come about.

One of the consistent differences between the ζ Oph-like clouds and many of the σ Sco-type regions is that the latter are often known to be associated with recent star formation. The ρ Oph cloud, for example, has many young stellar objects embedded in its dense interior, and has an estimated age of order 10^6 yr (Carrasco *et al.* 1973). Many, if not all, of the σ Sco-like regions have hot stars embedded in them. The ζ Oph-type clouds, on the other hand, rarely seem to have embedded stars; the ζ Oph and o Per clouds, for example, while both close to the star, are not thought to surround it (Morton 1975; Sancisi *et al.* 1974; Snow 1976).

Hence one outstanding difference between the ζ Oph clouds and the σ Sco regions may be the absence or presence of embedded early-type stars. These stars provide strong ultraviolet flux, thus directly contributing to the internal radiation field.

This alone, however, does not explain why the extinction curves are so different. Presumably the grain size distribution has been altered so that the small grains, usually held responsible for the rise of extinction toward short ultraviolet wavelengths, are deficient in σ Sco-like clouds. This may have been the result of processing that took place during or prior to star formation, or it may have resulted from the effects of the strong ultraviolet radiation field that was established by the presence of hot, young stars within these clouds. The high internal radiation field can drive out small dust grains through radiation pressure, which acts most effectively on grains whose size is similar to the wavelength of the radiation. Thus an intense ultraviolet field would tend to selectively drive out the small grains that are responsible for the steep rise in the far-ultraviolet extinction curve. On the other hand, some grain modification may well take place during the process of star formation, quite independently of the radiation field. As a cloud contracts on the way to forming stars, grains may grow in size due to accretion of thick mantles, coagulation (i.e. sticking together), or both (coagulation has been specifically suggested for the ρ Oph cloud, based on its low value of extinction per unit mass of dust; Jura 1980). Therefore the presence of hot, young stars within a cloud may be linked with the absence of the small grains that dominate the far-ultraviolet extinction curve.

Another process could act in the same direction as well. It was found by Seab and Snow (1989) that the newly-formed grains produced in the extended atmosphere of a red supergiant (α Sco, to be specific, which lies near the ρ Oph cloud) have a size distribution that is unlike the typical distribution of dust sizes in the diffuse interstellar medium. The circumstellar dust shows no 2175 Å bump, and has low far-UV extinction. The lack of a bump can be due to a lack of carbonaceous grains, since the study involved a normal M supergiant in which oxygen is thought to have converted all of the circumstellar carbon into CO molecules, but the lack of a far-UV extinction rise probably means that small grains are absent from the mix. Thus, in clouds associated with recent star formation and the recent formation of late-type supergiants, new dust injected into these clouds may be lacking in small grains from the outset.

All of these processes act in the same direction, and all of them help to explain why clouds associated with young stars tend to have modified dust size distributions lacking in small grains. From this it follows that the internal radiation field will be very intense, since the lack of steep far-UV extinction allows ultraviolet photons to penetrate throughout the cloud. In effect, then, the UV radiation field is enhanced for two distinct reasons: there are hot stars present in or very near the cloud, and the low far-UV extinction allows UV flux to penetrate. As pointed out by Mathis (1990), the effect of the dust size distribution alone can cause a factor of 100 range in internal radiation field intensities.

Once there is such a large contrast in internal radiation fields and dust size distributions between two clouds, other properties associated with the ζ Oph versus the σ Sco-like sightlines follow. The low molecular abundances in the σ Sco clouds can be explained as being due to photodissociation, which clearly will act to supress molecular formation and/or survival. For H_2, which forms on grain surfaces, the modified dust size distribution probably contributes to the low abundances. It was pointed out by Snow (1983) that dust coagulation reduces the grain surface area per unit mass, thus reducing the formation rate for H_2. The diffuse bands are also modified in the σ Sco-like regions, relative to those formed in ζ Oph-like clouds, but it is not clear whether this is an effect of the radiation field or the dust size distribution, since it is not known whether the bands are formed by molecules or dust.

One outstanding riddle remains in the scenario just described: are the depletions different between the two types of clouds, and if not, how do we explain that? As noted earlier, at present it appears that the depletion patterns are very similar for both cloud types (but not enough is known, particularly about such species as carbon and oxygen, which probably are the most important in grain composition). If this is true, then the process that has modified the grain sizes in the σ Sco regions has not modified the depletions. This would mean that the grain sizes are changed by some 'composition-blind' process (i.e. one that affects all elemental species in equal proportion); or that the grains that dominate the ultraviolet extinction curve are not the same ones that dominate the depletions.

The process of grain coagulation would not be expected to modify the composition of the dust, so coagulation remains a viable explanation of the modified size distribution in σ Sco-like regions. The expulsion of small grains by radiation pressure would affect the depletions, if the small grains had a composition different to the larger ones, and if the small ones contribute significantly to the overall depletion. In many dust models, carbon is thought to be the major constituent of the small grains, largely because this provides the best explanation for the 2175 Å bump (see Mathis 1990). Therefore it will be very important to obtain *accurate* carbon depletions for stars selected on the basis of the UV extinction curve (this will be possible using the Hubble Space Telescope; see remarks in the next section). Finally, if the modified dust size distribution in σ Sco-like clouds is due to the growth of grains by the accretion of thick mantles, it might be expected that this would modify the depletions, since it is likely that different elements would have different sticking probabilities.

If present indications withstand closer scrutiny, and it is found that the depletions are *not* significantly different between the ζ Oph and σ Sco cloud types, then it may be concluded that the grains that dominate the ultraviolet extinction curve are simply not the same ones that are responsible for the observed depletions. This would tend to imply that the depletions are largely due to a population of large grains that do not affect differential extinction in the ultraviolet. According to current dust models (e.g. Draine and Lee 1984; Mathis 1990), the small grains dominate the mass in the interstellar dust medium, as compared to the larger ones that produce visual and infrared extinction, and it is also the small grains that dominate the far-UV extinction. So where are the grains that are responsible for the depletions? Perhaps there is a population of very large grains that produces only grey extinction throughout the ultraviolet and visible spectral ranges, but which contains most of the mass in interstellar dust, thus being responsible for the depletions that are observed. Such a scenario may already be in serious conflict with dust models, which show a fair match between the amount of mass needed to produce the observed extinction and the amount depleted from the gas phase. Thus we may conclude that it is more likely that either the dust modification process between σ Sco and ζ Oph clouds is truly non-selective, or that some contrasts in depletions between the two cloud types will show up under closer scrutiny.

5. Prospects for the Future

Several directions for new research into the nature of regions that are intermediate between diffuse and dense clouds have been pointed out. It will be important to probe ever denser and darker regions; it will be of interest to carry out detailed analyses of additional clouds, so that the statistical basis for the differentiation into cloud types can be put on a firmer basis; and it will be very interesting to pursue the contrasts that are evident between the so-called ζ Oph-like and σ Sco-type clouds.

In order to probe more heavily obscured lines of sight, new technology will be needed. Today's 4-m class telescopes have not yet been fully exploited for observations of interstellar lines in dark clouds, but cannot go much deeper than they have already. The new 8- and 10-m (even 16-m) instruments now under development clearly will have important applications in this area; it should be possible to obtain high-dispersion spectra of interstellar lines through clouds having 10 or more magnitudes of visual extinction with these large telescopes.

Additional help in probing heavily obscured regions will come with the commissioning of new infrared cryogenic echelle spectrographs, which are expected to improve sensitivity for high-resolution near-infrared spectroscopy by a factor or 100 or more over current instruments such as the Fourier Transform Spectrograph at Kitt Peak National Observatory. Many important molecular species have vibrational transitions from the ground state in the near-infrared, which can serve as useful indicators of physical and chemical processes in clouds substantially denser and darker than any currently accessible to optical or infrared spectroscopy of interstellar lines (see Black and Willner 1984, for an example of what can be done). Cryogenic echelles are nearing completion at at least two observatories (Kitt Peak and the Infrared Telescope Facility on Mauna Kea). These instruments have only moderately high spectral resolution ($\lambda/\Delta\lambda$ around 20,000), which is less than optimum for molecular bands, but we may expect useful data nonetheless.

It will also be important, of course, to push for more sensitive ultraviolet instruments, since most of the interstellar absorption lines of interest lie in the UV. The Hubble Space Telescope is proving helpful in this, although long delays in reaching full operational mode, particularly for the Goddard High Resolution Spectrograph, are proving to be very frustrating. The GHRS on the HST is capable of obtaining ultraviolet spectra at high resolution toward stars with total extinctions as high as 2·5 magnitudes, a significant improvement over the capabilities of Copernicus and the International Ultraviolet Explorer (in the latter case, most of the improvement comes in the form of the enhanced spectral resolution and signal-to-noise properties of the GHRS, as compared to the IUE).

As mentioned in the preceding section, one of the most important observational diagnostics of the contrasts between the ζ Oph- and σ Sco-like regions will be to obtain *accurate* depletion measures of species that are important grain constituents, such as carbon and oxygen. The GHRS on the HST can do this, through the use of previously little-exploited semi-forbidden lines of C II and O I. Thus it would appear that surveys of carbon and oxygen depletions, using these lines, should be done in the next year or two, allowing us to answer some of the basic questions about how grains are modified in one type of region as opposed to the other.

A new ultraviolet mission, the Far Ultraviolet Spectroscopic Explorer (FUSE), is now under development and is expected to be launched by NASA (with participation by Canada and possibly the U.K.) around the turn of the century. FUSE will have a moderately high spectral resolution ($\lambda/\Delta\lambda$ near 30,000), and will be optimised for observations between the Lyman limit at 912 and 1200 Å, thus providing coverage of more of the important interstellar lines than even the HST. Among the features accessible to FUSE but not to the HST are the Lyman and Werner bands of H_2, as well as many lines of species not observable at longer UV wavelengths. The sensitivity of FUSE for obtaining UV spectroscopy of reddened stars will be similar to that of the HST, in terms of the total visual extinctions that will be reachable.

We may expect that, within a decade or so, most of the questions raised in this paper will have been answered. By then, no doubt, an entirely new set of questions, requiring further technology development, will have been raised. But perhaps by that time we will have a more-or-less complete understanding of the physics and chemistry of clouds that are intermediate between the diffuse and dark regimes in the galactic interstellar medium.

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