EFFECTS OF DUST FORMATION ON CHEMICAL ABUNDANCES

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ABSTRACT

Gas-phase abundances of C, Mg, Si, Ca, and Fe have been measured for a number of planetary nebulae on the basis of optical, ultraviolet, and infrared emission-line intensities. The abundances of Si, Ca, and Fe show characteristic depletions of one to two orders-of-magnitude as a result of grain formation. Magnesium shows a similar depletion in the outer parts of several planetary nebulae, but it is undepleted in their inner parts. Carbon is not detectably depleted by grain formation. Efficient condensation of refractory elements can easily occur during the early stages of formation of a planetary nebula; but the observed, residual gas-phase abundances are not understood. Observations of molecules in the envelopes of late-type stars may provide useful clues.

In his pioneering work on galaxies with broad, nuclear emission lines, Seyfert (1943) pointed out similarities of the relative line intensities to those of high excitation planetary nebulae (PN). An exception is that PN have very weak [FeVII] emission, compared with Seyfert galaxies. Since Nussbaumer and Osterbrock (1970) derived roughly solar abundances of iron in Seyfert galaxies, one might guess that the gas-phase abundance of iron in PN is low.

This possibility was confirmed for NGC 7027 by Shields (1974), who used nebular models and the observations later published by Kaler et al. (1976) derive [Fe/H] = -1.4 ± 0.4 relative to a solar value of 12 + log N(Fe)/N(H) = 7.6 (Aller 1980). Because NGC 7027 does not show depletions of the abundances of more volatile elements, such as oxygen and argon, the depletion of iron was attributed to incorporation into grains.

These results were extended to five additional, high excitation PN by Shields (1978), who found an average gas-phase depletion [Fe/O] = -1.2; the measured spread of values is ± 0.8, some of which may be measurement error. These objects all have roughly solar abundances of

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oxygen, and there is no tendency for O/H to decrease with decreasing Fe/H. A similar iron depletion is found far the nitrogen-rich planetary NGC 2440 by Shields et al. (1981), based on forbidden lines of [FeV], [FeVI], and [FeVII]. Collision strengths for these ions are given by Nussbaumer and Osterbrock (1970), Nussbaumer and Storey (1978), and Garstang, Robb, and Rountree (1978), respectively.

Calcium shows a similar pattern of depletions. On the basis of [CaV]λ5309 intensities, Aller and Czyzak (1982) give [Ca/H] = -1.3 for each of several groups of PN, including "nitrogen-rich" and "carbon-rich" objects. Shields et al. (1981) find [Ca/H] = -1.5 ± 0.4 for NGC 2440. On the other hand, sodium and potassium are not significantly depleted in these nebulae.

The abundance of silicon can be determined from the collisionally excited, ultraviolet lines SiIII]λλ1883,1892 and SiIV]λλ1394,1403. Blending with CIII]λ1909 and OIV]λ1400 makes this measurement somewhat difficult. There is also a strong temperature dependence of the emission coefficients and the familiar problem of allowing for unobserved stages of ionization. Harrington and Marionni (1981) find [Si/H] = -1.0 for three PN including NGC 2440 and indications of a weaker depletion for HU 1-2. This suggests that silicon is generally depleted, but possibly to a somewhat milder degree than for iron and calcium.

The behaviour of magnesium is especially intriguing. Pequignot and Stasinska (1980) found a gradient in the gas-phase abundance of magnesium in NGC 7027. The [MgV]λ2784 line intensity requires a solar abundance of magnesium, whereas the weakness of MgIIλ2800 implies an order-of-magnitude depletion in the outer region where Mg^+ is concentrated. Recent observations of [MgIV] 4.5μ and [MgV] 5.6μ emission by Beckwith et al. (1982) confirm that Mg is not depleted in the high ionization region of NGC 7027. For NGC 2165 and NGC 2440, Harrington and Marrioni (1981) find [Mg/H] ∿ 0.0 from [MgV]λ2784 but [Mg/H] ∿ -1.5 to -2.0 from MgII. Shields et al. (1981) confirm these results for NGC 2440. Thus, gradients in the Mg depletion appear to be common in high excitation planetaries. However, the low excitation planetary nebula IC 418 has strong MgIIλ2800, consistent with an approximately solar abundance (Harrington et al. 1980)

Abundances of gas-phase carbon are determined from optical permitted lines, some of which are thought to arise primarily from recombination, and from ultraviolet, collisionally excited lines of CIII] and CIV. Results vary from roughly solar in some objects, N(C)/N(O) ∿ 0.5, to strongly enhanced, with N(C)/N(O) ∿ 2 (e.g., Aller and Czyzak 1982; Kaler 1981; Harrington et al. 1980, 1981). Thus, although carbon in the form of graphite is highly refractory, carbon typically is not substantially locked into grains. This is particularly significant for objects with N(C)/N(O) > 1, since their gas-phase carbon cannot result simply from dissociation of CO molecules when the nebula became ionized.

To summarize the observations, Fe, Ca, Si, and Mg typically show gas-phase abundances one to two orders-of-magnitude less than the solar values, except for magnesium in the inner regions of PN. Carbon does not participate in this depletion.

Are these depletions the result of grain formation? The measurements mostly involve bright, high excitation planetary nebulae of types I or II as defined by Peimbert (1978). These are Population I objects with average heights above the galactic plane of about 150 pc or less and progenitors of mass roughly 1.5 $M_\odot$ or more. The abundances of oxygen, neon, and argon are roughly solar. This suggests that the intrinsic abundances of iron, etc., are also solar. Some halo stars do show deficiencies of iron relative to oxygen (e.g., Pilachowski, Wallerstein, and Leep 1980); but these objects are deficient in oxygen, relative to hydrogen. Moreover, Barker (1979) has studied the composition of three extreme halo PN and found argon abundances approximately 1/100 of those in the sun. In the case of K648 in M15, this agrees with the iron abundance in the stars, whereas oxygen is only deficient a factor of 10 with respect to the sun. Thus, the intrinsic abundances of argon and iron appear to vary in roughly constant proportion. Therefore, the fact that argon has roughly a solar abundance in the Type I and II PN indicates that the depletions of the refractory element abundances result from dust formation.

The idea that grains have locked up the refractory elements in PN is consistent with infrared observations of thermal emission from dust heated by the central star and by the nebular Lyman α radiation field (e.g., Becklin, Neugebauer, and Wynn-Williams 1973). Spectral features suggestive of SiC are seen in some objects (Aitken et al. 1979), but the interpretation of other features is unclear (Jones et al. 1980).

The theoretical implications of iron condensation in PN have been considered by Scalo and Shields (1979). If a PN shell of mass about 0.1 solar mass is ejected in a single event, then the temperature falls to the condensation point (1300 K) at a radius of roughly $10^{14.5}$ cm. The hydrogen density at this point is about 10^{12} cm^{-3}. For reasonable grain sizes, the grains should thoroughly accrete any residual gas-phase iron in the time available before the nebula expands substantially. This would leave a gas-phase abundance much lower than observed. Sputtering and grain-grain collisions are ineffective at restoring the observed amount of iron to the gas.

Alternatively, one may assume that the PN is ejected by means of a continuous wind with a mass-loss rate of perhaps 10^{-4} $M_\odot$ yr^{-1} for the last thousand years of the evolution of the red giant progenitor. Then densities of about 10^{10} cm^{-3} are likely to prevail at the point where iron condenses. In this case, rather small grains (10^{-6} cm) in large numbers are needed to present sufficient surface area to capture all but a few percent of the iron atoms. Furthermore, the final degree of depletion, achieved when the PN has expanded to low density, depends on the parameters of the nebula in a sensitive fashion.

The observed depletions are fairly uniform, and this seems unlikely to result from a universal ratio of the timescales for depletion and nebular expansion.

Thus, in either the ejection model or the wind model, there is some difficulty in explaining the presence of about 5 percent of the iron in the gas phase. Scalo and Shields (1979) noted that in the wind model, grains of different sizes can acquire, from radiation pressure, relative velocities possibly sufficient for shattering collisions. If roughly one layer of atoms is vaporized per collision, then a gas-phase iron abundance of the observed order can result from an equilibrium between shattering and accretion.

A different explanation was suggested by Shields (1980), who noted that mass lost by a fast wind from the central star might amount to a few percent of the nebular mass (c.f. Kwok et al. 1978). If the gas ejected by the red giant had no gas-phase iron but the white dwarf wind had all its iron in the gas, then the observed abundance might result. Aside from theoretical difficulties with cooling the white dwarf wind and mixing it into the nebula, this model has trouble explaining why gas-phase magnesium has a solar abundance in the cores of PN whereas iron and calcium remain strongly depleted in the same location.

The theoretical picture thus is uncertain, and there is room for other ideas to explain the residual gas-phase abundances of refractory elements in PN. Perhaps the outer layer of atoms on the grain is only weakly bound, so that it is easily sputtered off when the nebula is ionized. Then, for grain sizes of order 10^{-5} cm, a few percent of the total atoms are restored to the gas. This might explain the rough similarity of the depletions for different nebulae and different elements, but it also has trouble explaining the selective lack of depletion of magnesium in PN cores.

Finally, radio observations of molecules in envelopes of late type stars may be relevant (see Morris et al. 1979; and references therein). In IRC+10216, SiO and SiS account for roughly one percent of the total silicon; most of the remainder may be in grains. If this gas later becomes ionized as a PN, dissociation of the molecules could result in a gas-phase abundance of order one percent of the solar amount. This suggests that the gas-phase refractory atoms in PN may be traceable to molecules that escaped incorporation into grains during the formation of the nebula.

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TERZIAN: You clearly indicated that Si is depleted and C is not in PN. Can you conclude that the associated grains are primarily silicates and not graphite?

SHIELDS: As much as half the total carbon might be in grains, and that would exceed the amount of silicon. However, it seems unlikely that carbon is depleted to the same degree as iron - the large, gas phase abundance of carbon would then be only one twentieth of the total!

HOUCK: Mg S grains have been proposed to explain the 30 μm feature seen in the spectra of some carbon star shells and PN. Mg S is dissociated at a relatively low temperature, which may explain why the 30 μm feature is not seen in carbon star shells with high grain temperatures. This might also explain why Mg is not depleted in the inner parts of PN - either Mg S grains cannot form or pre-existing grains dissociate.

CLEGG: My impression from the last two talks is that S is not depleted by grains in PN. This is interesting because, in carbon-rich Red Giant shells, observations of CS and Si S suggest that S is depleted significantly on grains.

SHIELDS: The sulphur abundance measurements in PN are somewhat uncertain and may permit a factor of 2 depletion. However, sulphur clearly has not been depleted by about $10^{1.4}$, as in the case of iron.