The Elemental Composition of Interstellar Dust

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Interstellar dust is a nagging problem in observational astronomy. Its presence greatly complicates the measurement of both spectra and luminosities because it modifies the energy distribution of light passing through it. Sources in the galactic plane, toward the galactic center, are completely obscured in optical light, though they are often detectable in the infrared beyond a wavelength of 5 μm. One example of a serious consequence of generally distributed dust is that extinction of light by dust superimposes a noncosmological patchiness on top of the distribution of external galaxies measured from Earth. For all of this, the nature of the distributed dust is largely unknown. On page 209 of this issue, Cardelli brings the resources of the Hubble Space Telescope (HST) to bear in an attempt to understand the one aspect of the problem: abundances of heavy elements in the interstellar medium (*1*).

The existence of interstellar dust was confidently postulated in the 1920s to explain some ubiquitous observational trends among distant stars and clusters (*2*). Since then, proposals for its composition have included smoke, graphite, diamonds, solid hydrogen, iron particles, dielectric particles (mixtures of C, Si, Mg, O, and ice), and large molecules (Platt particles). The effects of dust on other astronomical observations vary with direction in the galaxy, presumably because dust properties vary with environment and direction within the galaxy. Apart from the intrinsic interest in determining the composition of the grains, it would be valuable to find some way of assessing dust properties so that appropriate observational corrections could be made.

One way to understand grain composition is to perform very high resolution spectroscopy on the absorption lines in starlight caused by intervening clouds of gas and dust. In principle, one can determine column densities (in atoms per square centimeter) for many elements, which can be then expressed as ratios relative to the column density of H I. These ratios can then be compared to the corresponding ratios in the solar system, which constitute the so-called cosmic abundances. The latter are corrected in various ways to represent the equivalent gas-phase abundance of the elements. Elements unobserved in interstellar gas must be trapped in a nonatomic or nonionic phase (molecules or dust grains). For some elements, the cosmic abundance is poorly determined, so deficiencies or excesses apparent in interstellar measurements may be simply calibration errors.

Ground-based observations show that K and Na are not much depleted (*3*), but the neutral species observed are not the dominant ionization state, and the corrections needed to obtain elemental abundances are large and uncertain. The other two interstellar species widely observed in the optical part of the spectrum are Ca II and Ti II. The ionization corrections are considerably smaller, and both are depleted by factors of 100 to 1000 in many directions (*4*), at least in clouds that move slowly relative to the local galactic rotation velocity. High-velocity clouds ($v \geq 50$ km s^{-1}) show much lower depletion of Ca and Ti. Presumably, one is observing some destructive process at work on dust particles in these fast-moving clouds that causes atoms to be returned to the gas phase from the solid phase.

Beginning in the 1960s, rocket-borne instruments opened up the ultraviolet region from 1200 to 3000 Å, and in the 1970s, the list of interstellar species was considerably extended by observations from rockets and satellites that included the spectral region from 900 to 1200 Å. Still, there were limitations in signal-to-noise ratio as well as in the tables of wavelengths and transition probabilities of resonance lines, so weak lines were overlooked.

These last two deficiencies have now been remedied, the one by better, more complete laboratory data, the other by the launch of the HST. Because the required observations are spectroscopic, they were not compromised by the faulty primary mirror that so much hampered the imaging science from HST before the corrective optics were inserted last year. For the spectroscopy relevant here, only the efficiency of some observations was affected.

Several researchers have used the telescope and its high resolution spectrograph to expand further the list of elements observed in the interstellar medium. Cardelli summarizes the results (*1*), focusing on results for ζ Ophuichi, a standard star used in studies of interstellar extinction and abundances. The new observations augment the list of observed elements with elements of much larger atomic number than previously studied, notably Ga, Ge, As, Kr, Sn, Tl, and Pb.

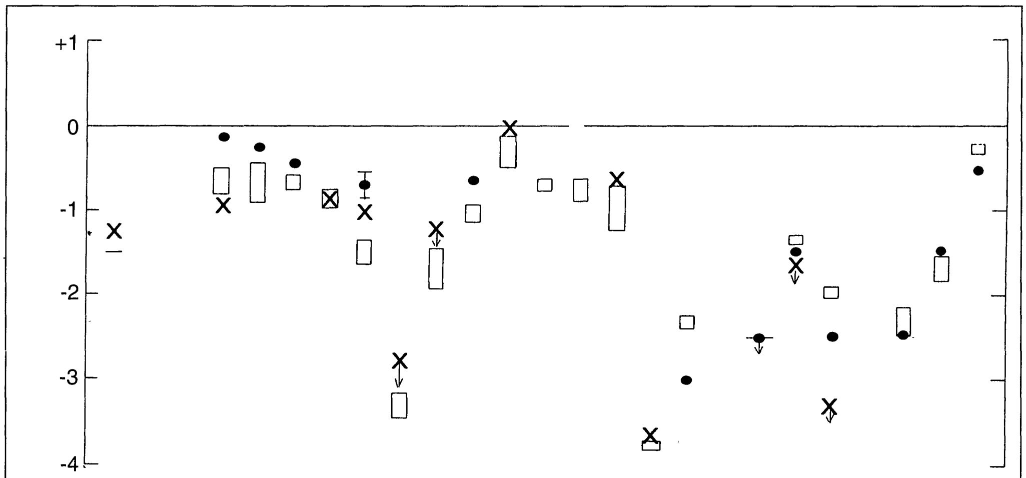

Fig. 1. Abundances compared to atomic number for the main dust cloud in the spectrum of ζ Oph. Open rectangles are from Copernicus data (*11*). Solid dots are new values from HST or high-resolution results from ground-based data (in the case of Ti II). The x's represent results from trace ionization stages (*12*), relative to neutral sulfur. Data for Na, Li, K, Al, and Ca, not covered by Cardelli's summary, are included.

Cardelli focuses on the physical interpretation of the depletion pattern of elements, which should one day lead to an understanding of grain makeup and to a correlation of the extinction properties with observable element depletions. Two widely compared views have been that depletion depends on condensation temperature (*5*) (the temperature at which a certain fraction of a given species is depleted by capture into solid phase at a given temperature and pressure) or that it depends on first

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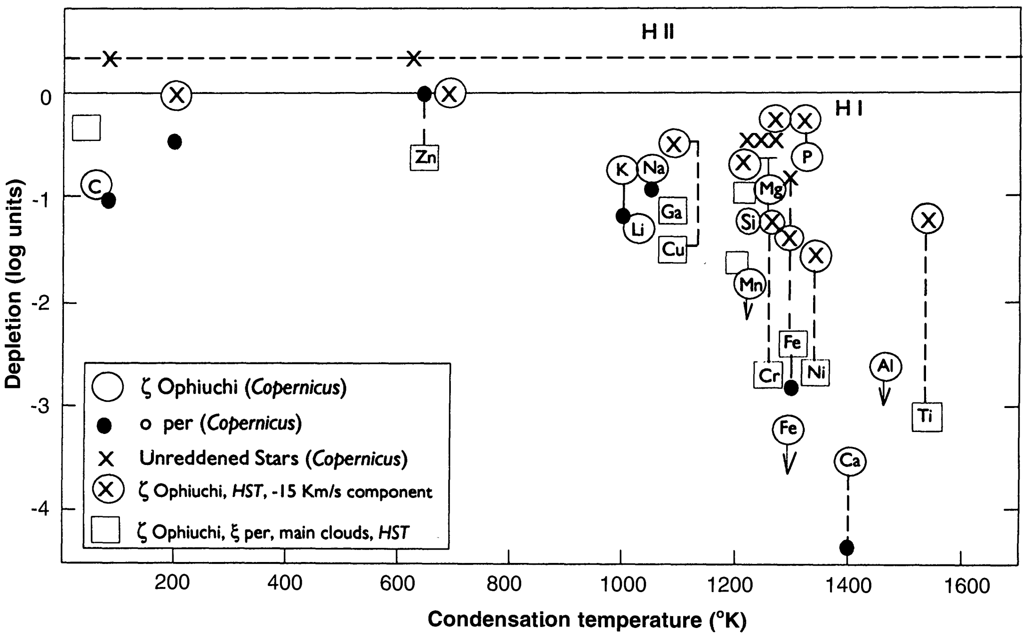

Fig. 2. Abundance versus condensation temperature for the main cloud in ζ Oph (circles or squares with elemental symbols), for the "high-velocity" cloud in ζ Oph (encircled x's) (*13*), for another reddened star (o Per) (*14*), and for unreddened stars (x's) (*15*). The data for Na, K, Li, Ca, and Al are also included in this plot. Small differences with specific abundance values given by Cardelli arise from different adopted values of oscillator strengths and reference solar abundances.

ionization potential (FIP) (6). The latter has no particular physical basis but was suggested by data from the Copernicus satellite. The former fits the general astrophysical picture that grains come, in part, from atmospheres of red giant stars and are injected into the interstellar medium by slow mass outflow. The elements with condensation temperatures below 800 K have little depletion, possibly a sign that the observed grains come from regions that do not get much cooler than that minimum temperature, for astrophysical reasons.

With the new data for heavier masses, Cardelli suggests that depletion is related to the number of valence elections, hence, to general chemical reactivity. In the condensation picture, certain elements have long stood out as destroying any simple correlation, including Na, Li, and P. These were supposed to form particular molecules under interstellar conditions that saved them from the ultimate fate of depletion into the solid phase (7). By contrast, Cardelli appeals to a general view that the formation process for grains is chemical, that higher reactivity leads to more channels for condensation, and that the probabilities for effective reaction decrease as the valence shells fill up.

The significance of the noted trends compared to those expected from the condensation temperature picture, the reactivity picture, and the FIP picture is hard to assess. None of the three explains the observed values to within a factor of 5 from a trial mean value. Evidently, the particular chemistry of each element will need to be understood in detail. Once that is done, there may turn out to be obvious reasons why one element or the other deviates by a factor of 15 or even 50.

In the reactivity picture emphasized by Cardelli, Na, K, Li, and Al may require some special explanation. Figure 1 shows the results of three techniques for measuring abundances of ζ Oph. While based on some of the Cardelli results, the figure includes estimates for Ca, Na, K, Li, and Al, the last four of which deviate considerably from the pattern suggested by Cardelli. In the condensation picture, the observed abundances of P, Li, As, and to some extent Mg, require special explanations. In the FIP picture, K, Na, Li, and Ga stand out as not fitting the scheme well (8).

In any event, much work remains to be done. Although the new data from HST mean that the column densities are now accurately known for some elements, there are considerable problems with the interpretation of the data for other elements. For instance, almost all the elements in row 3 of the periodic table have easily observable lines, but they are saturated. The result is that the actual column densities are ambiguous. Only when the intrinsic spectroscopic profile width, attributable to the finite slit on the instrument, is smaller than the full width at half maximum of the thermal profile of the gas cloud can the ambiguities be removed. Recent widespread detection of hyperfine structure in the Na D lines in interstellar absorption (9) emphasizes the need for resolutions of 0.3 km s^{-1}, 10 times better than that available from HST. Such observations will probably not be achieved, in our lifetime, from space.

An alternative approach, mentioned by Cardelli, is to obtain the wide range of elements discussed by him in lines of sight to stars with less dust and less saturated lines. Figure 2 shows a condensation plot for three types of gas: a dense cloud (ζ Oph), a medium velocity cloud with little depletion (also in ζ Oph), and generally low–column density gas without measurable extinction (near the sun). The depletion patterns are similar in shape, but different in absolute amount, for the three cases, a fact that should provide additional information on not only the elemental content of the dust, but also on form of the condensates (10).

Perhaps by piecing together such observations in numerous lines of sight, further insights can be obtained into the depletion patterns and hence into the makeup of interstellar dust. Some progress can be made in this case without the extremely high resolving power cited earlier, if the saturation is small (or, more technically, the optical depth is near unity). Some additional work in this direction will be done with HST. For elements with critical diagnostic lines below 1150 Å (Ar, and in some cases, N, O, Si, and P), researchers must rely on existing data from Copernicus or await the launch of the Far Ultraviolet Spectroscopic Explorer (FUSE) around the turn of the century.

Research along these lines is likely to eventually bear fruit. One would like to extend the studies to cover a range of physical conditions (such as temperature, density of atomic hydrogen, and density of molecular hydrogen) to learn more about the formation and destruction process of grains and molecules. Extending these studies to other galaxies may allow direct observation of element and grain formation in the early universe.

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