

Lives of Stars

*An Interview with Several Stars in the Milky Way
(5 Billion years in the Future)*

Cast of Characters:

Page – the photon reporter for the Local Group Times.

*Sol - our Sun in the distant future as a white dwarf (Sol was once a **yellow** star).*

*Apollo – a very large, hot, bright, young **blue** star.*

*Kronos – a very small, cool, dim, old **red** dwarf star.*

Iana – an interstellar cloud where stars are born.

Minerva – a red giant.

1) Fill in the blank spaces in the table (either while you are reading or after you have finished):

Character	Color while on main-sequence	Mass while on main-sequence (in solar masses)	Life-time on main-sequence (in years)	Luminosity while on main-sequence (in solar luminosity)	Diameter while on main-sequence (in solar units)	Type of Star After Collapse
<u>Kronos</u>				0.16	0.15	White Dwarf
<u>Sol</u>		1	10^{10}	1		
<u>Apollo</u>	Blue		7×10^6		9	

Prologue

PAGE: I'm here with three stars from the local stellar neighborhood: Sol, Apollo, and Kronos. Sol is a white dwarf, but for most of his life he was a yellow star. He's famous for being the star that was home to Earth and its humans about 5 billion years ago. They used to call him the "Sun". Welcome Sol.

SOL: Thanks Page, it's a pleasure to be here.

PAGE: Next to Sol is Apollo. Let me tell you, Apollo is gigantic! And extremely bright! I can barely see anything else through his glare.

APOLLO: Hey, what can I say? I'm a blue star, that's how we roll.

PAGE: And last but not least, there's Kronos. I almost didn't even notice you were here Kronos. You're so small and just barely glowing red.

KRONOS: Well, its not like I haven't heard that before. Thanks for having me.

PAGE: Okay guys, I'm curious about all three of your lives as stars. But Sol, since you've already reached the last stage of your life and are the most experienced, I'll be directing most of the questions towards you.

SOL: Sounds good to me.

PAGE: Alright, let's get started. So, Sol, how old are you?

SOL: Many ages of those hotter, brighter stars like Apollo. 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".

APOLLO: Whoa Sol, you're old! Using your galactic time-scale, I'm only like two weeks old!

KRONOS: Hey big guy, watch who you're calling old. I'm older than Sol. In fact I'm almost as old as the entire universe, about 80 galactic years.

PAGE: Wow Kronos, that's over 18 billion years.

KRONOS: Let's just say "80".

Act I: The Nebula

PAGE: So Sol, tell me about 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 shrank, 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 it's all 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!

APOLLO: Like the one that I came from!

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, or less than half of a galactic year.

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: "Hydro"- 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.

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 two hydrogen atoms collided, a new atom formed - deuterium. The deuterium then interacts with more hydrogen atoms in a series of reactions called the 'proton-proton chain'. 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.

KRONOS: 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. What you're basically saying is that deep inside of you, gravity caused your temperature and pressure to be so high that it triggered a nuclear reaction?

KRONOS: Exactly. The reaction converts hydrogen into helium and also releases energy that heats up all the surrounding gas.

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

PAGE: Wait, so this has happened to all three of you?

SOL: Yep, every stars begins its life in the same manner more or less. And as long as a star is fusing hydrogen into helium, it is considered to be a 'main sequence' star. Those are the good days of a star's life. I'm past that stage nowadays, but Apollo and Kronos are still there.

APOLLO: Right, and some stars got here more quickly and shine more brightly too, like me!

KRONOS: Yeah, yeah...keep bragging. I'm not impressed.

APOLLO: Whatever old man, you're just jealous because you're so small and dim.

KRONOS: (to Page) In my long life, I've seen thousands of stars like Apollo. Trust me, he won't be around for very long...his kind never are.

PAGE: I don't get it. If Apollo and Kronos are both main sequence stars, then how come they are so different?

SOL: Mass. Mass basically decides everything for a star, from how bright it is, to how long it will live, and even how it will end its life.

PAGE: Why is that?

SOL: When a star has more mass it will have a stronger gravitational field, especially in its core. More gravity means higher temperatures and pressure, and that affects the speed and type of nuclear reactions that can occur. More mass means more nuclear reactions and more energy.

PAGE: Okay, then how much do you weigh Sol?

SOL: Well, I've lost some weight recently, but when I was a main sequence star I weighed exactly one. One solar mass.

PAGE: And Kronos, what about you?

KRONOS: I weigh one-tenth of a solar mass, so 0.1

PAGE: Apollo?

APOLLO: Twenty-five solar masses! Booyah.

PAGE: Wow. Obviously we can't just put you guys on a scale to find out how massive you are. How might a distant observer figure out your mass?

SOL: There are several methods, some more complicated than others. But there is one very easy way to get a general idea of a main-sequence star's mass: Color.

KRONOS: Small red stars like me are usually the light weights.

SOL: Yellow stars like I used to be are the middle weights.

APOLLO: And blue stars , such as myself, are the heaviest. We're the brightest too...I'm 30,000 times brighter than Sol was when he was a main-sequence star.

PAGE: Good to know. Well I think we've covered how stars grow up to get to the main sequence...let's talk about what happens after that.

SOL: That's where each star's evolution really starts to become different, again depending on our mass.

PAGE: Then let's just focus on you for a while Sol. I believe we left off where 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: Sol's Post Main-Sequence Life

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 is a bit older than I was at that time in my life. She has already experienced this transformation. Meet Minerva, a red giant.

MINERVA: 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.

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/m³. Suddenly, the helium fused to ignite a "triple-alpha process":

Two helium nuclei collide and fuse to make beryllium and release energy:

$\text{He} + \text{He} \rightarrow (\text{yields}) \text{Be} + \text{energy}$

Then, just before the beryllium breaks down, another helium collides and fuses with it to make carbon and release energy:

$\text{He} + \text{Be} \rightarrow (\text{yields}) \text{C} + \text{energy}$

MINERVA: 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?

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

SOL: You paint quite a picture, Minerva.

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 to 30 percent of it out into space. So, my outer envelope of gas got hotter.

MINERVA: 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 before this stage 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.

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 red supergiant. I was huge, my outer atmosphere almost encompassed Earth's orbit.

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

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 – a planetary nebula.

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.

MINERVA: Now you can retire and write a book. Bye y'all, I'm headin' back to the home star cluster, husband, 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.

Act V: Apollo and Kronos Post Main-Sequence

PAGE: So Apollo, we haven't heard from you in a while. What's in store for your future?

APOLLO: Me, I've got big plans of course. Just like Sol, I'm planning on fusing more than just hydrogen...a lot more. Because I've got so much mass and gravity, my core will be able to keep creating elements as the pressure and temperature go higher and higher. We're talking at least 3-billion Kelvin (3×10^9 K). Also like Sol, my size, color, and brightness will fluctuate as I quickly evolve past the main-sequence.

PAGE: What elements will you be creating?

APOLLO: Helium, then Carbon, Neon, Oxygen, Silicon, and Iron. At my peak, I'll be creating all of these at once; each one in a different shell. My interior will look like layers of an onion.

PAGE: Then what?

APOLLO: Then I'll explode in the biggest, brightest, most awesomest explosion in the universe: a Supernova! For a brief time I'll outshine the entire galaxy!

PAGE: Wow! After that I'd assume there would be nothing left of you.

APOLLO: Actually, I've got so much mass that there will still be a lot of me left over. And without the outward pressure from nuclear fusion, I will no longer be able to maintain hydrostatic equilibrium. Gravity will cause me to collapse into an infinitely small and dense point.

PAGE: Really? What will you be then?

APOLLO: Only one of the most exotic and overpowering objects in the universe – a Black Hole. Pretty impressive right?

KRONOS: Thankfully, one of the key characteristics of black holes is that no information whatsoever can leave them, including bragging. It won't be very long until we don't hear from Apollo anymore.

APOLLO: It's sad but true. I'll be a black hole in less than a million years.

PAGE: That's a blink of an eye in astronomical time scales.

APOLLO: The blue star motto: "Live fast and die young."

PAGE: So Kronos, what are your future plans?

KRONOS: Well, not very much for a long, long time. I'll be fusing hydrogen for at least another six trillion years. I've got a long life on the main-sequence ahead of me. Even though I'm the oldest one here, I'm really just getting started.

PAGE: Six trillion years!? That's a six with twelve zeroes after it!

KRONOS: Yes, it almost seems like infinity, but there will be an end. Eventually I will fuse all my hydrogen into helium. And since I'm not massive enough to fuse helium, I won't have much of a post main-sequence life...I'll simply quietly collapse to become a white dwarf, kind of like Sol.

PAGE: What do you mean – "kind of"?

KRONOS: Well, I won't be going through any of the 'giant' phases, and in the end I'll only be made of helium.

SOL: And remember, I'm all carbon now. But we'll still both be called white dwarfs.

Act VI: Settling Down

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. And I'll continue to cool down until I eventually turn cold and dark, billions and billions of years from now.

KRONOS: When we get to that point, I guess you could call us "black dwarfs", though no such thing exists yet because the universe hasn't been around long enough for something like that to form.

PAGE: Red dwarfs and white dwarfs such as yourselves are the two most common types of stars in space right now, so I'm sure we'll be seeing a lot of black dwarfs in the far off future.

APOLLO: There's going to be a lot of black holes around too, though I wouldn't say you'll be "seeing" a lot of us.

PAGE: Well guys, that concludes our interview. Thank you very much and good luck with the rest of your stellar lives.

SOL, APOLLO, and KRONOS: Thank you!

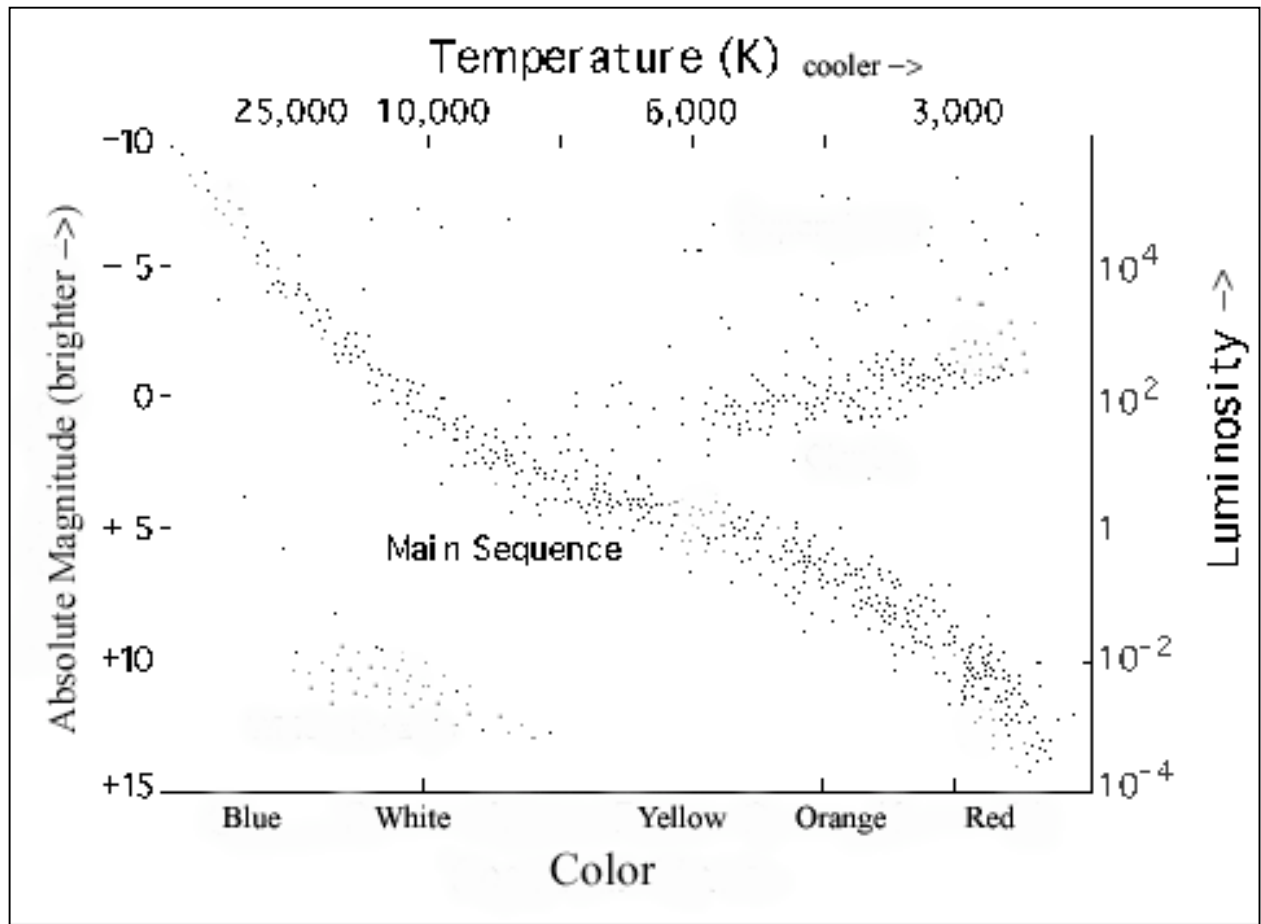
Evaluation:

2) What term in astronomy describes the balance between the force of gas/radiation pressure and the force of gravity?

3) Describe the process of hydrogen fusion that happens in the cores of stars.

4) We met two different red stars in the play: Kronos and Minerva. What are three major differences between these two?

5) Below is a Hertzsprung-Russell diagram which plots a star's color(temperature) vs. its luminosity(brightness). Each dot on the diagram represents an individual star. Main-sequence stars fall on the line that runs from the top-left to the bottom-right of the diagram:



On the diagram, write in the letter of each star in the part of the diagram where you think it belongs:

- A) Minerva the solar-mass star that is now fusing helium in her core
- B) Sol at the end of his life, after he collapsed
- C) Kronos the small old star
- D) Apollo the massive young star
- E) Sol while he was fusing hydrogen in his core

6) If you look at a distant galaxy and notice that it contains a lot of bright blue stars in its spiral arms and dim red stars in between the arms, where would you say that the most star formation is happening? Why?

7) If you look at a distant galaxy and notice that it contains many dim red stars but almost no blue stars, would you assume that this galaxy has a lot of extra gas, or very little extra gas? Why?

8) Scientists are very interested in finding planets around stars that may be able to support intelligent life. Should they be looking around high-mass stars or low-mass stars? Why? (hint: most scientists believe that it takes billions of years for intelligent life to evolve.)