

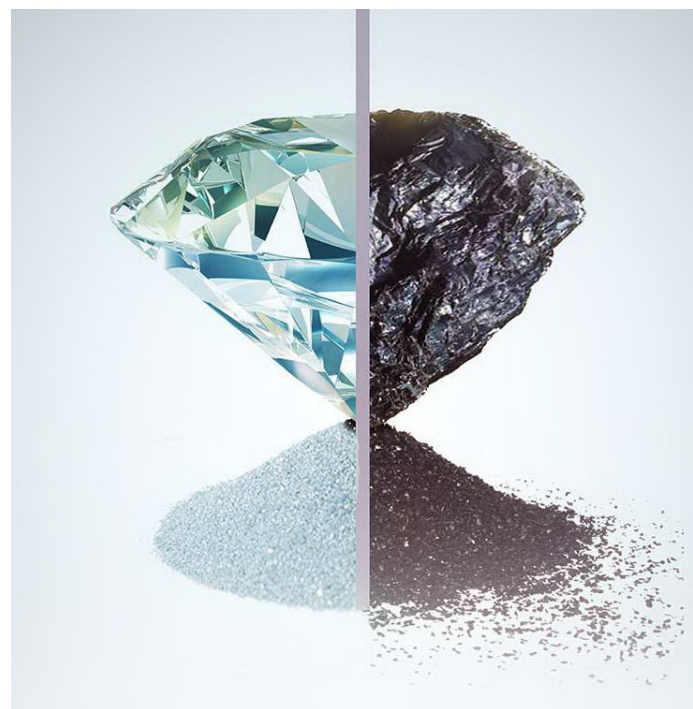


Diamonds in stars and interstellar medium

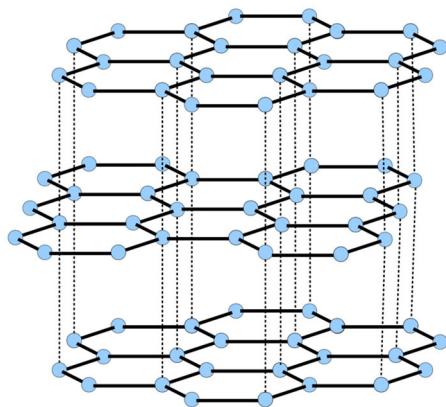
Seminar talk presented by
Dr. Boryslav Tkachenko

December 1st, 2019

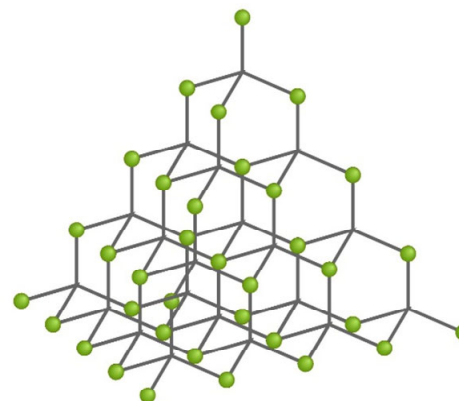
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Allotropes of Carbon



Graphite



Diamond



kinetically stable

$\Delta H_{f\text{diamond}} = 2.425 \text{ kJ/mol}$, thermodynamically stable



Diamond

- The hardest natural material
- Least compressible and stiffest substance
- Exceptional thermal conductor - 4 times better than Cu
- Extremely low thermal expansion
- Chemically inert
- Transparent from the far infrared through the deep ultraviolet
- Very dense (3.5 g/cm^3) given the low atomic weight of carbon
- Highest reflectance and index of refraction of any transparent substances
- Negative electron affinity

Diamond could be the oldest material you might own, natural diamonds are approximately 3.3 *billion* years old



- **Detonation Synthesis**
(ultradisperse nanodiamond or UDD)

gradient microstructure controlled by
the geometry of the shock front,
the direction of the pressure gradient



different
microstructures



- **Chemical Vapor Deposition**
(CVD process applied
for epitaxial growth
of ultrananocrystalline
diamond films or UNCD)

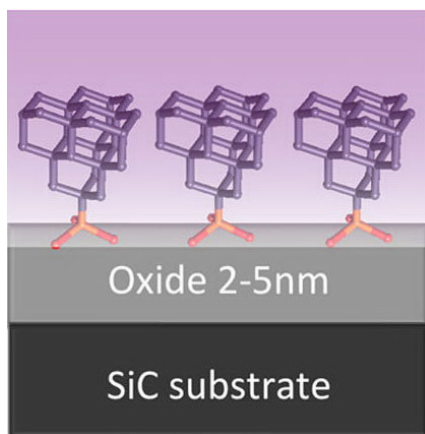
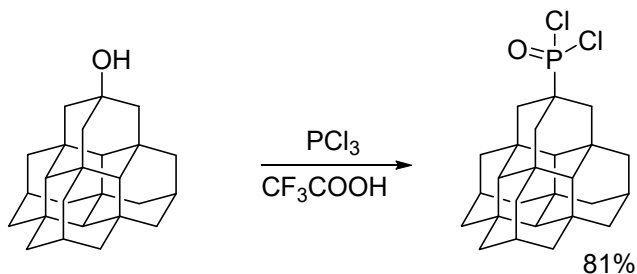
isotropic growth typical for direct
nucleation and homoepitaxial
growth from locally
homogeneous oversaturated gas

- **High-Pressure High-Temperature Synthesis (HPHT)**, useful as edges on cutting tools and drill bits
- **Radiation of carbonaceous materials** by laser, ultraviolet radiation, or fluxes of high energy particles

Fabricating Hybrid (Si-V) Diamond–SiC Devices with Microwave Plasma CVD



~ 500 nm Ø diamond–SiC nanowires

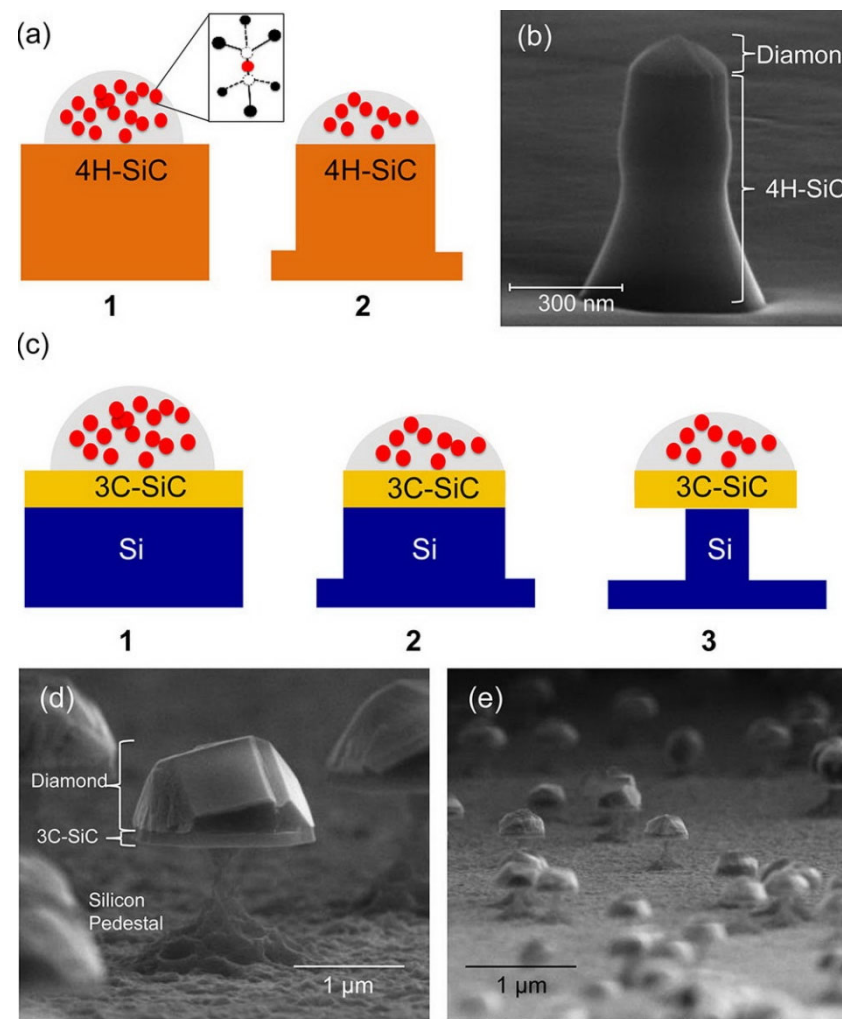


nucleation step

H₂ 5 sccm, CH₄ 10 sccm, Ar 90 sccm, 450 °C,
microwave 300 W, pressure: 23 Torr, 20 min

growth step

H₂ 300 sccm CH₄ 3–7.5 sccm, 830 °C
microwave 1300 W, pressure: 30 Torr



~2 µm Ø hybrid diamond–SiC microdome structures

Q
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D
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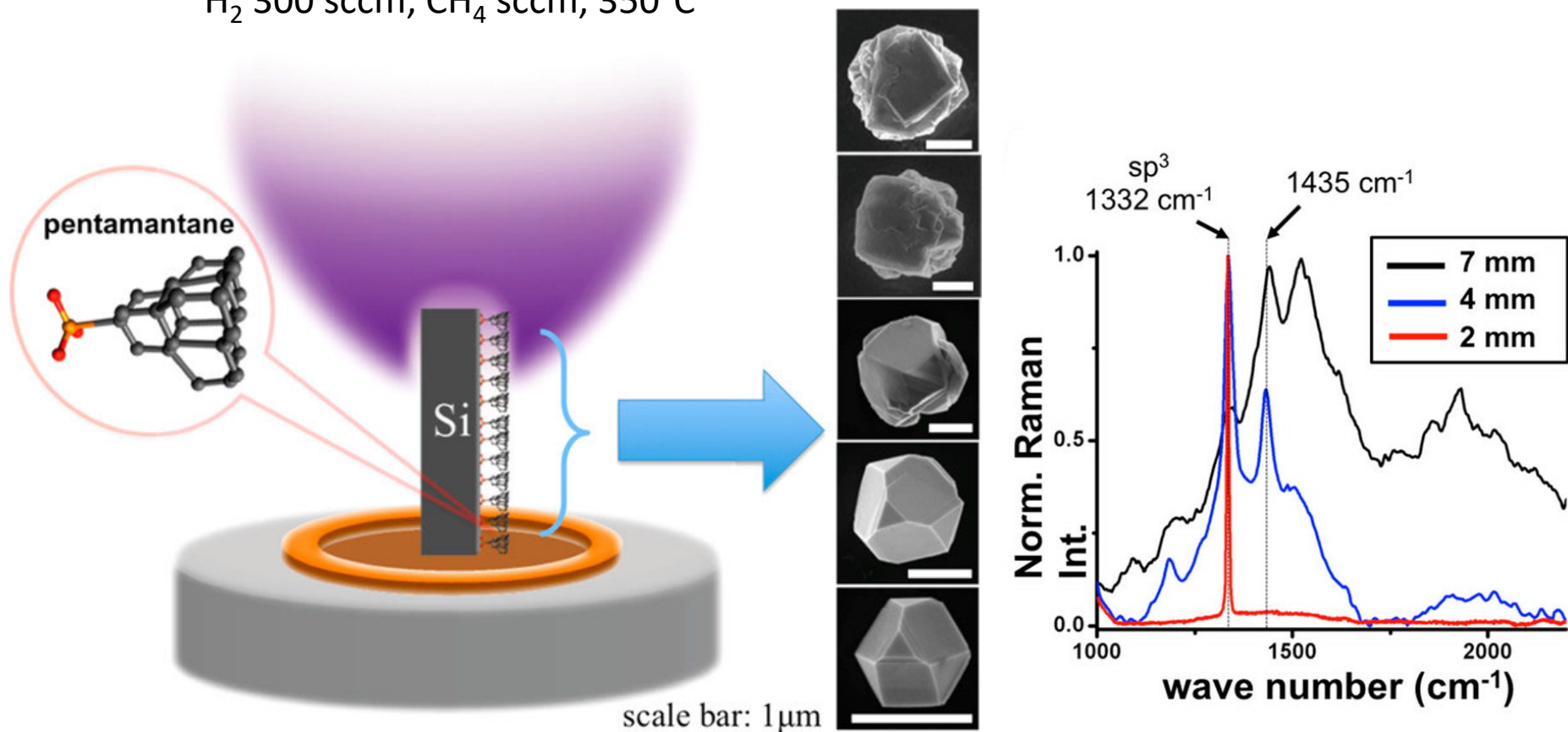
Vertical-Substrate MPCVD Epitaxial Nanodiamond Growth



Vertical oriented substrate geometry allows temperature, plasma density, and H density vary continuously along the vertical axis

10 nm $\varnothing$ single crystal diamonds
75 nm $\varnothing$ silicon-vacancy (Si-V) diamond

H₂ 300 sccm, CH₄ sccm, 350°C



Diamond in Meteorites: Discovery



The best-studied meteorite in history

- Carbonaceous Chondrites Represent 4 % of all meteorites
- Constitutes ~2000 ppm of graphite
100 to 400 ppm of diamonds



Allende C3V Meteorite
(Carbonaceous Chondrite)

HCl ↓ HF (– major minerals)

0.5% black residue

1. HNO₃ 90%, 16 h, 70°C ↓ 2. HClO₄ (– colloidal C) 2 h, 140°C

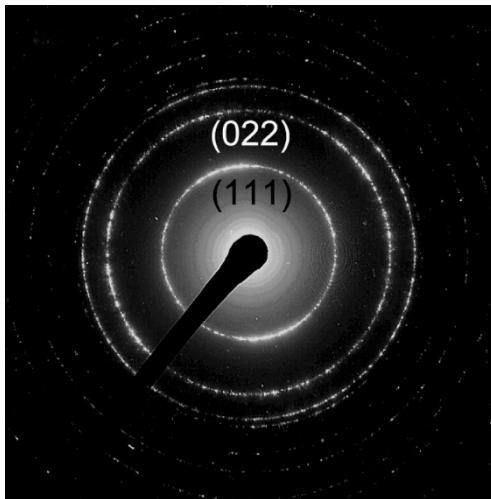
109 ppm light tan residue

HCl ↓ HF (– silicate contaminants)

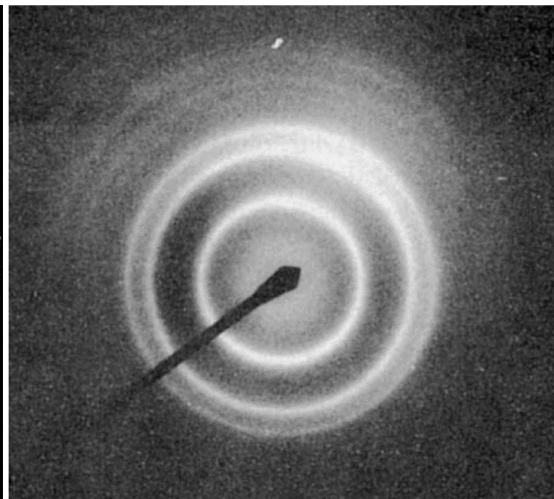
89 ppm diamond grains
(typically 50 Å Ø)

Electron Diffraction Pattern

Diamond coating on Si



Allende diamond grain





- Xe from meteorite ^{136}Xe / ^{132}Xe = 0,65 (on Earth = 0,32)
content (in $10^{-8} \text{ cm}^3/\text{g}$) 15 ± 1 24 ± 2
released at $1100\text{--}1600^\circ\text{C}$ $200\text{--}900^\circ\text{C}$
- $^{15}\text{N} = -330\text{‰}$ (compared to atmospheric N_2), Kr

Xe-HL = $2 \times (^{124}\text{Xe}, ^{126}\text{Xe}, ^{134}\text{Xe}, ^{136}\text{Xe})$ compared to solar Xe.

Xe-HL apparently formed in supernova and was trapped in carbon grains by:

- ☐ Ion capture by crystals during condensation
- ☐ Ion implantation of crystals during high energy processing of matter by shock waves (velocities of up to 1000 km/s necessary)



Shocks is not the reason:

- Meteorites are not brecciated, none shows strong shock effect
- All contain 10^3 – 10^4 ppm of graphite or amorphous C that
 - has no Xe-HL or N
 - C is isotopically heavier $^{13}\text{C} = -15\text{‰}$ compared to -38‰ in diamonds
- Composition of diamonds from various meteorites is rather similar (isotopes, gas)

Formation outside of Solar System:

- Metastable formation from hot gas at low pressures in expanding supernova remnants



- ❖ **low-pressure condensation** similar to CVD in expanding gas envelopes of C-rich AGB stars
log-normal grains distribution, grain growth Xe-HL
- ❖ **shock metamorphism of graphite** or amorphous-carbon grains driven by highvelocity (grain-grain) collisions in interstellar shock waves
no fragmentation of larger grains, power law distribution
no graphitic carbon with the same isotopic composition and the same noble gas components
- ❖ **annealing of graphite** particles by intense UV radiation (in type II supernova)
would form diamonds comprising <90 atoms
- ❖ **irradiation-induced transformation** of carbonaceous grains by energetic ions

Microstructural studies indicate that the meteoritic nanodiamonds formed by low-pressure condensation similar to the CVD process.

First Evidence of Diamonds in Interstellar Medium



First proposed by Saslaw & Gaustad (1969)

IR-Studies of dense molecular clouds around protostars

NGC 7538 IRS9,

W33A,

W3 IRS 5,

S140 IRS 1

2880 cm^{-1} band C–H stretching in tertiary C
Lack of strong features of CH_2 and CH_3



Carrier possesses
diamond like structure

Carrier is ubiquitous component of dense molecular clouds

Band strength analysis indicate that minimum 2 % of cosmic C are diamonds

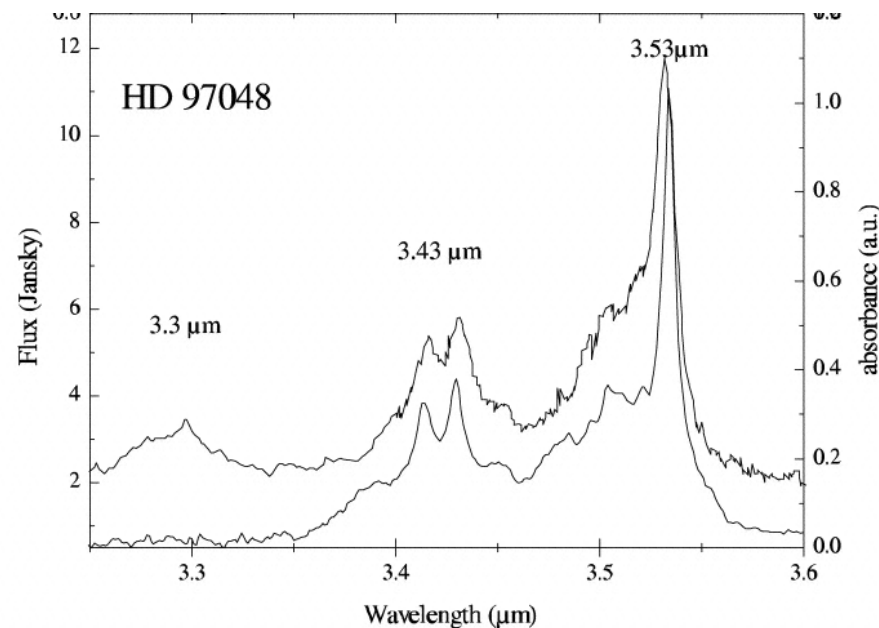
Diamond Infrared Emission Bands In Circumstellar Media



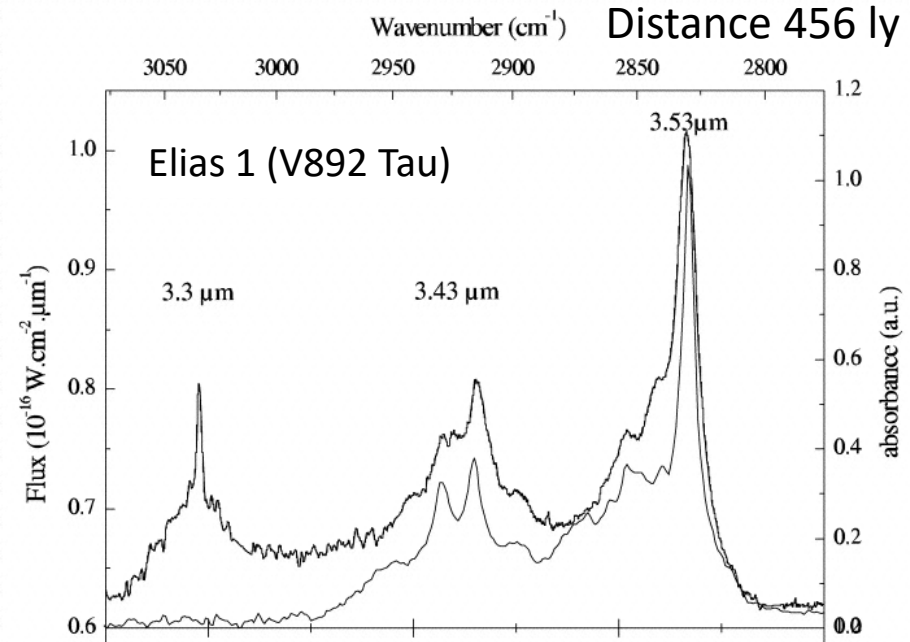
Detected in Herbig Ae/Be stars, young, intermediate-mass stars surrounded by extended envelopes of gas and dust

Taken with the short-wavelength spectrometer (SWS) on board the *Infrared Space Observatory*

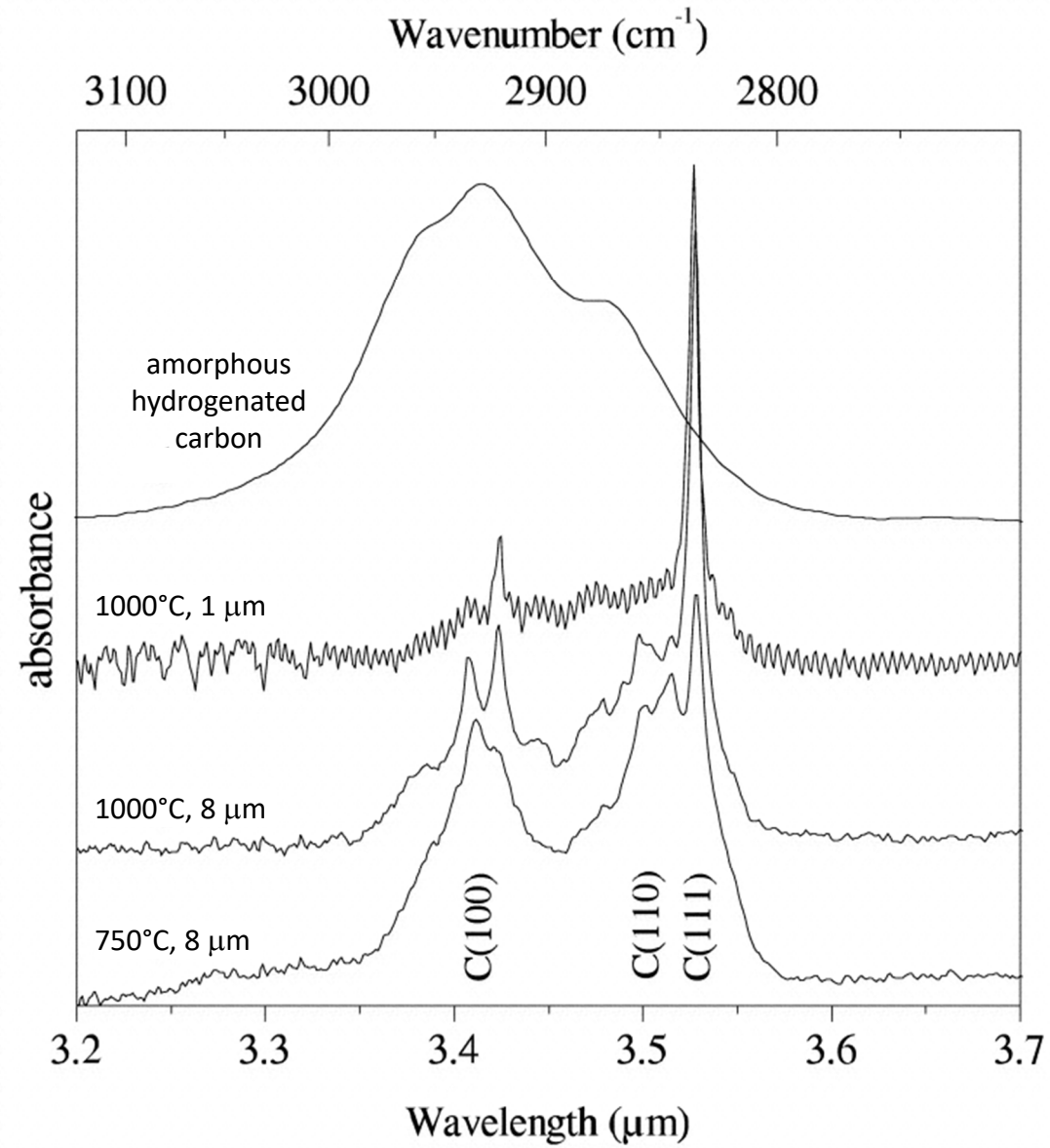
Distance 587 ly



Distance 456 ly



Diamond Infrared Emission Bands In Circumstellar Media



Diamond Microwave Emission Bands In Circumstellar Media

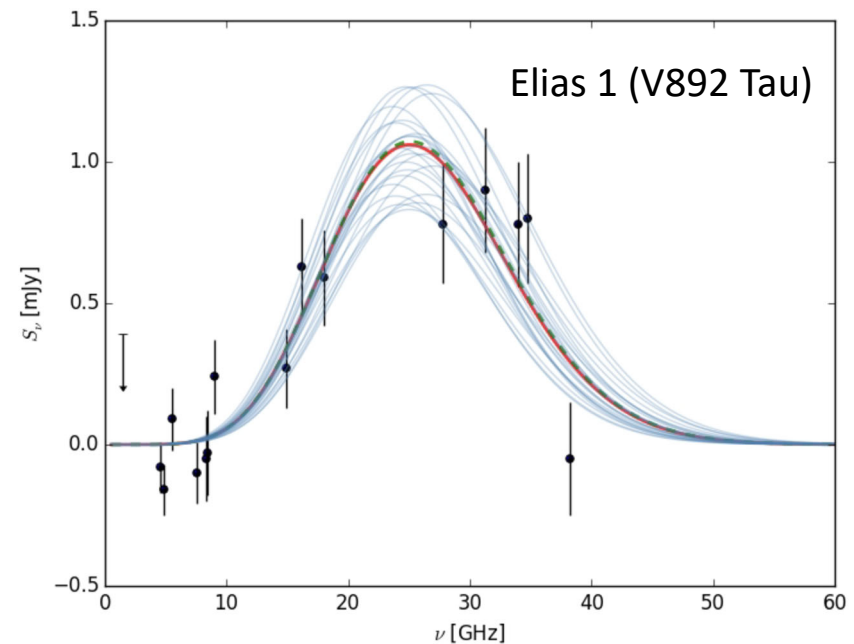
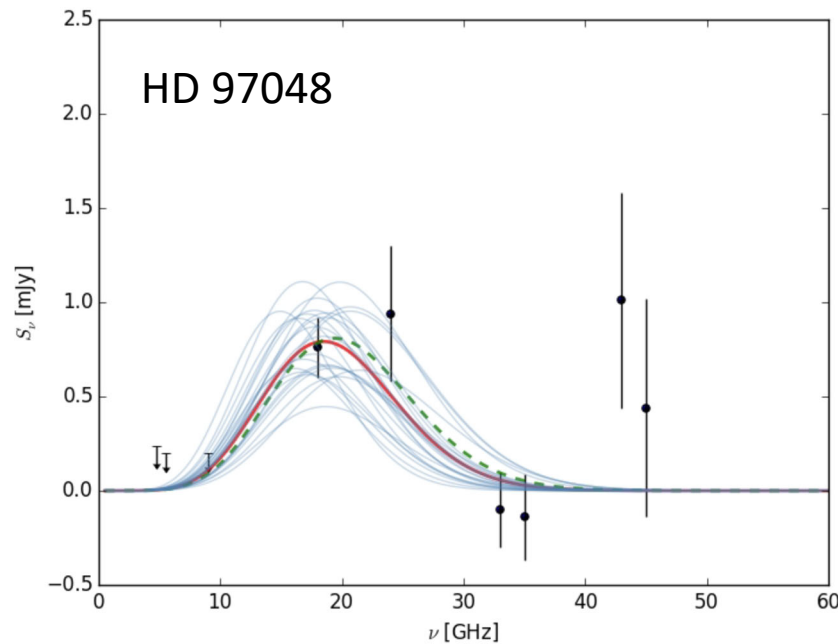


Anomalous microwave emission (AME) arise from the electric dipole of very rapidly spinning (10–60 GHz) extremely small (nanometer) particles

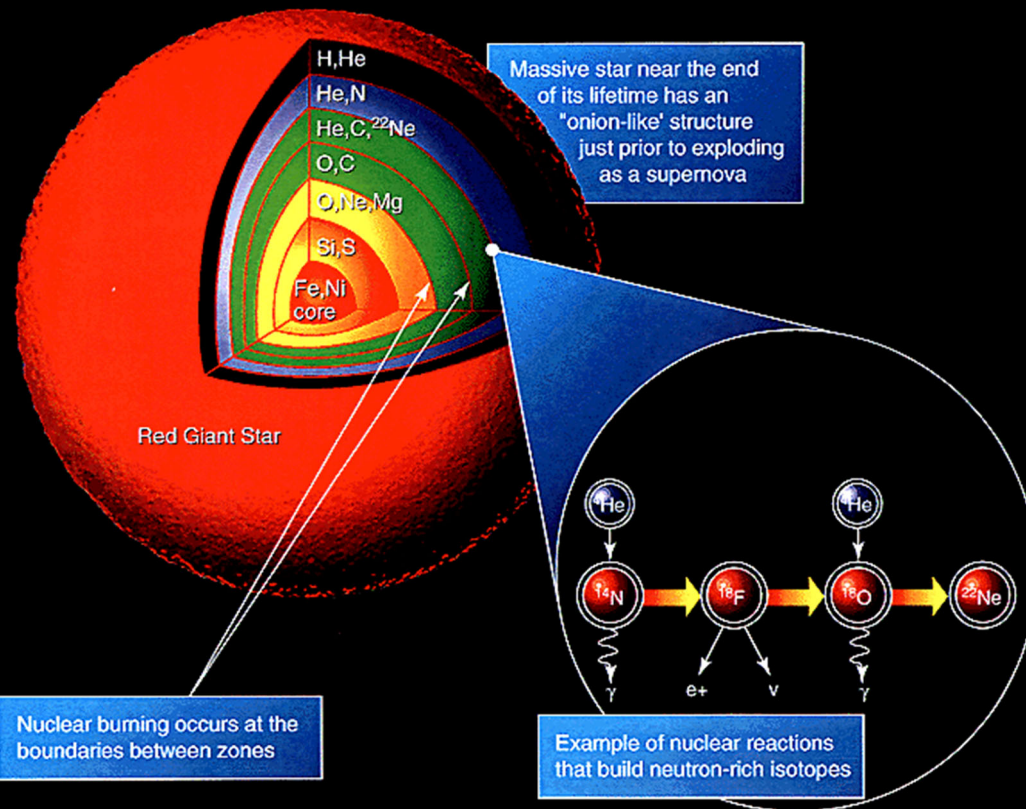
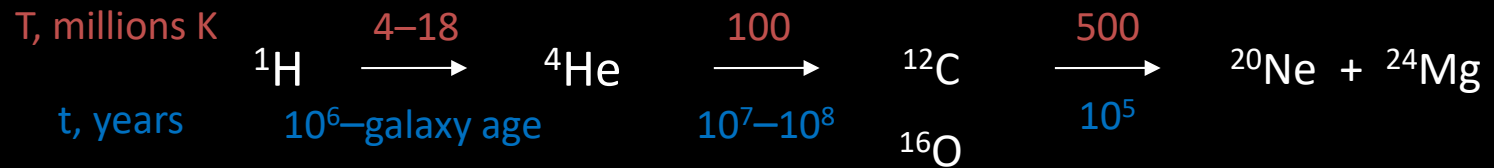
First discovered as a by-product of Cosmic Microwave Background "relic radiation" observations

Nanodiamonds across the size-range of ~10-700 C-atoms could explain AME from diffuse interstellar gas and from dense circumstellar discs

AME : stellar-luminosity ratios are approximately constant allowing nanodiamonds to be ubiquitous

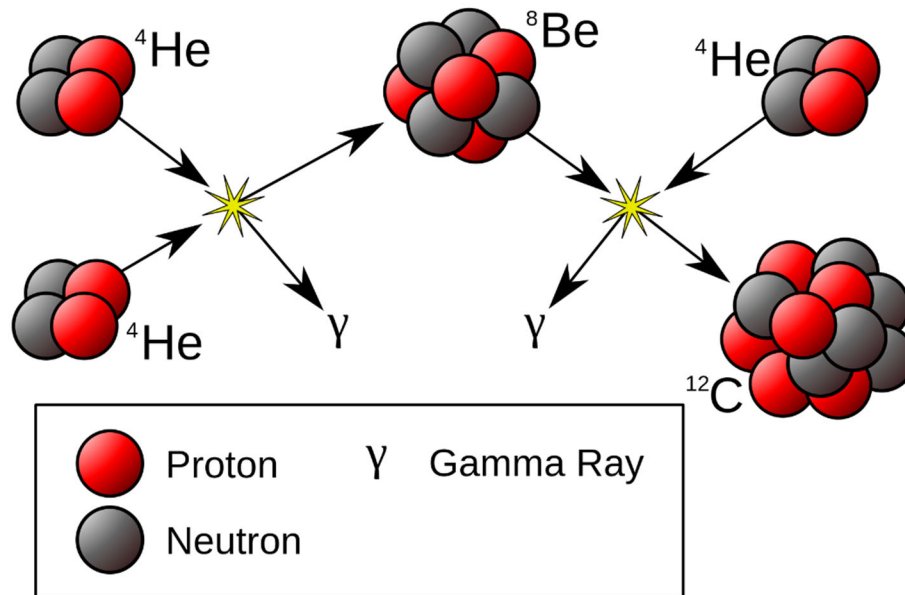


Evolution of Stars

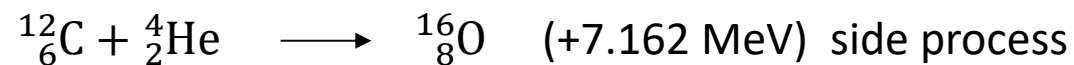
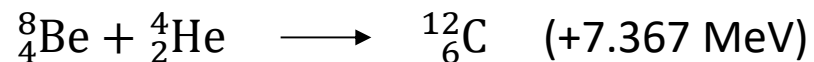
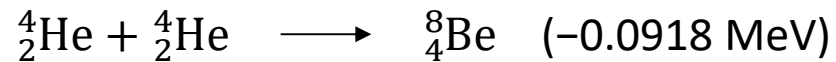




Triple-alpha process



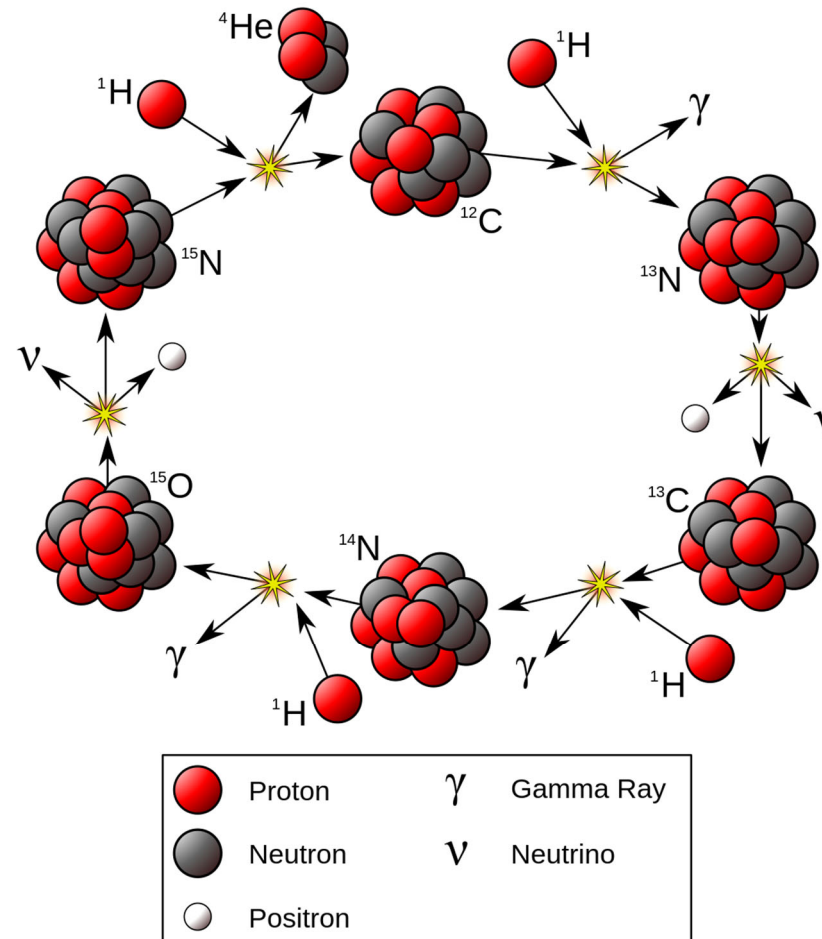
Main source of energy in red giants and red supergiants
 $T \geq 100$ million K



Carbon as a catalyst for Hydrogen Burning



CNO-I cycle



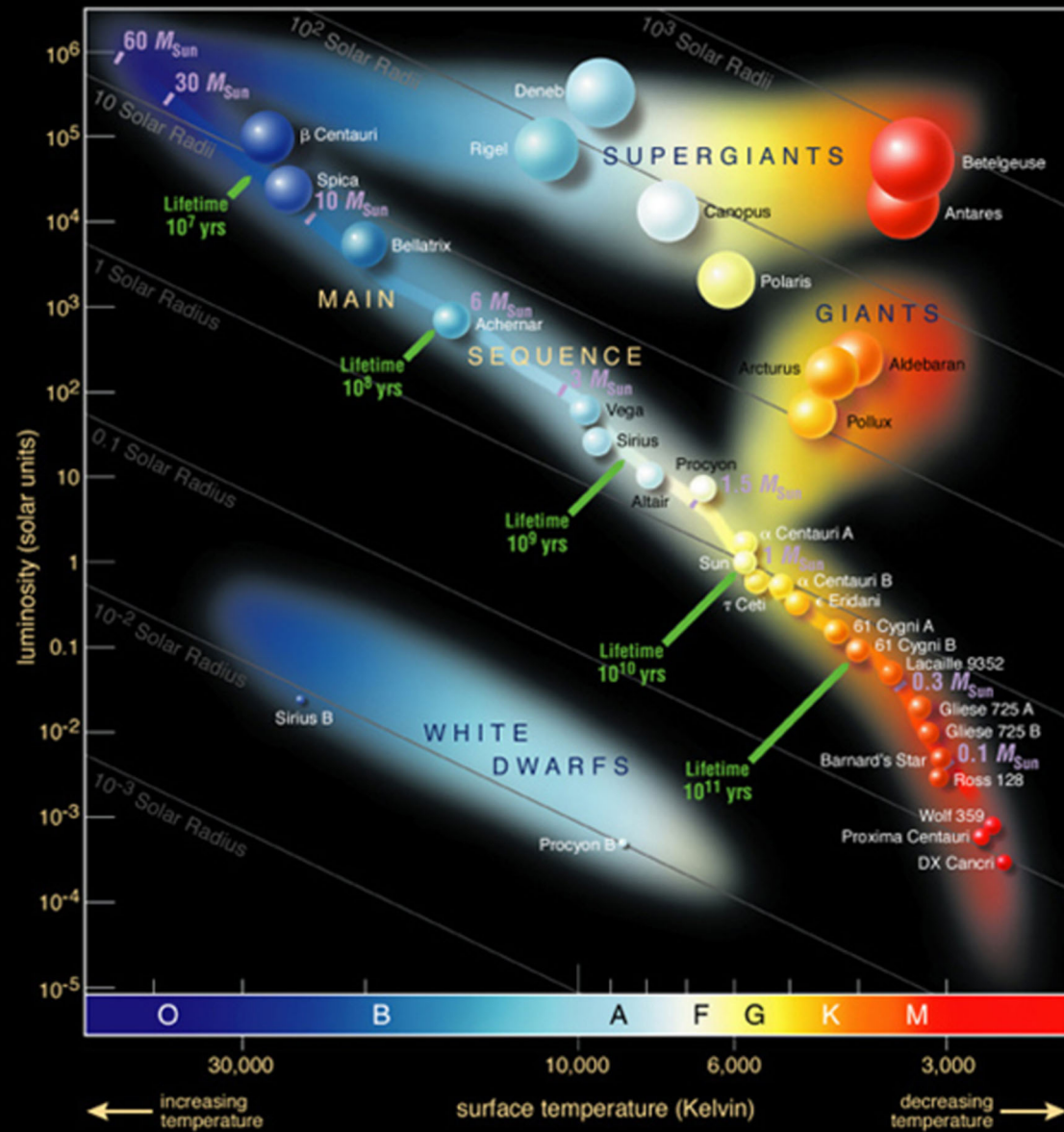
1.7% of ^4He produced in the Sun are born in the CNO cycle

Abundance of the Chemical Elements, % by Weight



Z	Symbol	Elements	Universe	Sun	Earth's Crust
1	H	Hydrogen	75	75	0.15
2	He	Helium	23	23	5.5×10^{-7}
8	O	Oxygen	1	0.9	46
6	C	Carbon	0.5	0.3	0.18
10	Ne	Neon	0.13	0.1	3×10^{-7}
7	N	Nitrogen	0.1	0.1	0.002
14	Si	Silicon	0.07	0.09	27
12	Mg	Magnesium	0.059	0.007	2.9
26	Fe	Iron	0.11	0.1	6.3
16	S	Sulfur	0.05	0.04	0.042

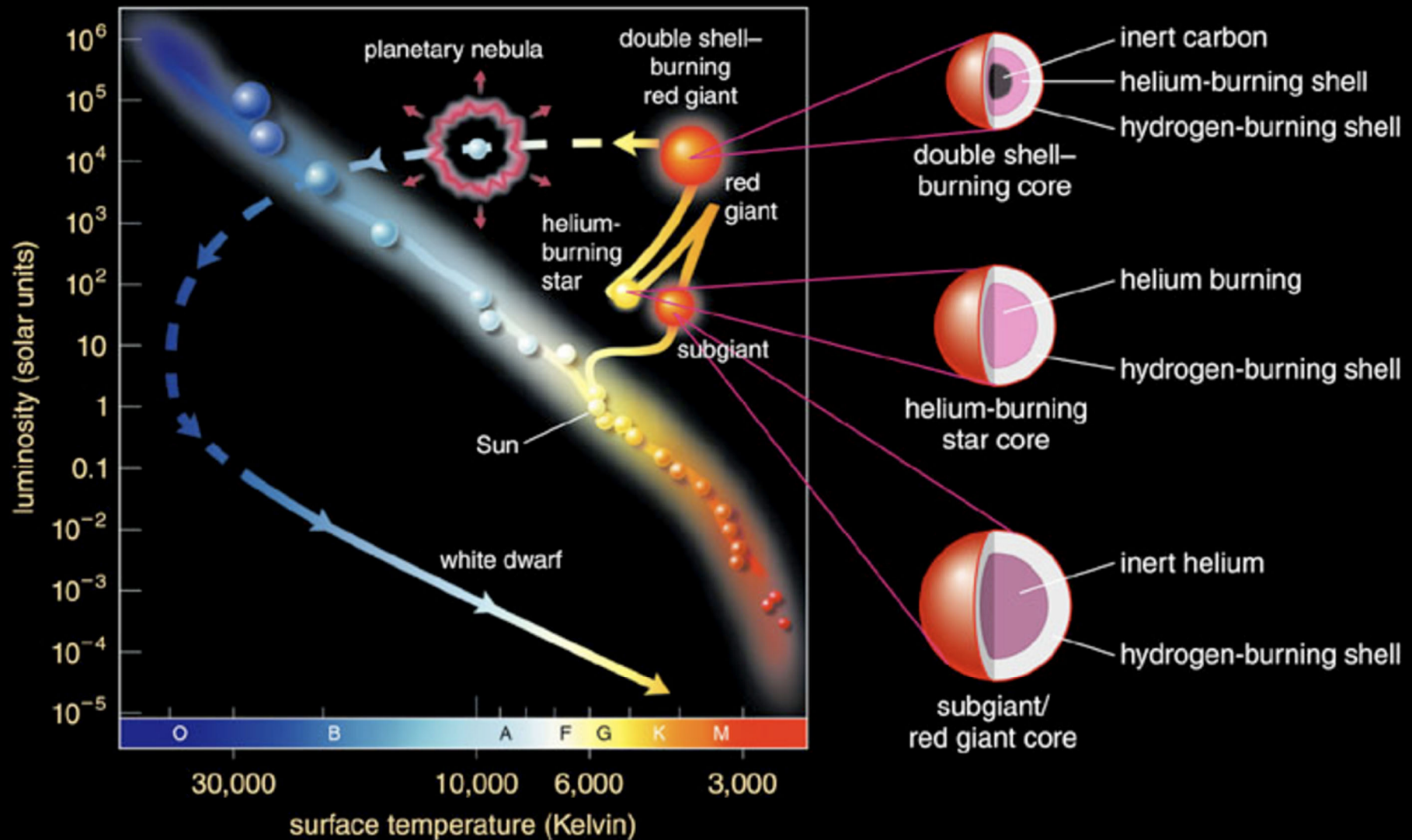
The Hertzsprung-Russell Diagram



Evolution of the Sun



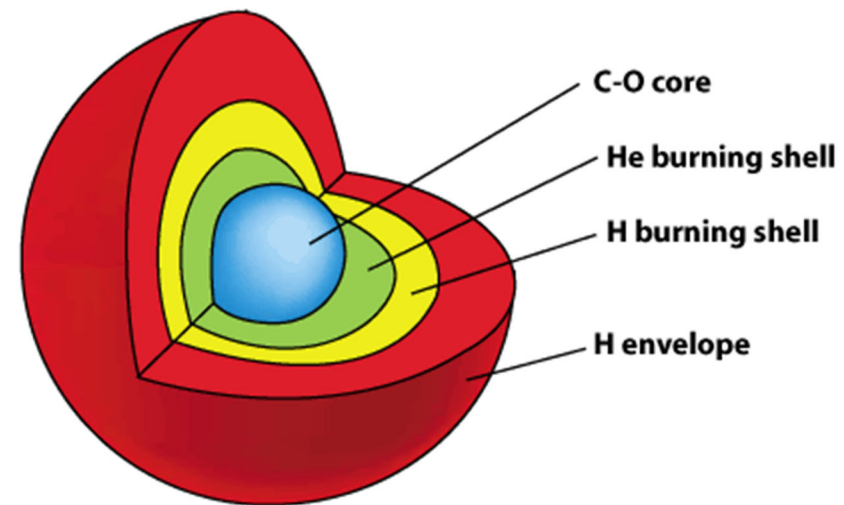
Evolutionary Track of the Sun Across the H-R Diagram



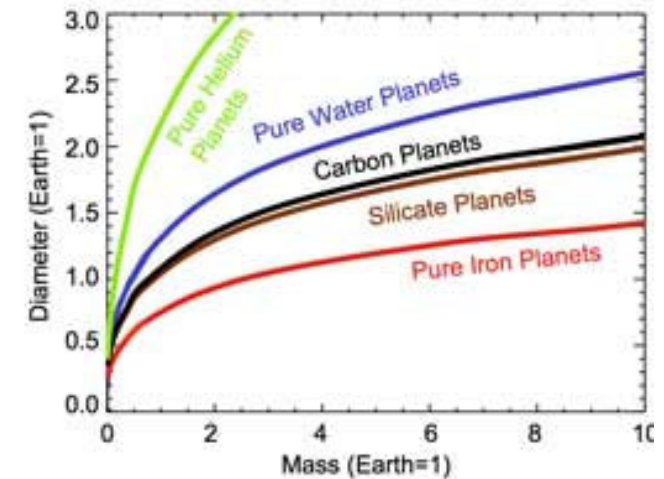
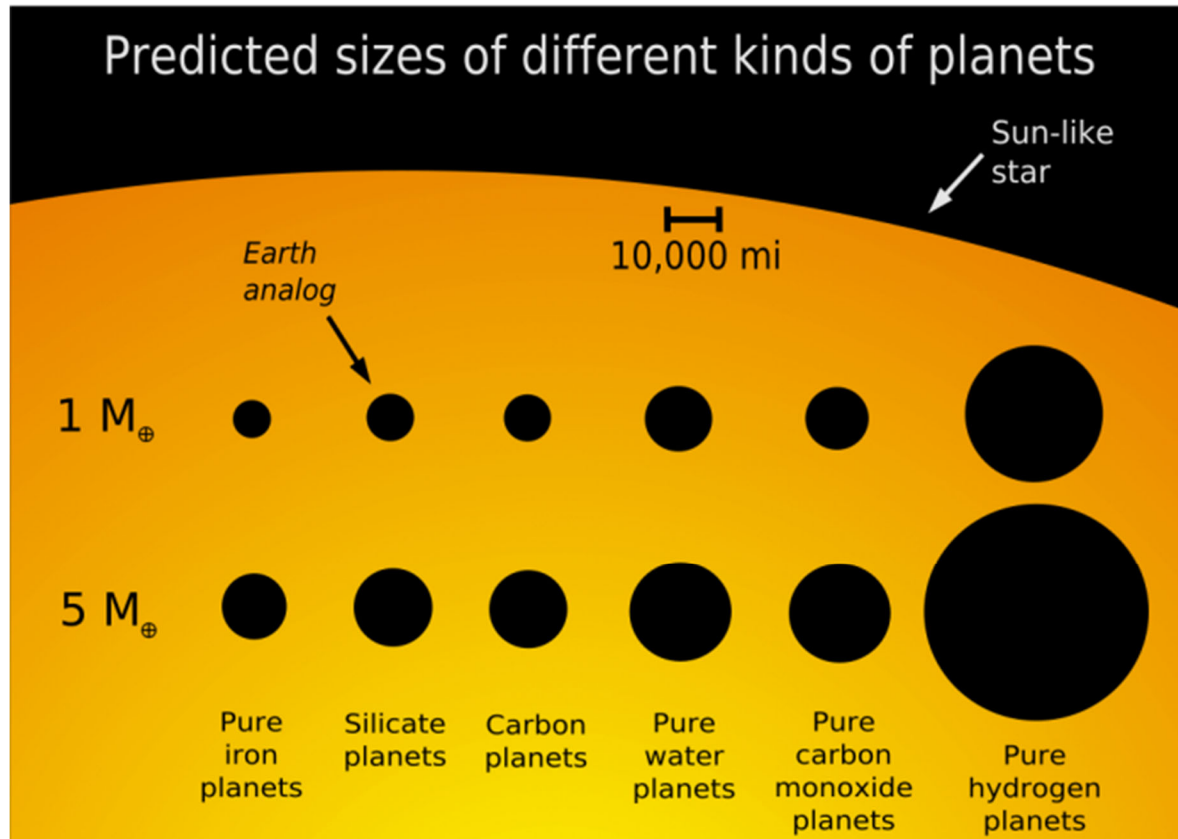
The Asymptotic Giant Branch (AGB) Stars



- evolved stars of 0.8 to 8 solar masses
- tiny, dormant core of C and O



- surrounded by a He and H burning shell (star's energy output)
- enormous convective envelope
- wind blows the outer layers into space
at a rate of 10^{-8} to 10^{-4} solar mass per year (carbon material)
- The Sun will eventually become an AGB star



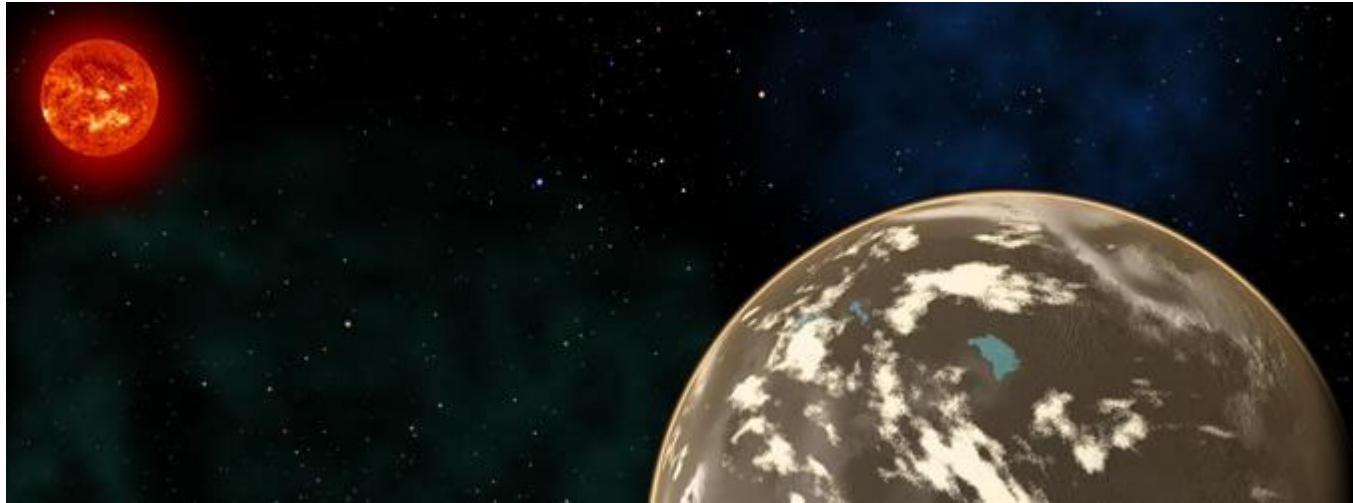
Transit technique

A large fraction of the known exoplanets were found via this technique.

Diamond Planets



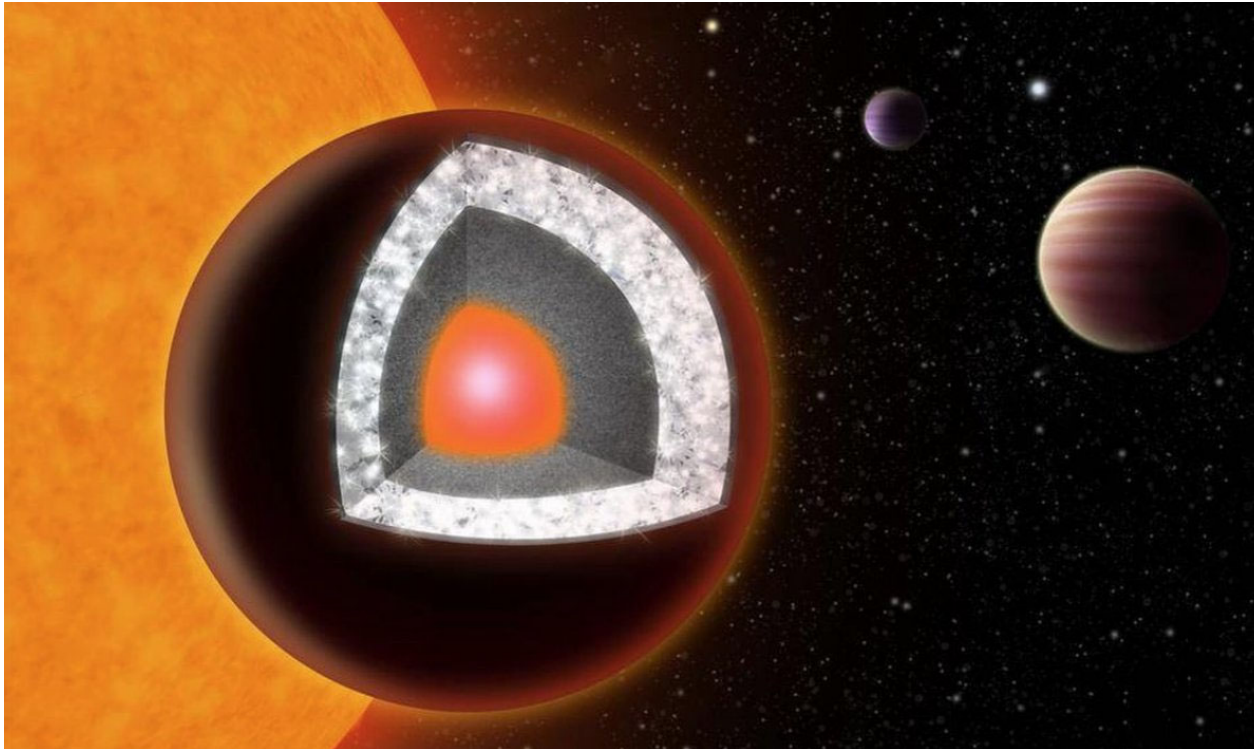
Suggested by Kuchner and Seager in 2005



- Orbiting carbon-enhanced metal-poor stars, or CEMP stars
 - 1/100000 of Fe in comparison to Sun
 - formed before interstellar space had been widely seeded with heavy elements
 - more carbon than would be expected given their age
- Consisting of carbides (SiC, TiC), diamond, graphite and covered with tar
- Atmosphere (if present) CH_4 , CO, lakes and seas of liquid hydrocarbons
- Carbon planets would be difficult to tell apart from more Earth-like world



55 Cancri e in the constellation of Cancer



- 40 light years away
- Surface 1600 °C
- Radius $2 R_{\oplus}$
- Mass $8 M_{\oplus}$
- $3 M_{\oplus}$ diamonds
- Orbits a C-rich sun-like star

detected in 2004 and its radius was estimated through transiting

Diamond Drizzle on Saturn and Jupiter



0.5% CH₄ Atmosphere 0.2% CH₄



CH₄ (upper atmosphere)

lightning



Carbon atoms

Carbon soot



Graphite



Diamond (10 million tonnes)
mostly mm size, some up to 10 cm

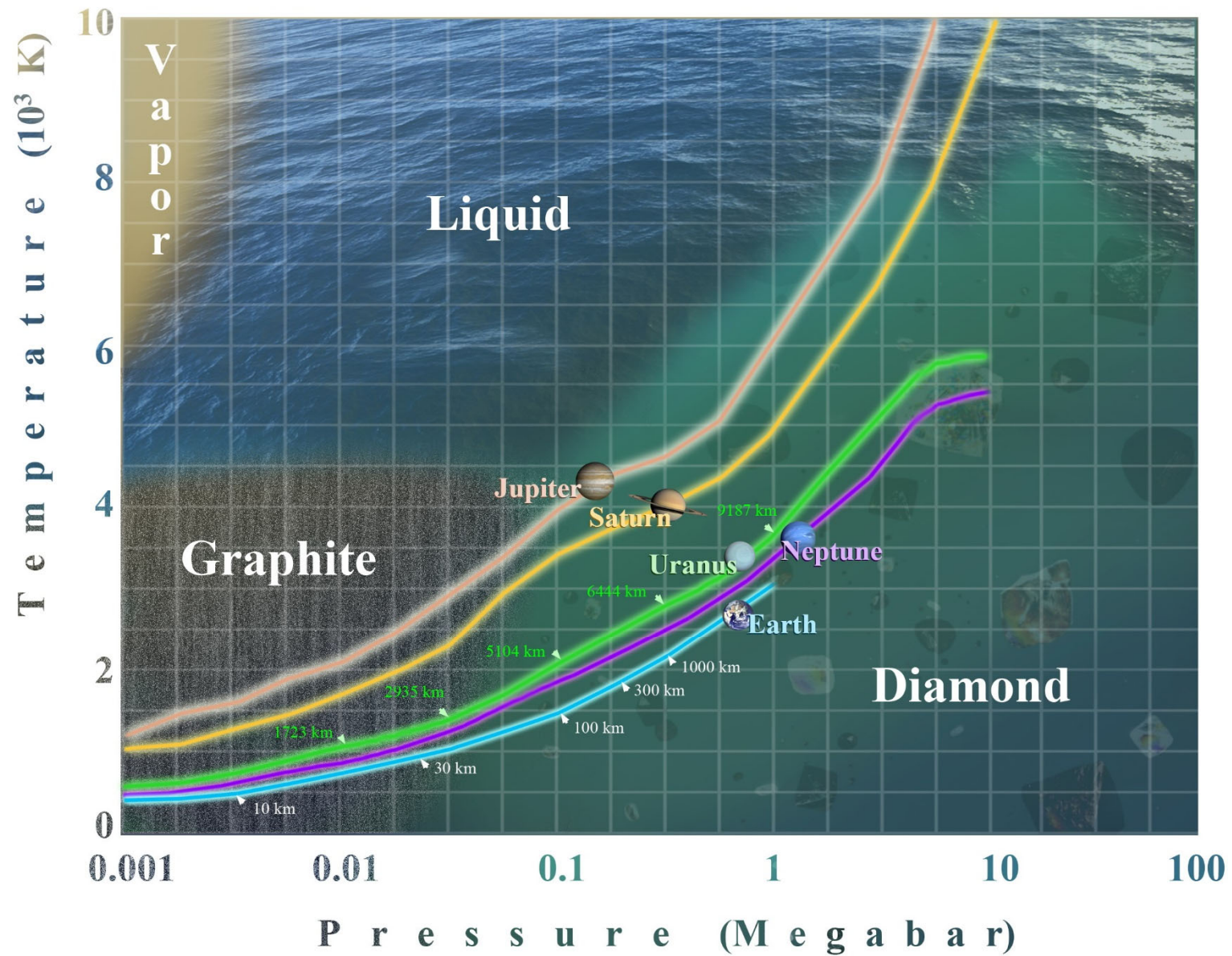


3 000 km

30 000 km



Diamond Drizzle on Saturn and Jupiter



Lucy White Dwarf



Most massive **pulsating white dwarf**

nickname of Lucy after the Beatles song
"Lucy in the sky with diamonds"

- BPM 37093 (Lucy)
- Located in constellation of Centaurus
- 53 light years away
- 4,000 km across (Sun 1.4 million km)
- Diameter $\frac{2}{3} \varnothing_{\oplus}$
- Mass $\approx M_{\odot}$
- 1/2000th of the Sun's brightness



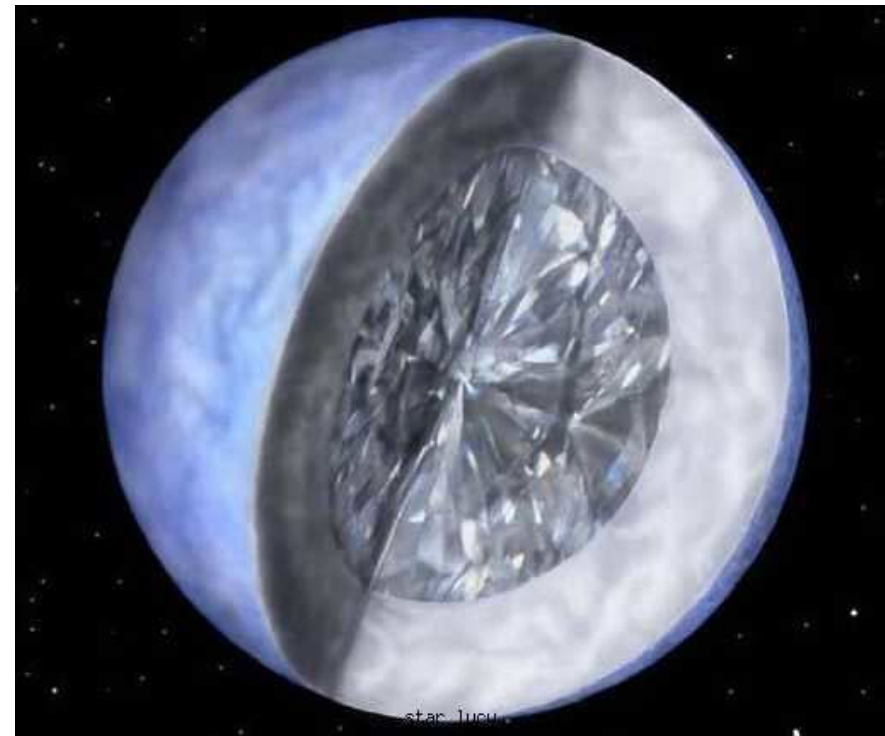
545 carats (109 g)

Golden Jubilee Diamond



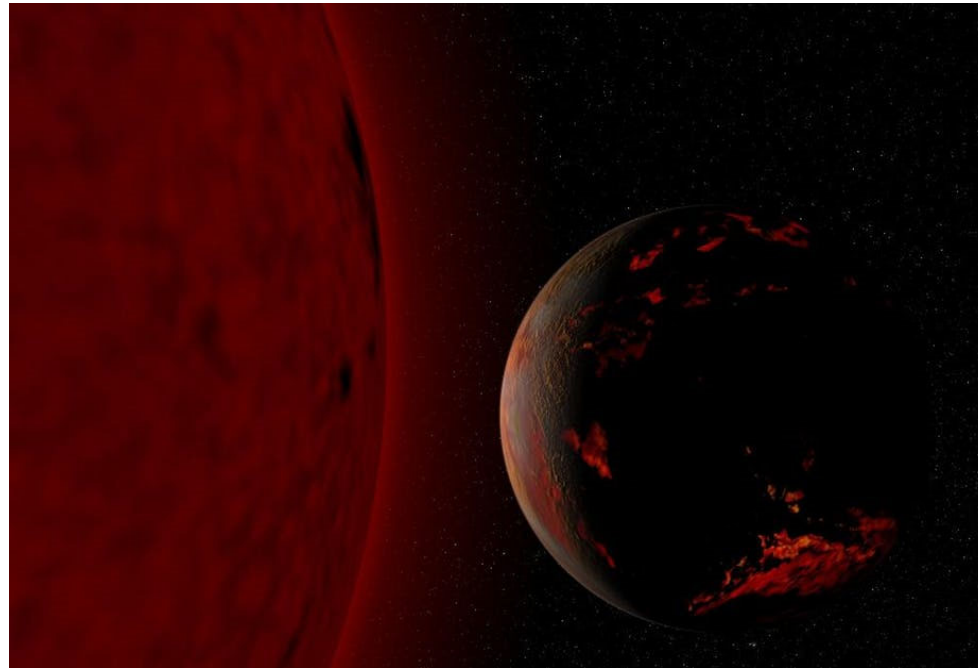
530 carats (106 g)

Great Star of Africa



10 billion trillion trillion carats
(2.3 million trillion trillion kg)

Sun in the (Distant) Future



- After about a billion years the sun will become hot enough to boil our oceans
- The surface of the Red Giant Sun will probably reach the current orbit of Mars
- Sun will deplete its nuclear fuel and die in 5 billion years, and then become a white dwarf
- About two billion years after that, the cinder Sun will be a similar diamond like Lucy.



Acknowledgements

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Thank you for your attention



Milky Way halo structure

