Life of a Star

An Interview with a White Dwarf, Sol

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: Conservation of energy – the kinetic and potential energies balance

$$2E_K + E_P = 0$$

When I started to collapse, then the kinetic energy of the atoms no longer balanced the potential energy of the gas.

$$2E_K < E_P$$

PAGE: But all it's just gas. It's not a liquid or solid. How can gas collapse?

SOL: Gas is matter. Matter (and energy) tells space how to curve, and space tells matter how to move. A very intelligent human that once lived on Earth said this – he was called "John Wheeler." Let me introduce you to Iana. She can tell you how a huge volume of gas can form a star.

IANA: Thanks Sol. Anyway, for a star to form, a huge mass of gas has to curve space enough so that the gas would rather move toward a central point instead of bounce around randomly. And by huge mass, I mean a few hundred times Sol's mass. Other interstellar gas clouds are even bigger!

Reflection Point 1: Interstellar Cloud

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

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.

IANA: To put it another way, the speed of the atoms zipping around increased. But as all the gas moved toward the same central point, the volume of the whole cloud decreased. You would think that as the temperature of the gas increased, the cloud would expand. But because there was so much gas, and the volume was contracting, the gravitational force won.

SOL: Thanks for the subtle foreshadowing there, Iana.

PAGE: So, how much time are we talking about?

IANA: Oh not very long – a moment in a star's life. 100,000 years.

PAGE: Okay Sol, you are getting smaller and hotter. When do you 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. I was also very big and felt bloated.

PAGE: With all these changes going on in your youth – the shrinking and the heating - 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: I stopped shrinking when the gas and radiation pressure balanced my weight throughout my interior.

PAGE: So that's the end of your protostar youth?

SOL: Not quite.

Reflection Point 2: Protostar

Milestone	Duration years	Duration 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

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Act III: Life on the Main Sequence

PAGE: 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 rose so high that when hydrogen atoms collided, a new atom formed - deuterium. That is only step one of the reaction. In the end, four hydrogen nuclei (protons) become one helium nucleus, 2 positrons, and 2 neutrinos.

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

HESTIA: You're right. The positrons quickly found electrons inside the dense core. The positron and electron completely annihilated each other in a gamma-ray photon flash. And the two neutrinos just flew away.

PAGE: Oh, so that's where the energy comes from.

HESTIA: Yes. The reaction releases energy that heats up all the surrounding gas.

SOL: Eventually, the energy makes it to our photospheres where it escapes as light into interstellar space.

HESTIA: How's it goin', Sol? Haven't seen you in a while.

SOL: When you get to be my age, you tend to stay out of sight.

Reflection Point 3: Main Sequence Star

Milestone	Duration years	Duration 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	1.5×10^7	5,770

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; that's 10^8 years in numbers. 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	Duration 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 that 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	Duration 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 quite 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	Duration 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 gas in there.

Reflection Point 7: Red giant becomes super giant

Milestone	Duration years	Duration 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	Duration 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

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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	Duration 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

Extend

On a separtate sheet of paper: 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 the 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?

PLOTS

Life of a Star – Interview With a White Dwarf

Instructions: On each graph, plot Sol's properties for each milestone using the numbers given in the reflection points throughout the play.

Hint: the diameter of the sun is about 1.4×10^{9} *meters*

1.E+ is the same as **10^** (for example 1.E+18 = 10^{18} and 1.E+-05 = 10^{-5})