Chapter 18 - Origin and Evolution of Stars

The test of all knowledge is experiment. Experiment is the sole judge of scientific truth. – Richard P. Feynman

Chapter Preview

One of the greatest advances in astrophysics in the second half of the 20th century is the study of star formation. Prior to the development of infrared astronomy in the 1970s, little observational data existed on star formation, for stars in their infancy are enshrouded by clouds of dust that are opaque to visible radiation. Observational data was not keeping pace with theoretical models of star formation. Now radio, microwave, and infrared technology allow the study of clouds of gas and dust collapsing into fragments that eventually form infant stars and star clusters and the study of young stars still covered by their dusty cocoons. Now it is the theorists who must struggle to keep pace with observational data.
Key Physical Concepts to Understand: the process of star formation, the use of star cluster H-R diagrams in studying stellar evolution, the relationship between a star’s mass and the tempo of its evolution

I. Introduction

The premise is the same, that stars form from the collapse of clouds of gas and dust. Gravity is the ever-present and essential ingredient in the formation process. First let us look at the medium in which the star birthing process takes place.
The Interstellar Medium

- Our Milky Way galaxy is composed of stars and the near-perfect vacuum between them. This vacuum is near-perfect by Earth standards, but at a density of one million particles per cubic meter it holds 10% of the mass of the Milky Way and is the raw material out of which new stars condense.
- The gas and dust composing this interstellar medium is 74% hydrogen, 25% helium, and 1% heavier elements by mass.
- The temperatures of dark interstellar clouds are incredibly cold, typically between 10 and 20 K.

Giant Molecular Clouds

- It is populated by giant clouds where gas and dust are 10,000 times denser than the ambient interstellar medium.
- These clouds have typical densities of $10^{10}$ hydrogen molecules per cubic meter, masses
of one million solar masses, and are 50 to 300 light years in diameter.

- Roughly 6,000 of these giant molecular clouds are known to exist in the Milky Way, many are seen in the Orion region of the sky (Figure 1).

![Image](image-url)

**Figure 1.** Star formation in the Eagle Nebula (M16). The Eagle Nebula, a site of current star formation, is also illuminated by a cluster of stars that formed about two million years ago, seen in the upper right hand part of this image. **FMW 398-20.1.**
1. Giant molecular clouds are opaque to visible light from the silicate and ice dust grains spread throughout their volumes.
2. Because of their high density relative to the rest of the interstellar medium, molecular clouds are the active sites of current star formation, nurseries for newborn stars.

Supernovae Trigger Star Collapse

- A Supernova is the violent explosion at the end of the life of a high-mass star that destroys the star and blows away most of its mass at supersonic velocities, several thousand kilometers per second (Figure 2).
- As this supersonic gas plows through the interstellar medium it smacks into giant molecular clouds, compressing them enough to trigger their collapse.
Infrared observations show compact regions or dense cores in giant molecular clouds with temperatures of about 10 K that are likely to collapse to form stars.

Giant molecular clouds typically contain 100s or 1000s of such dense cores.

The result is that a molecular cloud is eventually expected to form an open cluster of stars from the collapse of its core condensations (Figure 3).
A collapsing molecular cloud core is a region of enhanced density thousands of times larger than our own Solar System.

The inner part of the contracting core will eventually collapse into a visibly self-
luminous protostar with its energy generated by gravitational collapse.

- The protostar has yet to commence nuclear fusion.
- If the core is not spinning it is expected to collapse directly into a sphere, eventually becoming a single star.
- If it is rotating it will collapse into a spinning disk of gas and dust, similar to β Pictoris (Chapter 12) forming a multiple star system or a single star with orbiting planets.

II. Evolution of Protostars onto the Main Sequence

*Computer-Scenarios of Pre-Main Sequence Stellar Evolution*

- Computer models are required to simulate the collapse and birth of a star from a cloud of gas and dust in our own galaxy.
- Computers are required for the extensive bookkeeping needed to model the gravitational forces everywhere in a collapsing knot of matter in a gas cloud and to follow its evolution in time. (Figure 6).
Figure 4. Evolution of a one solar mass star. Upper Panel: The evolution of a one solar mass star onto the main sequence. **Original.** Lower Panel: The appearance of a one solar mass star over its lifetime. **Wikimedia Commons.**
Figure 5. The evolutionary tracks of stars of a range of masses, evolving onto the main sequence. The numbered dots indicate the ages of these stars at different phases of their evolution. The more massive a star, the faster it evolves at every phase. Points above the dashed line represent stars that are probably hidden by their dust cocoons. Modify to include Hayashi track. FMW 406-20.11.
Protostar Formation

A dense gas clump breaks off from molecular cloud and collapses. Angular momentum turns the irregular clump into a rotating disk.

The central region is denser and forms into a protostar, the nebular disk forms slower to become a planetary system. Infalling matter increases the size of the protostar by a factor of 100.

Infall is stopped when the protostar begins thermonuclear fusion and produces a strong stellar wind.
Scene I: A star is born.

The knot in our stellar cloud, soon to birth a star, before contraction it has the following vital statistics: a mass of one-solar mass, a temperature of 10 K, a radius of one light-year, and a density of $10^{11}$ atoms/cm$^3$. (This a large number, but don’t be fooled, it is only $10^{-16}$ the density of the air we breath.) This knot is cold, large, and very tenuous.

A small core seeds the center of the knot. The center of our one solar mass knot becomes opaque, and as a result, the energy it generates from gravitational collapse is not completely radiated into space; instead the knot becomes warmer. The core now contains 0.5% of the mass of the entire knot and has a temperature of about 170 K. The density of the core is $10^{-7}$ of our air pressure at the Earth’s surface and the core diameter is 4 A.U. Matter falls from the outer regions of the knot onto the core and releases energy.
Scene II: A year later…

The core of the collapsing protostar has contracted to a diameter of twelve times the diameter of the Sun. It has grown to 1% of the entire mass of the knot and its temperature has risen to 20,000 K.

Scene III: 80,000 years later…

Gravity is winning its war with this molecular cloud knot. The protostar core now contains more than 50% of one solar mass. It has a surface temperature of 8,300 K and a luminosity 30 times that of the Sun. The protostar is beginning to look like a real star. It won’t be this luminous again until it becomes a red giant, in some 10 billion years time. With this fantastic luminosity, still generated by gravitational contraction, the properties of the protostar are changing rapidly.

Scene III: A million years later…
The breathlessly rapid evolution of the protostar is beginning to slow. Its properties are starting to approximate the fully formed main sequence star that it will be. It is now twice the diameter of the Sun with 1.3 times the Sun’s luminosity. It has a 4,400 K surface temperature and its contraction has slowed to a walk. The core temperature is now up to several hundred thousand K, still far short of thermonuclear ignition. The star’s interior is transporting energy to its surface by convecting hot bubbles of gas, mixing the hot interior with the cooler surface gas.

Scene IV: 24 million years later…

The core temperature of the star has reached 10 million K. The star has replaced gravitational contraction with a new energy source. Hydrogen fusion to helium finally begins! Over the next 25 million years gravitational contraction will cease,
and our star will settle into hydrostatic equilibrium on the main sequence for the next 10 billion years.

**How long does it take for a star to form?** Table 18.1 shows the length of time from initial core formation until thermonuclear ignition takes place. The phases of pre-main sequence evolution are the same for stars of all masses, but the pace of evolution is tied to the mass of the protostar (Figure 7). The more massive the protostar, the more rapid is its evolution through all of the phases of pre-main sequence evolution.
Table 18.1: Time for a Star to Evolve onto the Main Sequence

<table>
<thead>
<tr>
<th>Mass of Star (Solar masses)</th>
<th>Time to Evolve to Main Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>Never fuses hydrogen</td>
</tr>
<tr>
<td>0.1</td>
<td>1 billion years</td>
</tr>
<tr>
<td>0.5</td>
<td>150 million years</td>
</tr>
<tr>
<td>1</td>
<td>50 million years</td>
</tr>
<tr>
<td>3</td>
<td>2.5 million years</td>
</tr>
<tr>
<td>5</td>
<td>580,000 years</td>
</tr>
<tr>
<td>15</td>
<td>60,000 years</td>
</tr>
</tbody>
</table>
III. Current Examples of Star Formation in Star Formation Regions

In this section we will look at typical regions in the Milky Way where star formation is going on or is known to have happened recently, at least by astronomical standards.

Roadmap of Star Formation in an HII Region

Emission nebulae are regions of gas surrounding unusually hot stars, called O and B stars, 15,000 to 35,000 K, which ionizes the gas surrounding them (strips electrons off atoms) with their intense ultraviolet radiation (Table 19.2 and Figure 8). Once the electrons are stripped off an atom, they become available to mate with the first atom with which they collide, emitting photons as they cascade from a higher energy state to the atom’s ground state. Particularly prominent is the so-called hydrogen alpha line, produced by the transition of an electron from the third to the second energy state in hydrogen. The result is a red photon at 656
nanometers (10^{-9} \text{ m}) wavelength. These hydrogen alpha photons give emission nebula their red glow. Emission nebulae are also called HII regions (HII signifies ionized hydrogen, HI unionized hydrogen).

Figure 8. The newly formed open cluster NGC 2264. This star formation complex is at a distance of about 2,500 light years and contains a dark cloud of gas and embedded dust, and recently formed stars embedded in the gas and dust which illuminate it, causing the characteristic red hydrogen line emission. FMW 423-21.8.
Table 19.2: *Stellar Temperature Classes* put in previous section

<table>
<thead>
<tr>
<th>Class</th>
<th>Temperature</th>
<th>Wavelength of Peak Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>$&gt; 25,000 \text{ K}$</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>B</td>
<td>$11,000 – 25,000 \text{ K}$</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>A</td>
<td>$7,500 – 11,000 \text{ K}$</td>
<td>Blue</td>
</tr>
<tr>
<td>F</td>
<td>$5,000 – 7,500 \text{ K}$</td>
<td>White to blue</td>
</tr>
<tr>
<td>G</td>
<td>$5,000 – 6,000\text{K}$</td>
<td>Yellow to white</td>
</tr>
<tr>
<td>K</td>
<td>$3,500 – 5,000 \text{ K}$</td>
<td>Red to orange</td>
</tr>
<tr>
<td>M</td>
<td>$&lt; 3,500 \text{ K}$</td>
<td>Infrared to red</td>
</tr>
</tbody>
</table>
HII regions are seen as areas of intense hydrogen alpha emission in giant molecular clouds, and are the sites of recent star formation.

Since the hot main sequence stars illuminating HII regions only fuse hydrogen on the main sequence for a few million years, by definition these were active star-forming regions not long ago, at least by stellar evolution standards.

A few hot, blue stars at the core of an HII region is called an OB association.

An example of an OB association embedded in a molecular cloud is the Orion Nebula, which contains four OB stars that ionize the surrounding HII region, surrounded by a giant molecular cloud of 500,000 solar masses (Figure 10).

The winds and radiation blow out a tenuous cavity of ionized gas in the giant molecular cloud, compressing hydrogen gas in front of it (Figure 11).

The result is compression of the gas at the intersection between the giant molecular cloud and the HII region.
• This compression spurs the collapse of cores at the edge of the giant molecular cloud, triggering star formation.

• An association of recently formed stars is triggering the formation of the next generation of stars, which will form another association.
Protostar Formation

A dense gas clump breaks off from molecular cloud and collapses. Angular momentum turns the irregular clump into a rotating disk.

The central region is denser and forms into a protostar, the nebular disk forms slower to become a planetary system. Infalling matter increases the size of the protostar by a factor of 100.

Infall is stopped when the protostar begins thermonuclear fusion and produces a strong stellar wind.
Figure 9. Star formation in molecular clouds: the Eagle Nebula. **Panel A:** This schematic shows the stages of star formation in a molecular cloud progressing from right to left. First stars condense out of molecular cloud fragments. These stars in turn ionize and compress the face of the molecular cloud out of which they formed, causing a second round of compression, cloud collapse, and eventually star formation. As a young association of stars form, without sufficient mass to bind the group, the stars will spread out and eventually separate, each going its own way. **FMW 401-20.7, modified.** Panel B: The Eagle Nebula (M16): the “Pillars of Creation.” Molecular cloud columns are illuminated by recently
formed, bright young stars. Star-forming molecular cloud cores are emerging from the ends of the columns of molecular cloud. HST. APOD. Panel C:
**Figure 10.** The Orion Nebula at different wavelengths and "magnifications". **Panel A:** The bright stars in Orion outline the hunter of Greek mythology (demarcated by lines). Dangling from Orion’s three-star belt is his sword. One of the bright sword stars is the Orion Nebula a noted site of recent and ongoing star formation. **FMW 399-20.2, Modified.** **Panel B:** An expanded view showing the Orion Nebula (lower right hand corner). The entire image covers a dark giant molecular cloud lurking in the background. The Orion Nebula itself is a recently formed OB association reflecting light from the dusty background molecular cloud. **FMW 399-20.3?** **Panel C:** A close-up of the central part of the Orion Nebula, 2 light years across, taken with an infrared camera which is sensitive to emission from hot dust. This is a false color image, with blue indicating high temperature emission. Seen in blue is a cluster of hundreds of recently hot stars, purple and red demarcating hot and cool dust, respectively.
FMW 400-20.5? Panel D: Star and planet forming cocoons in the Orion nebula. This false-color image was made by combining a red nitrogen emission line image with a green hydrogen emission line image and a blue oxygen emission line image. The gas in the Orion Nebula is set aglow by a young massive star outside of this image toward the bottom left. Visible on this image, and its inset, are teardrop shaped cocoons of gas and dust surrounding forming stars. FMW Chapter Photo.
IV. Hayashi track

- As a protostar begins to form, contracting from a cloud of gas and dust, it is initially very large with a low temperature.
- As a result its rather large luminosity and low temperature place it in the upper right corner of the H-R diagram.
- As contraction continues the temperature of the "surface" of the protostar remains nearly constant while the surface area decreases, the protostar continuously becoming fainter. The result is that the evolutionary path of a protostar is expected to follow a vertical downward path on the H-R diagram, called the Hayashi track (Figure 5).
T-Tauri Stars:

Once a protostar has become a hydrogen-burning star, a strong stellar wind forms, usually along the axis of rotation. Thus, many young stars have a bipolar outflow, a flow of gas out the poles of the star. This is a feature which is easily seen by radio telescopes. This early phase in the life of a star is called the T-Tauri phase.
One consequence of this collapse is that young T Tauri stars are usually surrounded by massive, opaque, circumstellar disks. These disks gradually accrete onto the stellar surface, and thereby radiate energy both from the disk (infrared wavelengths), and from the position where material falls onto the star at (optical and ultraviolet wavelengths). Somehow a fraction of the material accreted onto the star is ejected perpendicular to the disk plane in a highly collimated stellar jet. The circumstellar disk eventually dissipates, probably when planets begin to form. Young stars also have dark spots on their surfaces which are analogous to sunspots but cover a much larger fraction of the surface area of the star.

The T-Tauri phase is when a star has:

- vigorous surface activity (flares, eruptions)
- strong stellar winds
- variable and irregular light curves

A star in the T-Tauri phase can lose up to 50% of its mass before settling down as a main sequence star, thus we call them pre-main sequence stars. Their location on the HR diagram is shown below:
The arrows indicate how the T-Tauri stars will evolve onto the main sequence. They begin their lives as slightly cool stars, then heat up and become bluer and slightly fainter, depending on their initial mass. Very massive young stars are born so rapidly that they just appear on the main sequence with such a short T-Tauri phase that they are never observed.
Figure 12. Protostars. Panel A: An infrared image of the protostar S106. S106 contains a protostellar dust disk seen nearly edge on which coincides with the narrowest point in the nebula. **Gas is seen to flow in the two directions perpendicular to the disk.** FMW 403-20.9. Panel B: *HH2 P 424-24.5.*
V. Star Clusters and the Determination of Stellar Ages

- Trying to determine the ages of stars is one of the greatest challenges in astronomy. Stars far outlive human beings and change only on time-scales of millions and even billions of years.

- Star clusters are key to stellar age determination. Star clusters are groups of stars, from dozens to millions, found in the same small region of space.
• Because stars in a star cluster are found together, they are generally believed to have been formed at roughly the same time and in the same neighborhood.

• In our Milky Way galaxy there are two main types of star clusters: open clusters and globular clusters (Figure 15).

• Open clusters are small and irregularly shaped, typically containing 1000 members. They have a large range of ages from very young to 10 billion years old. The color of an open cluster as a whole ranges from blue to red, and as we will see, this depends on the cluster’s age. Open clusters are loosely bound and it is usually easy to identify individual stars in nearby open clusters.

• Globular clusters are large spherical clusters of stars, containing as many as 1 million members, but 100,000 constituent stars is more typical. Globular clusters are all red and are all old, typically 10 billion years old. Globular clusters are always larger than open clusters and appear to be so dense at their
center that it is not possible to pick out single stars there.
Figure 15. Star clusters. Panel A: The central portion of the largest known globular cluster, Omega Centauri. This image is approximately 90 light years across and contains roughly 10 million stars. APOD or FMW 422-21.5 Panel B: The Jewel Box, a young open star cluster approximately 8,000 light years distant. FMW 422-21.6.
**The Tortoise and the Hare: Small Stars Finish Last**

Consider the evolution of a star’s in a cluster as a race, from the initial stage of pre-stellar cloud collapse through main sequence hydrogen fusion to stellar death (Figure 16).

In today’s race we have three contestants. In the pole position is the odds on favorite a 10 solar mass star, nicknamed the Hare. In the middle lane is the darling of the crowd, a well-known 1 solar mass underdog, the Sun. On the outside is the unknown and underweight 0.5 solar mass star, the Tortoise.

They’re off! After 1 million years the Hare is in the lead having already contracted onto the main sequence. The Sun isn’t far behind, having completed half of its contraction onto the main sequence. The Tortoise is in back, still in an early contraction phase.
After 100 million years (the race-goers are becoming somewhat bored already), the Hare is in the stretch; it has finished its core hydrogen fusion and has moved into the super-giant phase. The Sun is on the main sequence and the Tortoise has just commenced main sequence hydrogen fusion.

Whoops, we dozed off. At 10 billion years, it appears that the Hare has already won the race, it erupted in a supernova some time ago. The Sun is now a red giant and the Tortoise is still in the middle of main sequence hydrogen fusion.

The moral to this story is that small stars finish last. Whether this is viewed as a win or a loss is up to the viewer. What is relevant is what we expect to see from a cluster of stars, all viewed at the same time. The most massive stars have the highest stellar metabolism; they use up their fuel rapidly, become blazingly bright, and die out quickly. The least massive stars conserve fuel, they have a rather dull and common luminosity, but their longevity is outstanding. Let’s see what this picture looks like on
a series of H-R diagrams, each diagram essentially a snapshot of a group of stars at a single instant in the "race".

Figure 16 shows H-R diagrams for clusters of the epochs used in our "race": 1 million years, 100 million years, and 10 billion years. These are H-R diagrams based on mathematical models of stellar evolution, using all of the known physics of hydrostatic equilibrium of a gas and thermonuclear energy generation. Compare these H-R diagrams with H-R diagrams measured for real star clusters in Figure 17.
Figure 16. *H*-R diagrams representing star clusters in our race at 1 million years, 100 million years, and 10 billion years. **Modify. Arny.**
Figure 17. The H-R diagrams of a number of open clusters and one globular cluster (M3) in the Milky Way. Individual H-R diagrams, like the two shown on the right, are superimposed. Differences between the appearance of the plots are largely due to cluster age. Stars in the upper main sequence evolve off the main sequence and become giants first, as high mass stars in a cluster evolve and die the most quickly. The result is that the turn-off point, the point at which the giant branch joins the main sequence, moves to lower luminosities and temperatures as a cluster ages. The dashed regions of the giant branches represent the so-called Hertzsprung gap where few stars are seen, because stars evolve through these regions quickly. P 381-22.25.
The theoretical H-R diagrams can be characterized by (Figure 17):

1. The point at which stars are just beginning to leave the main sequence, or the turn-off point, when they finish core hydrogen fusion.
2. The point at which pre-main sequence stars are just beginning to enter the main sequence and begin hydrogen fusion.
3. The shape of the red-giant "branch" on the H-R diagram.

- The point at which pre-main sequence stars are just beginning to enter the main sequence is only seen in the youngest clusters and would be relatively hard to see as it represents the faintest stars in a young cluster.
- The shape of the red-giant branch is sensitive to both age and the chemical composition of the star cluster, so it is not straightforward to use this as an age-indicator.
- The turn-off point is the best age-indicator for a cluster because it is reliable and since it
is in the high-luminosity portion of the H-R diagram, it is easy to see.

What are the results of age-determinations for star clusters? When H-R diagrams are constructed from star cluster measurements and compared with theoretical H-R diagrams based on computer models, ages can be assigned to observed open and globular star clusters in the Milky Way. Open clusters are seen with ages from 0 to 10 billion years; globular clusters are all about 10 billion years old.

The ages and colors of star clusters are related. Globular clusters are all old, and contain only low temperature main sequence stars and red giants. All of the globular cluster stars have low temperatures and are red; as a result, all globular clusters appear red. Similarly, old open clusters contain only red stars and appear red.

However, young open clusters contain both high-luminosity, high temperature main sequence
stars and low-luminosity, low-temperature main sequence stars. Young open clusters contain high-luminosity blue stars in their mix; globular clusters don’t. As a result, young open clusters appear bluer than older globular and open clusters. There is a direct correlation between the age of a cluster and the color of its stars, with younger clusters appearing bluer, on average, than older clusters.
Stars are born when giant molecular clouds in the galaxy collapse and fragment into multi-solar mass contracting knots. As the cores of these knots shrink they become luminous, generating energy by their gravitational collapse. Eventually they become hot enough in their cores to begin stable thermonuclear fusion. At this point they acquire a luminosity and photospheric temperature that places them on the main sequence of the H-R diagram.

H-R diagrams of star clusters provide a snapshot of the evolution of a group of stars of the same age and varying mass. Such diagrams confirm the theory that the more massive stars evolve more rapidly throughout their lifetimes than do lower mass stars. The age of a star cluster is related to the shape of its H-R diagram, in particular the oldest clusters have the lowest temperature turn-off points.
Extra Information: Brown Dwarfs:

- If a protostar forms with a mass less than 0.08 solar masses, its internal temperature never reaches a value high enough for thermonuclear fusion to begin.
- This failed star is called a brown dwarf, halfway between a planet (like Jupiter) and a star.
- A star shines because of the thermonuclear reactions in its core, which release enormous amounts of energy by fusing hydrogen into helium. For the fusion reactions to occur, though, the temperature in the star's core must reach at least three million kelvins.
- And because core temperature rises with gravitational pressure, the star must have a minimum mass: about 75 times the mass of the planet Jupiter, or about 8 percent of the mass of our sun.
- A brown dwarf just misses that mark—it is heavier than a gas-giant planet but not quite massive enough to be a star.
• In 1963 University of Virginia astronomer Shiv Kumar theorized that the same process of gravitational contraction that creates stars from vast clouds of gas and dust would also frequently produce smaller objects.
• These hypothesized bodies were called black stars or infrared stars before the name "brown dwarf" was suggested in 1975.
• It was not until 1995 that they found the first indisputable evidence of their existence.
• That discovery opened the floodgates; since then, researchers have detected dozens of the objects. Now observers and theorists are tackling a host of intriguing questions: How many brown dwarfs are there? What is their range of masses? Is there a continuum of objects all the way down to the mass of Jupiter? And did they all originate in the same way?

The halt of the collapse of a brown dwarf during its formation occurs because the core becomes degenerate before the start of fusion.

With the onset of degeneracy, the pressure can not increase to the point of ignition of fusion.
- Brown dwarfs still emit energy, mostly in the IR, due to the potential energy of collapse converted into kinetic energy. There is enough energy from the collapse to cause the brown dwarf to shine for over 15 million years.
- Brown dwarfs are important to astronomy since they may be the most common type of star out there and solve the missing mass problem.
- Brown dwarfs eventual fade and cool to become black dwarfs.

Relative sizes and effective surface temperatures of two recently discovered brown dwarfs -- Teide 1 and Gliese 229B -- compared to a yellow dwarf star (our sun), a red dwarf (Gliese 229A) and the planet Jupiter, reveal the transitional qualities of these objects. Brown dwarfs lack sufficient mass (about 80 Jupiters) required to ignite the fusion of hydrogen in their cores, and thus never become true stars. The smallest true stars (red dwarfs) may have cool atmospheric temperatures (less than 4,000 degrees Kelvin) making it difficult for astronomers to distinguish them from brown dwarfs. Giant planets (such as Jupiter) may be much less massive than brown dwarfs, but are about the same diameter, and may contain many of the same molecules in their
atmospheres. The challenge for astronomers searching for brown dwarfs is to distinguish between these objects at interstellar distances.

Neither planets nor stars, brown dwarfs share properties with both kinds of objects: They are formed in molecular clouds much as stars are, but their atmospheres are reminiscent of the giant gaseous planets. Astronomers are beginning to characterize variations among brown dwarfs with the aim of determining their significance among the Galaxy's constituents.
Chapter 19 – Origin of the Life-Giving Heavy Elements: Dying Stars

This method of viewing the heavens seems to throw them into a new kind of light. They are now seen to resemble a luxuriant garden, which contains the greatest variety of productions, in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration. For, to continue the simile I have borrowed from the vegetable kingdom, is it not always the same thing, whether we live successively to witness the germinations, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once to our view?

--William Herschel (1738-1822) in Construction of the Heavens
Chapter Preview

As stars are born they must die. Although stars of all types appear to be born in a common way, the collapse and fragmentation of large clouds of interstellar dust and gas, the endpoints of a star’s life are highly varied. Some stars simply burnout, shrink, and fade away, into super-dense objects that slowly cool and grow fainter with time. Others end their lives in the fireworks of tremendous explosions, outshining a galaxy of billions of stars for a short but memorable time. In both cases stars shed some of their gaseous innards back into the interstellar gases from which they formed. In doing so, dead stars seed heavier elements, even metals such as gold and silver, which they brewed in their own interiors through thermonuclear fusion, into the interstellar medium, out of which future generations of stars will form. It is this recycling process that has brought the elements necessary for life on Earth, such as carbon, nitrogen, and oxygen, into our own Solar System. In a very real way, a previous
generation of dying stars has provided the conditions on Earth for the evolution of biological life.

Key Physical Concepts to Understand: the process of stellar death, supernovae, the origin of heavy elements in the interstellar medium and in our Solar System, electron and neutron degeneracy, the properties of neutron stars, white dwarfs and pulsars, how stars recycle material back into the interstellar medium

I. Introduction

- Astronomers have developed highly sophisticated mathematical models of stellar evolution which predict the change in stellar properties as stars of differing masses age.
- These models predict the photospheric temperature and luminosity of stars, and therefore their position on the H-R diagram, as they age.
• **How do astronomers check their mathematical models of stellar structure and evolution?**

The method that astronomers use for checking models of stellar evolution is somewhat akin to the botanist who walks into the forest to study the evolution of the redwood tree. It isn’t practical for a biologist to watch a tree grow from a seedling to a giant adult redwood. In the forest one may see redwood seedlings, young saplings, young adult redwoods, mature redwoods, and decaying logs. From this a complete picture can be inferred of the biological evolution of the redwood, from seed to decaying log. Similarly, the astronomer must piece together the complicated picture of the life cycle of a star from the measured properties of the vast numbers of stars seen in the sky. This is done by assuming that stellar properties are a function of a star’s mass, composition, and age. Current theories of stellar evolution are not perfect, but they explain most of the stellar properties that we can measure.

• **The tempo of a star’s evolution is tied to its mass. The more massive a star is, the faster it evolves through all phases of its life cycle.**

• The density of points on an H-R diagram of stars is related to the pace at which a star evolves through the different phases of its life.

• The reason that the main sequence is the most densely populated region of the H-R diagram for a random selection of stars ([Figure 1](#)) is that stars spend the majority of their lives there.
• When we randomly select a star in the sky to study, the probability is that it will be a low-mass main sequence star, for there are far more low-mass stars in the sky than high-mass stars, and stars spend most of their lives on the main sequence.

II. Red Giants and Supergiants

What happens when the hydrogen in the hydrogen-fusing core of a star has been converted to helium?

This happens to a one-solar mass star after about 10 billion years; it will happen to the Sun in another 5 billion years.

• As a star’s nuclear fuel runs out, it nuclear energy source is replaced by its gravitational energy source and it starts to contract (Figure 2).
• The core temperature increases as the core collapses.
• The core is mostly helium, but it is surrounded by hydrogen in a spherical shell extending from
the outer edge of the core through the photosphere.

• As the core temperature increases, eventually a shell of hydrogen surrounding the core will reach the temperature for thermonuclear ignition.

• As the core temperature continues to increase, the hydrogen shell fusion increases rapidly.

• The fusing shell moves outwards and the core diameter increases as hydrogen is consumed in the shell source.

• The outward appearance of the star is changing dramatically as the core is evolving.

• The outer layers of the star expand and become cooler, so the star becomes redder.

• As the aging star experiences a contracting helium core, a thermonuclear hydrogen shell source, and an expanding and cooling photosphere, it appears to become redder and more luminous, evolving into the red giant region on the H-R diagram.
Figure 2. The post-main sequence evolution of a one solar mass star.  

**a:** The star exhausts the hydrogen in its core, leaving the main sequence. As shell hydrogen burning takes place the star increases in size and decreases in photospheric temperature. **b:** The helium flash occurs. **c:** Helium is fused to carbon at the core of the star. Panel: When helium is exhausted the star again expands and experiences a decreasing photospheric temperature. **d:** Core helium is exhausted. The burned-out
star shrinks and cools, becoming a white dwarf.

**Modified. FMW 427-21.14.**

- The luminosity of a star evolving into a red giant increases even though it photospheric temperature decreases because it is expanding into a star of greater size.
- It takes a one solar mass star about 100 million years to evolve off the main sequence and become a red giant.

- When the increasing helium core temperature reaches 200 million K the helium core begins to fuse, becoming a new energy source for the star.
- Three helium nuclei fuse to form carbon nuclei ($3\text{He} \Rightarrow \text{C}$) and liberate the mass difference between the reacting helium and the carbon product as energy ($E = mc^2$), producing gamma rays (just as $4\text{H} \Rightarrow \text{He}$).
- In a one solar mass star the helium fuses rapidly and explosively, producing the so-called **helium flash** in a burst of luminosity.
- The helium flash doesn’t blow the star apart, but it does change the star’s composition and evolution.
• Stars much more massive than the Sun do not undergo a helium flash, but they burn helium in a stable helium fusing hydrostatic equilibrium like the hydrogen fusing hydrostatic equilibrium found in stars on the main sequence.

• After a time the core helium becomes exhausted in producing a carbon core.
• When the core helium becomes depleted, the star again evolves into the red giant region.
• If the star has enough mass its core temperature eventually increases to 600 million K, where carbon fuses into neon producing gamma rays \((2C \Rightarrow \text{Ne} + \text{He} + \text{gamma rays})\); our star has a new energy source.

For star exceeding 8 to 10 solar masses it will follow the following fusion sequence in its core, after fusing carbon to neon:

• Neon to Oxygen
• Oxygen to Sulfur
• Sulfur to Magnesium
• Magnesium to Silicon
• Silicon to Iron

As a star goes through this fusion sequence it acquires a very complicated shell structure and may concurrently have several forms of fusion generating energy in a core and multiple shell sources. For this reason the exact evolutionary path of high mass giants past the point of a helium-fusing core is not known (Figure 3).
Figure 3. The evolution of stars of varying mass through post-main sequence evolution. Each solid point is marked with the time elapsed since the star left the main sequence. Stars of the greatest mass
experience the most rapid evolution at all evolutionary stages. **FMW 420-21.3.**

**Figure 4.** Shell fusion in post-main sequence stars. **Panel A:** A schematic of the evolution of a ten mass star through it’s various core-fusion stages. The real path of a high mass star through all of its stages of post-main sequence evolution is complex and uncertain. **Original.** **Panel B:** A schematic of an iron-core star with a complex array of shell of differing composition with a hydrogen fusing shell source. This represents a high-mass star just before it supernovas. **Original.**
• A star that has burned silicon to iron has an onion-like layered structure with shells of differing composition from all the previous stages of fusion (Figure 4).

• The iron core is at least at a temperature of 2 billion K, the temperature required to fuse silicon to iron.

• As the core runs out of silicon, it contracts and its temperature grows even higher. One might expect the iron core to begin fusing to a heavier element at some temperature, but that can never happen.

• The iron nucleus is the most stable nucleus of all of the elements.

• Fusion of light nuclei to iron produce energy, in going from less stable nuclei of higher total mass into the iron nucleus with a smaller total mass (Figure 5).
• Mass is transformed into energy.
• Fusion of iron into heavier nuclei takes energy in going from iron nuclei of smaller total mass to heavier nuclei of higher total mass.
• An increase in mass requires the input of energy. This is why **fission** (splitting or breaking up atomic nuclei) produces energy for high-mass nuclei (**Figure 6**).

• Fission produces energy if the nucleus being split is of a higher mass than iron (uranium for example) and requires energy for splitting low-mass nuclei.

Similarly, fusion produces energy if the nuclei being fused produce a nucleus of mass equal to or less than iron (hydrogen fusing into helium, for example) and requires energy for fusing high-mass nuclei.
Figure 6. When a Uranium 235 captures a high-velocity neutron of sufficient energy it will fission forming less massive nuclei, two or more neutrons, and high-energy photons. KW 616-25.9.

III. Supernovae & Cosmic Recycling

- What happens to a star with an iron core as it collapses and heats beyond 2 billion K?
- The core begins to fuse iron, but instead of having an energy-producing source, the fusion of iron is an energy-removing sink.
- The iron-fusing core removes the energy needed to keep the high temperature and pressure needed to support the star through hydrostatic equilibrium.
- The star cannot maintain the pressure needed to support itself against gravitational collapse.
- The core begins to collapse to generate the temperature needed to supply the pressure to balance itself against gravity. But any additional
temperature makes energy-depleting iron-fusion proceed faster.

- The core collapses even faster, and eventually collapses catastrophically.
- The core no longer supports the material outside the star’s core, so it collapses as well and reaches temperatures of about one trillion K.
- At this temperature, all of the nuclei lighter than iron outside the core can fuse, producing energy explosively. The result is the rapid explosion of a star, a supernova, expelling most of its mass into space (Figure 7).
Figure 7. Supernovae. Panel A: Twin supernovae in the galaxy NGC 664, at a distance of 300 million light years. This pair of supernovae, one blue (hotter) and one red (cooler) is seen below and to the right of the galaxy nucleus. APOD. Panel B: A Hubble Space Telescope image of the Cygnus Loop, a supernova remnant in the constellation Cygnus. Gas from a supernova explosion 15,000 years ago has collided with a gas cloud, causing it to emit visible light. HST, APOD. Panel C: A Hubble Space Telescope image of the remnant of Supernova 1987a in the Large Magellanic Cloud. The origin of the loops is an enigma. HST, APOD. Panel D:
Before and after pictures of Supernova 1987a. The position of the supernova is indicated by the arrow in the lefthand image. P 463-26.15.

- This explosion takes place on a time scale of hours.
- For a period of days after the explosion the supernova can appear brighter than a galaxy of billions of stars.
- In the supernova free neutrons can combine with nuclei to build up atoms that are heavier than iron.
- This is the only means by which elements heavier than iron can be made.
- Astronomers think that the early Universe was composed mainly of hydrogen and a little helium.
- But the existence of life on Earth depends on molecules made of carbon, nitrogen, and oxygen, as well as hydrogen. The Earth itself is thought to be mostly iron in composition.
- Where do the elements on Earth heavier than iron originate?
Elements in the Earth that are heavier than iron, such as the gold and silver in our jewelry, and the uranium used in nuclear reactors, were produced in the supernova of a high-mass star that formed and regurgitated high mass nuclei into space.

At some later time the Sun and planets condensed out of this material, recycling it into a second or third generation star and its planets.

There are other means by which stars lose mass into space that can later be incorporated into future generations of stars, and reprocessed:

- **Stellar winds.** Some of a star’s mass is lost from its photosphere as high temperature gas exceeds the escape velocity of the star. This is typically a rather insignificant amount of material and it would not necessarily contain any of the heavy elements produced in the core.
• **Binary star systems.** In a binary star system where the stars are close together, strong gravitational forces can cause atmospheric gases to be exchanged between the stars, some of which can be lost into space (Figure 8). One particularly interesting example of this is the **nova**, the thermonuclear detonation of mass transferred onto the surface of a white dwarf.

![Figure 8. An artist’s conception of a binary star system with mass transfer from a companion onto the accretion disk surrounding a compact star, a white dwarf, neutron star, or black hole. Gas is spilled from the blue giant into a flattened disk surrounding the compact star. The gas spirals into the vicinity of the compact star, eventually falling onto it. Gas swirling in the inner part of the accretion disk is heated by friction, and may reach](image-url)
temperatures high enough to generate X-rays or gamma-rays. \textit{HST, APOD.}

- \textit{Planetary nebulae.} In a low-mass star, the core can heat up so that the gas pressure of its hot core can for a time exceed the weight of the overlying atmosphere. It simply pushes the atmosphere away from the star, forming a shell of gas illuminated by the core, called a \textbf{planetary nebula} because of its roughly extended disk shape, as seen through a small telescope, is vaguely suggestive of a planet (\textit{Figure 9}). The core remains in tact and will continue to evolve as a star. The outer envelope expands into space.
Figure 9. Planetary nebulae. Planetary nebulae form after some stars finish hydrogen core fusion and shed their atmosphere, including up to 0.1 to 0.2 solar masses of the star. Panel A: The Hourglass Nebula. APOD. FMW 440-22.6b. Panel B: NGC 5882. HST, APOD. Panel C: The Cat’s Eye Nebula. APOD. FMW 440-226a. Panel D: The Helix Nebula. APOD.
IV. White Dwarfs

- Stars less than about 8 solar masses can never ignite a carbon/oxygen core and get beyond the stage of fusing helium to carbon. In the last stages of their lives, after the core has finished helium fusion, the core pressure exceeds the gravitational force of the outer layers of the star, and the atmosphere is ejected into space, forming a shell of expanding gas, illuminated by the bare stellar core (Figure 10). This expanding gas shell is a planetary nebula. The exposed core is not massive enough to undergo further thermonuclear fusion, so it simply cools off by radiating its energy into space.

- This dead star is called a white dwarf. A white dwarf is a star that can no longer be supported by gas pressure; it has collapsed until it is supported by what physicists call electron degeneracy. Electrons can be packed together to a maximum density governed by the Pauli
exclusion principle, named after the Austrian physicist who proposed this rule in 1925 which later won him the Nobel prize. The Pauli exclusion principle dictates that two electrons cannot be at the same place at the same time. This electron degeneracy will support a stellar density of typically $10^7$ to $10^9$ kg/m$^3$ – (normal stars have densities ranging from 0.1 to 1000 kg/m$^3$) – a teaspoonful would weigh 1 ton on the Earth’s surface.

- One of the first white dwarfs to be discovered is Sirius B the companion to the bright star Sirius. In 1844 the German astronomer Friedrich Bessel measured the zigzagging motion of Sirius as it moved through space, due to the gravitational tug of an unseen companion (similar to the way unseen planets orbiting stars are detected, Chapter 13, Section IV). The companion was first seen in 1862. Measurements indicate that Sirius B has a blackbody temperature of about 30,000 K, but its low luminosity indicates a size close to that of the Earth’s.
As a white dwarf cools both its luminosity and surface temperature decline so that it eventually becomes cold and dark. When it reaches 1 million K, the matter in the white dwarf has solidified into one giant crystal. After billions of years the white dwarf will have radiated almost all of its energy into space. At this time the white dwarf is the size of the Earth, the mass of the Sun, with its matter cooled and solidified into a solid mass. This is the fate of our Sun.

White dwarfs can have no more mass than 1.4 solar masses, the Chandrasekhar limit, named after Subrahmanyan Chandrasekhar, who won Nobel prize in physics for his theory of white dwarfs. Stars more massive than 12 solar masses are thought to produce carbon/oxygen cores above 1.4 solar masses, which would exceed the Chandrasekhar limit and could therefore not produce white dwarfs.
Figure 10. A hot white dwarf is seen in the center of this planetary nebula, NGC 2440, imaged by the Hubble Space Telescope. HST, APOD.

V. Novae

Every once in a while star is suddenly observed to brighten by a factor of $10^4$ to $10^6$ (Figure 11).
Figure 11. Nova Cygni 1992 is an example of an explosion on the surface of a white dwarf, which occurs after enough mass has been transferred onto the surface of a white dwarf by its companion to detonate a thermonuclear explosion. Hubble telescope imaged an expanding shell of material around Nova Cygni in 1993-1994. APOD, HST.

These stars are called novae (supernovae brighten by a factor of billions). This abrupt increase in brightness is typically followed by a gradual decline in brightness over several months.

Novae occur in binaries where one star is a white dwarf. Hydrogen from the companion flows out of its atmosphere, gravitationally attracted by the white dwarf, and accumulates on the hot surface of the white dwarf. It becomes more and more
compressed with time, and as it is compressed it becomes hotter and hotter until it reaches the hydrogen fusion temperature. It this point the **hydrogen ignites and explodes, blowing itself into space.** Fresh hydrogen flows from the companion onto the white dwarf and the entire process repeats itself.

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**VI. Neutron Stars and Pulsars**

**Neutron Stars.** As is outlined above, a supernova terminates the end of the life of a star of 12 solar masses or greater. The dense central core which survives the supernova is unimaginably compressed matter, having the density of an atomic nucleus, called a **neutron star** (Figure 12).

The neutron was discovered in 1932. Because of this discovery and the theory of electron degeneracy in
white dwarfs, two American astronomers, Fritz Zwicky and Walter Baade predicted that stars above 1.4 solar masses would be supported by neutron degeneracy. As there is some ultimate density beyond which electrons cannot be compressed, so too is there a density beyond which neutrons cannot become compressed. But what happens to the electrons in a star above 1.4 solar masses? The stellar mass exceeds the crushing point of a degenerate electron gas but electrons cannot be compressed any further. The net result is that the protons and electrons in the degenerate gas are forced together, forming a degenerate neutron gas, essentially one enormous nucleus of neutrons.

The prediction of neutrons stars was not a popular one because of the outrageous properties that the star was predicted to have. Neutron stars would have a mass density the same as an atomic nucleus, about $10^{17} \text{ kg/m}^3$. If a teaspoon full of neutron star material were brought Earth it would weigh as much as a fleet of 2,000 battleships, 100 million tons. A 2 solar mass neutron star is predicted to have a diameter of
only 8 km (5 miles). The escape velocity would be one-half the speed of light.

**Figure 13.** A paper strip chart recording of the pulses from the pulsar PSR 0329+54, which has a period of 0.7145. P 474-27.3?

**Pulsars.** In 1967, Jocelyn Bell and Anthony Hewish of Cambridge University conducted an all-sky radio survey. In the course of the survey they discovered a mystery source with pulses generated precisely every 1.34 seconds ([Figure 13](#)). The regular pulsation was surprising and had never been seen before in astronomical sources. Bell and Hewish first looked for manmade radiation as an explanation and even thought of extraterrestrial radio communication. The situation was clarified when they found several new sources with precisely
regular pulsation with periods between 0.2 and 1.5 seconds. These objects were christened "pulsars".

Figure 14. The Crab Nebula, a supernova remnant 6500 light years distant. The Crab Nebula is an expanding cloud of gas from a supernova observed 900 years ago. The core of the supernova is a pulsar, a neutron star that pulses 30 times a second. APOD, AIUB.

An explanation to the nature of the pulsar became evident when a pulsar was found at the center of the Crab Nebula, a supernova remnant (Figure 14). This pulsar is now called the Crab pulsar. The period of
the Crab pulsar is 0.033 seconds. The periodic pulsation was thought to be associated with a star spinning with a 0.033-second period. This period demands a star with then-unheard-of compactness, for even a star as small as a white dwarf would fly apart at this spin rate. The Crab pulsar must be a neutron star.

All stars rotate and have magnetic fields, but as a star condenses from a sun-sized object to a neutron star, its rotation speeds up (as angular momentum remains constant) from once a month to perhaps once a second. Its magnetic field also becomes denser, perhaps a billion times denser.
The rotation axis and magnetic field axis in a neutron star are not expected to be the same anymore than the magnetic axes of the Sun and Earth coincide with their rotational axes (Figure 15). As the neutron star rotates its magnetic field is swept across the sky. The star’s sweeping magnetic fields would whip the electrons and protons in its atmosphere at high velocity, causing them to flow
out its poles. The result is a thin beam of electromagnetic radiation emanating from each of the pulsar’s magnetic poles. These beams are swept across the sky like a directed lighthouse beacon. If we are positioned fortuitously, one of the beams will sweep across the Earth, and as the beam sweeps through our field of vision we can see a short-lived pulse, once a rotation period. The Crab pulsar flashes on and off 30 times a second, and one of its polar beams happens to pass through a line-of-sight containing the Earth.

Web Note: Model of a Pulsar & Mass Transfer in Binaries

VII. X-ray binaries

The first X-ray Observatory Satellite was launched in 1979 from Kenya. To celebrate its African launch it was named Uhuru, for "freedom" in Swahili. In surveying the X-ray sky, Uhuru discovered X-ray pulses from the X-ray source designated Centaurus X-3 (for the 3rd brightest X-ray source in the constellation Centaurus). Centaurus X-3 was found to have a 4.84-second period. Later Hercules X-1 was found to be pulsing with a period of 1.24
seconds. These short periods were suspected to be associated with spinning neutron stars.

**X-ray binaries** are not ordinary pulsars like the Crab pulsar. Centaurus X-3 turns off every 2.087 days for 12 hours, perhaps because it passes behind an unseen stellar companion. Hercules X-1 is an even clearer case. Its pulses turn off 6 hours out of every 1.7 days and these pulses exhibit a periodic Doppler shift with a period of 1.7 days. The pulses slightly are slightly less frequent than 1.24 seconds for half of the 1.7 day period before the pulses turn off and then slightly more for the other half of the 1.7 day period, suggesting orbital motion about an unseen companion (**Figure 16**).
Searches in visible light near Hercules X-1 showed a faint companion which varied in brightness with the same 1.7 day period seen in X-ray radiation. It was thought that this must be the companion to Hercules X-1.
Both Centaurus X-3 and Hercules X-1 have been successfully modeled as binary systems containing neutron stars. The short period X-ray variations are associated with a very short orbital period; this indicates that the stars are very close together. In both cases it is thought that a red giant’s expanding atmosphere is attracted by the strong gravity of its neutron star companion and the giant spills some matter onto the neutron star. The neutron star is like an ordinary pulsar with a rapidly rotating magnetic field. The neutron star captures gas from its companion, which falls onto its magnetic poles at a significant fraction of the speed of light. The terrific impact of high velocity gas creates a 100 million K hot spot at each pole. The hot spots emit X-rays at 100,000 times the luminosity of the Sun. Each polar hot spot sweeps the sky, and is only visible from Earth during a fraction of the neutron star spin cycle. The result is an X-ray pulsing neutron star. As the neutron star passes behind its red giant companion, it is eclipsed for a matter of hours and its pulsing is not observed.
X-ray bursters are stars that emit X-rays at a constant low level for a time, then they exhibit an abrupt increase in X-ray luminosity, followed by a gradual decline. A typical burst lasts about 20 seconds.

These X-ray bursts are probably the result of mass transfer in binary systems from the atmosphere of one star onto the surface of a neutron star. The gas crashes into the surface of the neutron star; the impact heats the surface until it is hot enough to emit a modest level of X-ray emission. As soon as hydrogen gas hits the surface of the neutron star, it is hot enough to fuse, forming helium. A layer of helium collects on the surface until it reaches a thickness of about one meter, then it becomes hot enough to ignite, fusing into carbon and oxygen in a luminous burst of X-ray emission.

Summary

- The tempo of a star’s evolution is determined by its mass with more massive stars evolving more
quickly. A one solar mass star reaches the end of its main sequence lifetime in about 10 billion years when it runs out of core hydrogen to fuse to helium nuclei. At this point the star’s core will contract, raising its temperature to the point where it can fuse helium to carbon. The star has become a red giant. After running out of core helium it contracts and increases its temperature, but thermonuclear fusion has ended in its core. As it cools it will become a solid white dwarf, a one solar mass star the size of the Earth.

- A 10 solar mass star will reach the helium burning supergiant phase more quickly than a one solar mass star. After its helium-burning phase it will sequentially fuse carbon, neon, oxygen, sulfur, magnesium, and silicon. Next it will attempt to fuse iron, but iron is an energy sink and not an energy source. As a result the star will catastrophically collapse and then explode in a supernova. If the remaining supernova core is less than 1.4 solar masses it will form a white dwarf, if it is more massive it
may form a neutron star, with a diameter of roughly 10 km.

- Some spinning neutron stars are seen as pulsars, rapidly pulsing stars whose light is produced by matter falling through the neutron star’s magnetic field onto its magnetic poles.

- The heavy elements in the interstellar medium are produced by thermonuclear fusion in stellar interiors and then recycled into the interstellar medium with novae and supernovae explosions, solar winds, the shedding of a star’s outer atmosphere into a planetary nebula, and in the spilling of matter transferred from one star to another in a binary system.

Review for Understanding
1. Describe how elements other than hydrogen are produced.
2. Sketch an H-R diagram labeling the regions where protostars, the Sun, main sequence stars, red giants, and white dwarfs can be found. Label the axes, including units.
3. Explain what provides the pressure that keeps white dwarfs and neutron stars from collapsing.
4. What evidence is there for the theory that pulsars are spinning neutron stars?
5. Match the phrases below with the lettered points on the H-R diagram below.

   Hydrogen fusing core
   Hydrogen exhausted in the core
   Helium fusion begins
   Helium flash
   White dwarf

6. Summarize the ways that stars can return matter back into the interstellar medium.
7. Which lives longer on the main sequence, a one solar mass star or a ten solar mass star? Why?
Essay Questions

1. Compare white dwarfs, neutron stars, and black holes by describing their similarities and differences. Consider properties like range in mass, luminosity, density, method of support against gravity, and state of matter.

2. An observer 1 AU from a neutron star, white dwarf, and main sequence star would feel a gravitational pull from each. How would they compare? How would the gravitational pull compare for an astronaut standing on the surface of each in turn?

3. Discuss the probable origin of the following elements in our Solar System: carbon, iron, and gold.