CHAPTER 1: AN OVERLY CONCISE SUMMARY OF THE UNIVERSE

The human race has made great strides in the last few centuries, inventing the concept of science and applying it to understanding the world around us. We have gone from standing on the ground, looking at the stars with no understanding beyond their beauty to a rough outline of what the visible universe is and how it works. But even on the timescales that mankind has roamed this planet, the period of time since the invention of science has been brief indeed.

So while we are rightfully proud of our accomplishments, we have just scratched the surface of science. We really don't know all the much. Astrophysics is rife with challenging and fundamental problems, many of which we have not yet understood as problems. This chapter is a very brief overview of the problems that face modern astrophysicists – at least it is about the problems we know, where we know we don't know the solution.

I have been active as a student and researcher in astronomy since 1969. And during that period a great deal has changed. I have been privileged to be active as an astronomer during a period that will doubtless go down in history as a golden age of astronomy. This chapter was quite different when I first taught this course nearly 35 years ago.

1.1 WHERE IT ALL BEGAN

Why?

That is the ultimate question. It is perhaps unanswerable. Science has allowed us to ask ever more sophisticated versions of this question, but each discovery just pushes back the question to the next level. Can we even conceive of a Universe before time? Does the question even make sense? All we can do is study and explore.

We do not know the origin of the Universe. We do not know if it part of some grander yet hyperuniverse. We do not know the nature of time or space, but our current physics gives us some handles on the surface of the problem.

We do know that the Universe is expanding and it appears to have come from an unbelievably tiny, dense, hot sphere. Our current physics allows us to extrapolate back to what is called the Planck Era, about 10^{-43}seconds after time zero. Prior to that, the quantum wavelength of the Universe was larger than its curvature. Our physics just isn't yet equipped to deal with such extreme environments. Furthermore, our physics is being extrapolated into regimes where it is likely inadequate anyway.

Certain mysteries about the physical state of our current Universe give clues about the very, very early Universe. For example, our Universe is remarkably smooth and uniform. A theory dubbed Inflation hypothesizes that space in the early Universe came into being folded tightly around itself. At around 10^{-36}seconds this folding released, causing the Universe to grow in size vastly faster than the speed of light for the next 10^{-32}seconds. Adjacent particles were ripped apart so fast by the growth of the space between them that they became causally disconnected. It would take a warp drive travelling faster than light for the particles to ever communicate again. Inflation expanded the volume of the Universe by a factor somewhere in the vicinity of 1072. That part of the Universe that we can see is a smaller part of the Universe by volume than a single atom is compared to all the atoms in all the galaxies visible to the Hubble Space Telescope. Wow, what a concept. Do we know if it's right? Of course not, but it is a compelling concept that may turn out to true.

We don't even know for certain that the Universe is finite in volume. Some solutions of the equations of General Relativity that are used to describe the Universe suggest that it could be Open. An open Universe would be infinite in extent. Not just monstrously big, but infinite. There would be an infinity of galaxies, an infinity of stars, an infinity of Earth-like planets, an infinite number of copies of you, the reader. This is so very hard to believe that most astronomers are simply prejudiced in favor of a closed Universe, one of finite volume and mass.

So as the 20th Century closed, astronomers had failed to find enough matter to "close" the Universe. But our telescopes had reached unprecedented power and we were searching for the signs of the expansion of the universe slowing, an indicator of a finite lifetime and a finite size. Then, the Hubble Space Telescope in concert with telescopes on the ground discovered the inconceivable (yet again). The expansion of the Universe was accelerating! A sucking, negative pressure dubbed Dark Energy was hypothesized to explain this.

We stand in awe, clueless to the nature and grandeur of the Universe around us.

1.2 THE EARLY UNIVERSE

By the time that a microsecond has passed after the Big Bang, our physics is in better shape and our models have made remarkable and verifiable predications. We view the Universe as an expanding ball of hot plasma in thermal equilibrium with small density variations imprinted from quantum phenomena in earlier eras.

As the temperature of the Universe fell down below a trillion degrees, our nuclear physics became reliable, and calculations showed that hydrogen and helium would be the main elements created. It was too low density to create carbon when the temperature was right. So the first three minutes of the universe determined the starting point for the nuclear composition of the universe. And so, for the first 100,000 years the universe was a very smooth, expanding ball of fully-ionized hydrogen and helium with photons rattling around in thermal equilibrium.

Then, quite rapidly, when the temperature had dropped all the way to about 4000K, the electrons combined with the protons to create the first hydrogen atoms. But H atoms are transparent to radiation and the photons, which outnumbered the atoms by about 100million to one, were suddenly free to travel unimpeded. They are still travelling today.

Because of the expansion of the universe, those photons have been redshifted by a factor of over 1100, and are now visible as blackbody radiation of 2.7K coming uniformly from all directions. But this Cosmic Microwave Background is not perfectly uniform. Embedded within it are regions where the brightness is a tiny amount ($\sim 10^{-5}$) higher or lower than the average. We believe those regions are due to density fluctuations in the original plasma of the Big Bang, and their structure is giving astronomers very powerful constraints on the initial conditions of the universe.

But the atoms of the universe went dark for a billion years. At the start of these "Dark Ages" the universe was a nearly uniform ball of gas. At the end of it, the quasars were turning on and galaxies were forming rapidly. It appears that the giant black holes that drive quasars formed surprisingly quickly and created high energy outflows of energy. Some of this punched its way out of the forming galaxies into intergalactic space where it reionized the atoms. Because of the relatively low brightness and the high redshift, detecting these events has been very difficulties. But new techniques are now being developed to study the Era of Reionization.

During the Dark Ages, the basic structures of the universe began to appear out a nearly smooth gas. The small perturbations in density grew and were amplified by gravity. On a grand scale, the material fell into sheets with voids in between that constitute the Cosmic Web (no relation).

Most of the matter in the Universe is "Dark Matter", by a factor of six or so. This dark matter does not appear to interact with regular matter or even itself very strongly. But it does experience gravity. So, over time, it has fallen into large clumps that underlie the more complicated structures that regular matter has formed.

Regular material swirled into higher density regions where gas dynamics and frictional effects brought the materials into disk-like shapes that were galaxies. The galaxy distribution was lumpy, having major Clusters of Galaxies and even SuperClusters.

Even so, the bulk of the atoms in the universe were left behind in the vast stretches of nothing between the galaxies. Indeed, most of the baryons in the universe have yet to be detected directly. But the search is on.

1.3 EXTRAGALACTIC ASTRONOMY

As mentioned already, formation of Super Massive Black Holes started very early, and we now believe that virtually every major galaxy (Milky Way included) has a large black hole at the center, the very bottom of its gravitation well. This black hole is where everything goes when it loses its angular momentum and falls to the bottom. It is, in essence, a galactic disposal unit. What goes in is ground up and never comes out.

But when there is a lot of material falling in, for whatever reason, a huge, hot accretion disk and a relativistic jet are formed. These are the Active Galactic Nuclei that are so bright they are visible across the universe. The brightest of these, so distant that the host galaxy isn't visible, are called quasars or QSO's (Quasi-Stellar Objects).

The bulk of the matter settles into a flattened orbital structure (bulge and disk) around the center of mass of the galaxy. Here the gas, over time, further collapses into individual stars and clusters of stars, starting with the giant globular clusters. Our Milky Way has now converted about 90% of its gas into stars.

Most galaxies settle into either an elliptical or spiral shape. The elliptical galaxies are typically devoid of an active Interstellar Medium and thus have a paucity of young, blue stars, giving them a more yellowish appearance.

In spiral galaxies there is usually a rich interstellar medium that is forming new stars. Star forming regions appear red due to the extreme amount of ionizing radiation from the young stars. The star formation feeds on large, dark, cold interstellar molecular clouds that build up on the edges of spiral arms. The spirals are density waves in galaxy's mass distribution caused by passing galaxies.

1.4 GALACTIC ASTRONOMY

We, of course, live in the Milky Way, a spiral galaxy with about 100billion stars in it. We live about 8000pc from the Center.

In the very center lies the giant black hole known as Sagittarius A*. (pronounced A-star). The black hole is obscured in visible light by intervening gas and dust but can be observed in the infrared where the scattering by intervening dust is lower. For twenty years now, the region around Sag A* has been monitored, and we have seen a swarm of stars doing close orbits about a point that is presumably the black hole, even though it is not visible.. This is an amazing little movie. From their motions, astronomers have determined that the mass of the black hole is about 4 million times the mass of the Sun.

Most of the mass of the Milky Way is hidden in dark matter that envelopes the entire galaxy and drops very slowly in density with radius. The first stars to form were in the Globular Clustes – about 100 dense clusters of up to a million stars that surround the Milky Way in a large sphere. Then there are the bulge stars which appear like an elliptical galaxy in the first few kiloparsecs from the center. The bulk of the regular matter is to be found in the disk. About 90% of the matter that fell into this disk, which only a 100pc thick but 30,000pc in diameter, has now converted into stars.

The rest of the material is still in gaseous form in the Interstellar Medium. The gas is mostly hydrogen and helium created in the Big Bang. But early generations of stars have created heavier elements and returned them to the ISM. The gas is largely to be found in three phases that are in pressure equilibrium. There is a hot phase, with temperatures up to millions of degrees. This phase is energized by supernova remnants and is dynamic on timescales of millions of degrees, blowing giant bubbles that can burst out of the disk. The ISM is suffused with high energy cosmic rays that are also thought to have generated in supernova remnants. There is a component that sits at temperatures near 10,000K. And then there are cold, dense, dark molecular clouds that pile up on the edges of spiral arms. These dense clouds can become very cold and shield their material from radiation, allowing for the development of molecules. It is these cold regions that allow the collapse of gas into stars.

1.5 STARS

Stars are all formed from the collapse of large interstellar clouds. The physics of the initial collapse is still poorly understood. But as the gas falls in, angular momentum causes the material to flatten into a disk. The bulk of the material falls into the proto-star at the center. But a small amount stays in orbit and forms a planetary system. Frequently the disk breaks into several subdisks that each become stars – a binary or multiple star system.

The protostar continues to collapse, radiating away its gravitational energy and becoming increasingly hot in the center. When the core of the star reaches millions of degrees, nuclear fusion turns on and balances the radiation losses from the surface. Initially it is burning hydrogen in the core and is called a Main Sequence star. The Sun is still in its Main Sequence phase and will be stable for another 5 billion years.

When the hydrogen in the nuclear-burning core starts to be used up, the cores gets smaller and hotter. The density in this hydrogen-depleted core becomes so high that the electron identities are compromised and electron degeneracy pressure prevents further collapse at about the size of the Earth. The temperature continues to rise until, when it reached about 10^8K, the helium starts to burn by the triple alpha reaction to form carbon. By this time the star is a giant, much brighter than it was on the Main Sequence, and events are speeding up. The burning of the helium continues apace, and a degenerate core of carbon is formed when the star reaches the red supergiant phase. It is so bright that that the photon flux from the core starts to blow the outer layers of the star back into interstellar space as a Planetary Nebula.

If the star is below about 5 to 8 solar masses, it will blow off the bulk of its outer layers, relieving the pressure in the core. This electron degenerate core of carbon then cools into a White Dwarf star. A White Dwarf is about the size of the Earth but has a mass that is usually about 70% the mass of the Sun with a surface temperature comparable to or higher than the Sun. Electron degeneracy pressure can hold up a star of less than 1.44Mo forever but collapses above that Chandrasekhar Limit. White Dwarfs will still be here long all the stars have burned out.

If the red supergiant is massive enough, then the envelope can be held in place and the core can get hotter still, burning its way up the periodic table to iron, which cannot be nuclear burned. When the degenerate iron core reaches the Chandrasekhar Limit, it rapidly collapses. Vast amounts of energy are suddenly released as a supernova, mostly from the gravitational collapse. Some of the energy of this Type II Supernova is converted into kinetic energy and goes blasting out into the interstellar medium to form a supernova remnant. The luminosity of a supernova is so huge we can detect these events across the Universe. This happens once every hundred years somewhere in the disk of the Milky Way.

As the material collapses, the electrons are forced back into the protons to form neutrons. When the star settles it is held up by neutron degeneracy and is under 7km in radius though typically has 1.4 times the mass of the Sun. It is, essentially, a giant atomic nucleus. It will be spinning rapidly and can have a magnetic field of up to a trillion Gauss. The spinning magnetic field creates high energy particles that are thrown into space and make the neutron star a pulsar. The energy of the pulsar comes from the rotational energy of the neutron and as it ages, it slows down, losing its luminosity and then fades to near invisibility. Like White Dwarfs, a neutron star will last forever.

But neutron stars, like white dwarfs, have a Chandrasekhar limit, this time near 2.1Mo. So sometimes, in the course of a Type II supernova, enough material from the massive predecessor star rains down onto the neutron star to push it over its stability limit. This time, there is nothing to stop the collapse. It falls inside its own event horizon to form a black hole. The gravitation at the surface of a black hole is so intense that time essentially stops. Anything that falls through the event horizon is lost to the universe forever.

A black hole left to itself creates a very weak Hawking Radiation that carries energy away from the black hole at the expense of its mass. Given a ridiculously large amount of time, a black hole can radiate away its mass entirely, having converted itself into nothing but photons.

There is also a Type I supernova which involves a White Dwarf in a close binary system with a regular star. If that regular star can dump enough matter onto the white dwarf it can exceed the Chandrasekhar limit and start to collapse. But because the nuclear composition is carbon and oxygen, ferocious nuclear burning ensues and blows the white dwarf apart, leaving nothing but an expanding shell of gas.

1.6 THE SUN

The Sun is the star that we understand the best. We understand its nuclear processes in such detail that we were able to predict the neutrino flux created in the core and streaming past the Earth. Measurements of that flux were made and showed the neutrinos to be underabundant by a factor of three, creating a physics conundrum. This appears to have been resolved by the theory that the neutrino has rest mass and consequently can shift among the three types during the eight minutes it takes to travel from the Sun to the Earth.

The Sun has a magnetic activity cycle that has also been detected in other stars. Magnetic flux tubes wind up inside the Sun due to its differential rotation. Those tubes can pop out of the surface, leaving a sunspot as a footprint. The Sun has an eleven year sunspot frequency cycle.

Where the magnetic fields interact with the bulk motion of plasma at the surface, high energy phenomena are generated. Giant loops of confined, hot gas lift off the surface. Some material streams out into planetary space, forming a corona and a solar wind.

1.7 PLANETS

Until twenty years ago it was only theorized that there were planets around other stars. But since then, thousands have been found using indirect means, i.e. searching for indicators of planets in the light of the parent star.

The first exoplanets were detected using a spectroscopic technique. A star and its planet both orbit around a common center of mass. Though the orbital speed of the star is much less than that of the planet, it is, nonetheless, detectable in the Doppler shift of the stellar lines. The first discoveries were of “hot Jupiters” -- very massive planets in high speed orbits close to the star. We cannot yet detect Earth-like planets by this technique, but we are getting close.

Another extremely productive indirect technique is to search for the shadows of planets as they transit the disk of their parent star. This, of course, requires the orbital plane to be in alignment with our line of sight, so most systems cannot be studied this way. But the Kepler satellite, by staring at thousands of stars simultaneously has found over a thousand planets by this technique, including a handful that appear to be of the same size and temperature as the Earth.

It is now becoming clear that planets are a feature of every stellar system. Indeed, it is looking like wherever a planet can form it does so. A large fraction, over 30%, should have Earth-sized planets in the habitable zone.

So the next big push in astrophysics is to obtain direct imaging and spectroscopy of the nearby systems. We want to take pictures with the scatter from the bright central star removed, showing the planets as faint star-like objects. Then, by performing spectroscopy, we will be able to assess the nature of the planets we have found. Are they hell-holes like Venus, wind-swept barren rocks like Mars, or watery paradises like the Earth?