1989

# Predicting peculiar interstellar extinction from gaseous abundances

Charles L. Joseph

Theodore P. Snow

C Gregory Seab
*University of New Orleans*



Recommended Citation
Astrphys. J. 340 314 (1989)

THE ASTROPHYSICAL JOURNAL, 340:314–317, 1989 May 1


# PREDICTING PECULIAR INTERSTELLAR EXTINCTION FROM GASEOUS ABUNDANCES

CHARLES L. JOSEPH
Princeton University Observatory

THEODORE P. SNOW, JR.
Center of Astrophysics and Space Astronomy, University of Colorado

AND

C. GREGORY SEAB
University of New Orleans
*Received 1988 May 11; accepted 1988 October 4*

## ABSTRACT

Molecular and atomic abundances are examined for 19 lines of sight through dense clouds, each with a peculiar selective extinction curve. The interstellar clouds in the present study appear to fall into two distinct categories: CN-rich, with relatively small amounts of neutral iron, or CN-poor, with large amounts of neutral iron. Lines of sight, having a CN/(Fe I) abundance ratio about two ($\sim$0.3 dex) or greater, are found to have a shallow (2.57 $\pm$ 0.55 mag) 2175 Å feature relative to the underlying extinction, while the strength of the bump is 3.60 $\pm$ 0.36 for the other dense clouds in the present study. The difference in the strength of the extinction bump between these two ensembles is 1.03 $\pm$ 0.23.

Several atomic abundances are examined as potential indicators of peculiar extinction. Mn I abundances in particular are sought at 10 times greater sensitivity than previous studies because of a possible empirical connection between a small (Mn II)/(Fe II) abundance ratio and a weak 2175 Å bump reported in the literature. Unfortunately, the abundances of the neutral atoms do not appear to scale with the abundance of CN, reducing the effectiveness of Mn I as a diagnostic tool. Nevertheless, the Mn I upper limits in the present study support Mn being preferentially depleted. Fe I is underabundant relative to K I by 0.7 (dex) in the large (CN)/(Fe I) compared to the small (CN)/(Fe I) lines of sight. In addition, the data suggest that potassium is substantially depleted in both types of dense clouds.

*Subject headings:* interstellar: abundances — interstellar: grains

## I. INTRODUCTION

Understanding the selective extinction of star light not only provides important constraints for interstellar grain models, it is crucial for researchers attempting to determine the intrinsic luminosity of hot stars situated behind the clouds containing dust. The most prominent extinction feature in ultraviolet wavelengths is at 2175 Å, often referred to as the 2200 Å bump. For a detailed review of grains and the selective extinction curve at all wavelengths, see Savage and Mathis (1979) and references therein. For a detailed parameterization of the UV selective extinction curve, see Fitzpatrick and Massa (1988).

The shape of the UV selective extinction curve, normalized to a constant $E(B-V)$, is remarkably similar from one line of sight to another for the diffuse interstellar medium. From the beginning, however, surveys of the selective extinction curve reveal that a reasonable fraction of all diffuse sightlines depart significantly from the standard curve (Bless and Savage 1972; Nandy *et al.* 1976; Meyer and Savage 1981; Massa, Savage, and Fitzpatrick 1983; Witt, Bohlin, and Stecher 1984; Savage *et al.* 1985). The percentage of these so called "anomalous" extinction lines of sight rises dramatically for sightlines with $E(B-V) > 0.2$ (Savage *et al.* 1985), suggesting environmental factors might be influencing the selective extinction.

Peculiar extinction has been intensively studied in recent years in an effort to relate differences in the extinction to various other physical parameters. Seab and Shull (1983), for example, developed a theoretical shock model, which predicts enhanced far-UV extinction and an enhanced strength of the 2200 Å bump in lines of sight through shocked gas. While some aspects of the Seab and Shull model may be qualitatively correct, the predicted destruction efficiencies of the various grain populations has been questioned recently (Strazzulla, Baratta, and Magazzu 1985; McKee *et al.* 1986; Joseph 1988). Massa, Savage, and Fitzpatrick (1983) and Witt, Bohlin, and Stecher (1984) compared the selective extinction curves for lines of sight that appear to be associated with nebulosity on the Palomar Prints to those in clear fields. Witt *et al.* also examined possible weak correlations between various extinction features and the strength of the 4430 Å diffuse band. Both of these studies concluded that the far-UV extinction in dense clouds is generally lower than that of diffuse clouds. The density criteria for these studies, however, are based only on broad-band optical photography. In contrast, Joseph *et al.* (1986), using the presence of molecules as an indicator of density, found some lines of sight through dense molecular clouds have higher far-UV extinction and a weaker 2200 Å bump than do diffuse lines of sight. Cardelli and Savage (1988), likewise, found examples of enhanced far-UV extinction in dense clouds over that found in the diffuse interstellar medium.

The present study searches for possible empirical relationships between gas-phase abundances and differences in the selective extinction curves for dense clouds that are rich in either molecules or neutral atoms. An analysis of neutral atomic abundances is preferred because atoms serve as selective tracers of the densest regions along the line of sight, because their absorption lines are intrinsically weaker than the dominant singly ionized species so that curve-of-growth ambiguities can be avoided, and because they can be observed from ground-based observatories that are capable of probing deeper into dense clouds than can space-borne telescopes. The observed abundance ratios are compared to the selective extinction curves, most of which have been measured by Fitzpatrick and Massa (1988) or by Fitzpatrick (private communication).

## II. DATA

The CN, Fe I, Mn I, and K I observations were obtained with the coude spectrograph at the Canada-France-Hawaii Telescope in 1987 February and in December. At 4050 Å in second order, the spectrograph provided a dispersion of 1.48 Å $mm^{-1}$ and a resolution (2 pixel) of 0.074 Å, corresponding to a 2 pixel velocity resolution of 5.5 km $s^{-1}$. The detector, an 1872 element Reticon array, has 25 $\mu$m pixels.

For good exposure levels, the detector is read-out noise limited with the signal-to-noise (S/N) ratio being a logarithmic function of the total charge per pixel. The S/N ratios are determined empirically from the continuum and are in good agreement with the nominal S/N ratios provided from previous observatory tests. The equivalent width uncertainties are inferred using the formulation in Jenkins *et al.* (1973). Typical lines of sight have S/N $\sim$ 100 per resolution element, corresponding to $\sim$1 mÅ equivalent width.

All of the absorption features of the neutral atoms are assumed to be unsaturated and are calculated, using a formula in Spitzer (1987). Values taken from the literature have been redetermined directly from the published equivalent widths. The adopted oscillator strengths are 0.029, 0.056, and 0.0061 for Fe I ($\lambda$3860), Mn I ($\lambda$4031), and K I ($\lambda$4044), respectively. CN column densities are for the $R(0)$ line only, having an oscillator strength of 0.0338 (van Dishoeck and Black 1986) and being compared to a CN curve of growth with a $b$-value of 1 km $s^{-1}$ (van Dishoeck, private communication).

## III. DISCUSSION

Figure 1 shows representative examples of the two types of dense clouds. Only lines of sight that are rich in molecular CN and poor in atomic iron appear to have a shallow 2175 Å feature relative to the underlying extinction. Table 1 lists the column densities of CN, Fe I, K I, and Mn I along with the strength of the 2175 Å extinction feature. The table is organized into two groups based on the CN/(Fe I) abundance ratio. It should be noted that for a few lines of sight, the uncertainties are sufficiently large that the sightline could be placed in either group. A more extensive analysis of most of these lines of sight, incorporating high-resolution ultraviolet data, will appear elsewhere.

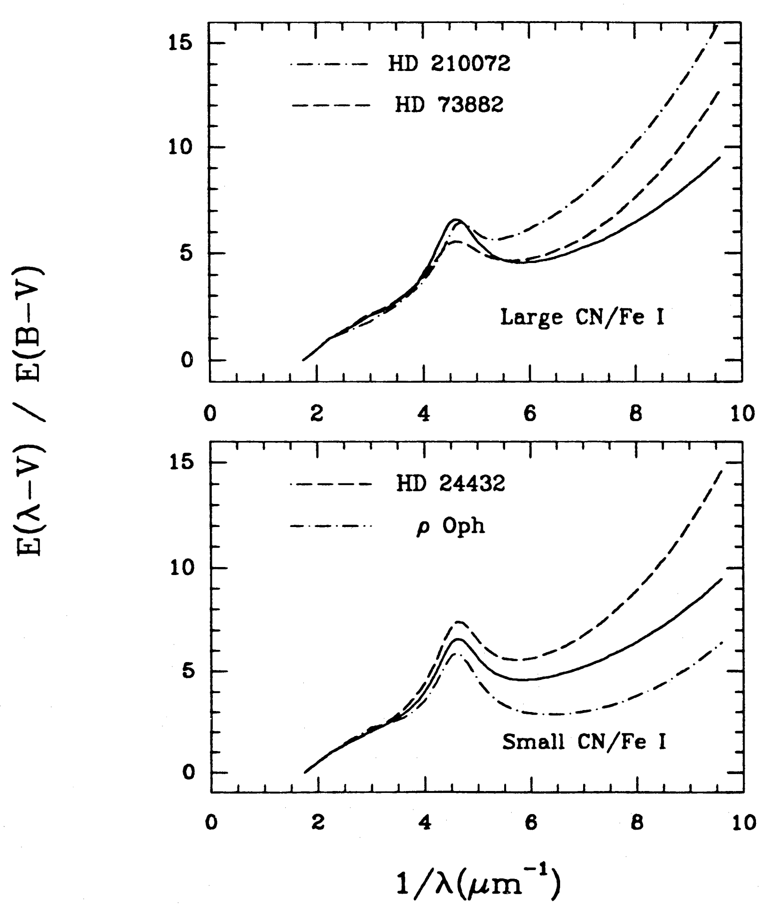


FIG. 1.—Representative examples of the selective extinction curves for each of the two categories of dense clouds, showing the differences in the strength of the 2200 Å feature. Solid lines are the Seaton (1979) average for comparison.

TABLE 1

LOGARITHMIC ABUNDANCES AND EXTINCTION

| Star (1) | $E(B-V)$ (2) | Bump (3) | CN/Fe I (4) | CN (5) | Fe I (6) | Mn I (7) | K I (8) |
|---|---|---|---|---|---|---|---|
| | | | CN > Fe I | | | | |
| HD 21483 ............ | 0.56 | 2.31 | 2.01 | 13.90[a] | 11.89[b] | <10.70 | 11.36 |
| HD 27778 ............ | 0.40 | 2.49[c] | >1.36 | 13.08 | <11.72[b] | <10.87 | <10.66 |
| HD 29309 ............ | 0.5: | ... | >0.88 | 12.60 | <11.72 | ... | ... |
| HD 29647 ............ | 0.99 | 1.51[d] | >1.94 | 14.20[e] | <12.26[e] | ... | <12.96[e] |
| HD 53367 ............ | 0.74 | 3.60 | >0.91 | 12.63 | <11.72 | <11.17 | 11.40? |
| HD 73882 ............ | 0.72 | 2.38 | >0.48 | 12.80 | <12.32 | <11.18 | <11.20 |
| ζ Oph ................. | 0.33 | 3.05 | 0.84: | 12.26[f] | 11.42:[g] | <11.57 | 11.36 |
| HD 199579 ........... | 0.37 | 2.94 | >0.67 | 12.09 | <11.42 | ... | ... |
| HD 210072 ........... | 0.46 | 2.35 | >0.38 | 12.70 | <12.32 | ... | ... |
| SAO 21019 ........... | 1.40 | 2.52 | >1.00 | 14.20[h] | <13.20[h] | ... | ... |
| | | | CN ≤ Fe I | | | | |
| HD 21291 ............ | 0.42 | 3.97 | 0.19 | 12.31 | 12.12 | <10.87 | <10.89 |
| HD 21389 ............ | 0.54 | ... | <−0.47 | 11.65 | 12.12 | <10.87 | <10.96 |
| *o* Per ................... | 0.32 | ... | −0.12 | 12.08[f] | 12.20[i] | <10.27 | 10.83 |
| HD 24432 ............ | 0.70 | 3.91 | −0.61: | 11.65: | 12.26 | ... | ... |
| HD 37903 ............ | 0.35 | 3.02 | −0.15: | 12.05: | 12.20: | <11.09 | <10.96 |
| ρ Oph ................. | 0.47 | 3.57 | −0.41 | 12.12[j] | 12.53[k] | <11.17 | <10.83 |
| HD 147889 ........... | 1.09 | 3.82 | 0.01 | 12.43[l] | 12.42[m] | ... | 12.30[l] |
| HD 193322 ........... | 0.41 | 3.10 | ... | <11.82 | <11.62 | ... | ... |
| HD 207198 ........... | 0.60 | 3.80[c] | 0.20 | 12.62[h] | 12.42[i] | <10.87 | 11.38 |

NOTES.—Col. (3): The bump strengths, except where noted, are from the parameter fit of Fitzpatrick and Massa 1988 or from Fitzpatrick (private communication).

Col. (5): In order to provide greater internal consistency, the CN measurements taken from the literature have been redetermined by comparison of the equivalent widths to a theoretical curve of growth provided by van Dishoeck (private communication; see text). We acknowledge a CN measurement for HD 147889 based on photographic work by Cardelli and Wallerstein 1986, which suggests a substantially larger equivalent width. The result for HD 147889, taken from Crutcher and Chu 1985, is consistent with independent measurements by van Dishoek (private communication).

[a] Roth, Meyer, and Hawkin 1988.
[b] D. Meyer private communication.
[c] Joseph *et al.* 1986.
[d] Cardelli and Savage 1988.
[e] Crutcher 1985.
[f] Meyer and Jura 1985.
[g] Morton 1975.
[h] Crutcher private communication.
[i] Chaffee 1974.
[j] Federman, Danks, and Lambert 1984.
[k] Snow, Joseph, and Meyer 1986.
[l] Crutcher and Chu 1985.
[m] Cardelli and Wallerstein 1986.

The strength of the 2200 Å bump, listed in column (3) is defined as the maximum observed extinction near 4.6 $\mu m^{-1}$ (determined from the fit parameters listed in Fitzpatrick and Massa 1988) minus the extinction in the absence of a bump. Formally, the latter is obtained by setting the bump coefficient $C_3$ (Fitzpatrick and Massa 1988) to zero. In lines of sight where the observed CN/(Fe I) abundance ratio is $\sim 2$ or greater, the 2175 Å extinction feature is shallow ($2.57 \pm 0.55$) compared to $3.60 \pm 0.36$ for the other classes of dense clouds in the present study and to 3.60 for the Seaton (1979) average. These averages are not strongly dependent on the values of the most deviant lines of sight in each of the two categories.

Even though the difference between these two types of selective extinction curves is substantial ($1.03 \pm 0.23$), the scatter about the mean values in the two cases is $\sim$3–4 times larger than that typically found between various stars in a open cluster (Massa and Fitzpatrick 1986). If the cluster results are indicative of the expected variations within a single cloud, then there is a lot of potential for refining our ability to predict the strength of the 2200 Å bump through high-resolution spectroscopic measurements. For example, the line of sight toward HD 53367, which could be placed in either category based on the strength of its bump alone, might consist of two components: a dense molecular cloud with a shallow bump plus a shocked region (perhaps with a larger than normal bump strength). Shocks are expected to be most effective at destroying grains in diffuse regions (where they would also further reduce the number of molecules and cause ionization) so that the shocked gas in principle may not contribute to either the Fe I or CN abundances. Part of the gas in the well studied sightline to ζ Oph is believed to be shocked, and its bump strength is large (3.05) compared to the 2.57 mean. While both of these lines of sight are within 2 σ of the mean for sightlines exhibiting a large CN/(Fe I) abundance ratio, shock indicators such as the $CH/CH^+$ abundance ratio perhaps may improve our ability to predict the bump strength precisely.

Part of the goal of the present study is to increase the number of lines of sight with large known abundances of CN.

Two lines of sight (HD 210072 and HD 73882) have been selected for detailed study because they have weak 2200 Å bumps and enhanced far-ultraviolet extinction (Massa, Savage, and Fitzpatrick 1983). The Mn I upper limits in both categories of dense clouds are consistent with manganese being preferentially depleted relative to iron in these lines of sight as suggested by Joseph *et al.* (1986). Further, the presence of large amounts of CN (and of CO based on recent *IUE* observations) support the possible connection between weak 2200 Å bumps plus enhanced far-UV extinction and large abundances of CN.

The column density of CN, however, is not as tightly correlated with the overall abundances of neutral atoms as one might naively assume. Larger densities increase the chance encounter of an electron and an ion to form a neutral atom or the sequence of chance encounters necessary to form a diatomic molecule. At the same time, the dense portions of the cloud normally are associated with diminished radiation fields that dissociate molecules and ionize atoms. While both neutral atoms and molecules are expected to have abundance enhancements in the densest regions along the line of sight, there is one crucial difference: CN is photodissociated primarily by photons shortward of ~1000 Å (van Dishoeck 1987), while Fe I is ionized by photons shortward of 1585 Å. In all of the large CN/(Fe I) lines of sight, the extinction is enhanced shortward of 1670 Å so that a large portion of the abundance differences between Fe I and CN are probably due to the wavelength dependence of the extinction. This dependence, however, cannot account for all of the differences since some of the small CN/(Fe I) lines of sight also have enhanced far UV extinction. Theoretical modeling by van Dishoeck and Black (1989) indicates that while CN photodissociation in these types of clouds can be suppressed by one order of magnitude over that generally found in diffuse clouds, CN destruction via interactions with oxygen is important. Depletion inside the cloud is probably important as well.

Fe I appears to be ~0.7 (dex) underabundant relative to neutral potassium in the large CN/(Fe I) lines of sight compared to the small CN/(Fe I) sightlines. K, being ionized by photons shortward of 2817 Å, is sensitive to a larger number of interstellar photons than is Fe. Despite the uncertainties introduced by the differences in the ionization potentials, relative element-to-element depletions can be determined, using a technique first employed by York (1980) and by Snow (1984). Iron is estimated from that technique to be preferentially depleted relative to potassium by ~0.74 for the small CN/(Fe I) lines of sight, yet Fe II observations imply that iron has a depletion typically $\sim \log \delta = -2.25$. Hence, K must be depleted by at least a factor of 10, consistent with the model of Joseph (1988). The ratio of the photoionization-to-radiative recombination ($\Gamma/\alpha$) rates are assumed to be 15.39 (Snow 1984) and 6.75 (Morton 1975) for Fe and K, respectively.

As already indicated, the present data appear to fall into two discrete groups. There may be additional groups or classes of dense clouds, which may be discovered once new data become available. While there appears to be a significant (4 $\sigma$) difference between these two ensembles of dense clouds, the individual dispersions are sufficiently large that the tail of one distribution overlaps with the tail of the other, making it difficult at the present time to predict the strength of the bump solely from the CN/Fe I abundance ratio. The overlap can be seen if one plots a scatter diagram of CN/Fe I versus bump strength. It is hoped that the dispersions of these ensembles may be reduced once additional observational constraints become available so that definitive predictions of the bump strength can be made from gas-phase abundances.

The authors would like to thank E. Fitzpatrick, E. van Dishoeck, B. Draine, and D. Massa for helpful conversations. E. Fitzpatrick provided fitting parameters for a few stars not in the literature. Also, the authors are grateful to the National Research Council of Canada for allowing them to propose for time on the CFHT, and are especially thankful for the hospitality and valuable assistance provided by the CFHT staff, particularly, R. Crowe. This research has been supported in part by NASA grants NSG-5248 and NAG-616 to Princeton University and by the National Science Foundation grant AST-8505587 to the University of Colorado.

## REFERENCES

Bless, R. C., and Savage, B. D. 1972, *Ap. J.*, **171**, 293.
Cardelli, J. A., and Savage, B. D. 1988, *Ap. J.*, **325**, 864.
Chaffee, F. H. 1974, *Ap. J.*, **189**, 427.
Crutcher, R. M., and Chu, Y. 1985, *Ap. J.*, **290**, 251.
Federman, S. R., Danks, A. C., and Lambert, D. L. 1984, *Ap. J.*, **287**, 219.
Fitzpatrick, E. L., and Massa, D. 1988, *Ap. J.*, **328**, 734.
Jenkins, E. B., Drake, J. F., Morton, D. C., Rogerson, J. B., Spitzer, L., and York, D. G. 1973, *Ap. J. (Letters)*, **181**, L122.
Joseph, C. L. 1988, *Ap. J.*, **335**, 157.
Joseph, C. L., Snow, T. P., Seab, C. G., and Crutcher, R. M. 1986, *Ap. J.*, **309**, 771.
Massa, D., and Fitzpatrick, E. L. 1986, *Ap. J. Suppl.*, **60**, 305.
Massa, D., Savage, B. D., and Fitzpatrick, E. L. 1983, *Ap. J.*, **266**, 662.
Meyer, D. M., and Jura, M. 1985, *Ap. J.*, **297**, 119.
Meyer, D. M., and Savage, B. D. 1981, *Ap. J.*, **248**, 545.
McKee, C. F., Hollenbach, D. J., Seab, C. G., and Tielens, A. G. G. M. 1987, *Ap. J.*, **318**, 674.
Morton, D. C. 1975, *Ap. J.*, **197**, 85.
Nandy, K., Thompson, G. I., Jamar, C., Monfils, A., and Wilson, R. 1976, *Astr. Ap.*, **51**, 63.
Roth, K. C., Meyer, D. M., and Hawkin, I. 1988, *Bull. A.A.S.*, **20**, 731.
Savage, B. D., Massa, D., Meade, M., and Wesselius, P. R. 1985, *Ap. J. Suppl.*, **59**, 397.
Savage, B. D., and Mathis, J. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Seab, C. G., and Shull, M. J. 1983, *Ap. J.*, **275**, 652.
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 73P.
Snow, T. P. 1984, *Ap. J.*, **287**, 238.
Snow, T. P., Joseph, C. L., and Meyer, D. M. 1986, *Ap. J.*, **303**, 433.
Spitzer, L. 1978, *Physical Processes in the Interstellar Medium* (New York: Wiley).
Strazzulla, G., Baratta, G. A., and Magazzu, A. 1985, *Astr. Express*, **1**:4–6, 143.
van Dishoeck, E. F. 1987, in *Rate Coefficients in Astrochemistry*, ed. T. J. Millar and D. A. Williams (Dordrecht: Kluewer), p. 51.
van Dishoeck, E. F., and Black J. H. 1986, *Ap. J. Suppl.*, **62**, 109.
———. 1989, *Ap. J.*, **340**, 273.
Witt, A. N., Bohlin, R. C., and Stecher, T. P. 1984, *Ap. J.*, **279**, 698.
York, D. G. 1980, in *Astrophysics from Spacelab*, ed. P. L. Bernacca and R. Ruffini (Dordrecht: Reidel), p. 109.

CHARLES L. JOSEPH: Department of Astrophysical Science, Princeton University, Princeton, NJ 08544

C. GREGORY SEAB: Department of Physics, University of New Orleans, New Orleans, LA 70148

THEODORE P. SNOW, JR.: CASA, University of Colorado, Box 391, Boulder, CO 80309-0391