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HOW ASTRONOMY CHANGED OUR VIEW OF THE COSMOS: FROM GRESHAM TO THE 21ST CENTURY

PROFESSOR JOSEPH SILK

The Babylonians

Astronomy began in a systematic way, some 3 millennia BCE, in Babylon with the first Sumerian clay tablets recording celestial phenomena. The 12 signs of the zodiac were named by the Babylonians. The oldest surviving planetary text is the cuneiform rendering of the appearances of Venus (1000 BCE), and there are many recordings of solar and lunar eclipses. Most remarkably, the Babylonian astronomers used centuries of observation to discover eclipse cycles, such as the 18-year Saros cycle of lunar eclipses. The first recorded Babylonian astronomer. Naburimannu (c. 3rd-6th century BCE) was a priest for the moon god, and a central activity of religious leaders at the time was writing horoscopes. They were able to predict eclipses, thereby acquiring immense power in Babylonian society. Much of this work, while shrouded in astrology, had a significant influence on the early Greek astronomers. For example, much of their historical astronomical data seems to have survived this transition in civilizations.

The Greeks

The Greek opened our eyes to the mysteries of the heavens. In the earliest surviving examples of Greek literature, including Homer's Iliad, one finds references to the constellations, nearby star clusters such as the Hyades and the Pleiades and bright stars such as Sirius and Arcturus. Greek thinkers, including Homer, and Hesiod before him, in the 6th and 7th centuries BC, assumed a flat earth, but Pythagoras and his followers in later centuries preferred a spherical earth

The Greeks were outstanding natural philosophers. They developed the notion of scientific enquiry about nature. Aristotle made the universe from four elements, air earth, fire and water. We attribute the concept of atoms to Democritus. Others introduced epicycles, notably Apollonius in the 3rd century BC. The first heliocentric model of the solar system was proposed at about this time by Aristarchus of Samos, who also calculated the sizes of the sun and the moon. But it was Hipparchus a century later, who discovered precession of the earth's axis, and tried to account for the variable speeds and brightnesses, and retrograde motions, of the planets. This was not a very successful approach until the next major advance occurred by the Roman mathematician Ptolemy in the 2nd century AD. His book *The Almagest* dominated astronomy for nearly 1500 years, from the 2nd to the 17th centuries. Ptolemy was the first to accurately calculate the orbits of the 5 known planets using a system of epicycles centred on the earth. The concept of epicycles initially involved some 10 wheels rotating on a common axis in a crystalline sphere, and was invented to describe planetary motions in terms of perfectly circular orbits. The earth was at the centre.

The Dark Ages

After the collapse of the Graeco-Roman civilization, there was little improvement in our understanding of celestial phenomena. Of course, there was immense progress in viewing the night sky, in charting the heavens, and in using instruments to measure stellar positions. The epicyclic theory had no serious challenger. It became more complex as more precise observations of planetary motions and changing brightnesses were made. There were epicycles, and epicycles within epicycles, all moving on circular orbits in order to account for the complexities of the planetary motions. Some were off-centre, but the Earth retained the central role. Epicycles were progressively refined to "wheels within wheels" in order to account for the retrograde motions of the inner planets.

Circular motions remained inviolate in order to preserve the conjectures about beauty and perfection postulated by the great Grecian philosopher Plato in the 4/5th centuries BCE. It all seemed complicated but it provided a working model of the cosmos. One could account for the natural phenomena of the planets. By the 16th century, there were some 80 epicycles at work.

The Enlightenment

As the dark ages continued, the Arab world bred a new variety of astronomers who charted the stars with devices called astrolabes that helped record stellar positions in the sky. Most of the visible stars were named by these astronomers. However, the earth remained at the centre of the universe. This was considered to be the biblical explanation of the cosmos. Aristotle's view was that celestial phenomena were unchanging. The heavens were perfection in the Platonic tradition. Before attacking Ptolemy, one had to dispense with Aristotle.

The Danish astronomer Tycho Brahe (1546-1601) discovered changes in the heavens, such due to as supernovae and comets that were at large distances from the Earth. He overturned the world view of Aristotle that the heavens were unchanging. He did not fully rise to the challenge of a fully heliocentric universe, however. Brahe's celestial system was still geocentric for the Sun and Moon, although all of the planets orbited the sun.

The Copernican Revolution

Nicolaus Copernicus lived in Torun, Poland, from 1572-1643. Science was still a branch of the humanities, and Copernicus received a broad education. He was a mathematician, astronomer, physician, classics scholar, translator, governor, diplomat, and economist.

Copernicus realized that there was an easier approach than epicycles, by dethroning the central role of the earth. The sun was central. Copernicus overturned Ptolemy's geocentric universe. However, Copernicus used circular motions. He still had some 34 epicycles. But these were soon to disappear.

Epicycles only vanished once the German astronomer Johannes Kepler (1571-1630) introduced the notion of elliptical orbits in the 17th century. These gradually replaced circular motions. Epicycles were now redundant. They were only understood once it was realised that the English mathematician Isaac Newton (1643-1727) 's new theory of gravitation perfectly accounted for elliptical orbits, with the Sun being at a focal point of the ellipse

There were also more philosophical arguments that foresaw modern views of the role of humanity in the cosmos, with those of Robert Fludd, also known as Robertus de Fluctibus, being an especially interesting case. A prominent English physician, Fludd (1574-1637) was an astrologer, mathematician, cosmologist, Qabalist and Rosicrucian.

He is most famous for his illustration of man as the microcosm within the macrocosm. This is the forerunner of the anthropic principle of modern cosmology.

Opening Up the Universe

The great distances to the nearest stars were revealed by parallax, due to the change of perspective as viewed from the earth between summer and winter. German astronomer Friedrich Bessel measured the first parallax distance to the star 61 Cygni, at a distance of 11 light years, in 1838.

The Transition to Big Astronomy

The nearby diffuse nebulae were studied with the aid of large telescopes. The real breakthrough came with the advent of astronomical spectroscopy. This exposed the chemical elements that were formed in stars. Spectroscopy allowed the measurements of Doppler shifts of distant galaxies and was responsible for one of the key confirmations of the Big Bang. Helium, the second most abundant element in the universe, was discovered first in the sun.

However stars cannot generate enough helium via thermonuclear reactions in their hot cores. They fall short by at least a factor of ten. Only the first minutes of the Big Bang provide a hot and dense environment where such reactions occurred to completion, yielding the one helium nucleus for every observed proton in the universe, long before the first stars were borne.

Radio astronomy provided the convincing case against the main alternative to the Big Bang, namely a steady state universe. This was a popular alternative in the 1950s. Radio galaxies were found to be far more numerous in the early universe, in violent contradiction with the expectations of a steady state universe, in which there was no beginning, no dense early phase, and indeed no cosmological evolution. Radio telescopes can be operated collectively over a large area. The largest single radio dishes are constructed in natural craters. As the earth turns, the sky is surveyed. One in Arecibo, Puerto Rico has a diameter of 350 m. The world's largest, in China, is 500 m in diameter.

Different radio telescopes across the earth can also be combined to look at a particular radio source in the sky and produce unprecedented resolving power. The principle of interference of the electromagnetic waves the make up the radio signal from widely separated telescopes allows the radio astronomer to add the signals from each telescope. Normally the added signal would be incoherent and diffuses, but the use of exquisite timing allows one to reconstitute an image of unprecedented resolution by reinforcing the wave peaks and troughs. This approach fabricates what is known as an interference pattern, due to the wave-like nature of radio signals. In this way, an array of radio telescopes can span the entire earth to yield unprecedented resolving power.

The Final Frontier

With the largest telescopes, we can see to the edge of the observable universe. Large optical telescopes have enormous light gathering power. The largest planned is a European project, the Extremely Large Telescope, with a diameter of 39 m, scheduled to gather its first light in 2025. The ELT in Atacama will collect 100 million times more light than the human eye. Other very large telescopes follow, including the 30 m. telescope to be built on Mauna Kea, Hawaii. These telescopes are mostly devoted to the optical part of the spectrum. We have mapped the diverse structures of the galaxies, and their evolution through cosmic time. We peer back billions of years in light travel time, and see galaxies as far back in time as a hundred million years after the Big Bang

Much information about distant stars, especially on their formation, can only be viewed at infrared wavelengths. This is because such regions are shrouded by obscuring dust. However the reach of infrared telescopes is very limited on the ground because of absorption by the earth's atmosphere. Water vapour and oxygen block most infrared wavelengths.

The great discoveries of infrared astronomy came from space observatories, with the Spitzer infrared telescope, diameter 0.85 m, launched in 2003, followed by the Herschel space observatory, a 3.5 m diameter far infrared telescope, launched in 2009. The nurseries of stellar birth were discovered in the cores of dense gas clouds throughout the Milky Way and in other galaxies

There are probably no more mysteries lurking in the depths of space, at least in the optical and infrared regimes, although the high energy universe is just beginning to be explored in depth. We still do not know where the highest energies cosmic rays or neutrinos originate. Massive black holes at the centres of galaxies are our best bet.

X-ray astronomy can only be performed in space. The first x-ray telescope UHURU was launched in 1970, and followed by many more. Currently, Chandra (diameter 1.2 m), resolution 0.5 arc sec, 0.1-10 keV), launched by NASA in 1999, and XMM-Newton, diameter 0.72 m, resolution 5 arc sec, 0.1-12 keV), launched by ESA in 1999 are still operating. The latest to launch was NUSTAR (3-79 keV, resolution 9 arc sec), launched by NASA in 2012. Others are planned in the next decade, most notably the ESA large x-ray telescope ATHENA (0.1-15 keV, 5 arc sec resolution, 1.4m) for launch in 2031.

Gamma ray telescopes operate at energies of MeV to TeV. The Fermi telescope was launched in 2008, with an energy range of 20 MeV to 300 GeV. Very high energy gamma rays leave atmospheric signatures, showers of cosmic rays. These produce a sequence of nanosecond light flashes that can be viewed by telescopes with crude surface quality but ultrahigh time resolution. These telescopes are relatively inexpensive and can be constructed, for example, on high mountain sites with sensitivity to gamma rays extending to 100 TeV. The Cerenkov Telescope array will consist of more than 100 telescopes, deployed on two sites, in Tenerife, Canary Islands, and Atacama, Chile, scheduled for completion by 2025.

Neutrino telescopes use the earth as a detector. High energy neutrinos from deep space impact the Earth and scatter off nuclei in the earth's mantle to produce energetic showers of particles called muons. These are short-lived and disintegrate with a light flash that can be detected in an extremely dark site. Since cosmic rays impacting the earth's atmosphere produce many muons, the search for a cosmic neutrino signals involves searching for upcoming events that must have been produced deep in the earth. These rare upwards events could only have originated via weakly interacting neutrinos for which the entire earth is a target.

The energetic neutrinos freely traverse the earth but occasionally scatter to produce a short-lived high energy particle, the muon. The entire earth is an effective neutrino telescope. In practice huge dark cavities are exploited to see the rare muon decays. These are 1.5 km deep under the South Pole where the transparency of the ice enables one to see distant light flashes, or deep in the ocean, where there is similar darkness and transparency. A cubic kilometre needs to be instrumented with sensitive phototubes to give the required sensitivity. Strings of photubes are deployed by hot water drilling in the South Pole icecap, or laid out in a parallel experiment using mini submarines in the Mediterranean ocean.

A parallel project will utilize half a million tons of highly purified water in a cavern 1km underground in a disused mine in Japan. The HyperKamiokande neutrino telescope is scheduled to begin operation in 2025. A precursor, SuperKamiokande, a tenth of this size, has been operating in the same mine for two decades. One aim is to study dark matter using the Sun as a gigantic collector. Dark matter particles are trapped by the Sun and fall to the centre where they annihilate with each other. The resulting neutrinos traverse the Earth, and generate muons whose decays in water can be seen as light flashes in dark deep underground caverns. The neutrino telescopes can resolve the Sun when it is below the earth, again by seeking upward events that cannot be of atmospheric origin, as a potential neutrino source from events originating in the centre of the Sun.

Cosmic rays are highly energetic particles that bombard the earth's atmosphere. At the very highest energies they travel almost undeflected by magnetic fields from distant sources, most likely exploding stars or supermassive black holes. Cosmic rays are detected as they trigger showers of charged particles in the atmosphere. The Auger cosmic ray observatory, on a high plateau in the Argentinian pampas near Mendoza, spans 1200 square miles and is the world's largest cosmic ray telescope, taking data since 2008. It deploys 1660 individual tanks each containing 3000 gallons of highly purified water and each a mile apart from its nearest neighbours. The tanks are completely dark except when particles from the cosmic ray-induced showers travel through the tank at greater than the speed of light of the water, emitting nanosecond duration flashes of blue light.

The ultimate telescope could be constructed on the Moon. One scheme envisages using a natural crater, and covering its surface with telescope mirrors. They would point to a camera at the central focus point strung on wires spanning the crater rim. Combining the light from thousands of mirrors would result in a hypertelescope a km or more in diameter. This would be capable of directly imaging the nearest exoplanets, around distant stars. One could resolve cloud structures, oceans and even night time glows from any extra-terrestrial cities, if they exist.