White Dwarfs; Neutron Stars, & Black Holes

So far our exploration of stellar births, lives, and deaths has led us to some very intriguing and unexpected objects. Red giants, Super-giants, white dwarfs, planetary nebulae, and the cataclysmic aftermath of supernova explosions all hint at the extremely fascinating stages of stellar evolution. Yet, we have many more surprises in store for us because stellar evolution, especially from the massive stars, can have even more bizarrely unique consequences.

We are going to next investigate some of the strangest states of stellar evolution that result from the catastrophic implosion/explosion of those medium and high-mass stars. It is very hard to grasp the titanic violence associated with the collapse of a stellar core during a supernova, but these conditions may bring into existence objects so mind-boggling that they require us to reconsider some of our views of the universe.

"We will first understand
How simple the universe is
When we realize
How strange it is." -- Anonymous

Well, after that rather auspicious start, you might ask, "where do we begin?" Rather cryptically, I will answer, "with after-death experiences."

The Possible After-lives of a White Dwarf:

We have already discussed that a white dwarf represents the end point of a low-mass (less than $8M_{\odot}$) star's evolution. Once you create a white dwarf it simply cools back into the darkness of the universe, eventually becoming a black dwarf. This is quite true for an isolated single star (like the Sun), however, should the white dwarf be part of a **binary star** system a couple new possibilities exist.

If the binary star system consists of a white dwarf star and a main-sequence or giant companion in which the distance between the stars is small enough, then the dwarf's tidal gravitational field can strip gases, primarily hydrogen and helium, away from the surface of the companion star! Astronomers call this a "**mass-transfer binary**" because the companion star ends up transferring mass to the white dwarf.

As the hydrogen and helium builds up on the surface of the hot white dwarf surface, the accreting hydrogen gas is getting hotter and denser. Eventually, after a time dependant on the rate of transfer, the temperature of the accumulating gas exceeds 10^7K, and hydrogen fusion will ignite on the **surface of the white dwarf star**! This surface burning is brief, but very violent and extremely luminous. The star suddenly increases to an enormous brightness then slowly fades away as the hydrogen fuel is exhausted. If the event can be seen from the Earth, we see a "star" that dramatically increases in brightness in the night sky (as much as 10,000 times brighter). We call these objects or events a "**NOVA**."

Novae

The word nova means "new" in Latin, and to early cultures, these stars did indeed seem to appear newly to the night sky.

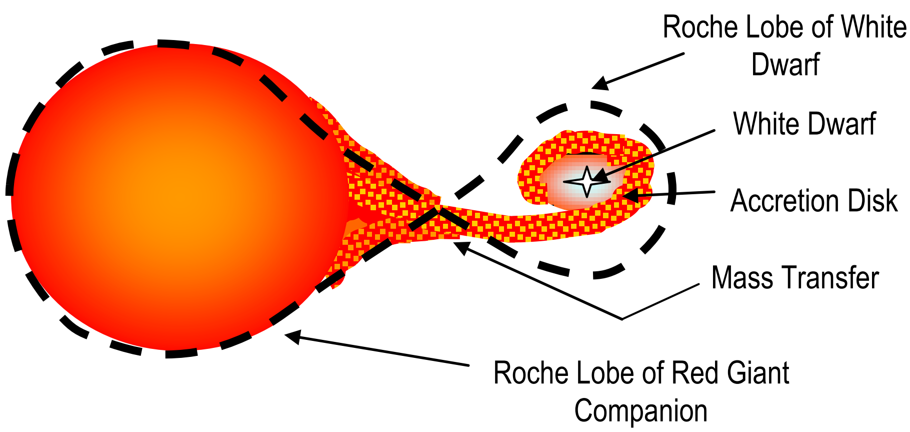


Figure 1: The white dwarf is able to acquire material from the companion red giant star. When it accretes enough material it can suddenly and explosively fuse hydrogen. The white dwarf will "nova" and greatly increase its rightness for a brief period of time until the hydrogen is again consumed. This process may repeat many times.

This repeating process will continue as long as the mass of the white dwarf does not exceed the **Chandrasekhar Mass Limit** of $1.4M_{\odot}$. If this limit is breached, the pressure of degenerate electrons in the interior of the white dwarf becomes unable to withstand the pull of gravity and the white dwarf immediately starts to collapse in on itself. The internal carbon in the white dwarf is now rapidly increasing in temperature and density. **Carbon fusion** begins everywhere throughout the white dwarf almost simultaneously. This incredible start to carbon fusion throughout the entire structure is too highly energetic to be maintained within the white dwarf and the star is literally blown apart in a **supernova explosion**! (Another Type!?)

- Whoa! Wait, didn't we learn that a supernova explosion came at the end of medium and high-mass stars at the moment their iron cores implode and bounce?

There are two types of Supernova:

Supernova Type II:

These are massive single isolated stars that have fused their way to an iron core that collapses, causing the rest of the star to be energetically blown outward. The spectroscopy of the light from these supernova show strong spectral lines of hydrogen because the rapidly expanding remnant of the star is rich in hydrogen.

Supernova Type I:

These are supernova explosions in binary star systems where a white dwarf has crossed the Chandrasekhar mass limit. These are often called **Carbon Detonation Supernovae**. The spectra show very weak hydrogen in the emission lines, and may have strong spectral features of heavier elements. There is good evidence that after these types of supernovae that there is nothing left of the original white dwarf and possibly the companion star.

What remains after a Supernova Type II?

[[Remember these involve the implosion, **neutronization**, and subsequent rebound of a massive star's core.]] In 1934, **Walter Baade** and **Fritz Zwicky** suggested that when a massive star reaches the end of its life, its gravity ultimately crushes its core making the star collapse. The collapse of the core will trigger an immense explosion, which they called a supernova. As an afterthought, they speculated that the collapsed core might be so dense that the star's protons and electrons would be driven together and merge into neutrons, forming an object made of nothing but neutrons, which they called a **neutron star**. Density of such an object would be 10^{14} gm/cm^3. [**Remember:** Atoms are mostly empty space!] Is there anything on Earth as dense as a Neutron Star? Yes! Neutrons.

Discovery of Neutron Stars ➔ Pulsars:

In 1967 **Jocelyn Bell** (1943 -) a graduate student working with a group of English astronomers, headed by her advisor **Anthony Hewish** (1924-), noticed an odd radio signal with a rapid and astonishingly precise pulse rate of one energetic burst every 1.33 seconds. [[**Joe Trivia**: The precision of the extraterrestrial signals led some astronomers to whimsically ponder if they had somehow stumbled upon signals from alien civilizations.]] Over the next few months the group found several more pulsating radio sources, some of which were definitely associated with the inner most regions of supernova (Type II) remnants. These repeating source were named, "**Pulsars**."

> [**Note**: Anthony Hewish received the Nobel Prize, but it was Jocelyn Bells persistence that really led to this discovery.]

It became quite clear that Pulsars were the observational evidence for rapidly spinning Neutron Stars. Why would the collapsed cores, left after supernova explosions, be rapidly spinning? What makes a neutron star a pulsar? What makes them pulse?

> **Joe Physics**: The spinning answer is quick and easy, you have experience with the phenomenon. Conservation of angular momentum causes the collapsing core to increase its spin as the star ends its life. Huh, you say? How about an analogy that you have probably already witnessed - ice skating, yup - ice skating. What happens when a spinning skater pulls in his/her arms? The spin gets faster! Any rotating body spins faster when it shrinks - a principle called **conservation of angular momentum**. Well, that takes care of the spinning part.

<u>Pulses??</u> The collapse of the core into such a small radius has another effect: it squeezes the star's magnetic properties and fields into a more compact and crowded state. This causes the **magnetic field strength of the star to be amplified millions to trillions of times**. The combination of the rapidly spinning, huge magnetic fields, and debris of the supernovae can cause the neutron star to emit light in a very interesting way, in beams that sweep by the observer (us on Earth, if we have the correct orientation!) like a "**lighthouse**."

Light House Model of A Pulsar

- (A rapidly spinning neutron star.)

Beams of radiation sweep across the line of sight like a Light-House does for ships off of the sea-coasts. The neutron star's strong magnetic field can induce strong electric fields. In turn, electric fields will make charged particles (mostly electrons) stream away from the magnetic poles and are not necessarily the same as the axis of rotation. Electrons spiraling around magnetic field lines produce electromagnetic radiation (light). Because this light is produced by accelerated charges not like a blackbody radiator it is called **non-thermal emission or synchrotron radiation**.

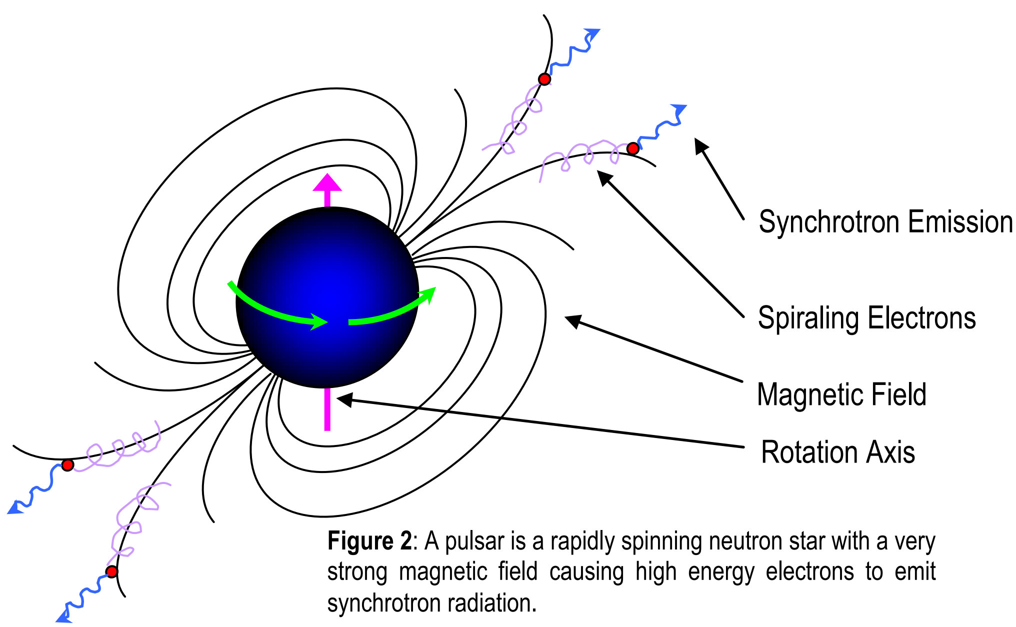
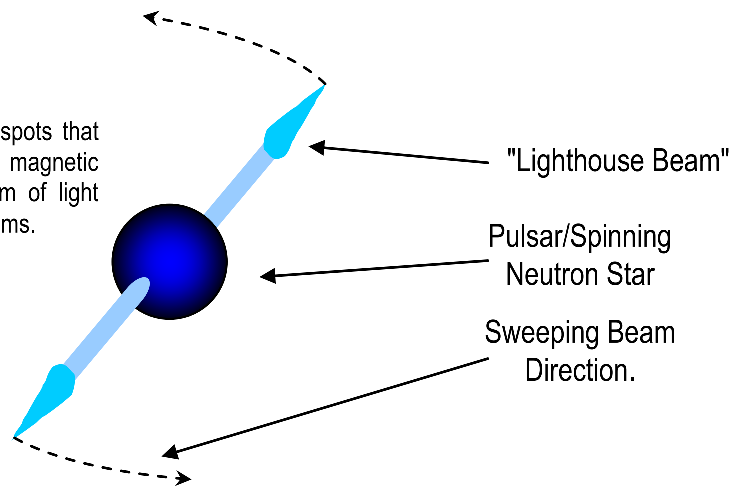


Figure 2: A pulsar is a rapidly spinning neutron star with a very strong magnetic field causing high energy electrons to emit synchrotron radiation.

The neutron star's magnetic field lines concentrate strongest near the magnetic poles causing "**hot spots**," any charged particles converge into a narrow cone and are emitted outward. If the beam sweeps across the Earth, you see a "pulse" of light. (However, it is more likely that the beam will miss the Earth.)

Figure 3: Two bright spots that correspond to the magnetic poles will spin a beam of light like two lighthouse beams.



Pulsars are grouped into two main types based on the timing of the pulses.

- Fast Pulsars ➔ millisecond pulses (young)
- Slow Pulsars ➔ second pulses. (old)

Why are there different times associated between the pulses of the pulsars? (What eventually happens to that spinning skater over time? The skater slows down.) Pulsars are no exception to the adage "things are getting slower all the time." It takes a great deal of energy to spin the huge magnetic field dragging it through the surrounding space and accelerating those charged particles. Astronomers can measure the "**spin-down**" of a pulsar by accurately timing how the pulse interval lengthens over time. The energy of radiation is slowing the pulsar down (10^7years). Also as a pulsar ages (spinning slower and slower) the energy of the pulse decreases because the magnetic field is not able to sweep through as much surrounding space as before. Young, rapidly spinning neutron stars emit in visible light while old, slowly pulsing ones only produce in meek radio waves.

Occasionally, pulse timing can adjust suddenly. Such jumps in timing are called "**glitches**." A star-quake has occurred that can suddenly change the radius of the neutron star. (As if the spinning skater suddenly re-adjusts her/his arms and the spin rate changes.)

Joe Physics: Neutron Stars are solid objects. You might even be able to stand on the surface of one provided it has had enough time to cool and spin down since its creation. However, this would not be a very pleasant experience because the gravity of such a small dense object is extremely powerful. Joe's weight (~220lbs on Earth) would register as nearly 50×10^{12}lbs. That is 50 trillion pounds. Talk about needing to diet and exercise. The incredible gravitational pull would squash me thinner than a sheet of paper.

Disappearing Matter: BLACKHOLES

(This is ***not*** science fiction anymore...)

Figure 4: Blackholes have gone from the realm of science fiction to science fact. Blackholes are, suprisingly, real objects that are impossible to observe directly. (Image: Courtesy unknown.)

The story so far…..

- **White Dwarfs**: Progenitor stars less than a total mass of $8M_{\odot}$ and ending core masses of less than $1.4M_{\odot}$ ($M_{\odot}$ = solar mass). White Dwarf is supported from further collapse by electron degeneracy pressure. About Earth sized.
- **Neutron Stars**: Progenitor stars less than about $25M_{\odot}$ and ending core masses between $1.4M_{\odot}$ and $3M_{\odot}$. Experience Fe core bounce and supernova. Rapidly spinning "pulsars." Supported against gravitational collapse by neutron degeneracy pressure. A final size of about 10km diameter.
- **What happens to stars greater than $25M_{\odot}$ with ending cores greater than $3M_{\odot}$?** There is an interesting, somewhat unsettling, answer to this question. It takes us a bit beyond the everyday understanding of the universe and makes us explore a more puzzling, yet predictable, corner of the physical cosmos.

There is one more surprise in store for us. This is actually a great detective story that includes many disciplines of science, insight, and philosophy. Let's now try to answer the question.

When a star reaches the end of its life with an **iron core mass greater than 3M$_\odot$** there will be ***NOTHING*** available to stop the core from a continuous collapse. Not the electrons, nor the neutrons will be able to resist the gravitational collapse of the core. The massive core will get smaller and smaller, denser and denser, smaller and smaller, denser and denser, smaller and smaller (getting the picture?), denser and denser. And here is the more interesting part. It will be a collapsing core "**FOREVER**". Gravity finally wins and compresses everything to a mathematical point at the center. Quite honestly, gravity causes the entire star (not just the core) to collapse in on itself. The star will simply wink out leaving a **black (spherical) hole** in space.

Come again? What is this willy-nilly stuff? Ok, let's back up a bit and see where this idea and theory (and now observation!) came from.

This is actually a rather old idea. **John Mitchell**, a Cambridge professor, around 1783 pointed out that a "star" (think massive object instead of star) that was sufficiently massive and compact (What does this sound like?) would have such a strong gravitational field that light could not escape: any light emitted from the surface of the star would be dragged back by the star's gravitational attraction.

Following the logic, mathematicians and astrophysicists can easily devise the radius (R) at which a body of a given mass (M) would become a black hole by equating its escape velocity to the speed of light (c).

$$R = \frac{2GM}{c^2}$$

[Notice, this only depends on R and M. The rest are constants! Schwarzschild radius]

This is a unique and novel idea, because it predicts objects that still exert a gravitational force but that are "black" because light cannot escape from them. **These objects are today called black holes because that is what they are, black voids in space.**

"Somewhere, something incredible is waiting to be known." -Carl Sagan

A **blackhole** has within it an object with zero radius and infinite density – the **singularity**. Or so we think. You must realize that scientific observation stops at the boundary of a blackhole. We will probably never really "know" what lies within them after all, how can we send in a observer to report what they see when they aren't capable of escape nor there message? We let the physics and mathematics take us into the blackhole, we **assume** that physics and math still apply inside. The boundary of the blackhole is called the **event horizon**. Any "event" or occurrence happening inside of it is invisible to an outside observer. The radius of the event is called the **Schwarzschild Radius** and is given by the formula above. Any object may become a blackhole if it shrinks becoming smaller than its Schwarzschild radius. (The Earth could become a blackhole if it collapsed in size to about 1cm in radius).

> Pish Posh you say? Let's explore some of the theoretical underpinnings of this idea.

In 1905, **Albert Einstein** published his famous **Special Theory of Relativity** and overthrew many commonsense assumptions about space, time, and how measurements are made.

Figure 5: An artists conception of a bright accretion disk surrounding a black hole. (Image: Courtesy unknown.)

Commonsense may get a person through the day, but it usually is not correct and often just plain wrong. Einstein was the first to realize that the universe behaves very differently when you explore the extremely massive, extremely fast, and extremely small realms. He was the first to understand puzzling observations of those realms that defied the commonsense interpretations of the macro world. The physical world, relative to the observer, of space and time is much different near the speed of light, near massive objects, or on extremely small scales of size: distances can seemly stretch; time itself passes more slowly, masses don't behave as particles but as waves. It is fundamental to realize that the universe isn't playing a trick on you and making the observations only "appear" so, but that is just the way the universe operates physically.

Einstein’s works further challenged conventional theory by describing gravity geometrically; as the warping of space-time, not a force acting at a distance as the Newtonian wisdom. Since then, Einstein's foundation shaking physical interpretations and uniquely ingenious predictions about his ideas have withstood the test of time.

First, what is “space-time?”

Well, you are trapped inside the geometry of space and time. An observer in our universe can describe the location of any object anywhere and anytime by simply giving its 3 coordinates in space (location – out, over, up) and time (when the object is at the location). **Second, “warping of space-time?”** Is this Star Trek stuff. Well, no. Let’s put this idea into the everyday experience. According to Einstein, any object that has at least a tiny mass curves the space-time around itself so that any object travelling close to it doesn't go in a straight line, but in a curve. Of course, the more massive the object is, the bigger the curvature of space-time.

> **Joe Physics**: Think of a nice flat surface of a waterbed. The flat surface is a geometrically flat space. Now what could we do to produce a curve on that surface? Well, let’s place a bowling ball on the waterbed. A circular “curved” depression is formed in that “space” of the bed! Ah ha! The mass of the bowling ball “curves” the geometrical “space” of the waterbed’s surface. What do you think happens if you lessen the mass of the object you place on the bed? How about greatly increasing the mass? What happens if you tossed a building onto the surface of the waterbed?

Einstein's theory of gravitation

The theory did something else - it predicted that there could be objects so very massive that they could curve space-time literally in on itself: the existence of black holes from whose extreme gravity nothing, not even light, can escape. These holes are spherical “curved space-time holes.”

More startlingly than curving and distorting the space around a black-hole, time too is affected. In the presence of a gravitational field time slows down as compared to being outside that field. You don't sit there and wonder why your watch is running slower. It has nothing to do with the mechanic of the watch, you see **Einstein also realized that “time” is not absolute and the same for every observer**. Everything slows down---your watch, your brain, your cells, your very atoms---everything. The observer farther away from the massive object would watch you and wonder why you're moving so slowly because you both can no longer agree about the passage of "time." This effect is called **time dilation**.

This effect is the most extreme where the gravitational field is the most concentrated, near a blackhole.

Cygnus X-1

The object is an X-ray binary that was one of the first X-ray sources discovered when it was detected in 1962. The visible object HDE226868 is a 9th magnitude blue supergiant star whose radial velocity curve shows an orbital period of 5.6 days. The fact that the object is a strong X-ray emitter and that the optical and X-ray emission varies on very short time scales (as short as one one-thousandth of a second) suggest that the companion might be a black hole. Analysis of the radial velocity variation of the primary under the assumption that it is a normal star suggests that the mass of the companion is about 6 solar masses.

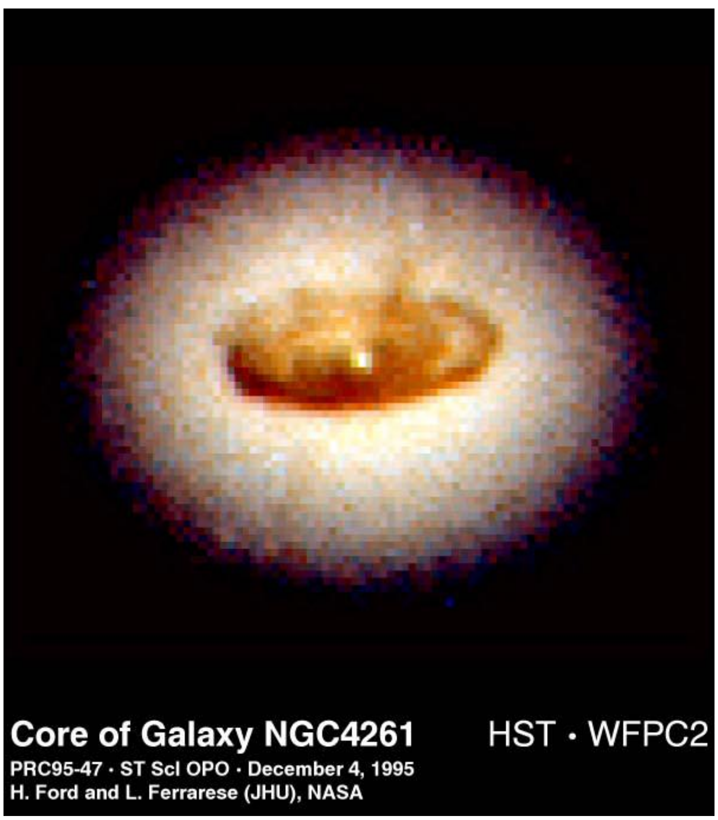


Figure 5: HST Finds Blackhole: The black hole and an 800 light-year-wide spiral-shaped disk of dust fueling it, are slightly offset from the center of their host galaxy, NGC 4261, located 100 million light-years away in the direction of the constellation Virgo.

This discovery is giving astronomers a ringside seat to bizarre, dynamic processes that may involve a titanic collision and a runaway black hole. This relatively nearby galaxy could shed light on how far more distant active galaxies and quasars produce their prodigious amounts of energy.

The new Hubble observations have moved us beyond the question of whether black holes exist. Now we can work on the demographics of black holes and address a number of other questions: does every galaxy have a black hole? How do they work in detail? (Image: Courtesy of H. Ford, L. Ferrarese, & NASA)

By measuring the speed of gas swirling around the black hole astronomers are able to calculate its mass to be 1.2 billion times the mass of the Sun, yet concentrated into a region of space not much larger than the Solar System (Image & Caption courtesy of STSci.).

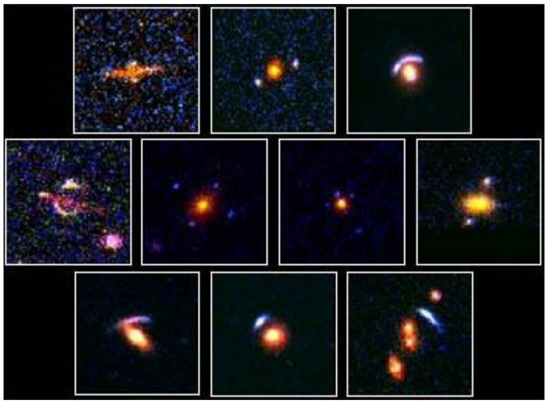


Figure 7: A Gravitational Mirage: Around the center of the red galaxy image lie blue "smudges." Each smudge is actually a different image of the same background quasar or galaxy. The central galaxy happens to fall directly in the light path of the quasar. Consequently, the huge mass of the galaxy is able to pull separate images of the quasar around it - an effect called **Gravitational Lensing**. Astronomers have hopes of using light differences between these quasar images to not only "mass" the central galaxy but even provide clues about the expansion rate and composition of the universe.

Shown are 10 lens candidates uncovered in the deepest 100 Hubble fields. Hubble's sensitivity and high resolution allow it to see faint and distant lenses that cannot be detected with ground-based telescopes whose images are blurred by Earth's atmosphere.

(Right) Sometimes a cluster of galaxies can produce the same type of gravitational mirage. This grouping of galaxies in the image distort the light from a background object and produce similar blue smudges. *(Images: Courtesy of NASA/HST)*