ABUNDANCES IN DIFFUSE INTERSTELLAR CLOUDS

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1. INTRODUCTION

Interstellar clouds are concentrations of cold ($T \lesssim 100$ K) neutral gas (cf. Spitzer 1978) which are immersed within an intercloud medium. It is worthwhile to distinguish between diffuse clouds (roughly those with $E[B-V] \lesssim 0.5$) and dark clouds (those with $E[B-V] \gtrsim 0.5$). This distinction is useful in the sense that diffuse clouds are relatively warm ($T \sim 100$ K), they are composed mostly of atomic species except for hydrogen which can be appreciably molecular, and they are dynamically controlled by their interaction with the intercloud medium. Dark clouds are relatively cold ($T \sim 10$ K), they contain a rich variety of molecules, and self-gravity is important in their evolution. Because the interstellar extinction is a rapid function of wavelength, most ultraviolet observations have been of diffuse clouds. The IUE satellite is sufficiently powerful that observations of some dark clouds are possible, and an important area of future research will be to delineate more quantitatively the similarities and differences between diffuse clouds and dark clouds.

With ultraviolet observations, considerable progress has been made in understanding the physical characteristics of clouds including determinations of their densities, temperatures, chemical compositions and dynamics (cf. Spitzer and Jenkins 1976). Because particular progress has been made on understanding the abundances within diffuse clouds and because of the limitations of space, we restrict this review to a discussion of abundances within diffuse clouds. These abundance measurements provide a set of fundamental astrophysical data.

2. MATERIAL IN GRAINS

At least half of the interstellar matter other than hydrogen and helium is contained within grains (cf. Spitzer 1978) and therefore the dust-to-gas ratio serves as a crude measure of the heavy atom abundance. Because they observed H_2 as well as H, the most precise study of the

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 293–300.

dust-to-gas ratio is that of Bohlin, Savage and Drake (1978). It appears from their data that the dust-to-gas ratio is uniform within diffuse clouds to within at least a factor of two. To be precise, their measurement of $E(B-V)/N_H$ where $N_H = N(H) + 2N(H_2)$ can be taken to be representative of the dust-to-gas ratio. With this measurement, it is important to consider only those stars with $E(B-V) \gtrsim 0.10$ so that the uncertainties in the reddening are not too large. We also should exclude the Be stars 59 Cyg and ϕ Per whose intrinsic colors are uncertain and the unusual clouds toward ρ Oph, so that there are 59 stars remaining on their list. Examination of the data of Bohlin et al. (1978) then shows (i) that all 59 clouds have $E(B-V)/N_H$ within a factor of two of the average value; and (ii) that the ratio of the standard deviation of $E(B-V)/N_H$ compared to the average value of this quantity is 0.30. Considering the measurement errors, the data are consistent with a uniform dust-to-gas ratio, and this implies that the "integrated" abundances of heavy elements are relatively uniform.

3. MATERIAL IN THE GAS

There have been at least two sorts of useful studies of gas phase abundances in diffuse clouds. The very detailed studies of particular clouds which are listed in Table 1, and the surveys of particular ions in a number of clouds are listed in Table 2. A striking result of all this work is that different elements have dramatically different average depletions.

Table 1. Intensively studied clouds.

Star	Reference
ζ Oph	Morton (1975)
γ Ara	Morton and Hu (1975)
α Vir	York and Kinahan (1979)
λ Sco	York (1975)
γ Vel	Morton (1978)
ζ Pup	Morton and Bhavsar (1979)
o Per	Snow (1976)
ζ Per	Snow (1977)

Table 2. Abundance surveys of interstellar cloud species

Species	Reference
Na I, K I, Ca II	Hobbs (1978) & References
Ti II	Stokes (1978)
Fe II	Savage & Bohlin (1979)
H I	Bohlin, Savage & Drake (1978)
H_2 (J = 0, J = 1)	Savage et al. (1977)
H_2 (J $\geq$ 2)	Spitzer, Cochran & Hirshfeld (1974)
Cl I, Cl II, HCl, P II	Jura & York (1978)
C I	Jenkins & Shaya (1979)
N I	Lugger et al. (1978)
Fe II, Fe I, Mg II, Mg I, Mn II	de Boer & Lamers (1978)
Mg I	Pettini et al. (1977)

3.1. "REFRACTORIES"

Field (1974) pointed out from the measurements by Morton (1974) of the ζ Oph cloud that the depletions of refractories (i.e., those elements with relatively high condensation temperatures) are typically at least an order of magnitude greater than the depletions of volatiles. His interpretation of this result was that the typical grain forms in a region near 1000 K where thermodynamic equilibrium prevails. This model is quite attractive because we know that grain cores are formed in the atmospheres of red giants and other relatively cool regions, although it is not certain that thermodynamic equilibrium prevails in these regions (Day and Donn 1978). However, Snow (1975) argued that the observed pattern of depletion is also consistent with the view that depletions of refractories occur mainly within the interstellar clouds where thermodynamic equilibrium definitely does not obtain. That is, in Snow's model, the correlation of depletion with condensation temperature is essentially coincidental. With the accumulation of data over the last several years, it now seems possible to make at least three strong points against Field's model.

First, Jura and York (1978) have found that phosphorus has a gas phase depletion of only about a factor of two or three below the solar value in contrast to iron which typically has a depletion by more than a factor of 50 (Savage and Bohlin 1979). However, phosphorus has nearly the same condensation temperature as iron (Grossman and Olsen 1974, Wai and Wasson 1977) so that it does not appear that thermodynamic equilibrium prevails when iron enters the solid state.

Second, it is clear on observational grounds that significant grain destruction occurs behind interstellar shocks (Jenkins, Silk and Wallerstein 1976, Jura 1976, Shull 1977, Shull and York 1977, Shull, York and Hobbs 1977), and this process seems to be reasonably well-understood (Spitzer 1976, Cowie 1978, Shull 1977). Since shocks are common in the interstellar medium (McKee and Ostriker 1977, McCray and Snow 1979), if grains form at thermodynamic equilibrium it would be necessary to recycle grains through high-density regions very rapidly to maintain the very high depletions that are observed (cf. Salpeter 1977). In particular, depletions sometimes approach a factor of 10^4 (Snow and Meyers 1979). According to the quantitative model of Dwek and Scalo (1979) for the evolution of stars and gas in the solar neighborhood, such high depletions are inconsistent with the hypothesis that the depletions of refractories occur before grains enter the interstellar medium. The basis of their argument is that the destruction of grains in the interstellar medium is rapid compared to the grain formation rates. Despite the number of apparently free parameters in the model of Dwek and Scalo (1979), their work is plausible since the destruction processes (shocks from supernovae, etc.) scale directly as the source processes such as grain ejection from dying stars and protostars.

Third, there is a correlation between cloud density and the depletion of iron, a refractory element (Savage and Bohlin 1979). While there are other possible interpretations of this result, perhaps the most straightforward is that depletion occurs within clouds.

In conclusion, it seems that the bulk of the evidence is against the view that depletion largely occurs before grains enter the interstellar medium. Some models have been presented on how depletion of refractories might occur within interstellar clouds (Barlow 1978, Duley and Millar 1978), and with detailed cloud-by-cloud studies of the depletions of individual elements, it may be possible to decide the best theoretical model to explain the observations.

3.2. "VOLATILES"

While it is clear that most refractories are largely contained within the grains, this is not so obviously the case for many of the volatiles. A major obstacle to determining accurately the abundances of volatiles is that many of their lines are saturated. However, there have been some measurements of weak lines. Toward ζ Oph, Zeippen, Seaton and Morton (1977) have used the O I line at 1355 A to derive a depletion of oxygen between a factor of 1.8 and 3.2. In contrast, de Boer (1979) has argued from essentially the same data that oxygen is depleted by only a factor of 1.3. With the large-scale survey of gas phase abundances now underway (Bohlin et al 1979), it may be possible to determine the average oxygen depletion. Other work on weak lines of volatiles has been on nitrogen (Lugger et al. 1978) and chlorine (Jura and York 1978). While there is some scatter in the data, it appears that these volatiles are depleted by a factor of two with about a factor of two uncertainty. It is quite interesting that the variability of the depletions of the volatiles is comparable to the variability of the dust-to-gas ratio. Further observations should be able to discover if there is any significant cloud-by-cloud correlation.

An important question that should be solvable in the relatively near future is the amount of depletion within dark clouds. Perhaps the most precise measurement of the gas phase abundance in a dark cloud is the recombination line study topward ρ Oph (Knapp, Kuiper and Brown 1976) where it appears that carbon is depleted by a factor of six. Unfortunately, we do not know very accurately the average carbon depletion in diffuse clouds, although it probably is not as pronounced as this factor of six (Jenkins and Shaya 1979). Further work may provide a clue as to why volatiles do not stick onto grains for any great length of time in diffuse clouds.

3.3. DEUTERIUM

The discovery of interstellar deuterium (Rogerson and York 1973) has received a large amount of attention. It is important to establish whether the observed deuterium has a cosmological origin, and one way to attack this problem is to search for variability of the local deuterium abundance. From observations of the profiles of Lyman α emission lines of nearby late-type stars, Dupree, Baliunas and Shipman (1977) have argued that deuterium has a substantial variation in the local interstellar medium. However, using similar data, McClintock et al. (1979) have argued that no case can be made for such variations. Until there is agreement on the interpretation of the Lyman α profiles from stars, it may not be possible to resolve this controversy.

Alternatively, absorption line studies of early-type stars can be used to measure the abundance of deuterium. Laurent, Vidal-Madjar and York (1979) have measured the deuterium abundance toward several stars in Orion, and they find reason to suspect that deuterium has an abundance of a factor of two lower in this region than its typical value. In particular, the variation between the lines of sight toward ζ Pup and the Orion stars appears to be real. Therefore, there must be some uncertainty associated with the cosmological interpretation of the interstellar deuterium abundance.

4. DISCUSSION

It now appears that abundances are uniform to within a factor of two within 1 kpc of the sun. It will be interesting to observe more distant regions to determine if there is a measurable abundance gradient of different species in the galaxy, and to determine the actual rms variability of abundances within the solar neighborhood. Finally, an important area for future study is the fate of atoms that strike grain surfaces. Specifically, since it appears that most of the depletion occurs within interstellar clouds, why do most refractories adhere to grains for a long time while most volatiles do not?

ACKNOWLEDGMENTS

I thank Dr. D. York for comments on this manuscript. This work has been partly supported by NASA and the Alfred P. Sloan Foundation.

REFERENCES

Barlow, M.J.: 1978, Mon. Not. R.A.S., 183, 417.

Bohlin, R., Hill, J., Jenkins, E., Savage, B., Snow, T., Spitzer, L., and York, D.: 1979, Bull. Am. Astr. Soc., 11, 413.

Bohlin, R.C., Savage, B.D., and Drake, J.F.: 1978, Astrophys. J., 224, 132.

Cowie, L.L.: 1978, Astrophys. J., 225, 887.

Cowie, L.L., Songaila, A., and York, D.G.: 1979, Astrophys. J., 230, 469.

Day, K.L., and Donn, B.: 1978, Astrophys. J. Letters, 222, L45.

de Boer, K.S.: 1979, Astrophys. J., 229, 132.

de Boer, K.S., and Lamers, H.J.G.L.M.: 1978, Astr. and Astrophys., 69, 327.

Duley, W.W., and Millar, T.J.: 1978, Astrophys. J., 220, 124.

Dupree, A.K., Baliunas, S.L., and Shipman, H.L.: 1977, Astrophys. J., 218, 361.

Dwek, E., and Scalo, J.: 1979, Astrophys. J., submitted.

Field, G.B.: 1974, Astrophys. J., 187, 453.

Grossman, L., and Olsen, E.: 1974, Geochim. Cosmochim. Acta, 38, 173.

Hobbs, L.M.: 1978, Astrophys. J. Suppl., 38, 129.

Jenkins, E.B., and Shaya, E.J.: 1979, Astrophys. J., 231, 55.

Jenkins, E.B., Silk, J., and Wallerstein, G.: 1976, Astrophys. J. Suppl., 32, 681.

Jura, M.: 1976, Astrophys. J., 206, 691.

Jura, M., and York, D.G.: 1978, Astrophys. J., 219, 861.

Knapp, G.R., Kuiper, T.B.H., and Brown, R.L.: 1976, Astrophys. J., 206, 109.

Laurent, C., Vidal-Madjar, A., and York, D.G.: 1979, Astrophys. J., 229, 923.

Lugger, P.M., York, D.G., Blanchard, T., and Morton, D.C.: 1978, Astrophys. J., 224, 1059.

McClintock, W., Henry, R.C., Linsky, J.L., and Moos, H.W.: 1978, Astrophys. J., 225, 465.

McCray, R.M., and Snow, T.P.: 1979, Ann. Rev. Astr. and Astrophys., in press.

McKee, C.F., and Ostriker, J.P.: 1977, Astrophys. J., 218, 148.

Morton, D.C.: 1974, Astrophys. J. Letters, 193, L35.

Morton, D.C.: 1975, Astrophys. J., 197, 85.

Morton, D.C.: 1978, Astrophys. J., 222, 863.

Morton, D.C., and Bhavsar, S.P.: 1979, Astrophys. J., 228, 147.

Morton, D.C., and Hu, E.M.: 1975, Astrophys. J., 202, 638.

Pettini, M., Boksenberg, A., Bates, B., McCaughan, R.F., and McKeith, C.D.: 1977, Astr. and Astrophys., 61, 839.

Rogerson, J.B., and York, D.G.: 1973, Astrophys. J. Letters, 186, L95.

Salpeter, E.E.: 1977, Ann. Rev. Astr. and Astrophys., 15, 267.
Savage, B.D., and Bohlin, R.C.: 1979, Astrophys. J., 229, 136.
Savage, B.D., Bohlin, R.C., Drake, J.F., and Budich, W.: 1977, Astrophys. J., 216, 291.
Shull, J.M.: 1977, Astrophys. J., 212, 102.
Shull, J.M.: 1977, Astrophys. J., 215, 805.
Shull, J.M., and York, D.G.: 1977, Astrophys. J., 211, 803.
Shull, J.M., York, D.G., and Hobbs, L.M.: 1977, Astrophys. J. Letters, 211, L139.
Snow, T.P.: 1975, Astrophys. J. Letters, 202, L87.
Snow, T.P.: 1976, Astrophys. J., 204, 759.
Snow, T.P.: 1977, Astrophys. J., 216, 724.
Snow, T.P., and Meyers, K.A.: 1979, Astrophys. J., 229, 545.
Spitzer, L.: 1976, Comments Astrophys., 6, 177.
Spitzer, L.: 1978, Physical Processes in the Interstellar Medium (J. Wiley: New York).
Spitzer, L., Cochran, W., and Hirshfeld, A.: 1974, Astrophys. J. Suppl., 28, 373.
Spitzer, L., and Jenkins, E.B.: 1975, Ann. Rev. Astr. and Astrophys., 13, 133.
Stokes, G.M.: 1978, Astrophys. J. Suppl., 36, 115.
Wai, C.M., and Wasson, J.T.: 1977, Earth Planet Sci. Letters, 36, 1.
York, D.G.: 1975, Astrophys. J. Letters, 196, L103.
York, D.G., and Kinahan, B.F.: 1979, Astrophys. J., 228, 127.
Zeippen, C.J., Seaton, M.J., and Morton, D.C.: 1977, Mon. Not. R.A.S., 181, 527.

DISCUSSION:

G.B. Field: The arguments against all depletion taking place in stellar atmospheres are persuasive, and I would like to retract my earlier suggestion.

M. Greenberg: In considering the apparent discrepancy of the point for ρ Oph in the $N(H + 2H_2)$ vs. $E(B-V)$ diagram, have you considered the fact that, if the grains in this region are larger than average, the ratio $E(B-V)/N_d$ (where N_d = the number of dust grains) is less than average, so that perhaps the correlation would be better if you plotted $N(H + H_2)$ vs. N_d; i.e., this moves the ρ Oph point to the right.

M. Jura: The point I wished to make was that the visual opacity per gram of hydrogen is lower toward ρ Oph than toward the average diffuse cloud. The simplest interpretation of this result is that the grains in the line of sight have adhered to each other.

J.C. Pecker: My question concerns the D/H ratio. If the differences between various determinations is real, and not due to differences in analysis technology, we have to be conscious of the cosmological importance of this statement. The D abundance would hence not be primordial, but mostly due to migration processes and/or to destruction/construction processes, which took place after the formation of the galaxy. This would rule out the use of D/H abundance as a quantity of cosmological significance. So, the question is: Are the discrepancies displayed really there?--Or are they artifacts of some sort? And if the latter is true, should not we enlarge the error bar on the accepted values of D/H? And in any case, avoid using D/H abundance as an argument of cosmological meaning?

M. Jura: In my opinion, the observed differences are almost certain to be real. Further work will be necessary.

G.B. Field: Do we know that A_V is low, or only that E_{B-V} is low?

M. Jura: R_V is somewhere between 4 and 4.5.

G.B. Field: Couldn't A be normal and E be small?

M. Jura: If you accept $R_V = 4$ and E/H lower than normal by a factor of 2.5, you are in trouble; you are forced to conclude that $R_V = 10$ and E/H is normal.

A. Vidal-Madjar: Concerning the question raised by J.C. Pecker on the reality of the D/H variations in the interstellar medium, I would like to present the following comment.

The variation presented on the slide shown by M. Jura is probably smaller than it is really. Indeed on that slide extracted from the work by Claudine Laurent, Don York and myself (Ap. J. 1979), a very important difference exists between two cases:

1) ζ Pup line of sight which presented a deuterium abundance larger than 2×10^{-5} which cannot be reduced because of low f value lines;

2) There exist at least two lines of sight toward Orion stars presenting an average deuterium abundance smaller than 10^{-5}. In these two last lines of sight there are at least three equivalent components for which the average deuterium abundance is already very low. A given component might be indeed much lower than this average.

Therefore the discrepancy between this component and the main one seen on the ζ Pup line of sight could be in effect much larger than the one presented on the slide.