Life of a Star

An Interview with a White Dwarf, Sol

Student Guide

Cast of Characters:

Sol - Our Sun in the distant future as a white dwarf.
Page – the photon reporter for the Local Group Times.
Iana – an interstellar cloud where stars are born.
Peter – a shrinking protostar.
Hestia – a new star.
Goliath – a red giant.

Prologue

PAGE: I'm here with Sol, a prominent white dwarf in the stellar neighborhood. So, Sol, how old are you?

SOL: Many ages of those hotter, brighter stars. I have orbited this Galaxy 45 times. So, I'm 45 Galactic years old.

PAGE: Well, let's put that in some perspective for our readers – 45 times around the Galaxy? For someone living this far out in the Galactic suburbs, that's about 10 billion years.

SOL: I prefer "45".

Act I: The Nebula

PAGE: Let's start at the beginning.

SOL: In the beginning? Oh, you mean my life and not the whole universe.
My memory is hazy for that time in my life. Like all stars, I was born in a giant gas cloud. The cloud was a vast cold clump of hydrogen, helium, a little lithium, and tiny bit of most everything else. A fragment of the cloud collapsed into a ball. As I shrunk, I got hotter and hotter.

PAGE: What happened to tip off this collapse?

SOL: There was just enough mass for gravity to pull it together against the outward push of atoms bouncing about. Throughout my life, I have been at the mercy of this balance between thermal pressure and weight. Oh, I could go on and on about this pressure I'm under.

PAGE: Hang on, let's talk about that balance.

SOL: Before I could collapse, I had to satisfy a few conditions:
Conservation of energy – the kinetic and potential energies balance

$$2E_K + E_P = 0$$

When I started to collapse, the mass and gravity made an energy potential greater than the kinetic energy of the atoms.

$$2E_K < E_P$$

PAGE: $\mathbf{E_K}$ is the average kinetic energy of the atoms in the nebula gas = $\frac{3}{2}$ **NkT**. And the mass created a potential energy $\mathbf{E_P}$. Sol, how can I mathematically model the potential energy of the nebula?

SOL: Well, let's start with the basic idea of gravitational potential energy.

$$E_P = -G\frac{Mm}{r}$$

Let's treat the nebula as a big ball, and divide it up into shells. And, let's just work with one thin layer, or shell, like the layer in an onion. That will be the little "m". The big "M" represents the mass of all of the onion from that layer inward.

$$m = 4\pi r^2 \times dr \times \rho$$

PAGE: Whoa, my readers will want to know how this works. What is that funny symbol "ρ" (rho) ? And that "dr" – what does that mean?

SOL: Oh, that a Greek letter, rho. It stands for the average density of the stuff that makes up the shell, like the onion layer. And the $4\pi r^r$ (four pi "r" squared) is the surface area of onion layer. And the "dr" stands for the thickness of the shell, which is actually *very* thin. The product of the surface area (in square meters) times the shell thickness (in meters) is the volume of the shell ($4\pi r^r$ dr). Multiply the shell volume by the average density (kilograms per cubic meter or m^3) to get the mass of the shell.

PAGE: Well that was a lot of work to find the mass of just one shell. What about the rest of the nebula? And what about big "M," the mass of stuff inside each shell?

SOL: Remember, the nebula is made up of gas. It is not solid. So, the mass and density change with radius. Don't worry, I have not forgotten about big "M". I think we can safely simplify our calculation if we express "M" as the volume of the shell times the average density.

$$M = \frac{4}{3}\pi r^3 \times \rho$$

PAGE: So that means we must mathematically add up the potential energies from each shell from a radius of zero to the outer edge of the nebula.

SOL: Exactly. Mathematically when you sum the potential energy of the shells, we get

$$E_P = -\frac{16\pi^2}{15}G\rho^2 {R_{nebula}}^5 \approx -\frac{3}{5}\frac{GM_{nebula}}{R_{nebula}}$$

PAGE: Oh I see. You did an approximation – that's what that wiggly equal sign means.

SOL: This expression for potential energy is good enough for our interview.

PAGE: So the size, or radius, **r** and the gas mass **M** were big enough to start the collapse.

$$3NkT < \frac{3}{5}\frac{GM^2}{r}$$

N: number of atoms
k: Boltzmann's constant 1.38 x 10^{-23} Joules / Kelvin
T: temperature in Kelvin
G: gravity constant 6.67 x 10^{-11} (Newton)(meter^2) / kilogram^2
M: total mass in kilograms
r: radius in meters

SOL: That's where my life began. Let's ask my friend, the nearby interstellar cloud Iana, what she thinks.

IANA: I can put it simply -- look at the numbers!

Reflection Point 1: Interstellar Cloud

Milestone	Duration years Galactic years	Diameter meters	Density kg / m^3	Core Temperature (Kelvin)	Surface Temperature (Kelvin)
1	2.13 x 10^6 9.47 x 10^{-3}	10^{17}	1.67x10^{-18}	10	10

Oh, you don't like just numbers. Think about this. If you squeeze a balloon or foam ball, the resistance you feel is like the thermal pressure from my gas pushing outward against the inward pull of gravity. Can you answer these questions?

1. What are the forces involved when I collapse?
2. What can cause me to collapse and become unstable (out of balance, $2E_K < E_P$) ? You know, there are other stars out there.
3. Although I really don't like to have my mass calculated, I'll let you guess it. I challenge you to calculate my mass. Use "solar mass" units: one solar mass = 2 x 10^{30} kilograms. Assume each atom is a hydrogen atom (1.674 x 10^{-27} kilograms)

Act II: Protostar

PAGE: (talking to Sol again) So as your size shrunk, you got hotter?

SOL: Yes. A lot like waking up, I suppose. As my density increased, my internal temperature had to go up. I was trading potential energy for kinetic energy.

PAGE: How much time had passed since the collapse to this point?

SOL: Oh not very long – a moment. 100,000 years.

PAGE: What about the gas law? Did that factor into this phase of your life?

SOL: Certainly. As the density and pressure increased, so did the temperature. At my core, I was about 10^6 Kelvin. And then, of course, the outer layers were cooler.

PAGE: Wow, that sounds hot.... a million degrees!

SOL: It is, but it's too cool to form a real star. You see, the pressure and temperature at my core were not high enough for me begin to fuse hydrogen, which - as you know - releases lots of energy. I was only releasing the potential energy of my size and mass – gravitational potential energy.

PAGE: Were you worried that you didn't have enough potential energy left to begin the fusion cycle, and become a star?

SOL: I was just a kid – it happened so fast you know. But I was getting hotter and hotter as I kept shrinking. It didn't seem like it was slowing down. I felt caught and unable to determine my own destiny, or even density.

PAGE: What about your luminosity – the energy you were releasing per second? Were you shining enough to be noticed?

SOL: Oh yes, I was young and bright for a time. My luminosity was huge – thousands of times more than when I became a star. That's when Earthlings called me "The Sun." Not only was I bright (getting top grades in star school), but very big – 100 times my expected radius as a stable star. I was feeling bloated.

PAGE: With all these changes going on in your youth, did you feel stable at all?

SOL: All stars enjoy their youth, but it was so turbulent. Sometimes, I wondered if I would ever reach hydrostatic equilibrium.

PAGE: "Hyrdo"- what?

SOL: Hydrostatic equilibrium: when the outward push of gas pressure and radiation pressure balances the internal pull of gravity – my own weight. When this balance holds throughout my interior, my size stops changing. Then I can settle down and just shine for many Galactic years.

PAGE: When did you know that you were almost there - reaching hydrostatic equilibrium? Compare yourself at the beginning and end of your protostar youth.

SOL: Well, things slowed down. Toward the end of my protostar days, I was ten times smaller than when I began. My core temperature increased from 10^6 to about 5×10^6 Kelvin, my surface temperature warmed up from 3,000 to about 4,000 Kelvin, and my density climbed 10,000 times higher. I was ready for fusion to begin.
We should talk to my young protostar neighbor, Peter.

PETER: Here's a table describing my life. It's really great being so large and so big. Sometimes I wonder what will happen when I collapse, but Sol has been a good mentor to me. In about 10 million years, I'll collapse and become a star!

Reflection Point 2: Protostar

Milestone	Duration years Galactic years	Diameter meters	Core Density kg / m^3	Core Temperature (Kelvin)	Surface Temperature (Kelvin)
2	10^6 4.44×10^{-3}	10^{11}	0.001674	10^6	3,000
3	10^7 4.4×10^{-2}	10^{10}	16.74	5×10^6	4,000

Can you figure out how bright I am? Here's an equation to use:
$L = (\sigma T^4) \times (4\pi r^2)$ This is power (energy per second per unit area) times my surface area.
L: luminosity in Watts
σ (sigma) is the Stefan-Boltzmann constant = 5.67×10^{-8} $(W/m^2)K^4$
T: temperature in Kelvin
π: (pi) is the ratio of a circle's circumference to its diameter = 3.14159…
r: radius in meters

PETER: I'm just getting to know this relationship between luminosity, temperature, and radius. The energy I radiate per second per square meter is σ□□. Since my surface area, $4\pi r^2$ (four pi "r" squared), is so big I am quite luminous.

Act III: Life on the Main Sequence

PAGE: Thanks Peter for explaining this. Sol, I'm starting to understand what a life you've had, and it has only begun! So far, you have aged only 13 million years, just about 1/20 of a Galactic year. You were ready to become a star.

SOL: That was a day to remember. My core temperature had risen to 10^7 Kelvin. And then it happened. Quietly, it just happened.

PAGE: What? What happened?

SOL: Fusion. Hydrogen fusion. The temperature and pressure in my core increased so that hydrogen atoms collided and changed into another form of hydrogen - deuterium. That began a process that converts four hydrogen nuclei (protons) into one helium nucleus, 2 positrons, and 2 neutrinos. There are several steps in the reaction.

PAGE: Wait, those two positrons did not last long in a core full of protons and electrons.

SOL: You're right. The positrons quickly found electrons. The positron and electron completely annihilated each other in a gamma ray photon flash. Two of them per process cycle. And the two neutrinos just flew away.

PAGE: I know from experience that two little gamma ray photons have a lot of energy. But don't you need to release lots of photons to maintain your hydrostatic equilibrium? I don't want to dwell on it, but you were pretty large.

SOL: That's true. When I became a star, my luminosity settled down to about 4×10^{26} Watts. So this fusion process needed lots of hydrogen to keep going. Let's talk to my young friend who just became a star, Hestia. She is about the same mass that I was 44 Galactic years ago.

HESTIA: I wanted to stop by and visit. You have been so supportive during my protostar days. But now I'm here, shining on my own.

Reflection Point 3: Main Sequence Star

Milestone	Duration years Galactic years	Diameter meters	Core Density kg / m^3	Core Temperature (Kelvin)	Surface Temperature (Kelvin)
4	10^{10} 44.4	1.4×10^9	10^5 kg/m^3	1.5×10^7	5,770

Okay, have you figured out what makes a star "A STAR?"
Sol has given you a lot of clues so far. Try these questions to focus your answer.

1. How fast was Sol fusing hydrogen to release energy?
   Hint: each fusion reaction yields 4.3×10^{-12} Joules.
2. Why was Sol in equilibrium?

HESTIA: Now, I'll turn the conversation back to our fearless and relentless Page.

PAGE: Okay, so your core was a busy place. What happened next?
SOL: Just shine. For a long, long time. I spent most of my life as a star.

PAGE: But something had to change eventually. You were consuming enormous amounts of hydrogen during fusion.

SOL: Ah, alas. My hydrogen mass in the core slowly decreased until there wasn't enough going into fusion. Those photons carried the energy to my outer layers, excited the gas, and held up my weight. They kept me in hydrostatic equilibrium, you know: the outward push of gas pressure and radiation pressure (I'm really hot) balances the inward pull of gravity.

PAGE: Uh oh. Gravity didn't let go, huh?

SOL: No, it did not. It controls my fate. I'm trapped. So as my hydrogen mass fell, and my core temperature fell, I felt gravity's grip once more. I began to collapse again.

PAGE: Hang on; I'll get the Kleenex… I didn't think that finally fulfilling your life's ambition and reaching star-status would be so upsetting...

Act IV: Red Giant

PAGE: Did you notice anything as the hydrogen in your core got used up? Did you feel empty and unfulfilled? What happened next?

SOL: Remember, the hydrogen fusion process results in helium. So after 40 Galactic years of fusion, a lot of helium remained. By that time, my core had mostly become helium, with only a shell of hydrogen still fusing.

PAGE: So, at that time, your core wasn't hot enough, nor dense enough, to begin fusing helium?

SOL: Not yet. As the helium core collapsed, its temperature and density increased to the point where the kinetic energy of helium nuclei collisions overcame electromagnetic repulsion. For the helium to stick and fuse, the core had to reach 10^8 Kelvin, ten times hotter than before.

PAGE: So, your core was getting hotter and hotter. What about the hydrogen fusion shell?

SOL: Oh, that just got hotter! The fusion rate went up, and my outer envelope of gas expanded. My outside layers were puffing up and my inside was collapsing at the same time!

PAGE: How awful and uncomfortable! How long did this last?

SOL: About half a Galactic year – 10^8 years. I just got bigger and bigger. At the end, I was back to my old protostar size and luminosity, but my interior was considerably different. My core kept shrinking, with its density and temperature increasing while the outer gas envelope just seemed to balloon away. I thought that I was just going to evaporate into space! I think it is time to meet another neighbor who was a bit older than I was at that time in my life. He has already experienced this transformation. Meet Goliath, a red giant.

GOLIATH: Good to see ya up close Sol. I'm feeling queasy these days. I remember that stage at the beginning of my red giant phase when my outer layers were beginning to expand and my core was collapsing. Oh, I felt awful. Still do.

Reflection Point 4: Red Giant

Milestone	Duration years Galactic years	Diameter present Sun diameters	Core Density kg / m^3	Core Temperature (Kelvin)	Surface Temperature (Kelvin)
5	10^8 0.44	3	10^7	5×10^7	4,000

PAGE: So, at the peak of your expansion, what finally happened to your core?

SOL: Oh the drama continued. Finally, the core temperature reached 10^8 Kelvin and its density got up to 10^8 kg/m^3. Suddenly, the helium fused to ignite a "triple-alpha process":
Two helium nuclei collide and fuse to make beryllium and release energy:
He + He → (yields) Be + energy
Then, just before the beryllium breaks down, another helium collides and fuses with it to make carbon and release energy:
He + Be → (yields) C + energy

GOLIATH: That ignition, or helium flash, released more energy than I had radiated over 30,000 years as a main sequence star. You might think that this ignition would of blown me apart. I just burped. The core was so compacted, most of that helium flash energy just kicked the motor on.

PAGE: Kicked what on?

GOLIATH: Oh, I meant started up the helium fusion.

Reflection Point 5: Red Giant - before helium flash

Milestone	Duration years Galactic years	Diameter present Sun diameters	Core Density kg / m^3	Core Temperature (Kelvin)	Surface Temperature (Kelvin)
6	10^5 4.44×10^{-4}	100	10^8	10^8	4,000

SOL: You paint a picture, Goliath.
Over the next moment, about 10^5 years, the core settled into stable helium fusion surrounded by a shell of hydrogen fusion.

PAGE: Did you lose any significant mass during this violent and brief time in your life?

SOL: Yes, these explosive core changes produced strong convection currents in my outer envelope that blew about 20 or 30 percent of it out into space. So, my outer envelope of gas got hotter.

GOLIATH: Yep, I remember feeling like I was gonna hurl that whole time.

PAGE: The helium core consumed helium rapidly, because of the high temperature. Plus, you didn't start off with a lot of helium.

SOL: Only about 24% of my initial mass was helium. As a red giant, most of it was inside an Earth-size core. This triple-alpha fusion lasted only a few million years. But I had a burst or two left.

Reflection Point 6: Red Giant – helium fusion after helium flash

Milestone	Duration years Galactic years	Diameter present Sun diameters	Core Density kg / m^3	Core Temperature (Kelvin)	Surface Temperature (Kelvin)
7	5×10^7 0.22	10	10^7	2×10^8	5,000

PAGE: Yet another? When does it end?

SOL: I was out of helium in the core. My core was mostly carbon, surrounded by a shell of fusing helium, and an outer shell of fusing hydrogen. My inside was like an onion with lots of layers! The core collapsed further, with little to support it against its weight. Since it was so small and massive, the gravitational force was incredibly strong.

PAGE: So, the core and shells must have been even hotter this time?

SOL: Yes, it's amazing how the core changes in such short time. But its fusion days were limited. The hydrogen shell dumped helium ash onto the helium fusion shell. Then the helium shell dumped its carbon ash into the carbon core. This core continued to contract, which shrank the outer shells. And that just drove the temperatures up in the whole core. As a result, I bloated up again, but even bigger, into a super giant.

GOLIATH: I may look big and bright, but there's not much of me to go around. Look at my diameter. I've only got about 0.8 solar masses of stuff in there.

Reflection Point 7: Red giant becomes super giant

Milestone	Duration years Galactic years	Diameter present Sun diameters	Core Density kg / m^3	Core Temperature (Kelvin)	Surface Temperature (Kelvin)
8	10^4 4.44×10^{-5}	500	10^8	2.5×10^8	4,000

PAGE: Well, finally all the available gravitational potential energy was spent. The fusion stops, leaving the carbon core. What happens next?

SOL: Just before the core went out, the outer envelope transformed into a beautiful sight. A series of helium fusion flashes destabilized the gas, and caused pulsations. The gas rose and fell a few times until finally, it rose fast enough and escaped. The gas shell rushed away from the core with a dazzling display of color.

PAGE: And the core stayed there, just to sit and cool?

SOL: That's it. And now, I have entered my second life. I am no longer a star, because I'm not shining by fusion. But at least I'm back in equilibrium.

GOLIATH: Now you can retire and write a book. Bye y'all, I'm headin' back to the home star cluster, wife, and kids. I adopted a protostar. That boy is nearly as big as me! Hopefully, he will shrink down to star size and shine on his own before long.

Reflection Point 8: Carbon core

Milestone	Duration years Galactic years	Diameter present Sun diameters	Core Density kg / m^3	Core Temperature (Kelvin)	Core Surface Temperature (Kelvin)
9	10^5 4.44×10^{-4}	10^{-2}	10^{10}	3×10^8	10^5

Act V: Settling Down as a White Dwarf

PAGE: Do you like the name "white dwarf?"

SOL: I think that the name is misleading. Not all of us are white. That color only depends on our surface temperature. At this point in my life, mostly what I do is cool down and radiate light.

Reflection Point 9: White Dwarf

Milestone	Duration years Galactic years	Diameter present Sun diameters	Core Density kg / m^3	Central Temperature (Kelvin)	Surface Temperature (Kelvin)
10	$10^?$?	10^{-2}	10^{10}	starts at 3×10^8 and cools down	starts at 10^5 and cools down

Explain

In about 500 words, write Page's column *A Star's Life* based on Sol's scrapbook, the Ranger Rick "Birth and Death of a Star" diagram, and your calculations of the properties of Sol throughout his life. As you compose your story, make connections to everyday life so that your readers understand answers to the following questions:

1. What are the primary characteristics of a star?
2. During the interview, Sol and his friends mentioned many variables: luminosity, temperature (core and/or surface), density, and diameter. Which of these could we (people on Earth) observe and measure with a telescope?
3. What was Sol's life long balance to maintain? How did that affect Sol's life over time?
4. During what phase of his life was Sol happiest? Why?
5. At the end, Sol mentioned entering a second life. What do you suppose his second life will be, and how long?
6. What are Sol's properties as a white dwarf?

Elaborate

What is Sol's ultimate fate?

