Life of a Star

An Interview with a White Dwarf, Sol

Teacher Guide

Introduction

This activity is an opportunity for students to apply their knowledge and understanding of the gas law, conservation of energy, and forces to stellar evolution. Students perform as members of an interview with our Sun at the end of its star-life, in the white dwarf stage. Students follow the life story of this white dwarf via text, plots, and pictures. For each evolution stage, they review the properties of the star and calculate a few others.

A star, like our Sun, is an enormous and complex system. In order to model and understand their properties and how they change with time, astronomers and astrophysicists apply the basic ideas in physics to mathematically model a star. Astronomers provide the observable clues to test the models. The current theory of stellar evolution is based on mathematical models of stars, and a wide variety of astronomical observations of every sort of object in the sky from black holes, supernovae, to nebulae.

NSES

Grades 9-12 Physical Science

- Structure and properties of matter
- Motions and forces
- Interactions of matter and energy

TEKS

112.42 IPC

4. Force and Motion: The student knows concepts of force and motion evident in everyday life.
    A. calculate speed, momentum, acceleration, work, and power in systems.
    B. investigate and describe applications of Newton's laws.

6. The student knows the impact of energy transformations in everyday life.
    A. describe the law of conservation of energy.

8. The student knows that changes in matter affect everyday life.
    D. describe types of nuclear reactions such as fission and fusion and their roles in applications.

112.47 Physics

5. The student knows that changes occur within a physical system and recognizes that energy and momentum are conserved.
6. The student knows forces in nature.
    A. identify the influence of mass and distance on gravitational forces.

112.45 Chemistry

7. The student knows the variables that influence the behavior of gasses.

A. describe the interrelationships among temperature, particle number, pressure, and volume of gases contained within a closed system.

Engage

Read the following to students:
"Our galaxy, by conservative estimates, contains 100 billion stars. The small number of stars we can see at night are the nearby stars in our tiny neighborhood of our galaxy. Stars are not eternal, but live long lives compared to our lifetime. Over time they change. Just like you can look at a family photograph and tell who is young or old, astronomers can observe stars to estimate their stage of life."

Pass out one 3 x 5 inch note card to each student.
Ask students to write about what physical processes they think are going on inside a star like our Sun. Tell them that grammar, punctuation, spelling, etc. does not count. Drawing is fine. But they must be writing or drawing for 2.5 minutes without stopping.

Ask students to share their responses. Summarize the responses on an overhead projector or blackboard for everyone to see.

Review the students' responses. Help students identify the ones related to forces, motion, conservation of energy, gas laws, and nuclear fusion. Tell students to keep these concepts in mind as they act out and discuss the interview with a white dwarf.

Explore

Duration
The interview, interpreting the plots, and writing a short column for the Local Group Times should take about 2 hours of engaged work. You may want to break the interview at the beginning of the red giant phase for the next class time, and/or assign a portion of the column writing for homework. The milestones are opportunities for students reflect on what has happened in terms of the physical changes in the star and apply their knowledge and skills.

The Cast
Sol: our Sun at the end of his life as a star. This interview takes place about 5 billion years into the future, after the Sun has become a white dwarf.
Page the photon reporter: an energetic but sensitive photon journalist who is interviewing the Sun for her column in the Local Group Times.
Iana the interstellar cloud: stars begin their lives as collapsing globs of gas and dust inside an interstellar cloud or nebula.
Peter the protostar: a young contracting mass of gas and dust that will soon become a star.
Hestia the main sequence star: Hestia is a new star that has just begun to shine on her own. She is called a main sequence star because she has reached an equilibrium between the inward pull of gravity and the outward push of hot gas pressure. In addition, for a star with her mass, the fusion process in her core will run smoothly for billions of years.
Goliath the Red Giant: Goliath is in the next phase of life - a bloated red giant star. His size could easily swallow up the planets in our inner solar system.

Assign Roles
As a whole class, students in turn, play/read the parts of the characters. Sol and Page have the dominant roles. You may decide to assign several pairs of students to the roles Sol and Page.

Act out the interview
There are five parts to the interview corresponding to five major phases of Sol's life.
Nebula – gas collapses into a protostar.
Protostar – Sol remembers his turbulent youth.
Main Sequence Star – stable shining star.
Red Giant –bloating, heating, and collapsing phase.
White Dwarf – the end of its life.

Ask Guiding Questions

As students act out the interview, ask guiding questions to focus students' attention on physics or chemistry concepts. For instance, as Sol is contracting under his own weight and getting hotter during his protostar stage, ask students to think about the ideal gas law.

Pressure × Volume = Number of particles × k × Temperature of the gas
$PV = NkT$

$$\frac{Force}{Area} = \text{Pressure} = \frac{N}{V}kT$$

In a star, the pressure changes with radius from extremely high at the center to nearly a vacuum at the surface. This changing pressure is what holds a star up, keeping it from collapsing. At each layer, the outward push of the gas is balanced by the inward pull of gravity on the gas.

Example:
If the core shrinks, its volume decreases. For the pressure to balance out the force of gravity, the temperature must go up. It's like a bicycle pump. Compressing the air inside the pump raises the temperature of the gas. That's why the tire feels hot after being inflated by the pump.

Group Work

There are ten milestones in the interview. At each milestone students should work in small groups for a short amount of time to update their plots and work out the questions. Once everyone is done, resume the reading as a whole class.

Review of Sol's Life

Sol is our Sun. This story takes place in the future, 5 billion years from now, when Sol is a white dwarf.

Connections to IPC and Physics

Kinetic and Potential Energy, Conservation of Energy: In order to collapse to form a star, the gas and dust must be offset from their equilibrium. If enough gas and dust clump up, the growing gravitational field raises the gravitational potential energy of all the surrounding particles. The kinetic energy of the particles can be associated with their temperature – some will be "hot" others "cool". If their gravitational potential energy becomes greater than two times their kinetic energy, they will move toward the growing clump of gas and dust.

Science Background

Our Galaxy, the Milky Way
The Milky Way galaxy is an enormous spiral galaxy. It has three main parts: **bulge:** a dense sphere of stars at the center of our galaxy.
disk: a relatively flat and thin (several thousand light-years) pancake of stars orbiting the center of the galaxy. The disk contains at least four spiral arms marked by dust, gas, and star formation.
halo: a sparse spherical distribution of stars orbiting the galaxy.
Your are here: We (our solar system) live a little more than halfway out from the central bulge. We complete one galactic orbit about every 220 million years.

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

$$2E_K + E_P = 0$$

Nebula
A beautiful nearby example is the Orion Nebula in the constellation Orion, about 1,500 light-years away. Look just below Orion's belt for a dim blurry light patch. Even a small telescope (4-inch reflector) will show the gas and dust, plus a few new born stars.
See the Hubble Space Telescope gallery: http://hubblesite.org/gallery/showcase/nebulae/n5.shtml
A nebula is a huge cloud of gas and dust. Some parts of the nebula collapse to form stars.

Star formation in a nebula
The force of gravity is related to two factors: mass / distance^2. If the gas and dust group together, they can pull in other material, slowly collapse, and form a star.

Review of Sol’s life

At this stage, the gas and dust from the surrounding nebula is collapsing: the density of this particular region of the nebula is increasing rapidly.

Connections to IPC and Physics

Temperature

Temperature is a measurement of the kinetic energy of the particles in a volume. The particles are whizzing (or moving) around at a wide range of speeds, but there is a function called the Maxell-Boltzmann distribution that describes how many particles are traveling at each speed. At the peak of this curve is the most likely speed for a particle in the volume – that’s the most likely kinetic energy a particle could have. So the temperature tells you both the total kinetic energy and the most likely kinetic energy particles have in a volume of a plasma, gas, liquid, or solid.

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, **3/2 NkT**. And the mass created a potential energy $\mathbf{E_P}$. 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 <u>my</u> 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, $\mathbf{2E_K < E_P}$) ? 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.

Connections to IPC and Physics

Mass vs. Weight: Mass is a fundamental property of matter. Weight is a force due to matter having mass
Power: work done on or by a system per second.
Energy Transformations: Gravitational potential energy → thermal energy (includes kinetic energy) → light.
Thermonuclear fusion: Once the kinetic energy of the particles (protons) is greater than the electromagnetic repulsion between them, the strong nuclear force fuses the protons and releases energy as light. There are some quantum mechanical effects here that are quite interesting.

http://zebu.uoregon.edu/textbook/energygen.html
http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Science Background

Luminosity: power – how much energy (light) a star radiates per second.
Sun's luminosity: 3.26 x 10^{26} Watts
Hydrostatic Equilibrium: the balance at every layer of a star between outward push of the gas and the gas layer weight. In a sense, a star wants to collapse and explode at the same time.

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.

Plots

Review of Sol's life

Sol has now become a protostar – not quite a star, because thermonuclear fusion has not yet begun in his core. But, he is getting hotter. As the temperature rises in his core, the protons have more kinetic energy. Soon, a few will have enough to overcome electromagnetic repulsion and fuse.

Science Background

Protostar: not quite a star, but extremely luminous. Most of the energy radiated falls in the infrared, not the visible region of the spectrum. Fusion has not yet begun in the core.

Main Sequence: astronomers use this term in conjunction with the Hertrzsprung-Russell diagram, which shows a star's luminosity (or absolute magnitude) vs. its temperature (or "color temperature"). This plot shows a prominent grouping or "main sequence" where most stars appear on the diagram running from hot (20,000 Kelvin) to cool (3,000 Kelvin) stars. The Sun is a main sequence star. Stars spend most of their life cycle "on the main sequence".

Proton-proton fusion:
A form of stellar thermonuclear fusion that converts four hydrogen nuclei (protons) into one helium nuclei, neutrinos, and energy (light) within several steps.

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 x 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 x 10^{-3}	10^{11}	0.001674	10^6	3,000
3	10^7 4.4 x 10^{-2}	10^{10}	16.74	5 x 10^6	4,000

Can you figure out how bright I am? Here's an equation to use:
$L = (\sigma T^4) \times (4\pi r^2)$ which 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 x 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.

http://zebu.uoregon.edu/textbook/energygen.html
http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Plots

Circle the milestones and review the trends on the plots. In particular, compare the changes in diameter, density, and luminosity.

Connections to IPC and Physics

Laws of thermodynamics: the energy from the core (15 million Kelvin) moves to the photosphere (6,000 Kelvin): the Sun shines. Depending on the physical conditions inside the Sun, energy transport can be dominated by radiation (core), conduction, or convection (convection zone). A lava lamp demonstrates convection very well.

Science Background

Positron: an anti-electron. It has many of the same properties as the electron. But it is positively charged. When an electron and positron meet, they *completely* annihilate each other.

Neutrino: a nearly massless particle that weakly interacts with matter. The fusion process creates two neutrinos per cycle. So, if astronomers could detect neutrinos, they could check their models for stellar thermonuclear fusion and the lifecycle of a star.

Photon Random Walk: Once photons are produced in the core (gamma ray photons) they quickly interact with the surrounding plasma. Slowly but surely, the net effect of all the energy transformations is a "random walk" that drifts up toward the photosphere. Over the course of about one million years, the energy is transferred from the core to the photosphere, then zips through interplanetary space. About eight minutes later, the photon finds Earth and scatters in our atmosphere. You may even catch one in your eye.

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.

Review of Sol's life

By now, Sol has lived out most of his life. He laments that his mass controls his fate – he is right. At this point, Sol's hydrogen reserve is low, and the fusion reaction rates are slowing down. It is an upsetting time!

Connections to IPC and Physics

Forces: gravity's relationship between mass and distance

The acceleration of gravity (g) depends on both mass and distance.

$$g \propto \frac{M}{R^2}$$

As the core shrinks, the weight of surrounding layers increases. So the pressure and temperature increases. But as the outer envelope expands, g decreases.

Science Background

Red Giant: a red giant is well named: red because of its low photosphere temperature (below 4,000 Kelvin), and giant because of its size and luminosity. Betelgeuse is a red giant star. On clear winter nights, look for the constellation Orion. Betelgeuse marks Orion's right shoulder – it's orange and bright. If you replaced our Sun with Betelgeuse, it would fill up the inner solar system. And because it is so large, it has plenty of surface area ($4\pi r^2$) to radiate light. If you treat every square meter of its surface like a blackbody, multiply the surface area by σT^4 to calculate the luminosity.

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 t 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.

In contrast to the outer layers expanding away, the core shrinks. At the resulting temperature, the core can sustain an new thermonuclear fusion cycle: the triple-alpha process. Helium nuclei fuse to make carbon nuclei, and release energy.

Fusion

Hyperphysics Website: Georgia State University
See http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Connections to IPC and Physics

Nuclear fusion: Triple alpha process combines three hydrogen nuclei into a carbon nucleus. Higher temperatures are necessary to initiate and sustain this reaction. The helium nuclei need the extra kinetic energy to overcome the electromagnetic force between them in order to fuse. And since helium nuclei have two protons, the barrier is much higher than for the proton-proton reaction.

Science Background

Helium flash: a rapid (flash) release of energy due to the ignition of helium thermonuclear fusion. This process runs much faster and releases more energy than the hydrogen nuclei based proton-proton process.

30,000 x 3.26 x 10^{26} (Sun's luminosity) = 9.78 x 10^{30} Watts.

The core is compacted (small radius) but still massive. Gravity depends on mass divided by the radius *squared*. So if the core shrinks and the mass remains nearly constant, mass/r^2 becomes bigger. Moving any mass away from the core will take an increasing amount of work. That's why Goliath so eloquently says that he "burped" and that the helium flash "just kicked the motor on" instead of blowing him apart.

Convection current: beyond the core, the gases transport energy via convection currents to the photosphere, where light escapes into space. The shock wave of the helium flash accelerates some gas over the escape velocity of the star (in the outer envelope), so it escapes. That's why Goliath felt like he "was gonna hurl that whole time."

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 x 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 x 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.

Plots

Review the changes over the past seven milestones. Note that the upswing in diameter goes along with a similar upswing in luminosity, despite a nearly even surface temperature. Also, look at the distribution of luminosity vs. temperature points. Throughout most of the star's life, its surface temperature doesn't change very much.

Carefully note the scales on the y-axis: these steps are powers of 10, with each step *ten times more* than the previous.

Review of Sol's life

This has been a tumultuous time for Sol. Rapid changes in the core have changed him from an easy going main sequence star to a bloated red giant. By now, his core sustains two thermonuclear reaction processes: a triple alpha process (helium fusion) and proton-proton process (hydrogen fusion). His outer envelop has ballooned out into space and cooled down.

Science Background

Planetary Nebula: this term is one of the biggest misnomers in astronomy – there's no planet in a planetary nebula. It just looks that way through the eyepiece of a telescope.

Actually, the object that looks like a planet in the middle of a blossoming flower of gas is a white dwarf. Ironically, a white dwarf is the size of a planet.

The nebula is the gas expanding away from the collapsed core, now white dwarf. Over the short span of human attention, the nebula looks static. Typically, the gas is rushing away from the white dwarf at a rate of a few kilometers per second.

Examples of planetary nebula are:

Ring Nebula	http://hubblesite.org/newscenter/newsdesk/archive/releases/1999/01/text/
Hourglass Nebula	http://hubblesite.org/newscenter/newsdesk/archive/releases/1996/07/
Others	http://antwrp.gsfc.nasa.gov/apod/planetary_nebulae.html

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 gas 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.

Plots

As students examine the plots for milestones 8 through 10, focus on the following trends:

- Both luminosity and diameter decrease dramatically.
- Surface temperature increases by about a factor of 10.
- The core density and temperature continue to climb.

Review of Sol's life

Sol can now retire as a white dwarf, and simply cool down. No more thermonuclear reactions to sustain. He finds new stability in an exotic state of matter called electron degeneracy.

Connections to IPC and Physics

Thermodynamics

Since thermonuclear reactions have stopped, the white dwarf radiates its thermal energy into space as light. As it cools down, its luminosity decreases. Some white dwarfs pulsate. This new field of research is called asteroseismology.

Gravity

Imagine the mass of the Sun packed into the Earth. Under these extreme conditions, the acceleration of gravity at the surface is enormous – over 300,000 times the acceleration of gravity on Earth (9.8 m/s^2).

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	10^7 ?	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?

Science Background

Dr. Don Winget and Dr. Travis Metcalfe and other astronomers have created a website about their research of white dwarfs.
http://www.whitedwarf.org/
Select the Education link and browse the FAQs to find in depth information and animations.

White dwarfs are everywhere in our Galaxy

Most stars become white dwarfs. However, as they cool they become faint and difficult to detect. Currently University of Texas at Austin astronomers are finding more and more white dwarfs using McDonald Observatory telescopes and the Sloan Digital Sky Survey running at Apache Point Observatory in New Mexico.

Explain

Students reform their cooperative groups and write their columns. They can review with one another the events of the interview, and refer to their script and plots. The column should answer the following questions:

1. What are the primary characteristics of a star?
A star maintains a balance between outward gas pressure and the inward pull of gravity. Stars follow the laws of conservation of energy, and therefore will adjust their size and temperatures to maintain that balance. Stars shine, therefore, they "evolve."

2. During the interview, Sol and his friends mentioned many variables: luminosity, temperature (core and surface), density, and size. Which of these could we (people on Earth) observe and measure with a telescope?
Surface temperature. If an astronomer knows the distance to the star and its apparent brightness, he/she can work out the luminosity and size. Mathematical modeling based on that information leads to the density and core temperature.

3. What was Sol's life long balance to maintain? How did that affect Sol's life over time?
Sol had to balance the outward pressure of gas against the inward pull of gravity. Maintaining this balance as the conditions of the core (temperature, density, luminosity) changed caused Sol to evolve. His appearance and properties changed over time.

4. During what phase of life was Sol happiest? Why?
As a main sequence star. His size and luminosity were nearly constant for 10 billion years.

5. At the end, Sol mentioned entering a second life. What do you suppose his second life will be, and how long?
His second life will be as a white dwarf. His life is calm again. He will slowly cool down - forever.

6. What are Sol's properties as a white dwarf?
Extremely dense, about one solar mass, and low luminosity. Initially they are hot, but intrinsically faint. They cool down over time, so their luminosity decreases over time. The luminosity relation of r^2 and T^4 holds even for small objects.

Elaborate

What is Sol's ultimate fate?

Generally, white dwarfs cool down and fade. But astronomers and astrophysicists know how fast they should cool and how bright they should be based on their mass. So when an astronomer observes a white dwarf and calculates its temperature, he/she has an idea of its age. In addition, after numerous observations of other white dwarfs, they can estimate the age of our Galaxy. The coolest white dwarfs will be the oldest. So if there is a set of white dwarfs that define a low temperature limit, astronomers can estimate the lifetime of these former stars, and the age of our Galaxy.

Evaluate

Rubric for students' story

