SECTION III.4

CHEMICAL COMPOSITION AND EVOLUTION OF THE DISK

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CHEMICAL COMPOSITION OF INTERSTELLAR MATERIAL

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SUMMARY

Abundances in interstellar clouds, as determined from interstellar absorption lines, are discussed first, including abundances in 'abnormal' (high-velocity) clouds. HII-region abundances are then discussed and compared to results from the interstellar clouds. The present status of an abundance gradient as determined from HII regions is given. Abundances in planetary nebulae are then given for various categories of nebulae, and compared to HII regions. Finally a short status report on abundances near the galactic center is given.

1. ABUNDANCES DETERMINED FROM ANALYSIS OF INTERSTELLAR ABSORPTION LINES

In general, the interstellar absorption lines yield information on the chemical composition of the interstellar gas only for regions within several kiloparsecs of the Sun. There are several reasons for this. First, the stars in which the absorption lines are measured are weaker as they are more distant. Especially close to the galactic plane, where extinction becomes very important, it is impossible to find suitable stars which are very distant. Second, and more fundamental, the analysis of the lines becomes very difficult when the stars are distant. This is because the velocity of the absorbing material has a greater variation (in most directions) along the line of sight to distant objects, and the uncertainty in the velocity dispersion is reflected in a large uncertainty in the derived abundance. The errors become greater as the line becomes more saturated. Thus the best-known abundances are determined in short lines of sight with little material. Sometimes transitions with very low oscillator strengths (f-values) can be measured, which circumvents the above problem.

1.1. Abundances within 1 kpc of the Sun ($|z| < 100$ pc)

The abundances in the direction of about ten early-type stars have been carefully and completely studied, while another hundred directions have been studied as well, but somewhat less completely. The results for two well-studied directions are given in Table 1. The first is the

H. van Woerden et al. (eds.), The Milky Way Galaxy, 575–584.

TABLE 1

Abundances (log X/H + 12) toward α Vir and ζ Oph

Element	Abundance α Vir	Abundance ζ Oph	Element	Abundance α Vir	Abundance ζ Oph
C	9.0 ±.3:	8.4±.2	Mg	6.8±.1	6.1±.2
N	7.66±.1	7.8±.3	Si	6.7±.2	6.3±.3
O	8.6 ±.1	8.7±.1	Fe	6.4±.2	5.4±.2
Ar	6.5 ±.1	5.9±.2	Mn	4.8±.2	4.1±.1
S	7.5 ±.05	7.0±.3	Ca	3.8±.1	2.7±.1
Zn		4.2±.1	Cl	5.8±.2	5.0±.2
Al		4.6±.3			

direction toward α Vir (York and Kinahan, 1979). This star is relatively close (88 pc), and has a low column density of neutral hydrogen (10^{19} cm^{-2}) and a small extinction (E_{B-V} = 0.03). The other direction is toward ζ Oph (Morton, 1975; Lugger et al., 1978; Jenkins and Shaya, 1979; de Boer, 1981). This well-studied star is only two or three times more distant, but the column density of material in this direction is much higher. The neutral-hydrogen column density is about 5 × 10^{20} cm^{-2}, while the combined atomic and molecular hydrogen is about 1.4 × 10^{21} cm^{-2}. The extinction (E_{B-V} = 0.32) is also substantially higher. It can be seen from Table 1 that for some of the elements listed, the abundance in the line of sight to α Vir is higher than that toward ζ Oph. When combined with data from other lines of sight, the following summary can be made of the abundances:

(1) Some elements, especially S, Zn, N, O and probably C, show only a small variation from one line of sight to another. These same elements show no correlation between their abundance (relative to H) and the extinction E_{B-V} or the hydrogen column density in the line of sight.

(2) Other elements, especially Si, Mg, Fe, Mn and Ca show substantially larger variations from one line of sight to another. These variations are correlated with E_{B-V} and the hydrogen column density in the line of sight, such that the abundance is lower when E_{B-V} and the hydrogen column density are higher. This effect is most strongly seen in Ca. A line of sight has been found, toward HD 147889, a star deeply embedded in the ρ Oph dark cloud, indicating an upper limit of log Ca/H + 12 = 1.2 (Snow et al., 1983).

1.2. Element depletion and its interpretation

The abundances may be compared to some standard values, for which the solar abundances are very convenient. The solar values are listed in Table 2 for elements which are of interest. Two values are usually listed for each element. The first is taken from Ross and Aller (1976) and is an average of photospheric and coronal abundances. The second is taken from Parkinson (1977) or Pottasch (1967) and represents only the coronal value. The purpose of the second column is to show that for some elements, notably oxygen, some discrepancy exists in the solar values. The value for neon is only measured in the corona, and it sometimes is

TABLE 2

Selected Solar Abundances (log X/H + 12)

Element	Corona + Photosphere	Corona	Element	Corona + Photosphere	Corona
C	8.68	8.7	Al	6.52	6.3
N	7.95	7.8	Mg	7.60	7.65
O	8.84	8.45	Si	7.64	7.65
Ne	7.57 (8.04)	7.65	Fe	7.50	7.65
Ar	6.0 (6.56)		Mn	5.42	
S	7.2	7.3	Ca	6.35	
Zn	4.45		Cl	5.5	

related to the photospheric values by using the coronal O/Ne ratio together with the photospheric oxygen value.

If the abundances found from the interstellar absorption lines are compared with the solar values, the following results are obtained:

1) The abundances of Si, Mg, Fe, Mn and Ca are almost always lower than the solar values, usually by factors varying from 10 to 10^3. These elements are thus usually depleted with respect to the Sun.
2) The elements S and Zn have abundances very similar to their solar value.
3) The elements N, O and C are more controversial and have been studied extensively in very recent years. As can be seen by comparing these elements in Tables 1 and 2, the interstellar abundance is close to, or perhaps slightly less than, solar.

The controversy centers about whether the C,N,O abundances are significantly less than solar. In spite of the care taken in the analysis of the observations, the errors in the abundances in individual objects remain as high as 50%. When lines of low f-value are not available, the error can be substantially larger. Carbon is probably the most difficult case, since the low f-value line of the most abundant ion, C^+, is rarely seen. The most reliable abundances of carbon come from a study of C^0, coupled with a rather large correction for the ionization equilibrium by Jenkins et al. (1983). These authors conclude "that most stars are consistent with no depletion of gas-phase carbon, except for a number of stars in the Scorpius region". Ferlet (1981) who studied nitrogen, and de Boer (1981) in a study of oxygen, also concluded that there was no compelling evidence for depletion of these elements. On the other hand York et al. (1983), studying N and O, conclude that evidence for a small depletion is present. These authors do not take into account the accuracy of the solar abundance.

The depletions of Si, Mg, Fe, Mn and Ca are believed to be caused not by their absence from the interstellar medium, but by their presence in the form of dust which has condensed out of the gas. Apart from the known presence of dust in the interstellar medium, evidence for such a formation is found in a rough correlation between the condensation temperature and the amount of the depletion (Field, 1974). It is generally believed that there is not enough material in the elements listed above to provide all the mass of the dust found in the interstellar medium (Spitzer, 1978). Only carbon and oxygen are thought to be abundant enough to supply the extra mass to the dust. This is an added reason for the importance of a possible depletion of these elements in the gas phase.

1.3. Variation of element depletion further from the plane

Measurements of some selected lines have been made to determine if depletions change with the distance $|z|$ from the galactic plane. Jenkins (1983) studied the ratios of lines of FeII and SiII to SII. He finds that the ratio of Fe/S is about 3×10^{-2} within 500 pc of the plane (similar to the line of sight to ζ Oph) and increases by about of factor of 2 at 1000 to 1500 pc. He finds no significant change in the Si/S or Al/S ratios. Albert (1982) studied the titanium abundance in the interstellar medium. He finds that the Ti/H ratio varies by about two orders of magnitude, with depletions with respect to the solar abundance from 2×10^{-3} to 2×10^{-1}. For high-latitude stars the lowest depletion (about 10^{-1}) is found.

A lower depletion at high latitudes is also found for Ca and may be true of other elements as well.

1.4. 'Abnormal'-velocity-cloud abundances

It has long been recognized that, when the absolute value of the velocity of an interstellar cloud is greater than 20 km s^{-1} with respect to the local standard of rest, the line ratios vary in a systematic way. Routly and Spitzer (1952) showed that the ratio of the column densities Na^0/Ca^+ decreased strongly with increasing velocity. The effect is quite large in this case, the variation in the ratio is at least three orders of magnitude. A possible explanation of this effect suggested by Routly and Spitzer is a change in the depletion of one of these elements.

Since then several studies have been made of the abundances in these 'higher-velocity' clouds. They confirm that for the higher velocities the depletions are less than for the lower velocities, and in fact there appears to be a rough correlation between the depletion and the velocity. The precise values of the column densities are often difficult to obtain for two reasons. First, the lines are usually quite weak and sometimes confused with other components. Second, the hydrogen column density to be used for comparison often cannot be determined for the high-velocity component, since the Lyman-α absorption is always dominated by the low-velocity component. The depletions are often measured with respect to sulfur which, as discussed above, may be expected to have a near-solar abundance.

The results of an abundance analysis in the high-velocity component ($v = -75$ km s^{-1}) of HD 175754 are shown in Table 3 (Pottasch et al., 1980). It can be seen that practically all abundances which could be

TABLE 3
Abundances (log X/H + 12) in the high-velocity component in HD 175754

Element	Abundance	Element	Abundance
C	8.7	S	7.2
O	8.7	Fe	6.8
Mg	7.5	Ca	5.9
Si	7.5	Na	6.3
Al	6.2		

measured are solar, with the exception of iron and calcium, which are depleted by a factor of 5 and 3, respectively.

These 'high'-velocity clouds may have different origins. It seems clear that those observed in the spectra of stars within the Carina Nebula (Walborn and Hesser, 1982), in which components of several hundred km s^{-1} are observed, are due to large motions very close to the nebula itself. These motions are probably derived from the energy of the many hot stars within the nebula. On the other hand, the similarly high velocities found in the region of Vela (Jenkins, Silk and Wallerstein, 1976) probably have their origin in the supernova explosion which occurred there. It is likely that other 'high'-velocity clouds derive their energy, directly or indirectly, from similar events.

2. RESULTS FROM HII REGIONS

The greatest source of error in determining the abundances in HII regions has traditionally been the determination of the electron temperature. This is because an accurate value is necessary: a 40-percent change in the electron temperature can change the abundance by an order of magnitude. Optically the electron temperature is usually obtained by measuring the intensities of [OIII] λ 4363 Å or [NII] λ 5755 Å, both very weak lines which are detectable only in relatively hot (>7000 K) and bright HII regions.

This dependence on optical spectra to determine electron temperatures has disappeared in recent years. Using radio recombination lines, electron temperatures can be determined with accuracies of a few percent (Shaver, 1980). These lines are easily detected in cool, highly reddened or obscured and relatively faint HII regions, so that the radio and optical methods are complementary.

Accurate electron temperatures are now available for almost 100 HII regions from close to the galactic center to about 15 kpc from the center (Shaver et al., 1983; Wink et al., 1983). These temperatures may be used in conjunction with the optical spectra, which are available for about 33 HII regions (Shaver et al., 1983 and references cited there), to determine the abundances of some of the lighter elements as a function of radial position in the Galaxy (from 5.9 to 13.7 kpc from the centre). The average values of abundance for five elements from the

TABLE 4
Abundances (log X/H +12) in the Orion Nebula and
in the average HII region in the solar neighbourhood

Element	Orion	Average HII region
C	8.5	
N	7.5	7.6
O	8.5	8.7
Ne	7.7	7.8
Ar	6.4	6.4
S	6.93	7.1
Fe	5.8	
Cl	5.0	

nearby HII regions are given in Table 4. The scatter in individual values is about 50%. Also shown in the table are the abundances in the Orion Nebula. For those elements not discussed by Shaver et al., the abundances were calculated using the same electron temperature (T_e = 8700 K). The carbon abundance is based on IUE measurements in the ultraviolet. The iron abundance is more uncertain than the others, because the electron collision cross-sections (Ω) are poorly known; the abundance given is based on an average value $\Omega = 1$ for all observed transitions (Olthof and Pottasch, 1975). Despite this uncertainty, it is clear that iron is at least an order of magnitude less abundant in Orion than in the Sun, and this is true of most HII regions as well. It is rather remarkable that the abundances in Orion are in almost complete agreement with those in the line of sight to ζ Oph. If the latter are depleted because of condensation onto dust particles, this same dust must exist in Orion.

Table 5 gives the abundances of oxygen and nitrogen as a function of distance from the galactic center (assuming the Sun is 10 kpc from the center). The abundance gradient is beyond any doubt. The scatter in the results for individual HII regions can be entirely accounted for by the remaining errors in measurement (especially in T_e). The gradients for N and O are essentially the same and it appears that Ar, and possibly Ne (despite the uncertain conclusion of Shaver et al.), also have the same gradients. Sulfur seems to be an exception, with a gradient less than half that of the other elements.

3. ABUNDANCES IN PLANETARY NEBULAE

The problem of determining the electron temperature from optical line ratios is not as difficult for planetary nebulae as it is for HII regions because the electron temperature is usually considerably higher in planetary nebulae, and the surface brightness is also higher so that spectra are more easily obtained. The biggest problem until very recently has been the rather large corrections which had to be made for unseen ions. Nitrogen and sulfur have presented the greatest problem. In the optical wavelength region only NII lines are seen, and in the ionization

TABLE 5
Variation of HII-region abundances with distance from Galactic Center

Galactocentric Distance	log O/H + 12	log N/H + 12
6 kpc	9.2±.2	8.1±.2
8	9.0 "	7.9 "
10	8.7 "	7.6 "
12	8.5 "	7.4 "
14	8.3	7.2

equilibrium which exists in many nebulae less than 1% of the nitrogen is in this stage of ionization. Thus the correction factors were often large as were the consequent uncertainties in abundance. A similar situation existed for sulfur and several other ions. Carbon was only represented by very weak recombination lines, which were difficult to interpret in terms of abundance.

The situation has considerably improved at present. The IUE ultraviolet measurements have made it possible to observe NIII, NIV and NV, as well as CII, CIII and CIV. Infrared measurements of SIV and SIII have made the sulfur abundance much more reliable. The most difficult problem at present is to take into account the effects of density and temperature gradients in the nebulae.

Results have been summarized by many different authors (see Kaler, 1983; Aller and Czyzak, 1983; Pottasch, 1983 and the references given therein). The median abundance for 'average' nebulae is shown in column 2 of Table 6. By 'average' nebulae those nearby (within 3 kpc) nebulae are meant which do not fall into one of the other categories to be listed. The first seven elements in the table are the non-depleted elements. Variations for these elements ususally do not exceed a factor of two from nebula to nebula. Within this factor the abundances strongly resemble the abundances in nearby HII regions and the Sun. The abundances of Si, Fe, Ca and Mg are less known and probably have greater variation from one nebula to the other. In this respect they probably resemble HII regions and interstellar clouds, the elements being substantially depleted with respect to the Sun.

In column 3 of Table 6 the abundances in the so-called 'Type I' nebulae are listed. These are nebulae with very hot exciting stars (often the star is not seen), are very close to the galactic plane and often have a very filamentary structure (see Peimbert and Torres-Peimbert, 1983). The exciting stars are probably more massive than for the average nebulae. The abundances of He and N are considerably higher than for the 'average' nebulae, N being an order of magnitude higher. These abundance changes probably occurred within the star in the course of evolution to the planetary-nebula stage. The other elements are slightly more abundant than their counterparts in the 'average' nebulae which, if it is significant, may reflect the fact that these are younger objects formed out of somewhat enriched material.

TABLE 6
Abundances in Planetary Nebulae

Element	Average Nearby Nebulae	Type I Nebulae	Halo Nebulae	Galactic Center Nebulae
He	11.02	11.13	11.03	
N	7.80	8.70	7.5	8.9
C	8.60	8.70	8.1	
O	8.61	8.81	8.0	9.5
Ne	7.91	8.10	7.0	
Ar	6.32	6.50	4.6	7.4:
S	6.83	6.92	5.9	7.4:
Si	6.6			
Fe	6.2			
Ca	5.1			

The fourth column of the table gives the abundances in 'halo' nebulae. These are nebulae distinguished by a high velocity perpendicular to the galactic plane or membership in a globular cluster. They are thought to originate from stars as old as globular clusters. Three such objects are known and a fourth has recently been discovered. The abundances in these nebulae are substantially less than in the 'average' nearby nebulae, with the exception of He and possibly N. Especially Ar is underabundant by two orders of magnitude. These abundances must reflect the original abundance at the time of formation of the central stars.

4. ABUNDANCES NEAR THE GALACTIC CENTER

Little is known concerning the abundances near the center. Because of the large extinction near the center, interstellar lines cannot be measured there. The same is true of optical spectra of HII regions. Planetary nebulae near the center can be measured. Because of the high but uncertain value of the extinction, abundances are difficult to determine unless the spectra are accurately measured and the radio continuum is also known. Webster (1976) concluded that the abundances were consistent with being solar for a sample of nebulae she studied, but the conclusion must be considered uncertain because of the above. The results of a single nebula studied by Price (1981) are shown in the last column of Table 6. In this nebula the O, and possibly Ar and N abundances are an order of magnitude greater than in the nearby nebulae, while S is at least a factor of 2 more abundant. Further observations are needed.

The decrease of electron temperature of HII regions toward the galactic center is probably a consequence of the increasing abundance of the elements responsible for the cooling. Since the temperature continues to decrease until about 3 kpc from the center, it is likely that the abundance increases at least to this radius. No further electron-temperature measurements are available closer to the center, except within 300 pc of the center. The temperature of these HII regions varies between 5000 K and 7000 K so that the temperature does not by itself argue for a high abundance. Argon and sulfur lines in the far infrared have been observed from Sgr A (Lester et al., 1981; Herter et al., 1983) which indicate an Ar and S abundance about 5 and 3 times that observed in Orion. In summary, there is an indication that the abundances may be considerably higher near the galactic center, but the present observational material is not decisive.

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DISCUSSION

C.J. Cesarsky: What is the current thinking about abundances and grains in HII regions?

Pottasch: Grains probably exist in HII regions and in planetary nebulae. They seem to have a rather long lifetime. The presence of grains can be seen from their infrared emission, not easily from extinction in HII regions. The composition of the grains may be inferred from the underabundance of certain elements both in planetary nebulae as well as in the general interstellar medium. It is likely that the grains consist mainly of iron, magnesium and silicon, possibly in oxide or carbide form.

Cesarsky: What about abundance determinations from X-ray spectroscopy for hot regions? I understand they would be difficult, because such regions are often out of equilibrium. But eventually we should be able to obtain abundances for regions with less depletion.

Pottasch: The physical parameters involved in this emission are well-known, so some day with better observations one will be able to determine the composition.