A Review of Stellar Remnants: Physics, Evolution, and Interpretation

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Abstract

Astronomers think that stars end their existence as one of three possible stellar remnants. In recent decades, astronomers have amassed a tremendous amount of observational data and theoretical models to support an evolutionary interpretation of stellar remnants. We survey this topic and discuss possible creationary responses to it.

Introduction

Recent issues of this quarterly have contained articles dealing with stellar remnants (Davies, 2007; DeYoung, 2006). In this article, we explore three topics. First, we review the types of stellar remnants recognized in the astronomical field. Second, we briefly describe the observations and physics that support the identification of these objects. Third, we discuss the evolutionary framework that astronomers generally think explains these different objects. In the conclusion we will discuss some of the possible creationary responses to these evolutionary ideas. As creationists, we reject evolutionary explanations and ought to respond to them with criticisms and creationary alternatives. However, in our critique of these evolutionary ideas, we must be very careful that we do not mistakenly "throw the baby out with the bath water" by dismissing some of the conclusions that are based upon good observations and physics. As difficult as it may be, we must separate the evolutionary speculations from the well-established ideas.

Stellar Remnants: Observations and Physics

Modern astronomers usually define a star as a hot, luminous, self-gravitating (roughly) sphere of gas that derives or has in the past derived a significant portion of its luminous energy from thermonuclear fusion. Detailed calculation of the theoretical interior structure of stars reveals that below about 7% of the mass of the sun, a hot sphere of gas lacks sufficient internal temperature to initiate the requisite fusion reactions. Therefore, astronomers recognize this 7% cutoff as the lower limit that a star can have. Over the past two decades or so, astronomers have computed the theoretical structure of gas spheres below this threshold. These calculations reveal that these substellar mass objects derive most of their energy from gravitational contraction (the Kelvin-Helmholtz mechanism), though during some stages they obtain a portion of their energy from nuclear reactions. Astronomers once thought that the Kelvin-Helmholtz mechanism powered the sun and other stars, as some creationists today do. This energy source ought to make these substellar objects appear similar to true stars in luminosity, temperature, and radius. In short, these "brown dwarfs," as astronomers have dubbed them, ought to appear similar to low mass, low luminosity stars. Indeed, in recent years astronomers have claimed discovery of a number of brown dwarfs.

As an interesting aside, astronomers now generally think that brown dwarfs have no clear minimum mass. Instead, with decreasing mass, brown dwarfs gradually morph into cooler objects that ordinarily we would call planets (objects that do not undergo nuclear fusion). This view results in a continuum from high-mass stars, to low-mass stars, to high-mass brown dwarfs, to low-mass brown dwarfs, to high-mass planets, and then to low-mass planets. Since there is no clear distinction between small planets and large asteroids, many astronomers extend the continuum down to very small (microscopic) asteroids. (In the summer of 2006, the International

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Astronomical Union attempted to define the minimum size for a planet, but this definition remains controversial and almost certainly will continue to be refined.) As long as the definition of brown dwarf stars and extrasolar planets remained theoretical constructs, stars and planets remained distinct objects. However, with the recent discovery of brown dwarfs and extrasolar planets within the gap, the distinction between stars and planets is now murky. It is easy to see that there are evolutionary ideas lurking in this, but we will not discuss this issue further at this time.

If the least massive stars must have at least 7% the mass of the sun, is there a maximum mass that a star may have? The answer to this question is less certain. First, low-mass stars are very common, but high-mass stars are very rare, so the statistics for high-mass stars are not as good as the statistics for low-mass stars. Second, there are theoretical problems with extremely high-mass stars. Stars up to 83 (WR 20a) times the mass of the sun are known to exist. With higher mass, stars likely become very unstable, so most astronomers think that the upper limit for the masses of stars is not much less than 100 times that of the sun.

Faulkner and DeYoung (1991) and Briegleb (1993) previously have discussed the Hertzsprung-Russell (HR) diagram in the creation literature. The HR diagram is a plot of some measure of stellar luminosity versus a measure of the stellar temperature. For historical reasons, luminosity increases upward, but temperature increases toward the left. Most stars appear to fall along the main sequence (MS), a roughly diagonal band from upper left to lower right. The hottest and brightest MS stars lie to the upper left, while the coolest and dimmest MS stars lie on the lower right. The most massive and largest MS stars are on the upper end of the MS. Descending the MS, stellar mass and size decrease. We have previously discussed the range in stellar masses; the largest MS stars are nearly 20 times the diameter of the smallest MS stars.

Not all stars lie along the MS. Some stars lie above and to the right of the MS. These stars generally are larger than MS stars, so astronomers call them giant stars. Some of the coolest appear red, so we call them red giants. To the lower left of the main sequence are stars about 1–2% the diameter of the sun, or about 1–2 times the diameter of the earth. We call these stars white dwarfs, because these stars are so small, and the first discovered were white in color. A white star is very hot. Eventually, astronomers found white dwarfs that were cooler, with colors trending toward blue and yellow, but we still call them white dwarfs.

White dwarf stars are common, and we find many in binary star systems. The latter is important, because the study of the orbits of binary stars offers us the only direct way to measure the masses of stars. We find that white dwarf (WD) stars may have as little as half the mass of the sun, but the upper limit is about 1.4 solar masses. Because WD's are so common and many are near us, we have learned much about their structure. For instance, we know the distances to a number of WDs. Knowing the distance, we can calculate a WD's luminosity from its observed brightness. Astronomers have various ways to determine temperatures of stars. They can use the Stefan-Boltzmann law to estimate a WD's size (and hence volume) from its luminosity and temperature. And they can determine the density by dividing the mass by the volume. We find that WDs are very dense—many thousands of times the density of water. This density is several orders of magnitude denser than any substance on earth. Astronomers discovered the first WDs a little more than a century ago. At the time, their high density was a mystery. It was not until the early 1930s that pioneering astrophysicists used then-new quantum mechanics to deduce the structure of WDs.

Hydrostatic equilibrium holds a star together. Hydrostatic equilibrium is the balance between gravity and pressure. Gravity pulls the star's matter toward the center, while pressure pushes the matter outward. Hydrostatic equilibrium is a well-understood principle that explains many phenomena, such as buoyancy. Hydrostatic equilibrium is self-regulating. Suppose that gravity exceeds pressure. Then gravity will shrink a star; but as the star shrinks, its pressure will increase, following the ideal gas law. While the star's gravity will also increase with shrinkage, the pressure increases much more rapidly. Soon, the two forces come back into balance. On the other hand, if pressure exceeds gravity, the star will expand until balance is restored.

The great mystery of WDs a century ago was the question of what held them together. One of the best examples of a WD is the binary companion to Sirius, the brightest star in our sky. Since it was in a binary star, astronomers could determine the mass of Sirius B, as the WD in the system is called. Because Sirius is so close (a little more than eight light years), astronomers also knew how much total radiation that Sirius B emitted. They also could estimate the temperature of Sirius B from its color. The brightness and temperature allow us to determine the WD's size. Newton's law of gravity reveals the surface gravity. From the temperature and density, astronomers could calculate the pressure from the ideal gas law. The gravity was far greater than the computed pressure, which meant that the WD was far out of hydrostatic equilibrium. Absent some unknown pressure, the WD ought to rapidly collapse, but obviously it did not.

What provided this pressure? According to quantum mechanics, electrons cannot be indefinitely compressed. This is because electrons obey the Pauli Exclusion Principle, which forbids degeneracy. Degeneracy exists when more than one particle occupies an energy state. Under normal conditions, there are far more energy states than particles, so this is not a problem. However, a WD is compressed to the point that all energy states available to the electrons are occupied. Thus, any more compression would result in degeneracy. Since quantum mechanics forbids this, the electrons provide an outward force that we call degeneracy pressure. In a WD, electron degeneracy pressure far exceeds normal gas pressure, and thus electron degeneracy pressure is responsible for nearly all the pressure to maintain hydrostatic equilibrium. Even in so-called normal stars, such as the sun, some electron degeneracy pressure exists in their cores.

We ought to mention one other peculiarity about WDs. Hydrogen is by far the most abundant element in the universe, accounting for about 75% of composition by mass. This is typical composition of stars. However, if any hydrogen existed within a WD, the pressure and temperature present would result in rapid thermonuclear fusion of the hydrogen into helium. Thus, WDs must consist of other elements. Helium is probably one of the more important elements present, but other elements, such as carbon and iron, probably are present as well. The only place where hydrogen may exist in a WD is near the surface, in a kind of atmosphere where even electron degeneracy pressure may not be significant. We will discuss the importance of this possibility shortly. Absent the possibility of flare-ups caused by the fusion of hydrogen introduced to a WD, a WD does not produce energy. Instead, WDs shine by gradually tapping their enormous store of thermal energy. The calculated lifetimes of WDs—the period of time over which we can see them—exceeds many tens of billions of years. Since WDs do not normally undergo nuclear fusion, by definition they are not stars but instead are the first type of stellar remnant.

One result of the theory of WDs is the prediction that there is a maximum mass for WD stars. We call the upper limit to WD mass the Chandrasekhar limit, after the Indian-born American astrophysicist who was one of the first to deduce WD structure. The exact value of the Chandrasekhar limit depends upon the composition, but the largest mass possible for any composition is about 1.4 times the mass of the sun. Since WDs are so common in binary stars, we have much data to test this theoretical result. We find WD masses range from about 0.5 solar masses to 1.4 solar masses, with a cluster of stars near this upper limit. This is powerful evidence in support of WD theory. Theoreticians have been able to explain many other aspects of WD stars. We do not have room to expound upon them here. Suffice it to say that we probably understand the structure of WDs better than any other stars, including the sun.

As strange as WDs are, there are stranger objects still. In 1967, astronomers discovered the first neutron star (NS). Since then, astronomers have found about 1,500 additional NSs. NSs have masses greater than 1.4 solar masses. The upper limit for a NS is less certain than with a WD, but most models suggest an upper limit of around 3 solar masses. NSs are very small, only a few km across. This means that the density of a NS is many orders of magnitude greater than the density of a WD. The density of a NS is comparable to the density of the nucleus of the atom. Because NSs are so small, they are not very bright and we cannot see them with ordinary means at typical stellar distances. There are two ways to detect a neutron star; we will describe one of those methods now, and we will discuss the other later.

In 1967, astronomers discovered point radio sources that rapidly flashed, or pulsed, on and off. Since these objects pulsed, astronomers called them pulsars. Pulsars have very regular periods between their pulses, so regular that they keep very good time. The identity of pulsars remained a mystery for a short while. Astronomers soon realized that a rapidly rotating NS could explain pulsars. NSs had been predicted three decades earlier, but normally they would be so faint that we could not see them. Pulsars appear to pulse because they rotate very quickly and have very intense magnetic fields. If a pulsar originally were a much larger star, then as that star shrank/collapsed to form the NS, conservation of angular momentum demands that the rotation period decrease dramatically. Additionally, a sort of conservation of magnetic flux requires that the magnetic field greatly increase as well. As the NS rapidly rotates, it carries its strong magnetic field along with it. The rapidly moving magnetic field would greatly accelerate any charged particles near the surface of the NS. Highly accelerated, charged particles radiate in a particular way. Given this setup, we would expect that the radiation would be concentrated along the magnetic field poles. As the NS rotates, the magnetic field, and hence this beamed radiation, would sweep out in a cone, much like a searchlight does. If we lie along the cone swept out by the beam, then we will see a pulse each time the star rotates.

Is there any evidence for this scenario? Yes. Theory tells us that the beam must be polarized in a particular way and that it has a power-law spectrum. We call this kind of radiation "synchrotron radiation," because scientists first observed it coming from a type of particle accelerator that we call a cyclotron. Synchrotron radiation is very distinctive and occurs only when there is a powerful magnetic field rapidly moving with respect to charged particles. The radiation from pulsars matches those predictions very well.

Once astronomers realized that NSs existed, they began to speculate that black holes may exist as well. A black hole (BH) is a region of space that contains so much matter packed into such a small volume that the surface gravity prevents everything, including light, from escaping. Presumably, a BH must have mass greater than the roughly 3 solar mass upper limit for a NS. Notice that there is no upper limit on BH mass. A BH that is near the lower limit of mass is slightly smaller than a NS. However, as BH mass increases, the size of the BH increases. For some time astronomers have recognized the existence of two types of BHs: those with stellar masses and massive BHs. There is now good evidence that massive BHs lurk at the centers of many galaxies, including our own Milky Way. The mass range of stellar BHs may extend to a few tens of solar masses. Massive BHs may contain a million times the mass of the sun or more. Recently, astronomers have begun to consider the possibility of the existence of intermediate mass BHs.

What evidence is there for the existence of stellar BHs? Binary stars are very common. Suppose that a BH exists in a close binary star. If the stars in the binary system are close together, then the gravity of one star may pull matter off the other star and onto itself. The BH would produce tremendous tides on its companion, leading to mass transfer from its companion. Because the matter in falling onto the BH possesses angular momentum, the mass does not fall directly onto the BH. Instead, the matter orbits in a disk close above the event horizon of the BH. Astronomers call this disk an accretion disk (AD). From the AD, matter slowly spirals onto the BH. As matter from the companion star falls onto the AD, it converts a huge amount of gravitational potential energy into kinetic energy. Collisions and viscous motions of matter falling onto the AD thermalizes the AD, leading to very high temperatures in the AD. The high temperature leads to copious x-ray emission from the binary system. It is difficult to produce so much x-ray emission, so these objects readily stand out in surveys done with x-ray telescopes. Astronomers call an x-ray emitting binary system an x-ray binary (XRB).

We know that an XRB requires the presence of a compact object, a very small, massive object. Only a compact object has a steep enough gravitational potential well to account for the x-rays. The only compact objects that we know of are NSs and BHs. That is, the existence of an XRB implies the existence of either of these compact objects, but the existence of an XRB alone does not tell us which one. Can we determine which one? Fortunately, there is a way. Binary stars provide us with the only direct way of determining stellar masses. Recall that there is an upper limit to the mass that a NS may have. If we solve the observations to determine the mass and find that the mass of the compact object is below the upper limit of a NS mass, the compact object probably is a NS. However, if the compact object's mass exceeds the upper limit of the mass of a NS, the compact object is almost certainly a BH. Astronomers have identified a number of BH candidates, compact objects in XRBs whose masses exceed the NS upper limit. Additionally, astronomers have found a number of NSs in XRBs. This is the second method of NS detection.

Ancient astronomers coined the word "nova" (meaning "new") to refer to a new star that occasionally appeared. Even the ancients noted that novae generally disappeared after a few days. We now understand that a nova is an eruption in a star that causes the star to brighten tremendously before fading back to normal. In the case of ancient novae, the stars that erupted were too faint for anyone to see before or after the eruption. Modern astronomers have managed to identify stars before and after eruption in many cases. Since the 1920s astronomers have known about the existence of supernovae. A supernova is about 10,000 times brighter than a nova.

Modern theories about novae and supernovae developed in the 1960s and 1970s along with the development of stellar evolution. Astronomers think that novae occur in close binary stars, where one of the two stars involved is a WD. In a close binary system, the two stars are tidally distorted so that instead of spheres, the stars may be estimated as prolate spheroids with their longer axes pointing toward one another. Astronomers have developed the Roche model to describe such stars. We can calculate the surface of the Roche lobes, the boundary around the two stars where material is at an equal gravitational potential. Matter on a Roche lobe is sort of shared by both stars, so material there can easily move from one star's lobe to the other star's lobe. If the stars are close enough to one another, one star may fill its Roche lobe so that matter may transfer from that star to the other. Is there direct evidence of this? Yes, particularly in eclipsing binaries. We often detect the hot spot where matter falls onto the recipient star's surface. In many eclipsing binary systems, the transferring matter does not fall directly onto the recipient star, but first falls into a hot gaseous AD orbiting the recipient star. In some close eclipsing binary star systems, we see the spectrum of the AD. Astronomers have been very successful in using the spectroscopic data to model ADs.

Suppose a WD is the recipient star. Most of the matter falling onto the AD and then ultimately upon the WD would be hydrogen. Soon a layer of hydrogen builds up on the WD's surface. The temperature and pressure in the base of this layer slowly increase until thermonuclear fusion begins. With the release of energy from the fusion, the temperature in the hydrogen layer rapidly rises, which triggers runaway thermonuclear fusion. Soon, all the hydrogen is consumed. Normally, thermonuclear fusion occurs in a star's core, but in this situation the fusion occurs on the star's surface. With no overlying layers to muffle and modify the eruption, the star rapidly brightens and then gradually fades. We see this eruption as a nova. Since the nova eruption does no serious harm to the stars involved, the mass transfer sets in again, setting the stage for future repeat eruptions.

This type of nova is a classical nova. For many years, astronomers have recognized that there is a continuum of many kinds of nova from the classical novae down to much fainter types. If the physical conditions allow the hydrogen fuel to build up on the WD over a long time, then much fuel will accumulate and the subsequent eruption will be very large. This is a classical nova. After an eruption, classical nova will repeat with thousands of years between each eruption. Since this is a very long time, we do not recognize that these events repeat. On the other hand, if the physical conditions do not permit the huge buildup of hydrogen on the WD, but instead the fuel is consumed over a short period, the eruptions will be far more frequent but not as large. Alternately, the hydrogen may not readily fuse. Instead, brief, low intensity flaring may result from the liberation of gravitational potential as matter falls upon the WD in a clump. These recurrent novae may take only a few minutes to repeat, and they result in a much smaller brightening of the host star. There is much evidence to support this theory of the binary nature of novae of all types.

Supernovae (SN) are very different from novae. By the 1930s, astronomers realized that there must be two types of SNs, type I and type II. This distinction was based upon the different spectra that we see—type II has strong hydrogen emission lines, while type I has weak or absent hydrogen lines. There are differences in the rate at which the two types of SN brighten and fade as well. By the 1960s astronomers began to develop theories that explained the two types. Astronomers think that a type I SN occurs when a WD in a close binary system gains enough mass to transgress the Chandrasekhar limit. When this happens, the WD implodes, releasing a huge amount of energy (the SN explosion). A number of exotic physical processes come into play during the SN. Most theorists think that the SN eruption completely disrupts the star so that no remnant remains. Incidentally, since all progenitors of type I SN are a consistent set of objects, the eruptions are very similar in characteristics, such as peak luminosity. Of particular interest is a subclass of SN, the type Ia. Since we think we know how bright a type Ia SN is, we can compare the observed brightness to find distance to a particular type Ia SN. Because type Ia SNs are extremely bright, they provide a very powerful method for finding distances.

A type II SN is very different from a type I. Type II SN progenitors appear to be very massive stars. Stellar models suggest that massive stars undergo nucleosynthesis in their cores up to and including iron. Nucleosynthesis beyond iron to release energy is not possible, so at this point a massive star has no further energy options, except for gravitational contraction. As the core contracts, the core is supported by electron degeneracy pressure, but that fails when the mass of the portion of the core that is supported by electron degeneracy pressure exceeds the Chandrasekhar limit. When that happens, the core catastrophically collapses to produce either a NS or a BH. The rapid contraction of the core releases an incredible amount of energy that works its way outward through the outer layers of the star. This takes a few hours, upon which the outer layers greatly heat and expand to produce the SN explosion. Over the ensuing months and years, the expanding gas cools, causing the SN to gradually fade. The exponentially fading light curve has been attributed mostly to the decay of radioisotopes produced in the explosion.

In 1987, we got an unprecedented opportunity to view a SN up close. Early that year, SN 1987a erupted in the Large Magellanic Cloud (LMC), a nearby small satellite galaxy of the Milky Way. This was the first naked-eye SN since the invention of the telescope four centuries ago. In good confirmation of theory, a neutrino detector on the earth measured a flurry of neutrinos for a few seconds about a day before the SN became visible. The neutrinos would have originated with the core collapse and traveled unencumbered through the outer layers of the star, which explains their arrival a few hours prior to the optical detection of the SN. However, SN 1987a was an odd event. For the first time astronomers were able to identify the progenitor star, but the progenitor was a blue super giant star, rather than the expected red super giant. Furthermore, SN 1987a was not as bright as most type II SNs. There were other peculiarities as well.

What becomes of the expanding outer layers from a type II SN? We have been able to identify several expanding gas clouds with some historical SNs. One obvious example is the expanding debris about SN 1987a, which astronomers continue to monitor. Another example is the famous Crab Nebula that coincides with the location of a SN first glimpsed on July 4, AD 1054. Astronomers have observed the expansion rate of the debris to estimate the size, distance, and age of the Crab Nebula. This age agrees very well with the historical date of the SN. As a bonus, the Crab Nebula contains one of the first pulsars discovered. This makes the Crab Nebula and its pulsar an exceptional lab for exploring SNs and their development (DeYoung, 2006). Astronomers have discovered many other similar expanding clouds that appear to be the debris from SN explosions. Astronomers call these clouds SN remnants. Readers may be aware that Davies (1994, 2007) has cited SN remnants as an evidence for recent creation.

Many people confuse a SN remnant with a planetary nebula (PN). Despite their name, PNs do not have anything to do with planets. Through a small telescope, brighter PNs have a small, disk-like appearance, similar to a planet, so astronomers a couple of centuries ago named them thus. A good example of a PN is the Ring Nebula. A typical PN is a roughly spherical shell of gas; however, astronomers have come to realize that PNs often have a much more complex structure. A PN is smaller, fainter, and far less bright than a SN remnant. Interestingly, PNs always have very hot WD-like stars at their centers. This suggests that there is an intimate relationship between the two.

Evolutionary Framework

Actually, we already have discussed some of the evolutionary framework. In this section, we will briefly present the evolutionary ideas that connect some of the various remnants already described. Modern theories of stellar structure and evolution began to emerge in the 1950s through a series of important papers. One of the most important was the landmark work of Burbidge, Burbidge, Fowler, and Hoyle (1957), usually referred to as BBFH. BBFH identified many of the important thermonuclear reactions that we think power stars. Using well-understood physics, we can model the physical conditions within the cores of stars. These calculations reveal that the temperature and pressure present in stellar cores permit thermonuclear reactions.

Thermonuclear fusion of lighter elements into heavier ones generally is exothermic up to and including iron. The first step, the fusion of hydrogen into helium, releases about $^{7}/_{8}$ of all the energy that fusion reactions can produce. Hydrogen is by far the most abundant element in the universe, so this reaction accounts for most of the energy that stars can produce. Astronomers think that this reaction powers stars on the MS. Hydrogen fusion results in very long lifetimes of stars. Lower-mass stars have longer MS lifetimes, while the higher-mass stars have shorter lifetimes. Calculation shows that the sun can last about 10 billion years while using this reaction. Incidentally, this is the major motivation of creationists who reject thermonuclear reactions in the sun in favor of the Kelvin-Helmholtz mechanism. If the sun were powered by gravitational contraction, then the sun and the earth could not be billions of years old. But, alas, the case for thermonuclear reactions in the sun is very good (See DeYoung and Rush, 1989, and Newton, 2002).

When a star exhausts its hydrogen fuel in its core, the star must find an alternate energy source. Since core hydrogen fusion is a characteristic of MS stars, stars that have exhausted their core hydrogen must leave the MS. Let us explore the theoretical development of post-MS stars that astronomers have developed. The first energy source available is gravitational contraction of the core. When a star's core contracts, the core gets hotter and denser and the pressure increases. Paradoxically, as the core shrinks and heats, the star's outer layers expand and cool, producing a red giant. This is because as the core heats, its energy radiates into the surrounding layers. The surrounding layers are a gas, so as that gas heats, it expands and cools. What happens next to a star depends upon its mass. Astronomers expect that an extremely low-mass star will not ignite any further reactions. However, since the MS lifetime of a low-mass star exceeds the big bang age of the universe, astronomers do not expect that this eventuality has yet happened.

With greater mass, the temperature and pressure around the core may be sufficient to initiate fusion of hydrogen into helium in a thin shell around the core. Astronomers think that most red giant stars get their energy from this mechanism, so they sometimes call red giant stars shell-source stars. The shell fusion gradually eats away the hydrogen from the lower part of the envelope (everything outside the star's core) and adds the product of the fusion, helium, to the core. The accumulation of mass to the core causes the core to slowly shrink, with corresponding increases in temperature, density, and pressure. Incidentally, through its evolution the core of a star increasingly relies upon electron degeneracy pressure to provide pressure to balance the inward force of gravity.

If a star has enough mass, the temperature and density may reach the point that allows the fusion of helium into carbon. This process is called the triple-α process, because it involves three helium nuclei, and helium nuclei are sometimes called α particles. As with most thermonuclear processes, the triple-α process critically depends upon temperature. Once the triple-α process begins in the core, it releases energy that rapidly heats the core, which rapidly increases the rate of the helium fusion. Astronomers call this the helium flash. The helium flash causes the core to re-expand and cool a bit, with a corresponding shrinking and warming of the stellar envelope. In other words, the star appears to heat and shrink gradually. On the HR diagram the star would move from the upper right down toward the MS. Astronomers think that the star eventually settles onto the horizontal branch, so called because stars there lie on a horizontal region above the MS. The horizontal branch shows up prominently on the observational HR diagrams of globular star clusters. The horizontal branch ought to be the longest-lived branch that a post-MS star experiences. This is because the fusion of helium into carbon produces most of the remaining energy available in fusion reactions (hydrogen fusion, as we already stated, produces the bulk of energy available from fusion).

Eventually the helium in the core will be exhausted, leaving only carbon. Generally there will be no more fusion source available to the star, so the core will gradually shrink and heat once again. As before, this process leads to an envelope that is extended and cooler—the star once again progresses into the red giant region of the HR diagram along a path that parallels the earlier jaunt up to become a red giant. Astronomers call this second ascent the asymptotic giant branch (AGB). The lower envelope of AGB stars is in contact with the hot, dense core. Astronomers think that a thin outer region around the core fuses hydrogen into helium, as happened along the red giant branch. Also as before, this fusion builds up helium around the core. However, an AGB star ought to permit fusion of this helium into carbon immediately around the core. Thus, astronomers say that AGB stars are double-shell source stars.

Recall that the triple-α process commences rapidly. We expect that the helium fusion in the inner shell would start abruptly, consume most of the helium, and expand the shell slightly, all of which causes a decrease in the triple-α process. Thus, the fusion in the shell will be episodic, and this episodic behavior will spill over into the outer shell, affecting the fusion there, and into the envelope. During these episodes of fusion, theoreticians expect that additional elements may be fused. Helium nuclei can fuse with carbon nuclei to form oxygen nuclei. The oxygen nuclei can in turn fuse with helium nuclei to form neon, and so forth. This process is called successive α capture, because it involves the successive fusion of helium nuclei onto gradually more massive nuclei. Since helium has an atomic number 2 and oxygen 8, successive α capture produces even numbered elements up to iron (atomic number 26). The process ends with iron, because fusion of heavier elements beyond iron is endothermic.

During some of the episodes of thermonuclear fusion, astrophysicists think that some elements heavier than iron are produced. Some of the energy released by fusion goes into producing transferric elements. The most efficient way to do this is through neutron capture. Some reactions release neutrons, which in turn can fuse with other nuclei. As a nucleus gains neutrons, its atomic mass increases, but its atomic number does not. With increasing atomic mass, the nucleus becomes unstable. An unstable nucleus can decay by ejecting an α particle, but more often it emits a β particle. A β particle is an electron or its antiparticle, the positron. Effectively, β decay happens when in the nucleus a neutron transmutes into a proton, shedding the electron in the process. A β decay does not change the atomic mass of a nucleus, but it does increase the atomic number, changing the nucleus into the next element on the periodic table. If a nucleus is bathed in a large number of neutrons, the nucleus may acquire a large number of neutrons before it decays. We say that the nucleus has undergone rapid (r) neutron capture, because the nucleus captured the neutrons too rapidly to decay between captures. On the other hand, if the nucleus acquires neutrons slowly enough to decay between captures, then we say that it has undergone the slow (s) neutron capture process. The products of the r- and s-processes are very distinct, because the two processes produce different atomic nuclei (elements). In the episodes of thermonuclear fusion in AGB stars, some neutrons are produced, but not enough to lead to the r-process. Therefore, AGB stars produce s-process elements.

Episodic nucleosynthesis also causes thermal instabilities throughout the envelopes of AGB stars. This allows for convection throughout the envelopes of AGB stars. This is unusual, because most stars are not fully convective in their envelopes, but especially not in the regions around their cores. The lack of deep convection in most stars confines the products of thermonuclear fusion to their cores. However, the deep convection in AGB stars dredges up the products of nucleosynthesis up to their photospheres where we can observe them in the spectra of the stars. This can lead to unusual composition in AGB stars. For instance, carbon stars have an overabundance of carbon compared to normal stars, which produces unusual spectra. The related metal stars have high amounts of s-process elements. Metal stars frequently have technetium, an element that has no stable isotopes. Since the half-lives of all isotopes of technetium are far less than the supposed ages of metal stars, astronomers reason that the technetium must have been recently produced and dredged to the surfaces in these stars.

How does a star end its existence? The answer depends upon the mass of the star. As stars process their nuclear fuel, the mass of the core gradually grows, while the core size slowly shrinks. The role that electron degeneracy pressure plays in the structure of the core gradually increases. Astronomers think that a very massive star will pass through all the stages described here and perhaps through much successive α capture. Eventually, the mass of the core exceeds the Chandrasekhar limit, resulting in a type II SN. The collapsed core remains as either a NS or a BH, depending upon how much mass remains in the core.

A less massive star will have a very different end. The core will never have enough mass to implode to produce a SN. As the star expands into a large red giant during its later stages, the matter in its photosphere will be poorly bound to the star. Gravity in the photosphere is so weak that any small push will lift the matter in the photosphere from the star. This produces a stellar wind. Astronomers have realized for some time that red giant stars are very windy. Wind loss rates can exceed 0.0001 solar masses per year. Obviously a star with this loss rate could not exist for more than a few thousand years. Once a strong stellar wind sets in, the wind rapidly accelerates. Eventually, most of the envelope escapes, revealing the core. The core is very hot and is mostly supported by electron degeneracy pressure. This is how astronomers think that WDs form.

What becomes of the gas driven off by the stellar winds? The first material to leave is moving the slowest, while the later material is moving progressively faster. The faster moving material overtakes and plows along the slower moving material, compressing and heating the gas. Ionizing radiation from the exposed core also heats the gas. In a simple model, the expanding gas assumes a spherical shell shape around the exposed core. In a more complicated model, the gas can assume other shapes, such as an hourglass. This expanding gas is what astronomers think that a PN is. PN's always appear to have a hot, WD-type star at their centers. This is good evidence of this scenario. On the other hand, most WD stars do not have a PN around them. How can this be? A WD will exist for a very long time, but a PN has a very short lifetime. Thus, if a WD is more than say, 100,000 years old, then the PN that once surrounded it has dissipated into the interstellar medium.

Conclusion

Astronomers have developed an elaborate evolutionary explanation for a host of astronomical bodies interpreted as stellar remnants—giant stars of various types, supernovae, planetary nebula, neutron stars, and black holes. How have/can creationists respond to all this? One extreme approach would be to note the vast time required to accomplish these processes and simply deny that any of these have happened. This attitude would obligate us to provide alternate explanations for these various objects. For instance, if a planetary nebula is not gas ejected from its central star, then what is it? The other extreme would be to embrace much of these explanations, but on our terms. For instance, some creationists have proposed that there was a time of rapid change sometime in the past. The accelerated nuclear decay proposed by the RATE project offers the possibility of rapid stellar development early in the universe. The Humphreys white hole cosmology allows for vast periods of time to have elapsed elsewhere in the universe while only a few days passed on earth during the Creation Week. The Humphreys cosmology might allow for much of the stellar development briefly described here. A very small minority of recent creationists believe that the Creation Week refers to the creation of the earth and its biosphere rather than the entire universe. This view would allow the acceptance of virtually all of evolutionary stellar astronomy.

Another alternative is somewhere in the middle, carefully choosing what interpretations of evolutionary astronomers to accept and reevaluating others. Indeed, this seems most promising and is already pursued by some creationists. We will raise a series of questions in this vein. For instance, most creationists seem to accept that supernovae are the deaths of some stars. Did the stars that exploded pass through the various stages of development briefly described here leading up to their deaths, or did God create these stars already in "aged" states that caused them to die not long after their creation? Since we know when the Crab Nebula supernova happened and that there was a neutron star left behind, at least in that particular supernova, then did other neutron stars originate in supernova explosions? Astronomers can estimate the ages of neutron stars by their slow-down rates, and those ages typically exceed a few thousand years. Many creationists would simply respond that God created neutron stars with various "ages." Many neutron stars have no surrounding supernova remnant, suggesting that they formed long enough ago that their associated remnants have dissipated. The dissipation time is far greater than a few thousand years, so did God create these neutron stars directly? Did God create "fossil" stars? Creationary geologists would object adamantly if this were suggested in the realm of fossils of biological origin (i.e. fossils of plants and animals were planted in the ground by God). Is the astronomical realm so different?

Or consider planetary nebulae and white dwarfs. We already discussed the fact that planetary nebulae have hot white dwarf stars at their centers, suggesting the link between the ejection of planetary nebulae and the birth of white dwarfs. We can estimate the approximate age of a planetary nebula from the time required to eject the planetary nebula from the central star. The typical age is tens of thousands of years, longer than the age of creation by about an order of magnitude. Did God create planetary nebulae already expanding as if they had originated from a central star, when in reality the gas in the planetary nebulae never actually left the star? Lacking an internal energy source, white dwarfs must tap their considerable store of internal heat and so they must cool as they age. From their temperature, we can estimate the ages of white dwarfs. These ages typically are far greater than a few thousands of years. Did God create white dwarfs with various ages? Many creationists would answer yes to both of these questions.

Or consider the various types of red giant stars. If astronomers' physical explanations for these stars are reasonably correct, then to get into such aged states the stars would have required considerable time. Since the creation model does not allow for such great time, did God make these stars already in their aged states? What of type II supernovae? If type II supernovae really are the death processes of very massive stars, then did God create them on the threshold of death? Again, many creationists would answer yes to both questions.

While these affirmative answers are certainly possible and are the choice of many creationists, these answers do cause philosophical and theological problems for other creationists. Many creationists view the aging and death processes of stars, as well as stellar remnants, such as black holes, as part of the curse. Indeed, many of these processes are dictated by the second law of thermodynamics, which many creationists think originated at the Fall. If so, then when did these aging and dying processes occur? If after the Fall, then how did the light get here? If before the Fall, then is that consistent with a creation that was declared "very good?" The answers to these questions rely upon one's answer to the light travel time problem, a topic that we will not explore here. The answer also depends upon how one views the physical extent of the Fall. For instance, if the Fall did not invoke the second law of thermodynamics and/or if the Fall had limited extent outside the earth, then these questions are not nearly as problematic.

We have posed many questions here, but offered few definitive answers. The field of creation stellar astronomy is still in its infancy. The author has few answers for many of these questions at this time, and he hopes that this brief discussion can lead to further discussion and research.

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