The travel diary of a micron-sized sphere, found in the Murchison meteorite

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By examining the thickness of graphitic layering around a pre-solar grain from the Murchison meteorite, in context of previous information about its origins in and around an asymptotic giant branch star, one can extrapolate back to conditions of formation within the atmosphere of that star. We outline this extrapolation for a micron-sized core/rim interstellar graphite onion first documented by Dori Witt while an undergraduate at UM-StL, in light of the newfound interest in "stardust at home". The extrapolation takes us all the way back to an outward acceleration ($\sim 5m/s^2$) of the particle's core due to radiation pressure from its parent star, as chances to thicken its graphite rim rapidly fade. We further examine the constraints that this information places on processes involved in forming the novel unlayered graphene in this particle's core, in light of recent work on the core structure of similar particles reported elsewhere at this meeting by Eric Mandell.

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CONTENTS

I. THE PARTICLE

Meet Vivian, our interstellar reporter (Fig. 1). She's been reduced to a thin slice of graphitic "onion" just under a micron in radius, with a core made of strange carbon that we call unlayered graphene. Currently she resides on a standard electron microscopy collection grid, entirely surrounded by LR White hard resin [1] and other onions like her. Vivian has quite a history, as evidenced by her preparation for the lab. Before she and her slender cohorts were mere slices, they were full-bodied interstellar spheres trapped in the medium of epoxy. Their "block" was then sliced using a diamond knife-wielding ultramicrotome, into divisions less than 100 nanometers thin. These were immediately floated on water to keep them from sticking to a dry surface, and caught with a collection grid to make the measurements. But where did she come from before that?

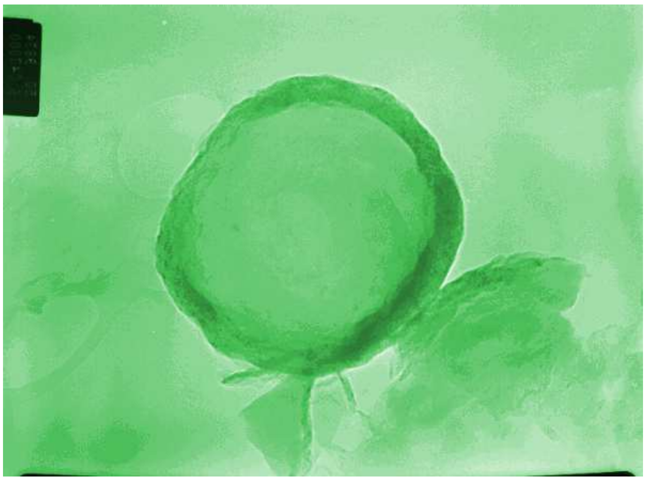

FIG. 1: A 0.9 micron diameter interstellar graphite sphere slice, first named informally by Dori Witt following tradition for circumstellar dust [2].

II. EXTRACTION FROM THE METEORITE

Vivian was extracted from the Murchison meteorite by cosmochemists at the University of Chicago, by immersion in a series of acids and bases, followed by centrifugation and other size-separation steps [3]. This is possible since oxides are more prevalent in these meteorites (and

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our whole solar system for that matter) than the carbon phases which form when there is more carbon than oxygen, and since graphite in particular is especially resistant to most solvents (except for molten iron and atomic oxygen). Researchers at the University of Chicago, and at Washington University, were then able to examine the remnants of the meteorite, and the composition of gases and solids that remained.

The Chicago group found that several noble gases were left inside the meteorite residue, in isotopic abundances (like nearly pure ^{22}Ne) not found elsewhere in our solar system. Except for the result of isolated nuclear processes, all materials in our solar system tend to have a uniform isotopic composition that incidentally seems to match with the "galactic average" composition as well. This is consistent with our solar system forming from a well-mixed average of gas and dust typical of our galaxy at the time of its formation. The isotopes of the various noble gases found in the meteorite residues, i.e. Ne, Ar, Kr, and Xe, break this pattern. Additionally, the fact that odd gases are there also means that the residues have not been heated significantly since they were exposed to those gases.

Work at Washington University on isotopes of the solid elements in these residues [4–6] have shown that they too differ drastically from solar system values (like ^{12}C/^{13}C $<$ solar = 89). Taken together with the noble gas data, these fit the signature of nucleosynthetic processes predicted to occur in diverse astrophysical objects, e.g. late stage red giants and supernovae. Vivian is one of the growing collection of such pre-solar (ancient stardust) grains in terrestrial laboratories. The residue that she's in, along with her fellow particles, carries the high ^{22}Ne expected for intershell matter brought up by third dredge-up episodes of a carbon-rich asymptotic giant branch star [7], while the low ^{12}C/^{13}C ratios of carbon in her sister particles confirm their pre-solar origins, and are expected to result from proton capture on ^{12}C in those same stars [8].

III. MURCHISON'S TRAVELS

Vivian's meteorite crashed into our planet near Murchison, Victoria in Australia on September 28th, 1969. Upon entering the Earth's lower atmosphere, the meteorite broke up into smaller pieces, which scattered across a sizeable area. The impact of the sample Vivian was found in was most likely preceded by the chunk's outer crust melting from the heat of friction due to air drag. Fortunately for us (and Vivian), this heat did not have much time to spread to the meteor's core as it fell; it may have had only a few seconds between atmospheric entry and impact. Also, much of the resulting shock from the impact would have been absorbed into the ground, with little damage to Vivian's nano-scale structure. Had Vivian's meteorite been much bigger, she might have vaporized on entry. Had it been smaller, conceivably smaller than a baseball, it would have melted on impact with the earth's upper atmosphere. (Note: Meteoroids smaller than 10 microns in size avoid this fate by slowing down before they hit the dense upper atmosphere, but that is the subject of another tale.) Thus for Vivian, our interstellar Goldilocks, the Murchison meteorite was just right.

IV. ORIGINS OF MURCHISON

Before impacting in Australia, the rock fragments now called Murchison were likely traversing the inner solar system in earth-crossing orbits for some time. Vivian's electrons were barely effected when radio was invented on earth about 100 years ago. She likely did not notice the dark ages in Europe about a 1000 years ago, the beginning of the current interglacial around 10,000 years ago (and our development of farming), or even the start of the most recent glaciation about 100,000 years ago (and domestication of the family dog). However around 800,000 years ago (not long after Homo Erectus had figured out how to control fire, and the land bridge to the island of Flores disappeared), cosmic-ray exposure ages [9] tell us that Vivian's piece of Murchison was broken into meter-sized pieces. This may have been the collision event that sent her careening into warmer regions of the solar system. Thus she likely felt a bit of a jolt at that time, followed by some periodic warming, even though neither of these was enough to cause her to share her ^{22}Ne with the grains sitting nearby.

Long before the breakup of her parent body, and even before acquiring Vivian and her gang of particles, the Murchison meteorite first accreted as part of a planetoid which was large enough to shield Murchison and passengers from cosmic rays. This was not a recent event. It took place before australopithecus walked the earth over 6 million years ago, before the meteorite impact which caused extinction of the dinosaurs over 60 million years ago, and before the Cambrian bloom nearly 600 million years ago when metazoan life forms flowered into amazing diversity. As with most meteorites, Murchison's parent body was assembled during the formation of our solar system around 4.5 billion years ago. Radiometric dating techniques [10] have long been used to estimate these formation ages. They pretty uniformly cluster between 4.4 and 4.6 billion years ago, a time also consistent with estimates of the time at which our sun "lit up" by starting to fuse hydrogen into helium.

Murchison is one of a select group of carbonaceous chondrites, which are themselves rare. Only 2-3% of all known meteorites are carbonaceous chondrites. Murchison is a "C2" carbonaceous chondrite, which in practice may mean that it has been heated less than the C3 meteorites (like the Allende meteorite that fell in Mexico's Chihuahua state in February 1969), and altered by water less than the C1 meteorites (like crumbly Orgueil, which fell in France on 14 May in 1864 when the non-earthly origin of meteorites was a topic of considerable debate). They represent organic material present at the beginning of the solar system, since they remain unchanged in the depths of space, while geological and biological forces on Earth often destroy the presence of such early volatiles. Such an object could preserve, out near the asteroid belt or further, what our solar system was like at its conception. At the same time as the planets' forming and our star collapsing, beginning to ignite nuclear fusion of helium at its core, so too was the Murchison meteoroid taking shape, over 4.5 billion years ago. And what of the interstellar hitchhikers on board?

V. VIVIAN'S YOUTH

Vivian has a crystalline graphite rim. This means that she (unlike grains exposed on the lunar surface) was not subject to the kind of heavy-ion bombardment (e.g. from solar flare ions) that would de-crystallize her outer layers. This is of course true for the period that she was inside Murchison and/or Murchison's parent body. Before that, we expect Vivian avoided active stars (much larger than our own sun, at least) because as we'll see radiation pressure overcomes gravity for spheres her size. On the other hand, before Vivian joined our solar system and Murchison she was likely traveling around in the interstellar medium on her own. This means that she was not shielded from cosmic ray primary radiation, which has a range in matter of about 150 g/cm^2. If Vivian was made up of insulating silicates, she might carry a detailed record of this irradiation history in the form of nuclear particle tracks [11]. Other byproducts of this irradiation may still turn up, but it appears that it was not sufficient to make her lose either her rim's crystallinity or her noble gases.

Galactic rotation takes place over a period of about 100,000 years. Since analysis of other pre-solar grains from meteorites suggest that they come from stars of different metallicity, and hence from stars begun throughout the early history of the galaxy [12], it is likely that Vivian spent at least a billion years alone as an interstellar grain. Hence her parent star might have been almost anywhere in the Milky Way.

Light emitted from fusion in that star was propagating outward, and this pushes away sufficiently small particles. Since both radiation pressure and gravity both fall off as one over distance squared, the critical size for ejection (i.e. below which the pressure force exceeds gravity) depends on the star's luminosity and the particle's mass and cross-section, but is independent of distance from the star. To explore this further, we asked Vivian about her mass with an electron energy loss spectrometer. Measurements of inelastic mean free path for 300 kV electrons show that her unlayered graphene core has a density between 1.5 and 2 grams per cubic centimeter, somewhat less than the 2.2 g/cc density of the graphite in her rim. A core radius of 0.67 microns (Fig. 1) then implies a mass of 2.3×10^{-15} kilograms before acquisition of the graphite rim. Thus the time that Vivian had to acquire that graphite rim was likely limited.

To explore this more quantitatively, consider a 3 solar mass AGB (asymptotic giant branch) star like that discussed by Lodders and Fegley [13]. Neglecting the relatively small gravitational force, and aerodynamic drag as her velocity with respect to the surrounding gas began to pick up, the acceleration due to radiation pressure of Vivian's core may be estimated as follows:

$$F = ma \simeq \frac{L}{c}\frac{\pi r^2}{4\pi R^2}. \tag{1}$$

Here L is the star's luminosity, r is Vivian's radius, and R is Vivian's distance from her parent star's center, m is Vivian's mass, and a is the acceleration due only to radiation pressure. As mentioned above, Vivian's mass relates to her density and radius as follows:

$$m \simeq \frac{4}{3}\pi r^3 \rho. \tag{2}$$

Here $\rho \sim 1.8g/cc$ is the density of Vivian's core, and $r \sim 0.675\mu m$ is her core's radius.

As surface temperature of that 3 solar mass star fluctuates from maximum phase (photosphere temperature of 2800K) to minimum phase (photosphere temperature of 2500K), the photosphere radius increases from R of 160× to 510× solar [13]. This (and the reason giant stars are red) is because the virial theorem [14] requires that gravitationally-bound systems gain larger size (more gravitational potential) at the expense of average thermal energy (and hence surface temperature) as luminosity increases. However, the ratio between luminosity and photosphere area remains essentially constant for a given surface temperature [15], in accordance with the Stephan-Boltzmann Law. Solving the above equations for acceleration gives

$$a \simeq \frac{3L}{16\pi c\rho R^2 r} \sim \frac{3\sigma T^4}{4c\rho r}. \tag{3}$$

Hence acceleration at the photosphere surface is similar for all stars of comparable surface temperature, and using these numbers for a red giant would have been on the order of 5 m/s^2. Corrections to this acceleration for gravitational force are small, and Mie-scattering corrections for wavelength-dependent cross-section are under development.

VI. DISCUSSION

The graphitic rim on Vivian might have been deposited as carbon atoms in the surrounding gas encounter these graphite particles by virtue of their thermal motion. On the other hand, if the particles were moving quickly with respect to the gas, they might have swept up carbon atoms in dust-forming regions outside the photosphere, thus creating the rim. This raises an interesting question. Why don't the carbon atoms in the way and surrounding her move even faster than her? They too should be affected by both the gravity of the star and radiation pressure from light. In fact, because they are so much smaller, the surface area to volume ratio is higher than Vivian's. Since radiation pressure depends on an object's surface area, and gravity depends on its mass - which is in direct correlation with volume - the radiation pressure to gravity ratio is higher, which should result in a greater acceleration outwards. Why not? Because the wavelength of light (on the order of hundreds of nanometers) is far larger than the size of the atoms, light merely passes through them, while it forces the particles outwards.

Thus Vivian may well sweep up her carbon atom rim on the way out. This is consistent with observations that dust particles in cool AGB outflows (which contribute most of the carbon to the interstellar medium) in fact drag the gas along with them [16, 17]. Combining information on presolar onion sizes and rim thickness, with models of gas density and temperature, might allow us to determine if the rims can be acquired under conditions that have been observed in stellar outflows, or if special events and/or locations are instead required to get the job done.

A related question involves the structure of Vivian's core itself. Electron diffraction quickly reveals it to be composed of graphene sheets which, unlike carbon in graphite or even much terrestrial "amorphous carbon" shows little to no sign of graphitic layering [1]. Recent work at UM-StL moreover suggests evidence for single-walled nanocone structures, with possible faceting [18]. Formation mechanisms involving single atom growth, collisional aggregation of polycyclic aromatic hydrocarbons, or dendritic crystallization of liquid carbon droplets are all under investigation. Once candidate processes have been identified, the things Vivian had to tell us here may be helpful in determining how such rimmed graphene spheres (likely vehicles for transport to Sol of many of the carbon atoms inside you) are being assembled as we speak in red-giant atmospheres across the Milky Way.

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REFERENCES

[1] T. Bernatowicz, R. Cowsik, P. C. Gibbons, K. Lodders, B. F. Jr., S. Amari, and R. S. Lewis, Astrophysical Journal **472**, 760 (1996).

[2] C. Pillinger, Nature **294**, 517 (1981).

[3] S. Amari, R. S. Lewis, and E. Anders, Geochim. Cosmochim. Acta **58**, 459 (1994).

[4] E. Zinner, Ann. Rev. Earth Planet. Sci. **26**, 147 (1998).

[5] T. J. Bernatowicz and R. M. Walker, Physics Today pp. 26–32 (1997).

[6] T. K. Croat, T. Bernatowicz, S. Amari, S. Messenger, and F. J. Stadermann, Geochim. et. Cosmochim. Acta **67**, 4705 (2003).

[7] R. Gallino, M. Busso, and M. Lugaro, in *Astrophysical implications of the laboratory study of presolar materials*, edited by T. J. Bernatowicz and E. Zinner (American Institute of Physics, Woodbury NY, 1997), no. 402 in AIP Conference Proceedings, pp. 115–154.

[8] J. C. Lattanzio and A. I. Boothroyd, in *Astrophysical implications of the laboratory study of presolar materials*, edited by T. J. Bernatowicz and E. Zinner (American Institute of Physics, Woodbury NY, 1997), no. 402 in AIP Conference Proceedings, pp. 85–114.

[9] M. W. Caffee, J. N. Goswami, C. M. Hohenberg, K. Marti, and R. C. Reedy, in *Meteorites and the Early Solar System*, edited by J. F. Kerridge and M. S. Matthews (U. Arizona Press, Tuscon AZ, 1988), pp. 205–245.

[10] E. Anders, *Meteorite ages* (1962).

[11] J. P. Bradley, D. E. Brownlee, and P. Fraundorf, Science **226**, 1432 (1984).

[12] L. R. Nittler, in *Astrophysical implications of the laboratory study of presolar materials*, edited by T. J. Bernatowicz and E. Zinner (American Institute of Physics, Woodbury NY, 1997), no. 402 in AIP Conference Proceedings, pp. 59–81.

[13] K. Lodders and B. F. Jr., in *Astrophysical implications of the laboratory study of presolar materials*, edited by T. J. Bernatowicz and E. Zinner (American Institute of Physics, Woodbury NY, 1997), no. 402 in AIP Conference Proceedings, pp. 391–423.

[14] D. V. Schroeder, *Thermal physics* (Addison Wesley Longman, San Francisco, 2000).

[15] M. Harwit, *Astrophysical concepts* (Wiley, New York, NY, 1973).

[16] M. Lugaro, *Stardust from meteorites: An introduction to presolar grains* (World Scientific, New Jersey, 2005).

[17] E. Sedlmayr and D. Krüger, in *Astrophysical implications of the laboratory study of presolar materials*, edited by T. J. Bernatowicz and E. Zinner (American Institute of Physics, Woodbury NY, 1997), no. 402 in AIP Conference Proceedings, pp. 425–450.

[18] P. Fraundorf and M. Wackenhut, Ap. J. Lett. **578**, L153 (2002).