Do black holes exist?

Reference webpages:

http://en.wikipedia.org/wiki/White_dwarf
http://www.astro.umd.edu/∼miller/nstar.html
and Chapters 4, 5, and 6 in Thorne.

Questions to keep in mind are:

1. Does the existence of matter not found on Earth change our philosophical stance, e.g., in terms of the unity of the heavens and the Earth that had been the standard since Newton?
2. How might we be convinced that a particular object is a white dwarf or a neutron star instead of a normal star?

Introduction

Last time we discussed the basis of black holes within general relativity, and their rejection by Einstein and others. Indeed, it is proper to require strong evidence for such bizarre objects; to quote Carl Sagan, "extraordinary claims require extraordinary proof", but can we provide it? One difficulty about black holes in contrast with other astronomical objects is that (to oversimplify) evidence for black holes is largely negative in the sense that you have to rule out other explanations before black holes are your best bet. For other objects, such as ordinary stars, you can simply look at them and recognize their unique characteristics. In two lectures we will discuss the direct evidence for black holes, which by now is compelling. In this one, we will follow the historical sequence by discussing two other types of bizarre objects, white dwarfs and neutron stars, and how not even these strange states protect the universe against black holes.

White dwarfs

Recall that one of the great successes of Newtonian mechanics was when the heretofore invisible stellar companion of the bright star Sirius, called Sirius B, was predicted and then detected in 1862. This demonstrated that Newtonian principles applied far outside the solar system as well as inside it. Observations of the effect of Sirius B on the motion of Sirius A (the bright component) indicated that Sirius B had about as much mass as the Sun. It was, however, very dim; about 1,000 times dimmer than Sirius A. This did not cause any particular concern for the astronomers of the 19th century, however. It was known that the spectra of stars are close to "blackbodies", which are theoretically perfect absorbers and emitters of radiation. The luminosity (energy emitted per time) of such an object is proportional to its area times the fourth power of the temperature, so for a sphere of radius

R emitting at a temperature T, we have $L \propto 4\pi R^2 T^4$. Therefore, even if the radius of Sirius B was about the same as that of the Sun, having it be somewhat cooler (2300 K at the photosphere instead of the Sun's 5800 K) would explain its low luminosity.

It was therefore a rude shock in 1915 when Walter Adams discovered that instead of being a relatively cool star, Sirius B was actually very hot! Its temperature of 25,000 K makes it hotter than the Sun and even a good deal hotter than its much brighter companion Sirius A. The hot temperature, combined with the very low luminosity, meant that its radius had to be ridiculously small. In fact, Sirius B, with a mass about 300,000 times that of the Earth, has a radius about equal to that of the Earth. Putting that in more picturesque terms, a teaspoon of Sirius B would weigh more than an elephant!

This was stunning. Up to this point, Newton's unification of the heavens and the Earth had been secure. Yes, stars were hotter than anything we had here, but the same processes appeared to operate. But Sirius B was another story. It was about 1.6 million times denser than water; for comparison, the densest element is osmium, at a mere 22.6 times the density of water. This had to be a completely new form of matter. Might it in fact be that different physical laws apply to astronomical objects than to the Earth?

To make it even worse, there was a paradox about this object, now called a "white dwarf" because it was hot (thus looked white) and small. As pointed out by Eddington in his semi-popular book "The Internal Constitution of the Stars", the difficulty was that as understood at the time, stars live in a state of balance between inward gravitational acceleration and outward pressure gradients produced by gas; the hotter the gas, the greater the pressure. A more compact star means greater gravitational acceleration, hence to counterbalance this requires hotter gas. But the radiation we see means that the star is losing energy, hence the stars have to heat up as they lose energy (this is not as weird as it seems; just in the same way that planets closer to the Sun move faster in their orbits than the more distant planets, more compact objects with the same energy in a gravitational field are hotter). The problem is that this appeared to be a cycle that could not end. As stars cool they have to contract and heat up, but their total energy can never go up. The only way they could actually reduce their temperature would be to puff up again using some reservoir of energy no one had yet thought of. In Eddington's immortal words: "We can scarcely credit the star with sufficient foresight to retain more than 90% [of its energy] in reserve for the difficulty awaiting it. [...] Imagine a body continually losing heat but with insufficient energy to grow cold!"

It required quantum mechanics to resolve this conundrum, so let's make a diversion into that strangest of modern physics theories.

Quantum mechanics

Towards the end of the 1800s the cracks in Newton's universe were not limited to those that led to special and general relativity. The spectra of blackbodies was explained by Max Planck only with the ad hoc assumption that light came in discrete packets, or "photons". There were, in retrospect, also puzzles about how molecules behaved at different temperatures.

In the 1900s the puzzles multiplied quickly. The spectrum of hydrogen gas showed discrete lines, which meant that hydrogen could emit or absorb energy only in very narrow ranges of energy, but not anything in between. Even worse, the discovery of the electron (in 1897, by J. J. Thomson) and proton (in 1919, by Ernest Rutherford) led to an inescapable conflict with classical physics. The difficulty is that it had been established that anything with an electric charge radiates if it is accelerated. Electrons in atoms would certainly be accelerated by protons, and according to classical theory this would cause the electron-proton assembly to collapse in much less than a microsecond. Clearly, something drastic was wrong.

The ultimate resolution of these difficulties came from quantum mechanics, about as counterintuitive a theory as you will ever meet. According to quantum mechanics, what appear to be solids to us are actually fuzzy, if you jumped against a brick wall enough times you would eventually teleport through, and lots of other stuff that makes no sense at all. It is, however, very important to keep two things in mind:

- All the weirdness happens at the level of the very small (e.g., atoms or molecules). In our domain of familiarity (large, slow-moving things in weak gravity) we know that the laws of quantum mechanics must very closely approximate Newtonian laws. Just as the discovery of relativity did not change how baseballs fly through the air, the development of quantum mechanics does not mean that pool balls are suddenly fuzzy. With that in mind, any time you see or hear some guru claiming quantum effects at the macroscopic level (e.g., quantum consciousness or some garbled "explanation" for psychic powers that don't exist anyway) you can be certain that it is the purest BS.
- Bizarre though quantum mechanics is, it makes thousands of predictions, and not one of them (even the really insane stuff; see Bell's inequalities) has been disproved. Therefore, whether or not we like the implications, the predictions are right. There are different interpretations that give the same predictions, and we can't differentiate between them, but the predictions are solid. It could of course be that future experiments that are more precise or in a different domain may violate the expectations of quantum mechanics, but for now it is the most successful quantitative theory ever produced, and that is why we take its implications seriously.

When I consider the mind-boggling implications of relativity and quantum mechanics, I think that they provide clear disproof of the strongest version of the Sapir-Whorf hypothesis, which is that language restricts how we can perceive the universe. No language, ever, had the concepts of quantum mechanics (note that after-the-fact books sometimes claim this of Eastern religions, but this isn't true and in any case the main people who developed quantum mechanics weren't Eastern mystics!). It is possible to learn truly new things.

But what does all this have to do with white dwarfs? A key aspect of quantum mechanics is the uncertainty principle. Colloquially, this says that you cannot simultaneously measure the position and the momentum of a particle with absolute precision. For example, if you use light to measure the position of a particle, you get a higher precision measurement if you use a shorter wavelength of light. But that shorter wavelength means that the energy of the photon, and hence its momentum, is larger. The process of measuring position therefore imparts a kick to the particle, thus shifting its momentum in an unknown direction, by an amount that is inversely proportional to the precision of position measurement. More quantitatively, the product of the position uncertainty Δx with the momentum uncertainty Δp is bounded from below:

$$\Delta x \Delta p \geq \hbar/2 \tag{1}$$

where $\hbar = 1.05 \times 10^{-34}$ J s is Planck's constant.

The relevance to white dwarfs emerges upon closer examination of the uncertainty principle. Suppose that we imagine taking matter and squeezing it more and more. Upon squeezing it to densities greater than that of normal matter, the electrons move freely instead of being confined to individual atoms. But the higher the density is, the less volume there is per electron, and hence the smaller Δx is. A small Δx implies a large Δp. This also means that p itself must be large, otherwise (if p were very small) the uncertainty in p would also be small. Therefore, just from the high densities, we find that the particles acquire a purely quantum mechanical momentum, called the Fermi momentum after the Italian physicist Enrico Fermi. The existence of this momentum, and the corresponding pressure that results, does not require *any* temperature, just density! This realization, by Fowler in 1926, led to the understanding that white dwarfs are supported in a purely quantum mechanical way, thus solving Eddington's paradox. Such matter, where Fermi pressure is larger than normal gas pressure, is called *degenerate matter* (this is not a commentary on the matter's morals!). Even if all heat is radiated away from a white dwarf, it can sit there happily as a cold degenerate object.

Kip Thorne has an interesting analogy to degeneracy pressure. He asks us to imagine an evil scientist conducting an experiment on claustrophobic people sealed into a room. If there are not many people in the room, each has enough space to themselves that they are only mildly nervous. However, as more people are crammed into the room, they become more nervous, then frantic. As a result, their energy/momentum/pressure goes up with an increase in the density of people, just like degenerate electrons!

The picture is thus that a star such as our Sun lives for several billion years supporting itself against gravity with the pressure produced by the fusion of hydrogen into helium in the core. This eventually runs out, and after some exciting times throwing a lot of mass into space, the core settles down into a white dwarf, where it spends eternity (well, not quite) cooling and doing nothing else.

The Chandrasekhar mass

For a few years, astronomers and physicists assumed that any star would eventually settle down into this configuration. Although black holes were not in the discussion at the time, had physicists of the time been asked they might have said that stars never enter this state because they are held up by degeneracy pressure.

This changed in 1930, when a 19 year old Indian physicist named Subrahmanyan Chandrasekhar took a long boat trip from Madras, India, to Cambridge, England, to work with Eddington. He decided to examine whether the white dwarf solution was stable. That is, suppose we have a white dwarf of a given mass and radius. If it is stable, then squeezing it will cause it to spring back. If it is not stable, then a squeeze will cause it to keep contracting. This is like the classic example of a triangle on its base (stable, because a slight push causes it to go back to its original configuration) versus a triangle balanced on its points (unstable, because a slight push will cause it to tip more and more). What Chandrasekhar found was that below a certain mass now called the *Chandrasekhar mass* (about 1.4 times the mass of our Sun), white dwarfs supported by degeneracy pressure are indeed stable. Above it, however, they are *not* stable. Therefore, the protection against black holes might not exist after all!

Eddington was not amused. At a meeting where he had invited the young Chandrasekhar to present his ideas, Eddington presented afterwards and announced, without any calculations to back it up, that something had to be wrong with Chandrasekhar's calculations and that "there should be a law of nature to prevent a star from behaving in this absurd way." Not fair, and not true either, but Eddington's prestige meant that most astronomers agreed with him, even though all the prominent physicists that Chandrasekhar consulted (including Einstein and Niels Bohr) agreed with the calculation.

In any case, by the end of the 1930s most scientists understood and accepted that white dwarfs had a maximum mass. Therefore, at least in principle, massive stars might leave behind a remnant that could not be supported by electron degeneracy pressure. Could anything else prevent black holes from forming?

Neutron stars

The next candidate requires that we go back a bit, to explore the atom. The discovery of the electron and proton gave us two components of atoms, which were completed with the discovery of the neutron in 1932 by James Chadwick. The neutron is a particle without electric charge that is a little more massive than a proton; protons and neutrons together make up atomic nuclei. When news of the discovery came to Russia, the great Soviet physicist Lev Landau held a dinner party at which he suggested that just as white dwarfs are held up by electron degeneracy pressure, there might be "neutron stars" that are held up by neutron degeneracy pressure. The much greater mass of neutrons than electrons (a factor of more than 1800) turns out to mean that such stars would be even more compact; whereas a white dwarf the mass of the Sun has a radius about that of the Earth, a neutron star one and a half times the mass of the Sun has a radius of only 10 kilometers, which would allow it to fit inside the Capital Beltway! This means that a teaspoon of neutron star matter would have more than the combined mass of every person on Earth. Amazing.

Shortly thereafter, in 1934, Walter Baade and Fritz Zwicky submitted an abstract with the remarkably prescient suggestions that (1) supernovae represent the formation of neutron stars, and (2) supernovae also generate cosmic rays. Pretty impressive. However, the lack of other support for these ideas combined with Zwicky's general nastiness meant that no one really considered these ideas for more than three decades. Indeed, until 1967 there were only occasional papers about neutron stars because there was no observational evidence for them (and naturally so; very small objects are dim, hence quite hard to see!).

This changed in 1967 when an Irish graduate student at Cambridge University named Jocelyn Bell was finishing up her thesis work on radio observations of quasars (note that "radio" here means radio waves, i.e., long-wavelength electromagnetic radiation). Quasars were puzzling objects of great distance and high intensity but that were small enough that they were not resolvable in telescopes (and hence were "quasi-stellar", thus the name). After she had set up the radio telescope and developed experience with reading the charts, she discovered that when the telescope observed in a particular direction there was a bit of "scruff" in the charts that turned out to be regular blips with an interval of 1.3 seconds. Initially she and some others thought that the regularity might indicate an artificial signal (and she was annoyed that the aliens had chosen the last stages of her thesis as the time to contact Earth!), but subsequent discovery of other similar sources convinced everyone that these were natural phenomena. These "pulsars" were explained a year later as rotating magnetic neutron stars; the pulsations are like a lighthouse beam that lights us up when it points in our direction.

The discovery of pulsars was one of the most important astrophysical discoveries of the last 50 years, and we will see them later when we discuss the tests of the predictions of gravitational waves. Given that Bell built the instrument, discovered the effect, and recognized its significance, it is not surprising that the 1974 Nobel Prize in Physics was awarded to... her advisor, Anthony Hewish. I have met Bell personally, and she appears not to be bitter about the exclusion, but the community credits her with the discovery.

So neutron stars exist. Can they protect against the formation of black holes? Not necessarily. Like white dwarfs, neutron stars have a maximum mass. It is more uncertain than the maximum for white dwarfs because neutron stars have complicated nuclear structure, but it is certainly no more than three solar masses. The picture is therefore that when a massive star evolves, its core fuses hydrogen into helium, then helium into carbon, then oxygen, neon, silicon, and finally iron. No more energy can be extracted from iron, so for sufficiently massive stars the iron core grows and acts like a hot white dwarf, until it finally exceeds the Chandrasekhar mass. The core then collapses and (at least temporarily) forms a neutron star, and the energy released by the collapse blows the star apart in a supernova.

So far, so good. But if there is enough mass around, and more stuff falls back onto the neutron star, it might exceed the maximum mass for neutron stars as well. If so, there is nothing to prevent further collapse, and black holes could form.

Given the numbers I've indicated, you might imagine that (1) stars that start their lives below about 1.4 times the mass of the Sun live out their lives and then become white dwarfs, (2) stars that start with masses more than 1.4 times the mass of the Sun but below the maximum mass of neutron stars ultimately become neutron stars after the supernova, and (3) stars that begin with masses more than the maximum for neutron stars end up as black holes. But it's more complicated than that. Stars that have exhausted their core hydrogen become red giants or supergiants for at least a short time, and during that time they are so bright that they blow away a large amount of mass in winds. The more massive they are at the beginning, the more mass they blow away. This turns out to mean that stars that begin with less than *eight* times the mass of the Sun end up as white dwarfs, because the rest of the mass is blown away. Stars that start with masses between eight and 20-30 times the mass of the Sun probably throw off enough mass that they become neutron stars. Stars that start with even higher masses (meaning about one in every 2,000 stars, roughly) probably end up as black holes.

Given that black holes are quiet, solitary things other than in exceptional circumstances, they are therefore very tough to find. However, we now know of a number of sources that pretty much have to be black holes unless you are allergic to event horizons or want to go for ad hoc exotica. We will discuss these, and the mathematical proofs related to black holes, in the next lecture.