

Extraterrestrial Helium Trapped in Fullerenes in the Sudbury Impact Structure

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Fullerenes (C_{60} and C_{70}) in the Sudbury impact structure contain trapped helium with a $^3\text{He}/^4\text{He}$ ratio of 5.5×10^{-4} to 5.9×10^{-4} . The $^3\text{He}/^4\text{He}$ ratio exceeds the accepted solar wind value by 20 to 30 percent and is higher by an order of magnitude than the maximum reported mantle value. Terrestrial nuclear reactions or cosmic-ray bombardment are not sufficient to generate such a high ratio. The $^3\text{He}/^4\text{He}$ ratios in the Sudbury fullerenes are similar to those found in meteorites and in some interplanetary dust particles. The implication is that the helium within the C_{60} molecules at Sudbury is of extraterrestrial origin.

Fullerenes (C_{60} and C_{70}) have recently been identified in a shock-produced breccia (Onaping Formation) associated with the 1.85-billion-year-old Sudbury impact structure (1). The presence of 1 to 10 parts per million (ppm) (1) of fullerenes in these samples from the Onaping Formation raises questions about the origin of fullerenes and about the potential for delivery of intact organic material to Earth by a large bolide (for example, an asteroid or comet). Because the Sudbury target rocks are poor in carbon (C), we have suggested that the fullerene C was extraterrestrial in origin (1). There are two possible scenarios for the presence of fullerenes in the Sudbury impact deposits: (i) that fullerenes are synthesized within the impact plume from the C contained in the bolide (1), or (ii) that fullerenes were already present in the bolide and survived the impact event. We examine here these possible sources of the Sudbury fullerenes by searching for noble gases trapped inside the fullerene molecule.

The correlation of C and trapped noble gas atoms in meteorites is well established (2). Primitive meteorites contain several trapped noble gas components that have anomalous isotopic compositions. For example, Black and Pepin (3) found anomalous Ne values in several primitive unmetamorphosed meteorites, and Anders and co-work-

ers (4) reported Kr and Xe values in the Murchison and Allende meteorites that are indicative of a presolar origin. Several C-bearing phases have been recognized as carriers of trapped noble gases, including SiC, graphite, and diamond (5). Fullerenes have been suggested as a carrier of noble gas components in carbonaceous chondrites (6); however, so far, the identification of fullerenes (C_{60} and C_{70}) is limited to a single occurrence in the Allende meteorite (7).

The C_{60} molecule is large enough to enclose the noble gases He, Ne, Ar, Kr, and Xe but is too small to contain diatomic gases such as N_2 or triatomic gases such as CO_2 . Recent experimental work has demonstrated that (i) He is incorporated into C_{60} during fullerene formation in a He atmosphere and (ii) noble gases of a specific isotopic composition can be introduced into synthetic fullerenes at high temperatures and pressures; these gases can then be released by the breaking of one or more C-C bonds during step-heating under vacuum (8). The unique thermal release patterns for He encapsulated within the C_{60} molecule ($\text{He}@C_{60}$) are similar to the patterns for acid-resistant residues of carbonaceous chondrites (9), suggesting that fullerenes could be a carrier of trapped noble gases in meteorites.

To determine the noble gas abundances and isotopic ratios for the fullerenes, we undertook a systematic study of acid-resistant residues generated from samples collected at the Dowling and Capreol townships within the C-rich layer (Black Member) of the Onaping Formation (10). If the fullerenes were formed in the impact plume, then the isotopic ratios of the trapped gases would reflect the composition of Earth's atmosphere (that is, terrestrial) at the time of the impact. If, on the other hand, the fullerenes were present in the bolide before

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C_{60} molecule is also of extraterrestrial origin. In order to retain extraterrestrial He, fullerenes must have survived the impact that produced the Sudbury crater (23).

If the fullerenes had formed as a result of the impact event, it seems likely that the $^3\text{He}/^4\text{He}$ ratio would reflect some contribution from Earth's atmosphere, resulting in a $^3\text{He}/^4\text{He}$ ratio lower than solar wind values. The rigid-sphere incorporation model developed for the synthetic fullerenes (8) suggests that the probability that a noble gas atom will be trapped within a fullerene molecule during formation is a function of the size of the fullerene cavity and the density of the gas. According to this model (8), the ^3He partial pressure for the Sudbury fullerenes at the time of formation is estimated to have been 0.5 torr (versus 10^{-10} torr in the present-day atmosphere), suggesting that a mechanism other than a terrestrial synthesis is needed. The ratios of the C_{60} isotopic mass peaks for the fullerenes (1) show a possible enrichment in ^{13}C , which would also indicate an extraterrestrial source of C.

Other possible terrestrial production mechanisms for the ^3He , such as cosmic-ray bombardment on Earth, may account for only a tiny fraction of the total ^3He in the C_{60} because surface exposure of the Sudbury rocks for more than 5×10^9 years would be necessary to generate the measured amount (24). Nuclear reactions in the terrestrial environment over geologic time are also capable of generating high $^3\text{He}/^4\text{He}$ ratios, and this process has been invoked to explain the high $^3\text{He}/^4\text{He}$ ratios determined in some diamonds (25). The dominant pro-

Table 1. Concentration of the He released during step-heating (17). The $^3\text{He}/^4\text{He}$ ratio (R) is compared to the average value for terrestrial air (R_{air}).

Temperature (°C)	^3He (10^{-9} cm 3 /g)	^4He (10^{-6} cm 3 /g)	$^3\text{He}/^4\text{He}$ (R/R_{air})	Fraction of ^3He released per minute
<i>Dowling 1</i>				
400	7.51	22.06	245	0.0018
500	31.17	51.93	432	0.0046
600	22.43	34.79	464	0.0043
700	27.59	41.36	480	0.0069
800	22.77	48.86	335	0.0138
850	3.56	10.25	250	0.0167
Total	115	209	393	
<i>Capreol 2</i>				
350	0.51	0.61	601	0.00012
450	3.32	7.66	312	0.00082
550	9.20	15.98	414	0.00239
650	9.11	15.75	416	0.00276
750	25.62	40.88	450	0.00932
800	18.88	32.10	423	0.01557
850	1.33	2.67	358	
Total	68.0	115.6	423	

duction mechanism is $^6\text{Li} + n \rightarrow ^3\text{He} + ^4\text{He}$ (^3H decays to ^3He). However, in typical crustal rocks, the $^3\text{He}/^4\text{He}$ ratio of this nucleogenic component is 10^{-8} , or 10^{-4} times that observed for Sudbury fullerenes. Experimental results (26) indicate that, even under ideal conditions in which the Li atom is attached to the C_{60} molecule and then irradiated with a low thermal neutron flux (10^{14} neutrons per square centimeter), only four ^3H atoms were incorporated per 10^{10} C_{60} molecules. The irradiation also destroyed a large portion of the fullerenes. The experimental yield is only 11% of the

concentration (37 ^3He atoms per 10^{10} C_{60}) observed, demonstrating that nuclear reaction implantation is not an effective mechanism for getting He into fullerenes.

The presence of extraterrestrial He@ C_{60} in the Sudbury impact deposits suggests that fullerenes may indeed be present in some meteorites or comets and that fullerenes may also be a unique carrier of noble gases in certain extraterrestrial environments. In addition, on the basis of the He release and temperature-pressure stability estimates for

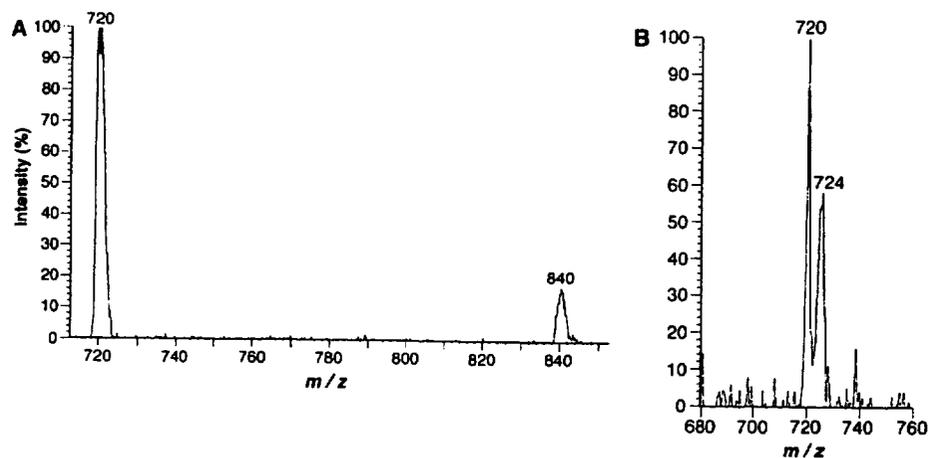


Fig. 1. (A) Laser desorption (reflectron) mass spectrum (LDMS) of the Dowling sample showing peaks at m/z of 720 and 840 amu. Intensity is given in arbitrary units. The Dowling sample had significantly more C_{70}^+ (804 amu) than the Capreol sample (the C_{70}^+ peak for Capreol was barely above background). (B) The LDMS of the Capreol sample. By carefully calibrating the mass spectrometer at an acceleration voltage of 5 keV, we were able to observe a mass spectrum that included C_{60}^+ and $C_{60}\text{He}^+$ at 724 amu (a peak for 724 amu was not observed in any of the authentic fullerene standards). This analysis maximizes the detection for C_{60}^+ and $C_{60}\text{He}^+$, and thus the peak intensities shown are exaggerated and do not reflect the absolute abundances of the ions. Under the LDMS conditions, it is unlikely that $C_{60}\text{He}^+$ would survive if He were bound to the exterior of the C_{60}^+ molecule. These results suggest that He is in the interior of the Sudbury C_{60}^+ molecule, indicating an endohedral complex (16).

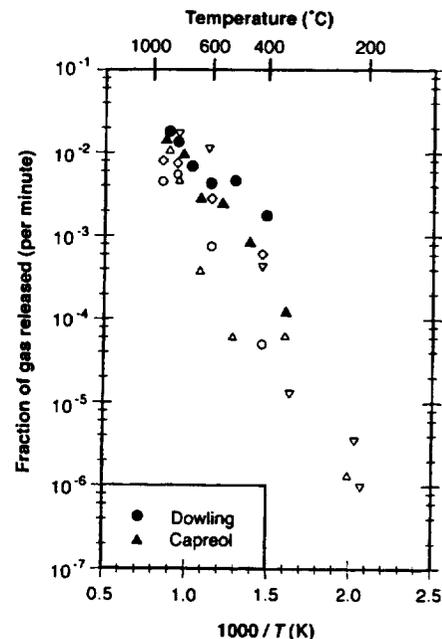


Fig. 2. Temperature (T)-dependent ^3He release for the Capreol (\blacktriangle) and Dowling (\bullet) samples. Open symbols are the release rates for the synthetic fullerenes (C_{60} and C_{70}) taken from (8): (∇ and \triangle) ^3He , (\circ) ^4He , and (\cdot) Ne.

He@C₆₀ [see Fig. 2 and (8)], some portion of the Sudbury bolide must have remained well below the He@C₆₀ stability temperature (1000°C). The survival of He@C₆₀ during a bolide impact such as the one that created the Sudbury crater is unexpected (27) and suggests that the exogenous delivery of organic material to the early Earth may be more favorable than has been previously assumed. The extensive fragmentation of a bolide during passage through Earth's atmosphere may be one way of preserving some of the extraterrestrial organic material during an impact event.

An important remaining consideration is the type of environment that would favor fullerene formation. The diffuse interstellar medium (ISM) is a hostile environment, and several processes may act to destroy fullerenes (for example, sputtering or shocks). However, there is evidence for the existence of a solid form of C that is of the size of a large molecule or a small particle, having survival characteristics against ultraviolet photodissociation and destructive shocks (28). Whether this material is in the form of polycyclic aromatic hydrocarbons (28, 29) or is related to fullerene molecules (30) remains an intriguing question.

Because the Sudbury fullerenes exhibit ³He/⁴He ratios that exceed those associated with the solar wind and because of the high He pressure of incorporation (~1000 torr at 1000°C), we favor a scenario in which He is trapped in the Sudbury fullerenes before the condensation of the solar nebula (30). However, alternative mechanisms occurring in the ISM, such as spallation reactions and selective He implantation, may also be responsible for the higher than solar ³He/⁴He ratios. The paucity of H appears to be necessary to promote the C shell closure required for fullerene formation (31). Environments in which the formation and preservation of fullerenes may be favorable (30, 31) include those for which the H concentrations are much lower than the mean cosmic abundance (H/He < 10⁻⁹), the C/He ratio is ~0.004, and the C/O ratio is >1. These conditions are similar to the outflows from Wolf Rayet and R Coronae Borealis stars (30–33). Confirmation of a presolar origin for the Sudbury fullerenes will require the identification of anomalous isotopic compositions of Ne, Kr, and Xe [for example, the pure ²²Ne component (5)] that may be contained within the fullerene molecule (34) and precise determination of the Sudbury fullerene C isotopic ratio.

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10. The Dowling samples were collected in Dowling Township, 300 m east of Highway 144 in the High Falls area, a type location for sampling the Onaping Black Member (46°36'N, 81°24'W). The Capreol samples were collected in Capreol Township, 3 m west of Highway 545 (46°42'N, 80°55'W).
11. We have considered the possibility that some of the Sudbury fullerenes may have opened up as a result of metamorphism (temperatures of 300° to 400°C at pressures of 3 to 5 kbar in the Onaping rocks). If exchange of He took place, atmospheric He (³He/⁴He ~ 1.4 × 10⁻⁶) or radiogenic (³He/⁴He ~ 10⁻⁹) components typical for crustal rocks would have been added to the fullerene molecule.
12. The common approach for the demineralization of meteorites is to use HF–HCl acids to concentrate and isolate organic matter and C. This procedure often leads to the formation of fluoride salts, which are insoluble and could potentially trap organics and carbonaceous materials. Here we selectively dissolved neofluorides in a two-step process by reaction with BF₃, a water-soluble gas, generated by the reaction of H₃BO₃ with HF and water. Then BF₃ reacts with fluoride salts to form water-soluble fluoroborates. The demineralized portion (typically 80 to 100 g of powdered bulk rock treated with acid yields ~1 g of carbonaceous residue) of the Onaping rock was then put into an extraction thimble, placed into a Soxhlet apparatus, and refluxed with toluene for 24 hours. The excess toluene was evaporated to dryness, leaving a small amount (microgram quantities) of residue. This residue was then redissolved in toluene and concentrated to ~1 ml, yielding a bright reddish solution.
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2000. A microliter of concentrated solution was placed on a stainless steel slide. Once the toluene had completely evaporated, the fullerene extract was transferred by a rapid sample change port into the high-vacuum chamber (~2 × 10⁻⁷ to 2 × 10⁻⁸ torr). Neutral and ionized particles were desorbed by a 337-nm ultraviolet nitrogen laser at low power densities (10⁸ W/cm²). Mass spectra of positive ions emitted directly in the desorption process from the sample were collected. Blanks were run between sample analyses. Standards of C₆₀ and C₇₀ (Aldrich) were used to calibrate measurements of fullerenes detected in the sample extracts.
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17. The toluene extracts containing the Sudbury fullerenes were loaded into a metal tube furnace within a glove box under a N₂ atmosphere in preparation for noble gas analyses. After heating the samples in vacuum for 3 days at 100°C, which completely removed any residual toluene, we then incrementally heated (60 min per step) the microgram quantities (about 200 μg of C₆₀ per aliquot) of fullerene residues to release the trapped noble gases (8). Noble gases He, Ne, and Ar were cryogenically separated and then sequentially measured with a VG 5400 noble gas mass spectrometer fitted with a Johnston electron multiplier with pulse counting electronics on the axial collector [R. J. Poreda and K. A. Farley, *Earth Planet. Sci. Lett.* **113**, 129 (1992)]. A resolution of 550 (*m/Δm*) achieved complete baseline separation of ³He⁺ and HD⁺. Absolute abundances of ³He, ⁴He, ³⁶Ar, ⁴⁰Ar, and ²²Ne were calculated by peak height comparison to a standard of known size (0.101 cm³ of air at standard temperature and pressure) with an accuracy of ±3%. The small amount of ²²Ne and ³⁶Ar at all temperatures (10⁻¹¹ and 10⁻¹⁰ cm³, respectively) was equivalent to the average blank. Average blank levels were 1 × 10⁻¹⁰ cm³ for ⁴He and 2 × 10⁻¹⁰ cm³ for ³He. The contribution of adsorbed atmospheric He can be estimated from the measured ²²Ne and the ⁴He/²²Ne ratio in air of ~3.1. In all of the temperature steps above 200°C, this contribution was negligible (<1% of ⁴He and <0.01% of ³He). In comparison to the fullerene toluene fractions, heating 10 mg of the bulk acid residue to 800°C released ³He and ⁴He at levels about three times the extraction blank.
18. Atmospheric isotopic ratios of Ne and Ar were measured for the Dowling and Capreol samples in all temperature fractions. The measured gas indicates that the presence of an adsorbed atmospheric component or that a certain percentage of the fullerene molecules has opened up over geologic time, allowing atmospheric gases to be incorporated. Blank levels of ²²Ne were about 10⁵ times the blank levels for ³He (~10⁻¹¹ cm³ for Ne versus ~10⁻¹⁰ cm³ for He). If the anomalous gas component has a solar ³He/²²Ne ratio of 1.3 [M. Ozima and F. Podosek, in *Noble Gas Geochemistry* (Cambridge Univ. Press, Cambridge, 1983)], then we need to achieve a factor of 10 reduction in our ²²Ne background to observe any anomalous Ne isotopic ratios.
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23. Once the fullerenes were deposited in the Sudbury structure (Onaping Formation), they were protected from oxidation and irradiation by a surrounding sulfide-silicate matrix, which allowed them to survive to the present (7).
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33. Carbon soot formation in these stars is expected to be initiated through the formation of polyenes [acetylene-like C chains without H, such as C_2 , C_3 , and C_4 (30)]. The lack of H minimizes saturation of dangling C bonds, allowing pentagons to be incorporated into the aromatic structure. The introduction of pentagons induces warping and curling of the aromatic planes, which would lead to closure and fullerene formation. It was the laboratory experiments used to probe these questions (laser ablation of graphite in an inert environment) that resulted in the initial discovery of fullerenes (C_{60} and C_{70}) and the proposal that this unique form of C may be involved in the C nucleation process (30–32).
34. Recent calculated equilibrium constants for the incorporation of noble gas atoms inside the C_{60} molecule (two different models were used to calculate the potential between the noble gas atom and each C atom) indicate that the potentials agree for encapsulation of He and Ne but disagree strongly for encapsulation of Kr and Xe. If this is the case, then the C_{60} molecule may preferentially incorporate the lighter noble gases over the heavier noble gases (H. A. Jiménez-Vásquez and R. J. Cross, *J. Chem. Phys.*, in press).
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