Chapter 21: Stellar Explosions

Novae, Supernovae, and the Formation of the Elements

Outline

Summary

The life cycle of the stars is more than a curiosity. Our understanding of this entire process answers questions about the origin of our very substance. Throughout human civilization there have been creation myths and philosophies that attempted to provide answers to our curiosity about the matter of our environment. We finally have found a rational explanation, one based on naturally occurring processes, one that irreversibly links us to the rest of the universe. This is a good time to reflect back on the formation of the solar system and how the Earth was formed. Humans have an origin, not only linked to the Earth, but to the very stars. Our carbon, oxygen, nitrogen came to us through the stellar evolution of countless numbers of stars, billions of years ago, that died out, and whose many elements mixed together to finally rest here. It is a marvel, indeed, but it is all the more so because it is now understandable.

Major Concepts

- Novae
- Supernovae
  - Type I and II
  - Remnants
- Formation of the Elements
  - Stellar Nucleosynthesis
  - Helium Capture
  - Neutron Capture
    - s-process
    - r-process
- Observational Evidence
- Overview of Stellar Evolutionary Cycle

Teaching Suggestions and Demonstrations

Section 21.1

You will likely find that more students will have heard the word "nova" than the word "supernova." After all, there are no PBS programs named "Supernova" nor have there ever been cars of that name. Anyway, you will definitely want to make sure that the students understand the difference between the two. This section and the rest of the chapter will help with that. Rather than wait until this chapter to introduce the **nova**, however, you may have already found it proper in Chapter 20 while discussing the death sequence for stars, with the added complication of doing so in the presence of a binary companion. At that time, it is usually a good test of the students' comprehension of the relationship between temperature, mass/pressure, and the fusion process. Alone, a **white dwarf** will quietly cool off and fade away. If it has a companion, then all bets are off. As the companion evolves and makes much of its mass available to the white dwarf, interesting things can happen. The newfound mass falls to the surface of the white dwarf and the existing intensely high temperatures combined with the newly increased pressure results in very rapid fusion once again, but primarily at the surface.

This discussion will lead directly into the discussion of Supernova in general and **Type I Supernovae** in particular. If the mass of a white dwarf is increased sufficiently, spontaneous fusion can occur throughout the star rather than only at its surface. All of a sudden, we have a different monster. The students should be able to think about the processes that would occur within the depths of a white dwarf with the addition of considerable mass. Take your time and walk through these different processes.

Section 21.2

In the last chapter, white dwarf matter was compared to ordinary matter using a marble to represent 1 cubic centimeter of matter. That white dwarf marble had a mass of 10,000 kg, which is, as you know, rather high. The same question can now be asked for the iron core of a massive star. The text gives a **density** of 10^{12} kg/m^3, that is, 10^9 gm/cm^3. So our marble will have a mass of 1,000,000 (one million) kg. This is one hundred times greater than the white dwarf core. Comparisons become difficult but this mass is about equal to the mass of all the books in a large university library. That's a lot for a marble!

When an **iron core** finally forms in a massive star, it immediately **collapses**. For reasons explained in the text, little can stop this collapse. It is one of the most catastrophic and energetic events known to exist in the universe. It is genuinely hard to believe the amount of energy that is capable of being released and the short amount of time during which the collapse occurs.

As a core collapses, energy is released by particles as they fall toward the center of the star. How much energy is released by a falling object? Quite a bit, actually. Drop a bowling ball from 1 meter and it develops a lot of energy on the way down! Actually, it had that energy while you held it, it was gravitational potential energy. This energy is easily calculated from the formula E=mgh, where m is the mass, h is the distance it will fall, and g is the acceleration of gravity on Earth. If we imagine the collapse of the iron core being simply modeled as a solar mass falling a distance of 5 million meters, we should get a rough idea of the energy that will be released. Of course, we will need the acceleration of gravity in the core to do this simple calculation.

Newton's law of gravity tells us this is just Gm/r^2 at the surface and will keep increasing while the collapse occurs. Let's be a bit conservative and use twice the initial surface gravity $\approx 10^7$ m/s^2 (about a million times what it is on Earth). There is about one solar mass of matter that will collapse over a distance of its radius (it's about the size of the Earth). So the mass is 2×10^{30} kg and the radius is approximately 5×10^6 m. Now we calculate $mgh = 2\times10^{30} \times 10^7 \times 5\times10^6$, mgh = 10^{44}J.

This is just about right for a supernova. The light emitted totals about 10^{43} J but the neutrinos carry away about 10^{45} J. As the text notes, the light emitted is about what the Sun emits during its entire main sequence lifetime. That is also easily calculated by multiplying the Sun's luminosity by the number of seconds in a year and multiplying this by 10 billion years. $4\times10^{26} \times 10^{10} \times 3\times10^7 = 10^{44}$ J.

Now, how fast will the collapse occur? For falling bodies, simple physics tells us $h = 1/2gt^2$. Before we start doing a lot of arithmetic, notice that our h (5×10^2) has a numerical value equal to one half of our estimate of g (10^7). So $t^2 = 1$ and $t = 1$ second!

The mathematics and physics used here is appropriate even for a non-mathematically oriented class. It will be worth your while going through these simple calculations to show the power even of low-level physics to explain such interesting and energetic phenomena as supernovae.

Section 21.3

Both Type-I and **Type-II supernovae** become exceptionally bright. If a Type-II becomes about ten billion times brighter than the Sun, then this is 25 magnitudes brighter ($-2.5\text{Log}(10^{10}) = -25$) than the Sun's absolute magnitude. Since the Sun's absolute magnitude is 4.7, this supernova has an absolute magnitude of about -20. Type-I supernovae are also about as bright. If a bright supernova occurred at a distance of 300 pc (1,000 light years) it would appear as bright as the full moon!

Supernova SN1987A, although occurring in a nearby galaxy, is ideally placed for study. Since we know the distance to the Large Magellanic Cloud (LMC), we know the distance to the supernova. There is little dust in the direction of the LMC. Astronomers could then easily calculate the absolute magnitude, but were in for a surprise when they did. The LMC has a distance of about 50,000 pc and SN1987A reached a peak apparent magnitude of 3. This gives an absolute magnitude of -15.5, which is 2.5 magnitudes (10 times) fainter than predicted. The text explains why this occurred.

The supernova is also a very important **standard candle** used for determining distances to the most distant galaxies in the universe. Modern telescopes can detect a star as faint as magnitude 30. Knowing the absolute magnitude of a bright supernova allows us to calculate the distance to a supernova that is just barely detectable. Distance, d, in parsecs, apparent magnitude, m, and absolute magnitude, M, are related as $m - M = 5 \text{ Log } d - 5$. Using $m = 30$, $M = -20$, the distance is calculated to be $d = 10^{11}$ pc. This covers the entire observable universe! In principle, then, supernovae allow astronomers to see and measure the distances to all parts of the universe.

Unfortunately it is not this simple in practice. First, faint supernovae are extremely difficult to discover. A large telescope would have to continually observe a section of the sky and wait for a supernovae to occur. The galaxy in which the supernova occurs may not even be visible to the telescope. $M = -20$ is the maximum magnitude of the supernova. But it is important for astronomers to watch the supernova decline in brightness in order to determine which type it is. Finally, supernova 1987A reminded us that the peak brightness depends on the type of star going supernova. 1987A was not as bright as a "typical" supernova.

Why aren't more supernovae seen in our own galaxy? Supernovae occur, on average, about once every 100 years. If one occurred at a distance of 10,000 pc, and using $M = -20$, the apparent magnitude would be -5. But this neglects the effects of interstellar dust. Minimally, dust dims starlight by one magnitude for every 1,000 pc; it can be much more than this. So this supernova would appear at least at +5 and probably much fainter. Although searches are carried out on a nightly basis, the infrequency of supernovae and their probable faintness results in a low rate of discovery. We could easily miss a supernova in our own galaxy!

Once you make it through the description of the processes that result in supernovae, you can let the students relax a bit by showing images of **supernova remnants**. You can even sprinkle in a few planetary nebulae for review and contrast, pointing out that they are indeed different in many ways, but similar also. Both are signatures left behind by a dying star. You can discuss heavy element formation and distribution while viewing supernovae remnants as well. It can be quite dramatic to point to the wispy, colorful gas and dust in the Crab Nebula or Vela supernova remnant.

Section 21.4

Be sure to show Figure 21.5, which is a cross-sectional view of an evolved high-mass star with shells of different **heavy elements** fusing. One important idea to point out is that each successive fuel lasts for a shorter time in the core than its predecessor. The timescales become incredibly short compared to almost everything else students have studied so far in astronomy. For instance, silicon burning in the core of a 20 solar-mass star lasts about a week!

Show the transparency with Figures 21.14, 21.15 and 21.16 on it. This is a good way to walk through the production process for increasingly heavy elements. Figure 21.13 also has a tremendous amount of information. Starting with carbon, there is a sawtooth pattern to the abundance of the elements. It is hard for carbon to fuse with itself because of the 6 protons that the carbon contains. There is a strong repulsion between these nuclei as very high temperatures are required to bring them close enough for fusion to occur. But helium can fuse with carbon much easier and at a lower temperature. Since helium has 2 protons, the next element to form has 6 + 2 = 8 protons; this is oxygen.

Oxygen will fuse with helium to form neon, an element with 8 + 2 = 10 protons. This continues on for every other element. Notice the rise in abundances peaking at iron. This is an indication of the stability of the iron nucleus.

The elements that are skipped are formed by another process called **neutron capture**. When neutrons are captured inside a nucleus, they sometimes decay into a proton and an electron is emitted from the nucleus in order to conserve charge. There is no repulsive force between a neutron and the nucleus, so neutron capture is relatively easy. The neutrons don't even have to be moving very fast. ➲ **DEMO** In terms of the magnet demonstration used in Chapter 20, neutron capture is analogous to bringing a piece of non-magnetic material close to one of the magnets. Use a piece of aluminum shaped similarly to the magnets and show how it takes no force to move the two together.

Section 21.5

Figure 21.19 is a wonderful summary of the last few chapters. The idea of recycling (and enriching) matter in the universe is a powerful one. Show the figure and talk about the cycle of stellar birth (from the interstellar medium) back through stellar death, which returns material for more star birth to the interstellar medium.

Student Writing Questions

1. Explain why the composition of the Earth (mostly silicon and oxygen) is not so surprising in light of what you now know about nucleosynthesis, cosmic abundances, and the formation of the solar system.

2. A supernovae occurs at a distance of 10 pc away from you. Although it takes the light and neutrinos about 30 years to reach you, you can observe the growing supernova remnant. The outer envelope expands at 30,000 km/s; the inner bulk of the material expands at about 5,000 km/s. Describe what you observe, how quickly the clouds appear to grow, and how long it will take for the remnant to reach you. What will be the consequences of this event to life on your planet?

3. Trace the various steps that went into the making of the element silicon. Does any of the silicon get converted into other elements?

4. Astronomers typically say that we are overdue for a supernova somewhere in our vicinity of the Galaxy. Would you like to search for it? How would you go about it? What do you think your chances for success are? What would you do immediately after discovering it?

5. Several supernovae have been observed and recorded in distant times past. Choose a culture and a period of time long ago and imagine those people observing a supernova equivalent to the one seen in A.D. 1054. Describe what they would see and experience. What would be their understanding of this event? Answer this question from their perspective.

Answers to End of Chapter Exercises

Review and Discussion

1. A nova is a star in a binary star system that suddenly brightens and then slowly fades back to normal. It is caused by an evolving star in a binary that is expanding and losing gas to a companion white dwarf. After a while, the gas builds up on the white dwarf and reaches a high enough temperature to fuse. In doing so, it explodes off the surface of the white dwarf.

2. An accretion disk is a swirling, flattened disk of matter around a star or collapsed body such as a neutron star or black hole.

3. A light curve is a diagram that plots the changes in the brightness of an object such as a star, as a function of time. Time is plotted on the horizontal scale; brightness on the vertical scale. The light curves of novae and supernovae appear rather different. In particular, if the amount of brightening were observed, supernovae are known to brighten about one million times more than novae. How the light dims after the explosion is noticeably different for novae and supernovae.

4. A massive star will eventually build up a core of iron. But iron cannot fuse and release energy. As the core collapses under gravity it cannot produce additional energy to stop the collapse. As the collapse proceeds, high energy photons break up the iron nuclei, further absorbing energy and neutrinos are released when neutrons are formed from protons and electrons. This further destablizes the core, producing a catastrophic collapse.

5. Photodisintegration occurs when the core reaches 10 billion K and photons can break up the nuclei of iron and all lighter elements. Energy is absorbed in this process and the stellar core

becomes even more out of balance than it was before. Neutronization occurs when a proton and an electron combine to form a neutron. Electron degeneracy can no longer support the star and so collapse proceeds further until neutron degeneracy is reached.

6. Neutron degeneracy pressure is the resistance of neutrons to be crowded together beyond some point. It is what finally stops the collapse of a massive star's core.

7. A supernova is a very large explosion of a star that virtually destroys it. There are two different types of supernovae, Type-I and Type-II. Type-I are observed to have hydrogen-poor spectra and are fainter than the Type-II. There is also a difference in shape of the light curve as can be seen in Figure 21.8.

8. The Chandrasekhar mass is the limiting mass for a white dwarf, 1.4 solar masses. For a white dwarf in a binary system, where the white dwarf is accreting matter from its companion, the buildup of matter can proceed up to this limit. Then the electron degeneracy can no longer hold up the star. When this mass limit is exceeded, the star goes supernova; the entire white dwarf is destroyed.

9. Type-I supernovae occur in binary stars. The process is similar to a nova but with one big difference. The white dwarf initially has a mass near the upper critical limit for white dwarfs, 1.4 solar masses. As gas is accreted from the companion star, the white dwarf's mass exceeds this limit and collapses. Suddenly the carbon of the white dwarf detonates and blows the star up. Type-II supernova result from the collapse of the iron core of a massive star.

   In a Type-II supernova, the core is surrounded by a hydrogen and helium rich layer. The spectrum of such a supernova has lots of lines of these two elements. A Type-I supernova contains virtually no hydrogen or helium, so the spectrum is very weak in these elements. The light curve of a Type-I supernova is almost totally due to the radioactive decay of elements. Type-II supernovae have light curves appropriate for an expanding cloud of gas, blown into space by a shock wave.

10. Models of stellar evolution suggest that supernovae should occur about once a century. This is sufficiently long that it has not been possible to test this observationally.

11. When the supernova explosion occurs, it rapidly ejects a vast cloud of gas. This is called a supernova remnant. Supernova remnants can last for thousands of years and provide evidence of an earlier supernova.

    The supernova that created the Crab Nebula was said to be brighter than Venus, possibly as bright as the Moon. It was visible in the day time for almost a month.

12. The youngest stars have the highest abundances of heavy elements. Spectroscopic analysis of an isolated star, along with knowledge of stellar evolution, allows astronomers to determine an approximate age.

13. There are two lines of proof that heavy elements are formed in stars. First, the abundance of the elements varies greatly with atomic number. The variation in the abundances of the elements can be reproduced by the theories of nucleosynthesis. Second, observations of events like supernovae allow us to see elements virtually in the process of formation. The light curve, spectra, and neutrinos are all evidence of the explosion that allow our models to be tested.

14. The fusion of like nuclei, such as carbon with carbon, requires a higher temperature than the fusion of carbon with helium. The reason for this is that carbon has 6 protons and helium has only two. Because like charges repel, it is 3 times more difficult to bring two carbon nuclei close enough to fuse compared to bringing a carbon and a helium nuclei together. It depends on the product of their charges, $6 \times 6 = 36$ compared to $6 \times 2 = 12$, respectively.

15. The process of helium capture eventually leads to producing iron. This occurs only for the most massive stars. However, helium capture by iron does not produce energy and so the process stops with iron.

16. Nuclei heavier than iron are formed by neutron capture. The nucleus of an element captures one or more neutrons, which can then decay into a proton, forming a new and heavier element. This process can proceed slowly inside of massive stars or very rapidly during the supernova explosion.

17. The r-process stands for "rapid" neutron capture. It can occur only during a Type-II supernova explosion. Various isotopes of elements normally unstable are able to capture additional neutrons, resulting in the formation of elements that could not be formed by the s-process.

18. The LMC is the nearest galaxy to the Milky Way; its distance is very well determined. Knowing, then, the distance to the supernova allowed astronomers to immediately determine its brightness and total energy output. The LMC is also near enough that the supernova was bright and easy to see. Between us and the LMC is very little dust, so the supernova was not obscured. Lastly, because the supernova was the product of a supergiant star exploding, for the first time astronomers had observed a star and knew its basic properties before it exploded.

    Supernova 1987A will continue for a long time to be a very important supernova because astronomers have been able to follow it, from its progenitor stage completely through its development as a Type-II supernova.

19. Bursts of neutrinos are the first evidence that a supernova has occurred, arriving hours before the brightening of light occurs. They provide direct observational evidence of what has occurred in the core of the star.

20. Not only do supernovae create the heaviest elements, it distributes them back out into the interstellar environment. New stars (and solar systems) can then form from this enriched matter and the cycle starts anew.

Conceptual Self-Test

1. F
2. T
3. T
4. T
5. F
6. T
7. F
8. T
9. T
10. F
11. A

12. D
13. D
14. B
15. D
16. C
17. C
18. B
19. B
20. C

Problems

1. If M_{wd} is the mass of the white dwarf, M_{sg} is the mass of the subgiant, R is the radius of the subgiant, and D is the separation of their centers, simply calculate the gravitational attraction of both bodies on a mass element, m, on the surface of the subgiant facing the white dwarf and set them equal to each other. Solve for D.

$$G\, M_{sg}m \,/\, R^2 = GM_{wd}m \,/\, (D\text{-}R)^2$$
$$2 \,/\, 10^2 = 0.5 \,/\, (D\text{-}10)^2$$
$$D = 15 \text{ solar radii}$$

2. $v = \sqrt{}(2 \times 6.7{\times}10^{-11} \times 0.6 \times 2{\times}10^{30} \,/\, (1.5{\times}10^{7})) = 3.3{\times}10^{6}$ m/s = 3300 km/s

3. m - 5 = 5Log(10,000) - 5, m = 20 would be the limiting magnitude of this telescope.

   10^5 solar luminosities is an absolute magnitude of 5 - M = 2.5Log10^5, -7.5 is the absolute magnitude of the nova. The maximum distance at which it could be detected is 20 - (-7.5) = 5Log$d$ - 5, $d = 3.2{\times}10^{6}$ pc = 3.2 Mpc.

4. For the supernova, a similar expression is used as in the previous problem. 10^{10} solar luminosities is an absolute magnitude of 5 - M = 2.5Log10^{10}, -20 is the absolute magnitude of the supernova. The maximum distance at which it could be detected is 20 - (-20) = 5Log$d$ - 5, $d = 1{\times}10^{9}$ pc = 1000 Mpc.

   At a distance of 10,000 Mpc, its apparent magnitude would be m - (-20) = 5Log10^{10} - 5, m = 25, easily visible in the largest telescopes.

5. The apparent magnitude of the Sun is -26.8, -26.8 - (-20) = 5Log(d) - 5, d = 0.44 pc. There are no stars this close to us.

   -12.5 - (-20) = 5Log(d) - 5, d = 320 pc. It is possible that a supernova might occur this close.

6. (a) m - (-20) = 5Log150 - 5, m = -14 which is 1.5 magnitudes brighter than the full Moon or a factor of $2.512^{1.5} = 4$.

   (b) Venus gets as bright as -4.4. -14 is 9.6 magnitudes brighter than Venus or a factor of $2.512^{9.6} = 6900$.

7. The total energy output of the Sun over its lifetime is given by it current luminosity times the number of seconds in a year times its ten-billion-year lifetime.

$$4{\times}10^{26} \times 3{\times}10^{7} \times 10^{10} = 10^{44} \text{ J}$$

A supernova emits about 10^{43} J in visible light and 10^{45} J in the form of neutrinos.

8. The limiting magnitude of the *Hubble* is 30 or 6 magnitudes fainter than the supernova's peak. This is a factor of 250 in brightness or a Log(L) of 2.4, which is easier to use on the scale of the figure. The time is approximately 120 - 130 days.

9. Speed is distance divided by time. The distance is 1 pc or 3.1×10^{16} m. The time is 945 years (using 1999 and 1054). Since one year is 3.2×10^{7} s, the time is equal to 3×10^{10} s. The speed is then just 1×10^{6} m/s or 1,000 km/s.

   This answer assumes a constant expansion velocity which is certainly not too good. The expansion must take place very rapidly at first but then will slow down as the gas runs into the interstellar medium. Gravity probably plays almost no role in slowing it down.

10. From Figure 17.23 0.36 % of all stars have a mass greater than 8 solar masses. Multiplying the *fraction* by 10 gives 0.036 massive stars are formed each year. Taking the inverse gives 28 years for one of these stars to form and therefore to die out as a supernova.

11. 6 - (-19) = 5Log(d) - 5 + 2d/1000, 6 = Log(d) + d/2500. Solve by trying different values for d, solving the right side of the equation and comparing to the left side. Start with d = 5000, 6 = 5.7. Increase to d = 6000, 6 = 6.2. Keep trying to find d = 5600 pc.

12. 18 - (-19) = 5Log(d) - 5 + 2d/1000, 8.4 = Log(d)+ d/2500. Solve by trying different values for d, solving the right side of the equation and comparing to the left side. Start with d = 10,000, 8.4 = 8. Increase to d = 15,000, 8.4 = 10.2. Keep trying to find d = 10,900 pc.

13. Compare the area of visibility of the Galaxy to its total area = $(5 \text{ kpc})^2 / (15 \text{ kpc})^2 = 0.11$. We will see one out of every 9 supernovae. If they occur every 30 years, we would expect to see one every 270 years.

14. The visual magnitude of the full Moon is -12.5. How far away would a supernova have to be in order to appear brighter than the full Moon? -12.5 - (-20) = 5Log(d) - 5, d = 320 pc

$$(320 \text{ pc})^2 / (15000 \text{ pc})^2 = 0.000455$$

   This gives about one out of 2200 of the supernovae will appear brighter than the full Moon. On average, then, one of these would be visible every 30 × 2200 = 66,000 yrs.

15. There are about 10^{57} atoms in the Sun (Chapter 19). The iron group makes up 0.0001 of this, or 10^{53} atoms. Each atom has an average mass of 56 times the mass of hydrogen, or $56 \times 1.7\times10^{-27}$ kg = 9.5×10^{-26} kg. Multiplying by the total number of atoms gives 9.5×10^{27} kg. Comparing this to the mass of the Earth, 6×10^{24} kg gives 1600 times more iron group elements than the *entire* mass of the Earth. Compared to the mass of the Sun, 2×10^{30} kg, gives 0.48 %.

Resource Information

Student CD Media

Movies/Animations
Recurrent Nova
Supernova Explosion

Composition and Structure of the Ring Around Supernova 1987A
Shockwaves Hit the Ring Around Supernova 1987A

Interactive Student Tutorials
None

Physlet Illustrations
Supernova

Transparencies

T-198	Figure 21.5	Heavy-Element Fusion	p. 546
T-199	Figure 21.9	Two Types of Supernova	p. 552
T-200	Figure 21.10	Crab Supernova Remnant	p. 552
T-201	Figure 21.13	Elemental Abundance	p. 556
T-202	Figure 21.14/15/16	Proton, Helium and Carbon Fusion	p. 557
T-203	Figure 21.17	Alpha Process	p. 558
T-204	Figure 21.19	Stellar Recycling	p. 562

Suggested Readings

Birriel, J. "Searching for Supernovae To Be." *Mercury* (January/February 2003). p. 15. Excellent discussion of Type Ia supernovae, the events that lead up to their detonation and the ongoing research to predict them. Also, an overview of the differences between Type-Ia and Type-II supernovae are discussed.

Comins, Neil F. "We are all star stuff." *Astronomy* (Jan 2001). p. 56. Gives an overview of nucleosynthesis in stars.

Garlick, Mark A. "Recipe for disaster." *Astronomy* (June 2000). p. 36. Describes cataclysmic variables and the processes leading to novae.

Goldstein, Alan. "Touring a stellar graveyard." *Astronomy* (Dec 1997). p. 84. A guide to observing planetary nebula.

Goodman, Alyssa A. "Recycling in the universe." *Sky & Telescope* (Nov 2000). p. 44. Describes the cycle of stellar evolution and how it enriches the interstellar medium for future generations of stars.

Isles, John. "The dwarf nova U Geminorum." *Sky & Telescope* (Dec 1997). p. 98. Describes the history of observations of the first dwarf nova.

Krupp, E. C. "Engraved in stone: crab nebula." *Sky & Telescope* (Apr 1995). p. 60. Discusses possible historical observations of the Crab supernova in 1054 A.D.

Kwok, Sun. "What is the real shape of the Ring Nebula?" *Sky & Telescope* (July 2000). p. 32. Describes the structure of the Ring Nebula.

Patterson, Joseph. "Our cataclysmic-variable network: Center for Backyard Astrophysics." *Sky & Telescope* (Oct 1998). p. 77. Describes a network of amateur and professional astronomers who routinely monitor cataclysmic variable stars.

Robinson, Leif J. “Supernovae, neutrinos, and amateur astronomers.” *Sky & Telescope* (Aug 1999). p. 30. Describes how new neutrino observatories may be used to provide an early alert for new supernovae, and how amateur astronomers can contribute to observations of supernovae.

Tyson, Neil De Grasse. “Forged in the stars.” *Natural History* (Aug 1996). p. 72. Describes the formation of elements in stars and the historical context of our understanding of this topic.

Zimmerman, Robert. “Into the maelstrom.” *Astronomy* (Nov 1998). p. 44. Describes our understanding of the Crab Nebula.

Zimmerman, Robert. “When disaster strikes: extraterrestrial risks to earth.” *Astronomy* (Nov 1999). p. 46. Hypothesizes about possible risks to the Earth due to a nearby supernova.

Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

Demonstration and activity materials:

Notes for next time: