

White Dwarfs

Quantum Dots

1. Single White Dwarfs

White dwarfs are certainly the most common stellar “corpses” in the Galaxy. There may be more white dwarfs than all the other stars combined. The reason is that low-mass stars are born more frequently, and low-mass stars create white dwarfs. In addition, after a white dwarf forms, it sticks around, slowly cooling off, supported by the quantum pressure of its electrons. This means that the vast majority of the white dwarfs ever created in the Galaxy are still there. The exceptions are a few that explode or collapse because of the presence of a binary companion. There are probably ten billion and maybe a hundred billion white dwarfs in the Galaxy. Most white dwarfs have a mass very nearly 0.6 times the mass of the Sun. A few have smaller mass, and a few have larger mass. Exactly why the distribution of the masses is this way is not totally understood.

White dwarfs provide clues to the evolution of the stars that gave them birth. To fully reveal the story, astronomers need to probe the insides of the white dwarf. Ed Nather and Don Winget at the University of Texas invented a very effective technique to do this. The technique uses the seismology of the white dwarfs to reveal their interior structure, just as geologists use earthquakes to probe the inner Earth. Under special circumstances, depending on their temperature, white dwarfs naturally oscillate in response to the flow of radiation from their insides. The oscillations cause small variations in the light output. To do white dwarf seismology, careful observations must be made over extended times, days to weeks. The problem is that the Sun rises every day, and that makes observations difficult. Nather and Winget thus invented the “Whole Earth Telescope,” in which a network of small telescopes in various sites around the world is coordinated by telephone and the World Wide Web. The trick is that as the Sun rises and the target white dwarf sets in one part of the world, the Sun is setting on the opposite side of the world, and the target white dwarf is rising. With careful planning, the white dwarf can be observed constantly from somewhere on the globe for weeks at a time.

The results have been striking. The Whole Earth Telescope has measured the masses of some white dwarfs with exquisite accuracy. The team has measured the rotation of some of the stars and probed the inner layers of carbon and oxygen. The outer layers, thin shells of hydrogen and helium, have provided clues to the birth of the white dwarfs. By these techniques and others, measurements of the ages of some of the white dwarfs are possible.

Measuring the ages of the white dwarfs is especially interesting because the ages reveal the history of the Galaxy. Because essentially all the white dwarfs ever born are still around, the white dwarfs can tell the story of when the first white dwarfs formed when the Galaxy itself was young. The white dwarfs cool steadily, but they cool slowly. The oldest, coolest white dwarfs are dim and difficult, but not impossible, to see. Studies of the oldest white dwarfs reveal that the first white dwarfs formed about 10 billion years ago. The Galaxy itself presumably formed only

a few billion years before that. This argument leads to the conclusion that the Galaxy is relatively young compared to some estimates. The exact age of the Galaxy remains uncertain, but estimating its age with white dwarfs is now an established method.

2. Cataclysmic Variables

A significant number of the white dwarfs in the Galaxy are not alone, but in binary systems. These white dwarfs are especially interesting in the context of this book because they share properties with more exotic objects like neutron stars and black holes in binary systems. Most of the white dwarf binaries are the result of the first stage of mass transfer when the originally most massive star forms a white dwarf core and transfers the remainder of its mass to a stellar companion. In some cases, both stars have undergone mass transfer leaving two white dwarfs in orbit.

Some of the most common and interesting examples of the second stage of mass transfer are the *cataclysmic variables*. These variable “stars” are all binary systems in which mass flows from one star, first into an accretion disk and then onto a white dwarf. The basic components of a cataclysmic variable system are illustrated in Figure 5.1. The star losing the mass is often a small main sequence star that sometimes has less mass than the companion white dwarf. Emitted radiation tracks the stream of material passing through the inner Lagrangian point and merging with the disk. Most of the light from a cataclysmic variable comes from neither the white dwarf nor the mass-losing star but from the so-called *hot spot* where the transfer stream collides with the outer edge of the accretion disk. This collision is very energetic and so produces a great deal of heat and light. Some light also comes from the friction and heating in the inner reaches of the accretion disk itself as described in Chapter 4.

Several types of cataclysmic variables exist. The types are differentiated by their specific observational properties and the mechanisms thought to cause their variability. Cataclysmic variables all fall under the general category of the novae, or new stars. This is because historically the brightest flares would cause a “new” star to appear where none had been seen before. The star system is not new, of course, merely below the threshold of detectability until the system flares. The phrase “supernova” is an offshoot. For a long time all suddenly flaring events that caused a new star to appear were classified with the same general term, “nova.” With the discovery that some events were in distant galaxies, and hence intrinsically very much brighter, shining over great distances, the term “supernova” was applied. We now know that novae and supernovae involve very different phenomena, although they are not completely unrelated. Novae might eventually turn into supernovae, and some novae involve thermonuclear explosions.

Dwarf novae are the most gentle of the cataclysmic variables. Dwarf novae flare up irregularly to be about ten times brighter than they usually are. The flares occur with intervals of weeks to months and last for days to weeks at a time. This interval is too short to build up any reservoir of thermonuclear fuel. The energy involved comes from heating as material from the mass-losing star settles in the gravitational field of the white dwarf. There are two competing ideas of how the flare occurs. One is that the mass-losing star undergoes surges that throw over extra mass from time to time. The problem with this picture is that one would expect the hot spot to flare first, before the disk, but this is not observed. The alternative is that matter piles up in the accretion disk until some instability causes the matter to suddenly spiral down toward the white

dwarf leading to an increase in the frictional heating and the light output in the process.

Detailed studies suggest that the disk-heating instability described in Chapter 4 (see Figure 4.5) is the primary cause of dwarf novae. Matter piles up in the disk in a cool, dim storage phase until the disk becomes opaque and traps the heat. This very heating causes an increase in the opacity, yielding more heating, more friction, and yet more opacity. The result is a rapid transition of the disk to a hot bright state. When the central star is a white dwarf, the observed result is a dwarf nova outburst. During the outburst, the extra luminosity will heat the surface of the companion star and may cause the companion to transfer more mass. Both suggested mechanisms may thus play some role in the dwarf nova outburst mechanism.

Recurrent novae flare to become about a thousand times brighter than the conditions prior to the outburst. These flares occur every 10–100 years. The mechanism of the outburst is unknown. Although both kinds of systems involve mass transfer through an accretion disk onto a white dwarf, dwarf novae do not have recurrent nova outbursts, nor vice versa. The difference may follow from the rate of mass transfer. If the rate is fast enough, the disk will steadily channel all the mass to the white dwarf. The disk will not have the luxury of waiting until enough matter has collected to begin to drop the matter onto the white dwarf. A faster mass transfer rate might explain why a recurrent nova does not undergo dwarf nova outbursts, but that does not explain the nature of the recurrent nova outbursts.

Classical novae, or in casual terms, novae, flare from ten thousand to a hundred thousand times brighter than their normal state. None has ever been seen to recur. The suspicion that classical novae repeat on intervals of about 10,000 years has been around for decades. There is, however, little direct evidence for that particular time scale, which is too long for the brief recorded history of astronomy. The established evidence, both observational and theoretical, is that the mechanism of the classical nova outburst is a thermonuclear explosion. The idea is that as matter flows from the companion star, the matter settles onto the white dwarf in a dense layer supported, as is the white dwarf, by the quantum pressure, as shown in Figure 5.2. The inner white dwarf is probably composed of carbon and oxygen that require extreme conditions to ignite and burn. The material collecting on the outside is hydrogen, which burns more easily. As the hydrogen collects, the density and temperature increase until the hydrogen ignites. Because the hydrogen is supported by the quantum pressure, the thermonuclear burning does not increase the pressure and hence cannot at first cause expansion and cooling. Rather, the burning is unregulated, and an explosion ensues. The explosion does not involve the whole star like a supernova, only the outer layers. Nevertheless, the result is spectacular, giving a great flare of light and blowing matter off the surface of the white dwarf at high velocities. If the current theories are correct, the white dwarf will then begin to accumulate more hydrogen from its oblique companion until the conditions are yet again ripe for an explosion.

3. The Origin of Cataclysmic Variables

“Careful readers” (to which class the author never belonged) may have noticed that they were sandbagged earlier in the first general description of cataclysmic variables. The sleeper was the comment that in most cataclysmic variables the star losing mass is a small main sequence star. Let us think that through. If a small main sequence star is losing mass, the star must be filling its Roche lobe. Because the star is not large, the lobe must be small, which means that the stars – the main sequence star and the white dwarf – must be very close together, almost touching. How

then did the white dwarf form in the first place? The separation must have been large so that the progenitor of the white dwarf could form a well-developed core-envelope structure and become a red giant before mass transfer began. If the stars were very close together originally, the big star would eat the little one (Chapter 3, Section 7). No cataclysmic variable system could evolve. The conclusion is that the two stars must have been far apart initially, even though they are very close together now.

What is necessary to perform this bit of stellar legerdemain is to find a way to drag the stars together. The mechanism proposed to accomplish this is the *common envelope*, described in Chapter 3. We have discussed that matter can spill outward to orbit around both stars in a binary system. There is a strong suspicion that when a red giant goes into the first stage of rapid mass transfer, mass flows at such a rate that the second star is glutted. The matter falling on the star causes heat and extra radiation, and the pressure of that radiation will prevent the rapid flow of matter onto the star.

With a red giant pouring forth mass in copious amounts and the companion refusing to accept it, the matter will enshroud both stars. Unlike the case of an excretion disk where the matter orbits both stars in the orbital plane, this great amount of matter will form an approximately spherical red-giant-like envelope around both stars. Both the tiny white dwarf core of the original red giant and the innocent main sequence companion will orbit around inside this envelope. The result is a common-envelope or “double-core” system. The main sequence star and the white dwarf are not orbiting in the vacuum of space now but in the frictional medium of their common gaseous shroud. The friction causes the two stars to spiral together.

The developments that follow then are particularly unclear, but speculation goes as follows. The white dwarf and the main sequence star finally get very close together, so close that the Roche lobe of the main sequence star gets smaller than the star. Notice that the star does not evolve and expand to fill the lobe; the lobe shrinks along with the orbit to fit the star. At this point (perhaps from the heat of theoretical astrophysicists waving their arms), a burst of energy blows away the common envelope. As the ejected matter floats away, a fully formed cataclysmic variable emerges. In this view, the system is “born” within the common envelope as a main sequence star already filling its Roche lobe and transferring mass to a white dwarf. The beginning of the transfer of mass from the main sequence star to the white dwarf may be the energy source that ejects the common envelope.

The simplest, cleanest, mass-transfer process to imagine is that the red-giant envelope flows from one star to the other and thus bares the white-dwarf core. The second star subsequently expands to fill its Roche lobe and transfers mass back to the white dwarf to form a cataclysmic variable. This simple picture is probably relatively rare in practice. Even though many details must yet be understood, the formation of most cataclysmic variables probably involves the more complicated common-envelope process.

4. The Final Evolution of Cataclysmic Variables

The ultimate fate of cataclysmic variables is very uncertain. There are two general possibilities. These systems could just fizzle out. The ordinary star could eject its envelope and leave behind a second white dwarf so that mass transfer stopped. Alternatively, cataclysmic variables could end in a cataclysmic implosion or explosion. Even the fizzle could be interesting, involving some

fascinating contortions. Let us examine the catastrophic possibilities first, then return to the fizzle.

In some observed cataclysmic variables, the mass of the white dwarf is within about 10 percent of the Chandrasekhar limit, and the mass is increasing steadily. This situation immediately invokes speculation concerning the outcome if the white dwarf reaches the limiting mass. One possibility is that the nuclear fuel of which the white dwarf is composed – for instance, carbon and oxygen – ignites. For a white dwarf near the Chandrasekhar mass limit, the density is very high. With these conditions, the quantum energy of the carbon nuclei can trigger nuclear reactions even if the temperature and the thermal energy are at absolute zero. As we have described many times now, nuclear ignition under conditions where the star is supported by the quantum pressure is very unstable. Ignition of carbon under these conditions would lead to a violent explosion. This explosion would occur in a star devoid of hydrogen, save perhaps for a negligibly thin layer on the surface. Such a picture is the most probable origin of one kind of supernova, as we will explore in Chapter 6.

The white dwarf could possibly be made of iron that disintegrates upon compression, or, more likely, of oxygen, neon, and magnesium, elements that can absorb electrons rapidly. In these circumstances, when the Chandrasekhar limit is approached, the white dwarf may collapse rather than explode. This process will leave a neutron star in orbit around the main sequence star. This collapse may result in the ejection of little or no mass. The energy of the collapse might come out almost entirely in the form of neutrinos, so that there would be little or no optical display. A process this violent, however, is likely to be bright as well.

All these potential catastrophes depend on the mass getting very close to the limiting value of the Chandrasekhar mass, within a percent or so. One interesting open question is whether the mass ever gets that high. Nova explosions certainly blow off matter that has accumulated on the surface of the white dwarf. If all the matter that has accumulated is ejected in the outburst, the mass of the white dwarf will not increase. The situation could be even worse. Nova explosions are observed to expel an excess of carbon and other heavy elements. This strongly suggests that a nova explosion expels not just the outer layer of accumulated hydrogen but also some of the guts of the white dwarf itself. This would mean that the mass of the white dwarf shrinks as a result of nova explosions. If this is the case, the white dwarf will remain in the binary system until the companion star evolves and forms a white dwarf of its own. Thus nova explosions might lead to circumstances where the final fate of the cataclysmic variable is a fizzle rather than a catastrophe.

The cataclysmic variable might fizzle, but the story is not over just because the system produces two white dwarfs. We need to inquire about the ultimate fate of two orbiting white dwarfs. They can no longer evolve on their own. Supported by the quantum pressure, they will just cool off if left to their own devices. The white dwarfs do not remain unmolested, however. As they revolve about, their orbital motion generates gravitational waves. The gravitational waves carry off energy and angular momentum, and the orbit must shrink. As described in Chapter 3, gravitational radiation affects all stellar orbits. Gravitational radiation is a very small effect, so that any other normal interaction between the stars is more important. Only when the two white dwarfs reach a state of total quiescence can the small effect of gravitational radiation become important. This will inevitably happen to two white dwarfs, however, and they must spiral together. The outcome depends on the specific properties of the white dwarfs as stars

supported by the quantum pressure.

For a normal star supported by thermal pressure, the addition of mass causes the star to attain a larger radius. Remove mass, and the star shrinks. For a white dwarf supported by the quantum pressure, the opposite situation holds. The addition of mass causes an overall compaction of the star. The star thus shrinks in radius as the mass increases. Removal of mass from a white dwarf allows the star to expand in the smaller gravity and attain a larger radius. This behavior has crucial implications for the ultimate fate of one of the white dwarfs.

The two white dwarfs will spiral together until the separation, and hence the Roche lobes become small enough so that one of the white dwarfs fills its lobe. Which one will that be? The one with the smaller mass has a smaller Roche lobe but a larger radius. The smaller-mass white dwarf will fill its lobe first and begin to lose mass to the larger-mass dwarf. This is not good news for people rooting for the underdog! As the smaller-mass dwarf loses mass, its Roche lobe shrinks, but its radius gets even larger! The white dwarf will lose mass at an ever more rapid pace. The only outcome can be the disappearance of the small-mass dwarf. The larger-mass dwarf will simply gobble up the smaller-mass one. Some mass may slop out into space, but this will be little consolation to the disappearing dwarf.

The smaller-mass star may not disappear entirely. When the mass of the object gets down to the size of a planet – less than a thousandth the mass of the Sun – its structure may rearrange. If the material becomes rocklike, like the Earth, then the remains of the little white dwarf may cease expanding. The result could be one white dwarf orbited by a desolate rocky chunk. Given sufficient time for gravitational radiation to act, even that chunk could spiral down to the surface of the remaining white dwarf and be consumed.

Alternatively, the process of disrupting the smaller-mass white dwarf may not end gently at all. As the larger-mass white dwarf consumes the smaller-mass one, the larger-mass white dwarf gets more mass, shrinks to a smaller volume, and hence develops a higher density. This increase in density could result in the ignition of carbon burning in the more massive white dwarf. The resulting catastrophic burning in the more massive white dwarf would blow the star apart. This is yet another proposed mechanism to create a certain type of supernova from a white dwarf. We will see this in more detail in Chapter 6.

White dwarfs may just be small quantum-pressure supported dots, but they can do very interesting things. They may hold the key to understanding the fate of the Universe. We will see that in Chapter 11.