The Interstellar Carbon Budget and the Role of Carbon in Dust and Large Molecules

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Published data on stellar composition show that carbon in the sun is substantially more abundant than in other stars. A carbon abundance of 225 carbon atoms per 10^6 hydrogen atoms is representative of galactic stars, whereas published values for the sun range from 350 to 470 carbon atoms per 10^6 hydrogen atoms. Other elements are also present in enhanced quantities in the solar system, consistent with suggestions that a supernova event was closely associated with the formation of the solar system. The overabundance of carbon in the solar system has many important implications, including new constraints on nucleosynthesis models for supernovae and substantial modification of the so-called "cosmic" composition normally adopted in discussions of galactic and interstellar abundances. A reduction in the galactic carbon budget, as suggested by the stellar composition data, strongly constrains the quantity of carbon that is available for the formation of interstellar dust, and some dust models now appear implausible because they require more carbon than is available.

Carbon is essential to many physical and chemical phenomena on Earth and in the universe. It dominated the chemistry of our early atmosphere and is still the major atmospheric constituent on the other terrestrial planets; it forms the basis for biology on Earth; and in stars and interstellar space it is one of the most abundant and important elements. In stars carbon is a stepping stone to the formation of heavy elements, and in space carbon governs physical and chemical processes and probably forms the basis for interstellar dust, itself the precursor to newly forming solar systems. Therefore, it is important for us to know how much carbon there is in the universe.

The quantity of carbon available in the diffuse interstellar medium (ISM) for the formation of dust and large molecules is constrained by the quantity that is depleted from the interstellar gas. The amount depleted is inferred from a combination of measured gas-phase column densities and an assumed standard or "cosmic" carbon abundance. Recent developments have improved the accuracy of measured atomic carbon column densities while at the same time calling into question the cosmic carbon budget. Here, we analyze these recent developments, offer a recommendation for the values that should be accepted, and examine the impact on current models and hypotheses for the content of the dust and large molecules in the diffuse ISM.

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The Cosmic Carbon Budget

Astronomers tend to assume that the solar system was formed from material that is representative of the galaxy in general, and therefore we generally use solar abundances of the elements in establishing the standards for other stars and the ISM; that is, we assume that the sun represents cosmic abundances of the elements. However, doing so involves underlying assumptions that are rarely questioned, and the material in the sun's atmosphere and elsewhere in the solar system may not be representative of other nearby stars or of the diffuse ISM.

The solar abundance of carbon. It has been common usage to refer to solar elemental abundances and cosmic relative abundances interchangeably, even though solar abundances appear to be anomalous in several respects. Lambert (*1*) reported a solar carbon abundance of 468 C atoms per 10^6 H atoms; this early reference was used as an underpinning for models of interstellar dust containing substantial carbon or graphite components. A frequently used recent reference for the solar carbon abundance is Grevesse *et al.* (*2*), who reported 400 C atoms per 10^6 H atoms, with an uncertainty of ~50 C atoms per 10^6 H atoms. This value was found very consistently in a series of independent studies of lines from various carbon-bearing systems: CH (104 lines), C_2 Swan (20 lines), C_2 Phillips (20 lines), CH (A-X) (9 lines), C I (19 lines), and [C I] (1 line). The common feature in these analyses was a solar photospheric model by Holweger and Mueller (*3*). This solar model has recently been updated because of a reduction in the photospheric abundance of iron (from 47 to 32 Fe atoms per 10^6 H atoms) as a consequence of improved atomic data, particularly the oscillator strengths (*f* values) of the lines. For the same reason, the abundance of carbon calculated from C I lines has been revised to 355 C atoms per 10^6 H atoms (*4*). Studies of the other carbon systems confirm this number (*5*). Table 1 lists various determinations of the solar carbon abundance.

Carbon abundances in young stars. The sun formed about 4.6 billion years ago (Ga). Simple models for galactic chemical evolution suggest that the relative abundance of carbon in the sun might be indicative of conditions in the galactic ISM at 4.6 Ga, and that today, as a result of ongoing chemical evolution, the carbon abundance in the ISM might well exceed the solar value. According to these models, the current ISM should have heavy element abundances 30% greater than the solar value. However, observational evidence does not support this notion; rather, the opposite seems to be true.

Recently formed stars might be more meaningful sources of information about the true cosmic carbon abundance, provided several conditions are met: (i) Mass loss has been insignificant, so that photospheric abundances still reflect the original composition. (ii) The results of internal nuclear processing have not contaminated the surface layers. (iii) The photospheric physics is well represented by current local and nonlocal thermodynamic equilibrium (LTE and NLTE) models. Main-sequence B stars generally satisfy these conditions. A study of early-B main-sequence stars by Gies and Lambert (*6*) yielded a mean NLTE abundance of $160 \pm ^{70}_{50}$ C atoms per 10^6 H atoms (*7*). Cunha and Lambert's more recent investigation of 18 early-B main-sequence stars in the Orion association (*8*) produced a carbon abundance of 229 ± 34 C atoms per 10^6 H atoms, which is marginally consistent with the Gies and Lambert results, although both are substantially below even the most recently revised solar value of 355 ± 50. Other studies of field B stars also revealed reduced carbon abundances relative to the sun; Kilian (*9*) and Adelman *et al.* (*10*), in studies including some 30 stars in all, found an average carbon abundance of 195 C atoms per 10^6 H atoms. Analyses of B stars in clusters show similar results. The galactic cluster NGC 6231 has been particularly well studied (*11*) and shows a carbon abundance of 234 C atoms per 10^6 H atoms. Similarly, the clusters NGC 6611, S 285, and S 289 have values of 195, 120, and 380 C atoms per 10^6 H atoms (*12*). The average for all studies of these clusters is 232 C atoms per 10^6 H atoms.

An analysis of young, later-type stars might be a useful way to determine whether systematic errors arise from the differences in physics between the B-star atmosphere models and the solar photospheric model. Luck (*13*) derived elemental abundances in 40 late-type stars, ranging in age from 0.012 to 1.4 Ga, in eight open clusters within 1 kpc of the sun. These stars included main-sequence stars, giants, and supergiants of spectral types F through K. The carbon abundances were derived from six indicators: four lines of C I (5052, 5380, 7110, and 8335 Å), one line of [C] (8727 Å), and one line of C_2 (5135 Å). The mean carbon abundance for the entire sample was $214 \pm {}^{150}_{100}$ C atoms per 10^6 H atoms. The relatively large uncertainty makes this result consistent with both the B-star results and the solar abundance, but when CNO abundances are combined, the late-type stars in these young clusters appear to be deficient in CNO relative to the sun; their CNO abundances are much more consistent with those of the B stars.

Another check on the consistency of the solar carbon abundance with respect to that of other stars of similar type and history was recently provided by Tomkin *et al.* (*14*), who dealt with the carbon abundance in 107 field F and G disk dwarfs. The metallicity range in these stars, $-0.8 \leq$ [Fe/H] ≤ 0.2, reflects a range of ages or chemical environments. One interesting result of Tomkin *et al.* is that for stars within a given range of galactocentric distance, the increase in carbon abundance with decreasing stellar age (as measured by comparing the stars' positions in the magnitude–effective temperature diagram with theoretical isochrones) is either marginal or nonexistent. The mean carbon abundance among these 107 F and G dwarfs is 202 C atoms per 10^6 H atoms.

The uncertainties in the derivations of stellar abundances can be quite large (the errors quoted in the papers cited here are sometimes as large as ± 0.3 log units, but uncertainties on the order of ± 0.1 log units are more common). Thus, individual measures of the carbon abundance can be incorrect by as much as a factor of 2, whereas the more typical errors are 25% or so. Combining these uncertainties with the range of values (hence uncertainties) in the measured solar carbon abundance might allow for consistency between the sun and other stars. However, when the overall trend is considered or when averages of all the various measurements are calculated, there is no escaping the conclusion that the carbon abundance in the sun is much greater than in other stars.

The comparison of values for the solar carbon abundance with values for stars that should have similar or greater carbon abundances leads to a consistent and very interesting result: The sun appears to have an exceptionally large carbon abundance for a star of its age and position in the galaxy. There is no indication that the solar carbon abundance is in any way typical of the interstellar environment from which a large number of comparison objects have formed.

Carbon abundances in nebulae. Gaseous nebulae, especially the Orion nebula, afford yet another way to assess the carbon abundance in the current ISM near the solar neighborhood. However, several problems are inherent in this approach. We know that H II regions, and especially the Orion nebula, contain dust. Depending on whether the dust/gas ratio is normal or subnormal, a substantial fraction of the heavy elements—possibly including carbon—might be depleted and reside in the dust grains. On the other hand, regions of massive star formation such as the Orion region may have experienced fairly recent supernova explosions. The resulting enrichment with heavy elements (*15, 16*) could therefore distort the relative abundances of these elements. Several recent studies have provided values for the carbon abundance in the Orion nebula (Table 1). These values resulted from analysis processes that were affected by particular assumptions about temperature fluctuations in the ionized gas. The range of these values probably reflects the status of the certainty of such assumptions more than it reflects observational uncertainties. With these reservations, we conclude that the Orion nebula abundances are probably consistent with the abundances found in the Orion B stars (*8*); however, with respect to CNO abundances, the Orion nebula seems to be deficient in these elements relative to the sun.

Galactic chemical evolution and the cosmic carbon abundance. The various indicators discussed above suggest a local cosmic carbon abundance of $\sim 225 \pm 50$ C atoms per 10^6 H atoms, which is some 63% of the most recently determined carbon abundance in the sun. How can we reconcile this finding with current theories and observations relating to galactic chemical evolution? The "simple" model of galactic chemical evolution, which assumes a closed box, instantaneous mixing, and instantaneous recycling (*17*), would predict an opposite result; that is, the carbon abundance should increase monotonically with time. This simple model is not only inconsistent with solar data but also with the two principal observational constraints for chemical evolution models: the age-metallicity relation (*18–20*) and the abundance distribution function of long-lived stars formed in the vicinity of the solar annulus (*21*). The spread in metallicities in a given age bracket in the F-star data (*19*) is well in excess of observational uncertainties, and so is the spread in the age-metallicity relation for nearby clusters (*22*). A study of 189 field F and G dwarfs shows that considerable variation exists in the metallicities of stars formed in a given time in the disk (*23*). The abundance distribution function of G dwarfs in the solar neighborhood exhibits a deficiency of low-metallicity stars that deviates from the predictions of the simple model by nearly two orders of magnitude (*24*).

We are thus forced to consider inhomogeneous chemical evolution models that incorporate the effects of self-enrichment of star-forming regions (*15, 16, 25*), realistic time scales for the dispersal of nuclear evolution products, infall of metal-poor gas from the galactic halo, and temporary removal of enriched gas from the star-forming state. Such models have been developed (*24, 26, 27*). The time scales for various mixing mechanisms in the ISM depend on the length scale considered (*27*). On intermediate galactic scales of 10^2 to 10^3 pc, efficient mixing can be expected only after $\sim 10^8$ years. This period is long compared to the time scale of triggered star formation in giant molecular clouds, which can then lead to localized enrichment with heavy elements; this enrichment is not communicated to other regions until much later, and then only in a severely diluted form.

Considerable evidence for such processes has emerged. Rolleston *et al.* (*28*), who investigated the metal abundance of several open clusters at a galactocentric distance of 13 kpc but situated within 1 kpc of each other, found abundance differences of as much as a factor of five. The CNO abundances in the Orion OB association show that the substantially greater scatter in the oxygen abundance among the stars of the Orion OB association, relative to the distributions of the carbon and nitrogen abundances, is to be interpreted as the result of local inhomogeneities in the oxygen abundance caused by supernovae among the massive stars in the association (*8*). The stars with the greatest oxygen abundances are tightly clustered at one end of the association and are spatially distinct from the other stars.

The age-metallicity relation for stars in the solar circle shows that the sun has one of the highest ratios of Fe/H among these stars, some of which are only half the solar age [figure 31 of (*23*)]. All the evidence discussed so far suggests that the sun was formed in a chemically enriched environment of limited spatial extent, possibly as a result of a triggered star formation process. As a result, the sun inherited a greater heavy element abundance than normal for stars forming at that time. The local ISM may have undergone an evolutionary history that could well have included infall of metal-poor gas from the galactic halo, and the currently observed abundance differences between the sun and stars formed from the local ISM more recently (*29*) may be one result.

Adopted carbon abundance. The wide variation in values for the C/H ratio creates substantial uncertainty in deciding what cosmic value to adopt. The data in Table 1 strongly suggest that the preferred value should be smaller than the canonical 400 C atoms per 10^6 H atoms, and probably also considerably smaller than the solar value of 355 C atoms per 10^6 H atoms adopted by Grevesse *et al.* (*5*). We believe the evidence points toward a value in the range of 200 to 250 C atoms per 10^6 H atoms, and we adopt a value of 225 ± 50 C atoms per 10^6 H atoms. On the logarithmic scale (relative to 10^{12} H atoms) that is often used, this corresponds to a value of 8.35 ± 0.10. The value we infer for the C/H ratio implies that interstellar carbon depletions have been overestimated; that is, there is not as much carbon missing from the gas phase as is commonly supposed. The data also offer the unsettling suggestion that the cosmic carbon abundance may, in fact, be locally variable on distance scales that are comparable to or less than typical lines of sight to reddened stars.

Implications for the Solar System and for Other Planetary Systems

The enhanced carbon abundance in the solar system may have resulted from a particular event. It has long been suggested that the formation of the solar system was associated with a nearby type II supernova, the collapse and explosion of a massive star (*16, 25*). This suggestion originally was based on an enhanced oxygen abundance in the solar system and was supported by high values for other elements such as iron. However, these suggestions did not necessarily include carbon among the elements that would have been enhanced, because nucleosynthesis theory indicates that most of the carbon formed in the interior of a massive star during its lifetime would be destroyed in the supernova explosion. The destruction mechanism is the α-capture reaction $^{12}C + \alpha \rightarrow {}^{16}O$, which is thought to consume nearly all the ^{12}C; however, the cross section for this process is poorly known, and the uncertainties in its value allow for a substantial quantity of ^{12}C to survive. Although recent experimental evaluations of the cross section (*30*) have refined its value, it is still imprecisely known because only one of the two major contributing terms to the cross section could be measured in the experiments. However, the carbon produced in type II supernovae is expected to be in the isotopic form ^{12}C, whereas carbon produced from less massive stars through the CNO cycle and expelled into the ISM by stellar winds should be dominated by ^{13}C. The solar system has a higher $^{12}C/^{13}C$ ratio than does the general ISM, which supports the notion that a supernova event contributed to the carbon budget in the solar system.

Supporting evidence for this view comes from the study of isotopic ratios in carbonaceous inclusions in meteorites. In recent reviews, Ott (*31*) and Anders and Zinner (*32*) have shown that the $^{12}C/^{13}C$ ratio ranges from ~2 to several thousand for small (~1 μm) graphitic inclusions in meteorites. A very recent analysis (*33*) confirms these results for the carbon isotopic ratio and extends them to isotopes of nitrogen and oxygen, all of which show anomalies in meteoritic inclusions that are consistent with an origin in massive stars. The high values for the $^{12}C/^{13}C$ ratio presumably represent carbon that has come directly from supernovae, with virtually no contribution from stellar winds. Therefore, the presence of particles with such isotopic ratios in the solar system specifically suggests that a supernova event may have played a role in the formation of the system.

If the solar system formed in a carbon-rich environment, we may expect that other planetary systems had lower carbon budgets available to them during their formation. Thus, the role of carbon in planetary atmospheres might be substantially different in other systems and could have an effect on planetary surface conditions. Although carbon dominates the atmospheres of Venus and Mars and played a strong role in the early evolution of Earth's atmosphere, on the terrestrial planets of other stars we may find carbon to have been less important. However, if the hypothesis that the carbon on Earth came primarily from cometary accretion (*34*) is correct, such a process might have the effect of concentrating carbon on the terrestrial planets of other stars even if the initial system carbon abundance was lower than in the solar system. Thus, it is not clear that the formation of carbon-based organisms in other planetary systems would be adversely affected by a lower overall carbon budget. The evolution of planetary atmospheres and of life in the context of a reduced carbon abundance is an area that deserves further attention.

The Abundance and Depletion of Gas-Phase Carbon

Before the Hubble Space Telescope (HST) was operational, most measures of carbon abundance in the diffuse ISM came from observations of C II lines with the Copernicus satellite (*35, 36*). Two strong lines were available to Copernicus, at 1036.3367 and 1334.5323 Å. Both lines were always highly saturated, even in lightly reddened stars, and this seriously compromised the accuracy of the results. The 1036 Å feature has a large damping constant and displays damping wings in many cases, but because of confusion with the (5,0) Lyman band of H_2, few accurate column densities were derived from this line. The 1334 Å feature has no redeeming characteristics. However, there is a very weak, spin-forbidden line at 2325.403 Å, which should almost never be saturated in diffuse-cloud lines of sight. Hobbs *et al.* (*37*) were the first to take advantage of this phenomenon; they used a special observing technique with the noisy V1 phototube on Copernicus to marginally detect the line toward δ Sco. Later, Welty *et al.* (*38*) added further upper limits toward other stars with the use of data from the International Ultraviolet Explorer, but those limits were not restrictive and shed little light on the interstellar carbon budget.

The Goddard High Resolution Spectrograph on the HST has superior sensitivity, resolution, and signal-to-noise characteristics and has proven to be capable of detecting the C II] line. It was first detected in ξ Per (*39*) and then in ζ Oph (*40*) but has been pursued in only a few other cases (*41*). Column densities derived from this line are sensitive to uncertainties in its *f* value, but recent laboratory measurements of the lifetime of the upper state (*42*) and the relative line transition probabilities within the multiplet (*43*) have reduced the uncertainties. Only two definite and accurate detections

Table 1. Estimates of the cosmic carbon abundance.

Environment	Carbon abundance (C atoms per 10^6 H atoms)	Reference
Sun	370	(*65*)
	370	(*66*)
	468	(*1*)
	363	(*67*)
	400	(*2*)
	355	(*5*)
	355	(*4*)
Main-sequence B stars	160	(*6*)
Orion B stars	229	(*8*)
Field B stars	157	(*9*)
	218	(*10*)
B stars in NGC 6231	234	(*11*)
B stars in other clusters	213	(*12*)
Young late-type stars	214	(*13*)
F and G disk dwarfs	202	(*14*)
Orion nebula	214	(*68*)
	339	(*69*)
	282	(*70*)
	332	(*71*)
Recommended interstellar value	225 ± 50	

of the weak C II] line on the basis of HST data have been published to date, bringing to only three the total number of sight lines that have reasonably accurate gas-phase carbon abundances. A fourth line of sight, toward the distant O9.5Ib supergiant HD 154368, has been analyzed with the use of HST data, but the weak 2325 Å line was not clearly detected, and the derived column density was augmented by the analysis of damping wings on the strong 1334 Å line (*41*). The result, though less certain than in the cases where the weak line was cleanly detected, is consistent with those cases.

The best values for interstellar gas-phase carbon are shown in Table 2, which also includes the number of C atoms per 10^6 H atoms in the interstellar gas and the number available for the formation of dust or large molecules (on the basis of our adopted value of 225 ± 50 C atoms per 10^6 H atoms). The implied depletions are indeed smaller than previously assumed, although in their depletion study Sofia *et al.* (*7*) did include calculations on the basis of the lower cosmic carbon abundance implied by B stars. With the exception of ξ Per, the numbers show that only about one-third of the cosmic carbon is missing from the gas; that is, less than ~100 C atoms per 10^6 H atoms are available for dust and molecules. Oddly enough, for ξ Per, the carbon abundance is actually slightly greater than the cosmic value, indicating virtually no depletion for this line of sight. This anomaly was discussed in some depth by Cardelli *et al.* (*40*), who attempted possible explanations on the basis of the partial destruction of the dust grains toward ξ Per. However, they omitted from their discussion the possibility that this star lies behind a carbon-enriched region as a result of the evolution of massive stars, as may be implied by its association with a well-known supernova shell (*44*). The case of ξ Per suggests again that cosmic carbon abundances may vary with location. The H I data on ξ Per should be reexamined to double-check the column density from Bohlin *et al.* (*45*) for any possibility that the inferred low depletion of carbon is the result of an error in the hydrogen column density. Despite the difficulty in assessing accurate carbon depletions in individual cases, we argue that the low depletions implied by the carbon abundance in young stars are a realistic indication of the general state of the diffuse ISM, and that this must be taken into account by models of dust and large molecules that depend on carbon.

Carbon in Dust and Molecules: Constraining the Models

Whittet (*46*) attempted to constrain dust models on the basis of what was then known about the cosmic carbon abundance and the depletion of carbon from the interstellar gas onto the dust. His database came from Copernicus satellite observations of neutral atomic carbon (*47*), which can be accurately measured but requires a large correction for ionization to derive the quantity of ionized carbon, which is far more abundant. Whittet was ultimately unable to limit the allowed models for the dust because of the large uncertainties in the observed quantity of gaseous carbon. The HST has now provided more accurate measurements of ionized carbon, and we used these new values, along with our revised value for the cosmic carbon abundance, to reexplore the dust models.

Published models of specific spectral features are summarized in Table 3, which shows the quantity of carbon (relative to 10^6 H atoms) required to reproduce the observed features. A number of interesting conclusions can be reached. Most of the spectral features considered [the unidentified infrared emission features (UIRs), the 3.4-μm absorption attributed to hydrocarbons on dust grains, the 2175 Å extinction bump, and the optical diffuse interstellar bands (DIBs)] can be produced by the available carbon, even with the low value we have adopted for the cosmic carbon abundance. Only models for the 3.4-μm hydrocarbon absorption become implausible; for example, the amorphous carbon model of Adamson *et al.* (*48*) and possibly the coal model of Papoular *et al.* (*49*) apparently demand more carbon than is available. Thus, our revised value for the cosmic carbon abundance may rule out this class of models.

The 3.4-μm feature has been studied both in dense clouds and in the diffuse ISM (*50–52*), and it shows somewhat different behavior in dense and diffuse regions. In the diffuse-cloud lines of sight that have been studied, clear signatures of aliphatic structures (containing subgroups of $-CH_2$ and $-CH_3$) are seen in the band profile, whereas the dense clouds show featureless profiles thought to be caused by more amorphous hydrocarbons. The column density estimates are more secure for the diffuse clouds, and they show that a rather small fraction of the cosmic carbon is needed, even with our revised value.

Table 2. Measurements of the C II] 2325 Å line. Values for the number of C atoms per 10^6 H atoms that are available for dust and molecules are for conditions where the cosmic abundance of carbon is 175 to 275 C atoms per 10^6 H atoms.

Star	C (atoms cm^{-2})	H (atoms cm^{-2})	Carbon abundance (C atoms per 10^6 H atoms)		Reference
			As atomic gas	Available for dust and molecules	
ξ Per	5.1×10^{17}	2.0×10^{21}	262	−87 to 13	(*39*)
δ Sco	2.2×10^{17}	1.5×10^{21}	149	26 to 126	(*35*)
ζ Oph	1.9×10^{17}	1.4×10^{21}	134	41 to 141	(*40*)

Table 3. Carbon required for observed spectral features.

Feature	Assumed carrier	Carbon abundance (C atoms per 10^6 H atoms)	Reference
UIR emission	Hot gas-phase PAH ions	4	(*72*)
		4 to 15	(*73*)
		65	(*74*)
	Hot solid PAH (anthracene)	26	(*75*)
3.4-μm absorption	Amorphous carbon on grains	290	(*48*)
	Aliphatic hydrocarbon on grains	96	(*76*)
		11 to 154	(*50*)
3.3-μm absorption	Cold PAHs in diffuse ISM	15 to 20	(*51*)
4.67-μm absorption	Solid CO	9	(*77*)
DIBs (all)	PAHs in HAC; $f = 10^{-2}$	0.3*m**	(*78*)
DIB λ4430	Ionized pyrene	<1	(*79*)
DIB λ7141	Ionized naphthalene	<2	(*80*)
DIB λ4430	Ionized methyl pyrene	<1	(*81*)
DIBs λλ9577, 9632	C_{60}^+	<1	(*82*)
2175 Å bump	Amorphous carbon	70	(*83*)
	Small graphite grains	60	(*84*)
	Anthracite (coal)	106	(*49*)

*In this model, *m* represents the average number of carbon atoms per DIB carrier. For moderate-sized PAHs, *m* would be in the vicinity of 20.

The DIBs are of some interest because of the recent consensus that they must be formed by large carbonaceous molecules (*53*). There are now nearly 200 recognized bands throughout the optical and near-infrared, and they certainly do not all arise from a single carrier. Among the popular current suggestions are ionized polycyclic aromatic hydrocarbons (PAHs), ionized fullerenes, and carbon chain molecules, all of which are dominated by carbon. Even with our revised value for the cosmic carbon abundance, there appears to be no difficulty in producing the observed spectrum of bands. All of the models for spectral features that invoke PAH molecules require only modest fractions of the overall carbon budget, although this becomes potentially problematic when the enormous number of possible PAH forms is summed. However, spectroscopic considerations suggest that by some mechanism a limited number of PAHs must be selected in the ISM; if so, then there appears to be no abundance problem with invoking PAHs as the carriers of the UIRs and the DIBs, nor is the possible detection of cold gas-phase PAH absorption (*51*) ruled out.

The question of explaining the general extinction curve by various models presents more difficulties. Table 4 shows that several such models can be ruled out, or at least cast into doubt, by the revised cosmic carbon abundance value. All of the models that invoke hydrogenated amorphous carbon (HAC) to explain the general extinction lose credibility; this is potentially very important because HAC has been suggested as the explanation for other phenomena, such as the extended red emission (ERE) (*54*). These models generally postulate core-mantle dust grains, with HAC (or any icy mantle including hydrocarbons) overlying silicate cores, and they have a long heritage (*55*). However, there is just enough uncertainty in both the required quantity of carbon in HAC and the cosmic carbon abundance to leave some room for these models to fit, and therefore further scrutiny is warranted.

Table 4. Carbon required for selected general extinction models.

Model	Carbon abundance (C atoms per 10^6 H atoms)	Reference
Graphite + silicates	≥240	(*57*)
Small carbon grains + carbon in mantles	280	(*55*)
HAC	130	(*85*)
HAC + graphite	185	(*86*)
HAC + solid PAH	185	(*87*)
PAH + graphite	101	(*62*)
HAC coatings on silicates	75 to 300*	(*86*)
Very small amorphous carbon grains + PAH	45†	(*60*)
Graphite + amorphous carbon grains	110	(*61*)
Composite grains	265	(*59*)
Graphite + silicates	300	(*56*)
Graphite, PAH, and silicate grains	180 to 295	(*58*)

*The range in values represents the contrasting requirement for carbon in HACs for low far-UV extinction and high far-UV extinction. †This model fits far-UV extinction and the 2175 Å bump only; additional carbon in the form of large grains may be needed to reproduce the visual extinction.

It also appears difficult to attribute the general extinction to the presence of graphite. Graphite can produce the 2175 Å bump without encountering abundance constraints (Table 3), but in light of our revised cosmic carbon abundance value, it does not seem to be responsible for the general extinction. This implication contradicts the graphite-plus-silicate scenario of Draine and Lee (*56*) [which is based on the earlier Mathis *et al.* (*57*) model] as well as the recent work of Aanestad (*58*), who was able to reproduce observed extinction curves very accurately with a mixture of large and small graphite grains, large and small silicate grains, and gas-phase PAHs. Our results suggest that graphite may well be the carrier of the 2175 Å bump but that it probably does not also produce the general extinction.

The composite "fluffy grain" model of Mathis and Whiffen (*59*) also appears to be untenable with respect to the revised cosmic carbon abundance value. This model calls for dust grains made of small particles stuck together in an amorphous matrix, with a large fraction of the volume in vacuum, and it has many attractive features. It uses graphite to form the 2175 Å bump and amorphous carbon for the general ultraviolet (UV) extinction. The models that do appear to fit into our revised carbon budget are those that call for a combination of graphite and amorphous carbon grains (*60, 61*) or a combination of PAH and graphite grains (*62*), but substantial questions remain, particularly concerning the absorption efficiency of the amorphous forms of carbon.

Discussion and Outlook

It is interesting that many of the same conclusions that we have reached concerning the carbon abundance may also be true of oxygen. One difficulty faced by interstellar dust models is that they fall far short of accounting for the large amounts of oxygen thought to be depleted from the interstellar gas; silicates are the major form suspected to be present in the dust, and the dust models generally do not require all of the available oxygen if the solar oxygen abundance is assumed. The quantity of oxygen tied up in water ice and in solid CO is also known, and it also falls short (*63*). Meyer *et al.* (*64*) recently noted that gas-phase absorption measurements of oxygen in the Orion region revealed abundances that were lower than the solar oxygen abundance; they attributed this finding to infall from the galactic halo of gas that is not enriched. An alternative explanation would be that Orion has "normal" oxygen whereas the sun is enriched, as was suggested more than a decade ago by Olive and Schramm (*16*).

With respect to the measurement of interstellar carbon, it is clear that further observations of the C II] line at 2325 Å are required, in view of the small number of sight lines for which data now exist and the apparent variation in the carbon depletion. A larger data set will help to establish the uniformity of the relatively small carbon depletion as a general diffuse ISM characteristic, to demonstrate whether the carbon depletion is in fact variable, and to explore whether and how the carbon depletion varies with the shape of the UV extinction curve, as some models predict.

Note added in proof: Cardelli *et al.* (*64a*) have measured the CII] line in a few additional lines of sight, with results similar to those reported here.

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Venus Reconsidered

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The Magellan imagery shows that Venus has a crater abundance equivalent to a surface age of 300 million to 500 million years and a crater distribution close to random. Hence, the tectonics of Venus must be quiescent compared to those of Earth in the last few 100 million years. The main debate is whether the decline in tectonic activity on Venus is closer to monotonic or episodic, with enhanced tectonism and volcanism yet to come. The former hypothesis implies that most radioactive heat sources have been differentiated upward; the latter, that they have remained at depth. The low level of activity in the last few 100 million years inferred from imagery favors the monotonic hypothesis; some chemical evidence, particularly the low abundance of radiogenic argon, favors the episodic. A problem for both hypotheses is the rapid decline of thermal and tectonic activity some 300 million to 500 million years ago. The nature of the convective instabilities that caused the decline, and their propagation, are unclear.

Perceptions of Venus have changed significantly in the last 5 years, not only because of results returned by the Magellan spacecraft but also because of better experiments on the rheology of dry crustal rocks. As of 1990, it was generally but not universally agreed that plate tectonics was negligible on Venus, that Venus must have a stiff upper mantle, and that at least the northernmost 25% of the surface (the part observed by Venera orbiters) must average several 100 million years in age. The surface compositions measured at most Venera landing sites were considered to be consistent with a primitive basaltic crust, and two of the sites indicated further differentiations. The strength indicated by high depth/diameter ratios of craters was interpreted to limit the mean thickness of the crust to less than 20 km. Leading inferences in 1990 were (i) that Venus lacks water in its outer few hundreds of kilometers; (ii) that the energy delivery from the mantle must be less than Earth's, perhaps half as much; and (iii) that some appreciable energy sources persist at great depths to sustain the few great mountain complexes. The problem identified as the greatest was reconciling a voluminous crust with the indications of considerable strength at shallow depths of 20 to 100 km (*1*).

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The most important data from Magellan radar imagery are the impact craters, of which 915 have been identified. They have an abundance indicating an average surface age of 300 million to 500 million years and a geographic distribution consistent with randomness on a global scale (*2*). Furthermore, the lack of clusters of older craters implies a rapid decline in the resurfacing of Venus, perhaps within a few tens of millions of years. Although more detailed examinations infer that Venus is not entirely dead (*3*), they generally confirm inferences from Pioneer Venus altimetry (*4*) that recent tectonic activity on Venus is slight compared to Earth's. An important general characteristic inferred from Magellan imagery is that deformation on Venus is distrib-