present a real danger to Earth? To produce enough energy to disrupt the ozone layer, a magnetar would have to be located within the cloud of comets that surround the solar system, and we know no magnetars are that close. Nevertheless, it is a fascinating discovery that events on distant star corpses can have measurable effects on Earth.

23.5 THE EVOLUTION OF BINARY STAR SYSTEMS

Learning Objectives

By the end of this section, you will be able to:

- Describe the kind of binary star system that leads to a nova event
- Describe the type of binary star system that leads to a type Ia supernovae event
- Indicate how type Ia supernovae differ from type II supernovae

The discussion of the life stories of stars presented so far has suffered from a bias—what we might call "single-star chauvinism." Because the human race developed around a star that goes through life alone, we tend to think of most stars in isolation. But as we saw in **The Stars: A Celestial Census**, it now appears that as many as half of all stars may develop in *binary* systems—those in which two stars are born in each other's gravitational embrace and go through life orbiting a common center of mass.

For these stars, the presence of a close-by companion can have a profound influence on their evolution. Under the right circumstances, stars can exchange material, especially during the stages when one of them swells up into a giant or supergiant, or has a strong wind. When this happens and the companion stars are sufficiently close, material can flow from one star to another, decreasing the mass of the donor and increasing the mass of the recipient. Such *mass transfer* can be especially dramatic when the recipient is a stellar remnant such as a white dwarf or a neutron star. While the detailed story of how such binary stars evolve is beyond the scope of our book, we do want to mention a few examples of how the stages of evolution described in this chapter may change when there are two stars in a system.

White Dwarf Explosions: The Mild Kind

Let's consider the following system of two stars: one has become a white dwarf and the other is gradually transferring material onto it. As fresh hydrogen from the outer layers of its companion accumulates on the surface of the hot white dwarf, it begins to build up a layer of hydrogen. As more and more hydrogen accumulates and heats up on the surface of the degenerate star, the new layer eventually reaches a temperature that causes fusion to begin in a sudden, explosive way, blasting much of the new material away.

In this way, the white dwarf quickly (but only briefly) becomes quite bright, hundreds or thousands of times its previous luminosity. To observers before the invention of the telescope, it seemed that a new star suddenly appeared, and they called it a **nova**.[2] Novae fade away in a few months to a few years.

Hundreds of novae have been observed, each occurring in a binary star system and each later showing a shell of expelled material. A number of stars have more than one nova episode, as more material from its neighboring

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[2] We now know that this historical terminology is quite misleading since novae do not originate from new stars. In fact, quite to the contrary, novae originate from white dwarfs, which are actually the endpoint of stellar evolution for low-mass stars. But since the system of two stars was too faint to be visible to the naked eye, it did seem to people, before telescopes were invented, that a star had appeared where nothing had been visible.

star accumulates on the white dwarf and the whole process repeats. As long as the episodes do not increase the mass of the white dwarf beyond the Chandrasekhar limit (by transferring too much mass too quickly), the dense white dwarf itself remains pretty much unaffected by the explosions on its surface.

White Dwarf Explosions: The Violent Kind

If a white dwarf accumulates matter from a companion star at a much faster rate, it can be pushed over the Chandrasekhar limit. The evolution of such a binary system is shown in Figure 23.18. When its mass approaches the Chandrasekhar mass limit (exceeds 1.4 M_{Sun}), such an object can no longer support itself as a white dwarf, and it begins to contract. As it does so, it heats up, and new nuclear reactions can begin in the degenerate core. The star "simmers" for the next century or so, building up internal temperature. This simmering phase ends in less than a second, when an enormous amount of fusion (especially of carbon) takes place all at once, resulting in an explosion. The fusion energy produced during the final explosion is so great that it completely destroys the white dwarf. Gases are blown out into space at velocities of about 10,000 kilometers per second, and afterward, no trace of the white dwarf remains.

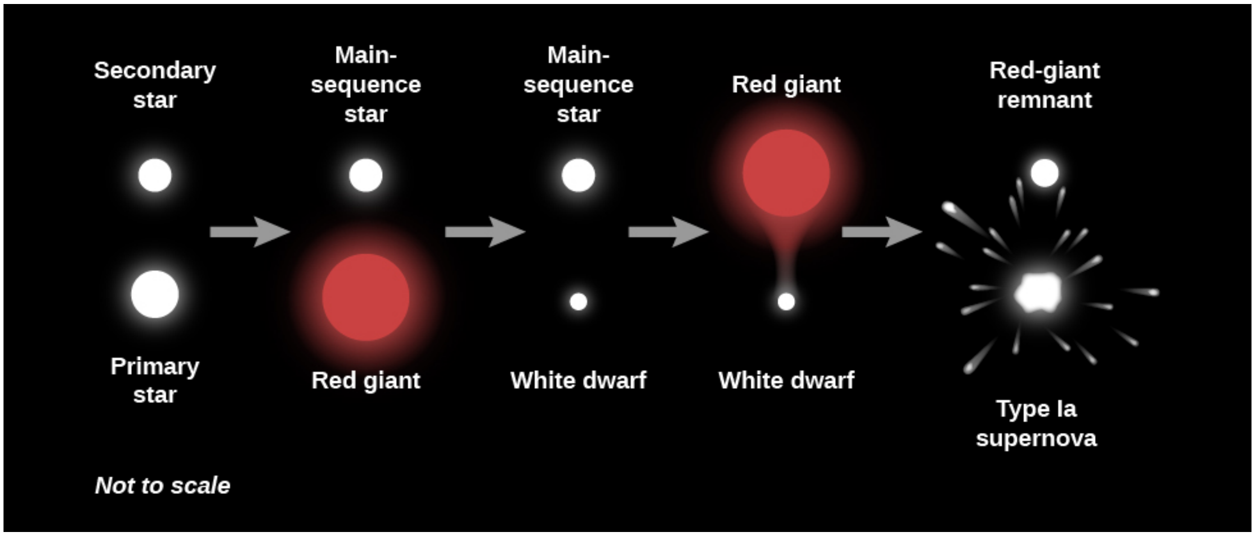

Figure 23.18 Evolution of a Binary System. The more massive star evolves first to become a red giant and then a white dwarf. The white dwarf then begins to attract material from its companion, which in turn evolves to become a red giant. Eventually, the white dwarf acquires so much mass that it is pushed over the Chandrasekhar limit and becomes a type Ia supernova.

Such an explosion is also called a supernova, since, like the destruction of a high-mass star, it produces a huge amount of energy in a very short time. However, unlike the explosion of a high-mass star, which can leave behind a neutron star or black hole remnant, the white dwarf is completely destroyed in the process, leaving behind no remnant. We call these white dwarf explosions type Ia supernovae.

We distinguish type I supernovae from those of supernovae of type II originating from the death of massive stars discussed earlier by the absence of hydrogen in their observed spectra. Hydrogen is the most common element in the universe and is a major component of massive, evolved stars. However, as we learned earlier, hydrogen is absent from the white dwarf remnant, which is primarily composed of carbon and oxygen for masses comparable to the Chandrasekhar mass limit.

The "a" subdesignation of type Ia supernovae further refers to the presence of strong silicon absorption lines, which are absent from supernovae originating from the collapse of massive stars. Silicon is one of the products that results from the fusion of carbon and oxygen, which bears out the scenario we described above—that there is a sudden onset of the fusion of the carbon (and oxygen) of which the white dwarf was made.

Observational evidence now strongly indicates that SN 1006, Tycho’s Supernova, and Kepler’s Supernova (see **Supernovae in History**) were all type Ia supernovae. For instance, in contrast to the case of SN 1054, which yielded the spinning pulsar in the Crab Nebula, none of these historical supernovae shows any evidence of stellar remnants that have survived their explosions. Perhaps even more puzzling is that, so far, astronomers have not been able to identify the companion star feeding the white dwarf in any of these historical supernovae.

Consequently, in order to address the mystery of the absent companion stars and other outstanding puzzles, astronomers have recently begun to investigate alternative mechanisms of generating type Ia supernovae. All proposed mechanisms rely upon white dwarfs composed of carbon and oxygen, which are needed to meet the observed absence of hydrogen in the type Ia spectrum. And because any isolated white dwarf below the Chandrasekhar mass is stable, all proposed mechanisms invoke a binary companion to explode the white dwarf. The leading alternative mechanism scientists believe creates a type Ia supernova is the merger of two white dwarf stars in a binary system. The two white dwarfs may have unstable orbits, such that over time, they would slowly move closer together until they merge. If their combined mass is greater than the Chandrasekhar limit, the result could also be a type Ia supernova explosion.

LINK TO LEARNING

You can watch a **short video (https://openstaxcollege.org/l/30supernovavid)** about Supernova SN 2014J, a type Ia supernova discovered in the Messier 82 (M82) galaxy on January 21, 2014, as well as see brief animations of the two mechanisms by which such a supernova could form.

Type Ia supernovae are of great interest to astronomers in other areas of research. This type of supernova is brighter than supernovae produced by the collapse of a massive star. Thus, type Ia supernovae can be seen at very large distances, and they are found in all types of galaxies. The energy output from most type Ia supernovae is consistent, with little variation in their maximum luminosities, or in how their light output initially increases and then slowly decreases over time. These properties make type Ia supernovae extremely valuable “standard bulbs” for astronomers looking out at great distances—well beyond the limits of our own Galaxy. You’ll learn more about their use in measuring distances to other galaxies in **The Big Bang**.

In contrast, type II supernovae are about 5 times less luminous than type Ia supernovae and are only seen in galaxies that have recent, massive star formation. Type II supernovae are also less consistent in their energy output during the explosion and can have a range a peak luminosity values.

Neutron Stars with Companions

Now let’s look at an even-more mismatched pair of stars in action. It is possible that, under the right circumstances, a binary system can even survive the explosion of one of its members as a type II supernova. In that case, an ordinary star can eventually share a system with a neutron star. If material is then transferred from the “living” star to its “dead” (and highly compressed) companion, this material will be pulled in by the strong gravity of the neutron star. Such infalling gas will be compressed and heated to incredible temperatures. It will quickly become so hot that it will experience an explosive burst of fusion. The energies involved are so great that we would expect much of the radiation from the burst to emerge as X-rays. And indeed, high-energy observatories above Earth’s atmosphere (see **Astronomical Instruments**) have recorded many objects that undergo just these types of X-ray *bursts*.

If the neutron star and its companion are positioned the right way, a significant amount of material can be transferred to the neutron star and can set it spinning faster (as spin energy is also transferred). The radius of the neutron star would also decrease as more mass was added. Astronomers have found pulsars in binary systems that are spinning at a rate of more than 500 times per second! (These are sometimes called **millisecond pulsars** since the pulses are separated by a few thousandths of a second.)

Such a rapid spin could not have come from the birth of the neutron star; it must have been externally caused. (Recall that the Crab Nebula pulsar, one of the youngest pulsars known, was spinning "only" 30 times per second.) Indeed, some of the fast pulsars are observed to be part of binary systems, while others may be alone only because they have "fully consumed" their former partner stars through the mass transfer process. (These have sometimes been called " black widow pulsars.")

LINK TO LEARNING

View this **short video (https://openstaxcollege.org/l/30scotronvid)** to see Dr. Scott Ransom, of the National Radio Astronomy Observatory, explain how millisecond pulsars come about, with some nice animations.

And if you thought that a neutron star interacting with a "normal" star was unusual, there are also binary systems that consist of two neutron stars. One such system has the stars in very close orbits to one another, so much that they continually alter each other's orbit. Another binary neutron star system includes two pulsars that are orbiting each other every 2 hours and 25 minutes. As we discussed earlier, pulsars radiate away their energy, and these two pulsars are slowly moving toward one another, such that in about 85 million years, they will actually merge (see Gravitational Wave Astronomy for our first observations of such a merger).

We have now reached the end of our description of the final stages of stars, yet one piece of the story remains to be filled in. We saw that stars whose core masses are less than 1.4 M_{Sun} at the time they run out of fuel end their lives as white dwarfs. Dying stars with core masses between 1.4 and about 3 M_{Sun} become neutron stars. But there are stars whose core masses are greater than 3 M_{Sun} when they exhaust their fuel supplies. What becomes of them? The truly bizarre result of the death of such massive stellar cores (called a black hole) is the subject of our next chapter. But first, we will look at an astronomical mystery that turned out to be related to the deaths of stars and was solved through clever sleuthing and a combination of observation and theory.

23.6 THE MYSTERY OF THE GAMMA-RAY BURSTS

Learning Objectives

By the end of this section, you will be able to:

- Give a brief history of how gamma-ray bursts were discovered and what instruments made the discovery possible
- Explain why astronomers think that gamma-ray bursts beam their energy rather than it radiating uniformly in all directions
- Describe how the radiation from a gamma-ray burst and its afterglow is produced
- Explain how short-duration gamma-ray bursts differ from longer ones, and describe the process that makes short-duration gamma-ray bursts
- Explain why gamma-ray bursts may help us understand the early universe