GRESHAM COLLEGE

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ULTRA-COMPACT OBJECTS: ASTRONOMY WITH GRAVITATIONAL WAVES

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A star like our sun is a huge ball of gas. It shines because it is an energy generator that far out-scales anything imaginable on the earth.

We have good times on the earth thanks to solar warming. Without our sustaining neighbour, life would be non-existent. Heat, in moderation, is crucial for the origin of the cells that evolved from the most primitive structures to the complex organisms that define humanity.

We complain about the threat from climate warming, but viewed over a long enough perspective, this is the least of our concerns. Some worry about the prospects for humanity by confrontation with the onset of artificial intelligence. This also will be played out over future centuries. Given the richness of our human heritage, there is every reason to be optimistic that the inevitability of an era of post-humanity, as some argue, is an illusion.

Solar power seems inexhaustible. The sun's energy output is 385 trillion terawatts. The earth receives less than a hundred millionth of this, or about 170,000 terawatts. Worldwide power plants generate about 20 terawatts. So solar power is a huge resource for the future. We are tapping a miniscule fraction so far. But the sun won't last forever.

Let's take the long-term perspective. Something bad will inevitably happen. The sun is destined to die. This will not happen millennia from now, nor even millions of years in the future. But rather about 4 billion years in the future. The fiery gases in the outer parts of the sun will expand and overwhelm the inner planets. The earth will be toast.

How certain are we of this prediction? The fate of a star like the sun is complicated, but so is a grain of sand.

> *To see a World in a Grain of Sand*
> *And a Heaven in a Wild Flower,*
> *Hold Infinity in the palm of your hand*
> *And Eternity in an hour.*
> *William Blake*

Indeed we understand the physics and chemistry of stars better than we understand a grain of sand. The properties of the particles in a grain of sand are elusive. Will the protons ultimately decay? We do not know. Until now, experiments to search for proton decay have not been sufficiently large. There is a bound from theory, but physicists have not gotten there yet. The good news though is that one day we will know as one experiment is under construction in Japan that is capable of detecting proton decay.

So we cannot yet predict the fate of a proton. But we can predict with certainty the fate of a star. The future of a star depends on its mass and its composition. That's all! The mass determines its energy reservoir and the composition controls the opacity, which determines the ability of radiation to escape from the star.

The sun is a gigantic thermonuclear reactor. It is composed mostly of hydrogen. The neutron and the proton are the two fundamental particles that define chemistry, and the periodic table of the elements. Now a neutron weighs very slightly less than a proton. At very high temperature we can fuse hydrogen atoms, predominant in the sun, into helium. Because of the mass difference, four atoms of hydrogen, each with a proton, weigh about 0.7 percent less than a helium atom, which contains 2 protons and two neutrons. And that gives energy, via Einstein's well-known equation that relates mass and energy, $E=mc^2$. This energy release converts 0.7 percent of a gram of hydrogen into pure energy. And this is what powers the sun, as well hydrogen bombs.

The sun is supported by internal heat. This is radiated as sunlight. It is regenerated by nuclear reactions in the centre of the sun. The sun is a gigantic nuclear reactor. Fortunately, all of the radioactive debris is trapped in the centre of the sun, only the heat escapes.

By now, the sun has already exhausted about half of the hydrogen in its core. So it's in its middle age, with about 4.5 billion years to go before its central fuel supply is completely depleted.

What happens at this point is dramatic. The core, with no source of heat and so with insufficient pressure to resist gravity, collapses. This collapse releases energy, and the outer parts of the star expand. As the layers expand, they cool. The star, once yellow in colour, now becomes a bloated red giant star, typically as large as a thousand times the radius of our sun, and red. The earth, at a hundred solar radii will be swallowed by the expanding, swirling, hot gaseous inferno, still hot enough to burn everything on Earth to a crisp.

The core heats up and can now burn helium. There is enough of this for the star to gain a new lease of life. The red giant phase is highly luminous, so it burns up helium at a prodigious rate. It survives for about a hundred million years. Once the helium supply is exhausted, the core collapse continues, and for the more massive stars, the core becomes hot enough to burn carbon in a briefer supergiant phase. Once this point is reached, all nuclear fuel in the core is so depleted that there is only one option: collapse.

What can stop the collapse? For the sun the answer is clear. The quantum theory comes to the rescue. The collapse eventually stops when the density of matter hits a brick wall: that of quantum pressure.

This is an effect that is hidden on ordinary scales. It is visualized as an intrinsic uncertainty on subatomic scales. One can never know the position of an atom. This is because fundamental particles are wave-like. A wave-like particle is described by a wavelength. On the smallest scales all particles are waves. One can test this prediction of the quantum nature of matter by an experiment that sends beams of particles through parallel slits. If the slits are spaced closely, the particle beams are found to interfere with each other. The observer sees a pattern of alternating peaks and crests, which demonstrates are ultimately not point-like.

Back to the collapsing core of the sun. The density in the centre of the sun is now about 100 gm/cm^3. Once it attains 100 tons per cubic centimetre, quantum uncertainty steps in. It acts like an atomic pressure, called degeneracy. Electrons are the source of pressure in the hot interior of the sun. But compress electrons sufficiently and one reaches the quantum limit. The wavelengths of electrons are overlapping. The quantum theory says one cannot compress free electrons any further. We call this the state of electron degeneracy. So collapse stops.

White dwarf. The star is now 1000 km in size. It is made of helium and carbon, and some oxygen. Initially it is white-hot. We call it a white dwarf.

Young white dwarfs are embedded in the most beautiful objects in the sky. The remnants of their mother star are seen as expanding gas called planetary nebulae. Centuries ago, before the age of stellar photography, astronomers were confused as to their nature. Now we even detect their still glowing central white dwarfs.

Neutron star. A star of mass 10 times or more that the sun exhausts its fuel rapidly. Its lifetime is measured in hundreds of millions, or sometimes only millions, of years. Gravity is so strong that the star continues to collapse until all its nuclear fuel is exhausted. Everything consumable burns. Only iron, the most stable of the elements is left. Iron is the ultimate slag heap of the universe.

As the star collapses, it now becomes so hot that neutrino cooling occurs. Neutrinos are tiny particles that carry energy and spin but interact incredibly weakly with matter. We detect otherwise invisible nuclear reactors, or even explosions, via their emitted neutrinos. The star collapses under the inexorable force of gravity, to reach a much higher density than that of a white dwarf, a million times denser. Consequently, much more energy is released, and the energy is radiated much more rapidly into space. Some of the emitted energy does interact with the outer layers of the dying star. During the collapse, 90 percent of the outer layers of the star are ejected as a supernova explosion. These are the most dramatic events in the sky, occasionally visible even without a telescope. The explosion occurs in seconds, and fades away over years, but the supernova remnant continues to be visible for many years afterwards.

The best-known supernova was observed in China in 1054. Its remnant is a beautiful turbulent nebula, the Crab, observed frequently by modern telescopes, which directly measure its rate of expansion. The last supernova recorded in the Milky Way was discovered by Tycho Brahe in 1607.

The core of the parent star collapses under so much gravity that electron degeneracy cannot slow the collapse. Most of the core is iron, but iron nuclei are so compressed that they merge together and are destroyed. Since the star is charge neutral, its final state is made up of protons and electrons. But the density is so high that electrons are forced onto the protons. They have disappeared as free particles, and hence provide no more pressure support. Only neutrons are left.

A new pressure saves the day, this time it's the neutrons. They are 2000 times heavier than electrons, so have wavelengths that are correspondingly smaller. They can be compress to a billion times the density of the electrons before they "touch" each other, or in the quantum view, their wavelengths overlap. The star is 1000 times smaller than the white dwarf. Quantum theory again has come to the rescue, and neutron degeneracy pressure enters the scene. The final ball of neutrons has the mass of the sun but is only 10 km in radius. The central stellar survivor of a supernova explosion often ends up as a neutron star. We detect a rapidly spinning neutron star in the centre of the Crab Nebula. It is a pulsar, emitting a beam of radiation, like a lighthouse, as it spins some 30 times per second.

A star more than 30 times the mass of the sun has the most catastrophic fate of all. Gravity is now too large, and even quantum pressure cannot slow the collapse. Although much matter is ejected in the explosion, the core contains too much mass to form a neutron star. The most massive neutron star is 2 times the mass of the sun. One cannot resist gravity and stop the collapse. A **black hole** inevitably forms. It is even smaller than a neutron star. The most massive stars that are 200 times the sun suffer violent explosions in their death throes but manage to still form black holes of up to 10 or 20 times the mass of the sun. Astronomers have observed dozens of black holes in our Milky Way galaxy. There should be many more. Here is how they find them: they have to be caught in action as bright x-ray sources. Optical counterparts are giant stars or even normal stars, which cannot be highly luminous x-ray emitters as they are too large. Gas has to fall in close to the black hole to intensely emit x-rays. But if stars have close black hole companions, mass overflow and transfer from the host, especially if a swollen giant, leads to intense x-ray emission as the gas streams accrete on to the compact companion object. Confirmation comes from optical spectroscopy that unveils the orbit of the black hole around its luminous companion. One can infer the mass of the compact companion and deduce that it is too massive to be a neutron star and hence is a black hole

Gravitational Wave Detection of Black Holes

The merger of two black holes or two neutron stars results in gravitational waves. Black hole binary mergers were first detected in 2015 by the LIGO telescopes. The merger generates oscillations in the gravity field as the approaching black holes orbit each other more and more rapidly. This dance of death culminates in a high frequency climax or chirp as the merger actually occurs. The changing amplitude of the waves, or wave form, directly gives the mass and even the spin of the black hole. This was the first direct detection of a black hole. The telescopes continued to take data. By now, some 5 black holes have been discovered by their gravitational wave emission.

Supermassive Black Holes

Galaxies such as our Milky Way contain hundreds of billions of stars. One of the most massive nearby galaxies, Messier 87, contains trillions of stars. The centres of massive galaxies have been found to harbour supermassive black holes. Our own Milky Way has a central black hole of four million times the mass of the sun.

The presence of a supermassive black hole is inferred from the speed-up in stellar orbits very close to the centre of the galaxy. The best example is that of the black hole in the centre of our galaxy, where the orbits of many stars can be followed over several years.

Gas cloud orbits are easier to detect in distant galaxies. We find that the more massive the galaxy, the more massive is its central black hole. One of the most massive black holes in the local universe black holes is at the centre of the giant elliptical galaxy Messier 87 in Virgo.

This supermassive black hole weighs in at some seven billion solar masses.

Gas clouds fall into these massive black holes. The feeding of the central black hole leads to x-ray and gamma-ray emission, as well as to growth. Interstellar gas accretes onto the central black hole. One obstacle that needs to be overcome is that gas clouds have predominantly circular orbits, hence do not easily accrete. This restriction disappears if the orbits are strongly shaken up. This occurs when galaxies merge together, especially if they are gas-rich. Most galaxies were gas-rich long ago, so most black hole growth occurs in the distant past. The merging redistributes the angular momentum of gas orbits, so gas can more easily fall into the centre.

There is a more violent mode for black hole growth. Entire stars can be swallowed. When stars approach a massive black hole too closely, they can be disrupted. The intense gravitational tides pull them apart. This produces explosions and jets, but most of the debris cools and falls into the black hole. The black holes grow in mass.

Supermassive black holes also grow by merging with other very massive black holes. This is also an aftermath of a galaxy merger, if the merging galaxies each contain massive central black holes. There is a way to validate this hypothesis, by observing the gravitational wave signal from the massive black hole merger. This occurs much more slowly than for stellar black holes, because the orbital and merging times are thousands of times longer. Instead of milliseconds, it's now minutes for the typical merger. This creates very low frequency gravitational radiation. To detect this signal, the telescope needs a baseline not of kilometres, as for LIGO, but of millions of kilometres. This can only happen in space. The LISA interferometer, to be launched in 2034, consist of 3 satellites a million kilometres apart. By sending triangulated laser signals, LISA will be able to measure passing gravity waves produced by a remote merger of two supermassive black holes.