ABUNDANCES OF REFRACTORY ELEMENTS IN THE ORION NEBULA

R.H. Rubin, E.F. Erickson, M.R. Haas, S.W.J. Colgan, and J.P. Simpson
NASA Ames Research Center, M.S. 245 – 6, *Moffett Field, CA* 94035 *USA.*
and R.J. Dufour
Dept. Space Physics &Astronomy, Rice University, Houston, TX 77251 *USA.*

ABSTRACT. We assess the gas-phase abundances of Si, C, and Fe from our recent measurements of Si^{++}, C^{++}, and Fe^{++} in the Orion Nebula by expanding on our earlier "blister" models. The Fe^{++} 22.9 μm line measured with the KAO yields Fe/H $\sim 3\times10^{-6}$ – considerably larger than in the diffuse ISM, where relative to solar, Fe/H is down by $\sim$ 100. However, in Orion, Fe/H is still lower than solar by a factor $\sim$ 10. The C and Si abundances are derived from new IUE high dispersion spectra of the C^{++} 1907, 1909 Å and Si^{++} 1883, 1892 Å lines. Gas-phase Si/C = 0.016 in the Orion ionized volume and is particularly insensitive to uncertainties in extinction and temperature structure. The solar value is 0.098. Gas-phase C/H = 3×10^{-4} and Si/H = 4.8×10^{-6}. Compared to solar, Si is depleted by 0.135 in the ionized region, while C is essentially undepleted. This suggests that most Si and Fe resides in dust grains even in the ionized volume.

1. Model for Orion Nebula

The model includes a detailed ionization and thermal equilibrium calculation for the ionized gas with an axisymmetric (2-dimensional) geometry. Details and results for the Orion Nebula blister model are in Rubin *et al.* (1991a = RSHE, 1991b). Here we emphasize the new work on fitting recent International Ultraviolet Explorer Satellite (IUE) and Kuiper Airborne Observatory (KAO) data to determine elemental abundances for C, Si, and Fe.

2. Abundances of Refractory Elements

2.1. Si/C RATIO

Silicon and carbon are major constituents of interstellar grains. Their gas-phase abundance ratio may be determined more reliably in nebulae than the ratio of either C or Si relative to H . This is the case presently for the ionized volume of Orion. In our model of the Orion Nebula, the dominant ionization states for C and Si are C^{++} and Si^{++} with fractional ionizations (RSHE) of 0.59 and 0.79. The important measurable UV lines from these species – Si III] 1883,92 and C III] 1907,09 Å – arise from energy levels comparably above ground at $\sim$ 6.57 and 6.50 eV. Therefore the Si/C abundance ratio derived from observations of these lines is extremely insensitive to errors in the electron temperature, T_e, distribution. Also, because the critical densities for these lines are well above the highest density in the model, their volume emissivities have essentially the same dependence on density. Hence, the ratio is insensitive to errors in the density structure. Additionally, because of the proximity of the wavelengths, differential extinction corrections will play a negligible role in the determination of Si/C. In Figure 1, we show the best fit of Si/C = 0.016 to our new IUE high-dispersion data. These new observations were made at positions to avoid the bar to the SE (which the model does not address) and greatly expand what had been available. We note that there are virtually parallel arguments for using Si II] 2335-50 Å and C II] 2324-29 Å to derive Si/C. However, according to our model, the fractional ionizations for $<Si^+>$ and $<C^+>$ are 0.14 and 0.41. None of these Si II lines are measurable in the IUE spectra.

P. D. Singh (ed.), Astrochemistry of Cosmic Phenomena, 281–283.

2.2. C/H RATIO

Important lines for determining C/H are C III] 1907,09 Å and the ratio of their sum to Hβ. We also used the ratio of the C II] 2326.1 Å ($^4P_{5/2} \rightarrow {}^2P_{3/2}$) line to Hβ. This line is the strongest of the 5 components that comprise the multiplet. At high dispersion, some of these are resolvable with IUE. Extinction is applied using C(Hβ) derived from Hα and Hβ imagery coincident with the actual IUE field observed and the Orion reddening function f(λ). This is from Walter (1991) and is similar in the optical to Torres-Peimbert *et al.* (1980) and in the UV with Bohlin & Savage (1981). Nevertheless, the differential extinction correction over such a large wavelength difference as well as the sensitivity to uncertainty in the T_e distribution renders the C/H abundance ratio more uncertain than Si/C.

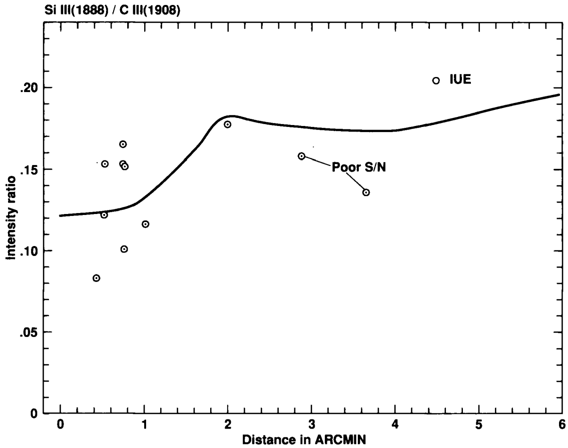

Figure 1. Model predictions for Si III (1883 + 1892 Å/ C III (1907 + 1909 Å) intensity ratio vs. projected distance from the center (θ^1 Ori C). We use the best-fitting model, as described in RSHE with the best fit to our new IUE observations determined for Si/C = 0.016. The data at distances larger than 2.5′ have poor S/N and are not used for fitting.

Our C/H is determined predominantly on the basis of the C III data from the dominant state of C. There is a problem with the model in that the typical off-axis electron density, N_e, values are too high in the singly ionized region (RSHE). Furthermore, the agreement of the N_e-sensitive ratio C III] (1907/1909) with the data is excellent. Tentatively, our best fit obtains for C/H = 3×10^{-4}. This value of C/H in the model overestimates C II (2326.1)/Hβ. This could be explained in a number of ways: **a)** The model is overestimating T_e in the C II region (RSHE); **b)** There could be a larger average extinction for the 2326 Å line, which is concentrated farther from the observer than the average for the Balmer lines; **c)** There could be a lower fractional ionization for C II; **d)** There could be an actual decrease in the gas-phase C abundance due to the fact that the C II region is both closer to the presumed source of grains in OMC 1 and further from the exciting stars. Because a lower C/H ~ 1.7×10^{-4} is inferred, this might indicate that the difference is due to less destruction of grains in the C^+ zone compared with the C^{++} zone.

2.3. Si/H RATIO

Based on the Si III] 1883,92 Å lines and using the results from Si/C and C/H in the above sections, we find Si/H = 4.8×10^{-6}. We repeat that this ratio is not as reliable as Si/C. This value may be compared with Si/H inferred by Haas *et al.* (1986) from observations of [Si II] 34.8 μm near the Trapezium. When they attribute all of the 34.8 μm emission to the photodissociation region (PDR), they find Si/H = 2.6×10^{-6}. Using RSHE, and adjusting that calculation for Si/H = 4.8×10^{-6} in the ionized volume, this model predicts 0.085 of the 34.8 μm emission arises in the H II region. Applying this correction to the PDR abundance, we find Si/H = 2.4×10^{-6}. Taken at face value, the conclusion is that about a factor of 2 enhancement in gas-phase Si has occurred in the ionized volume. Because the PDR, as the interface with OMC 1, would be the source of fresh grain (and gas) material, this implies some of the dust is destroyed in the harsher environment of the H II region. Based on a solar Si/H of 3.55×10^{-5} (Anders & Grevesse 1989), the depletions in the PDR and H II region are 0.068 and 0.135. Hence, if the total Si abundance were solar in Orion, most of the Si is locked in grains even in the ionized volume.

2.4. Fe/H RATIO

By far the dominant species of iron *observable* in H II regions is Fe III. In the present Orion model, the fractional ionization of Fe^{++} is 0.41 (Rubin *et al.* 1991b). The [Fe III] 22.9μm line is the first Fe line detected in the far-infrared from an H II region (Erickson *et al.* 1989). The statistical equilibrium computation for the populations of the lowest 17 energy levels uses the collision strengths of Berrington *et al.* (1991). Based on recent KAO observations of [Fe III] 22.9 μm centered on θ^1 Ori C and the Orion model, we derive Fe/H. The tentative flux observed with the KAO using the cooled grating spectrometer with full width half maximum beam of 22″, is $\sim 1.5\times10^{-18}$ W/cm^2. The best fit to this line occurs with Fe/H $\sim 3\times10^{-6}$. We note that the 22.9 μm line is predicted to be the brightest Fe III line in Orion and that the derived Fe/H is very insensitive to T_e-structure uncertainty or extinction. This ratio may be compared with the solar value. According to Anders & Grevesse (1989), Fe/H = 4.68×10^{-5}, while Holweger *et al.* (1990) find a lower solar ratio of Fe/H = 3.02×10^{-5}. Thus in Orion, the depletion of iron is in the range 0.064 – 0.099.

In Orion, gas-phase iron is considerably more abundant than in the diffuse ISM. Van Steenberg & Shull (1988), using Fe II lines in IUE spectra along the line of sight to 12 stars in Ori OB1, find an average depletion for Fe of 0.0087. However, in Orion, Fe/H is still lower than solar by a factor $\sim$ 10 which may indicate most Fe resides in dust grains even in the ionized volume.

References

Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, **53**, 197.
Berrington, K.A. et al. 1991, *J. Phys. B*, submitted.
Bohlin, R.C., & Savage, B.D. 1981, *ApJ*, **249**, 109.
Erickson, E.F., Haas, M.R., Simpson, J.P., Rubin, R.H., & Colgan, S.W.J. 1989, *BAAS*, **21**, 1156.
Haas, M.R., Hollenbach, D., & Erickson, E.F. 1986, *ApJL*, **301**, L57.
Holweger, H., Heise, C., & Kock, M. 1990, *Astron. Astrophys.*, **232**, 510.
Rubin, R.H., Simpson, J. P., Haas, M. R., & Erickson, E. F. 1991a, *ApJ*, **374**, 564 (RSHE).
Rubin, R.H., Simpson, J. P., Haas, M. R., & Erickson, E. F. 1991b, *PASP*, **103**, 834.
Torres-Peimbert, S., Peimbert, M., & Daltabuit, E. 1980, *ApJ*, **238**, 133.
Van Steenberg, M.E., & Shull, J.M. 1988, *ApJ*, **330**, 942.
Walter, D.K. 1991, *PASP*, **103**, 830.