Time and the Cosmos

a talk by Bill Baylis for the Dec. 31, 2017, service at the UU Church of Olinda

(illustrated with a few slides)

Introduction

[slide 1] At this time of year, we celebrate Winter Solstice and the return of the sun to the northern hemisphere on Earth. With the return of the Sun, the threat of ever colder, darker days is vanquished, temperatures will warm us and a new season of rebirth and growth will start. It's no wonder that this season has been widely celebrated with festivals of joy. Today, we can also celebrate not only the solstice, but that we understand why and how it occurs, and we do not have to appease any gods or fend off any evil spirits to make it happen.

That this evening marks the end of one year and the beginning of the next is pretty arbitrary. Calendars are human constructs, breaking a continuous cycle of celestial phenomena into weeks, months and years. Various calendars have started the year and day at different times. Spring equinox was a popular starting point in Roman times, and days often started at sunset.

It was important to have accurate time pieces in order to coordinate meetings and events. Clocks of useful accuracy that are independent of the sun usually depend on cycles or vibrations, from the pendula observed by Galileo around 1600 and made into time pieces by Christiaan Huygens in 1656, to tiny springs, to vibrating quartz crystals, to radiating atoms. Atomic clocks are made ever more precise, and new ones built at JILA in Boulder, Colorado, in 2017 with 3D arrays of up to 100,000 entangled Sr atoms cooled to less than 0.1 microkelvin have accuracies of one part in 3×10^{18}, meaning they will gain or lose less than a sixth of a second over the age of the universe, about 14 billion years. Higher frequency oscillations can give more precision. The ultimate vibrations may be those of matter waves (de Broglie waves), and these also provide the foundation of the quantum nature of the Universe.

[slide 2] Today we'll try to deepen our understanding of the nature of time. We want to discuss a few less common questions about time: Is it another dimension, somehow like a distance in space? Is time Universal, the same for everyone? And finally, was time actually created in the big bang?

Time as a dimension

Time is a measure of the separation of events. Our common understanding of time today is the classical one of Galileo and Newton [slide 3]. It was only during Galileo's time that the pendulum clock provided more useful accuracy than shadows of sunlight. Galileo had noted that the period (cycle time) of a swinging pendulum stayed the same as its amplitude decayed, but it took another half century (until 1656) before Christiaan Huygens built a pendulum clock from this. Galileo himself used the steady rhythm of common songs as a time keeper in his ground-breaking experiments with balls rolling down inclined planes. Both Galileo and Newton assumed that time was *universal* in nature [slide 4]. It did not depend on position. Everyone could synchronize their clocks and agree on the time. Since distances are additive, and velocities measure of how much distance is covered in a given time, then if time is universal, velocities must also be additive: if Jane throws a ball at 30 km/hr eastward while she herself is bicycling at 10 km/hr eastward away from John, the ball must be moving at 40 km/hr relative to John. Furthermore, John might be moving with respect to Jim, etc., so that there could be *no maximum speed* with which objects could move through space. This is the common perception of time today, but it is flaweed!

The invention of music notation around the 11th century [slide 5] showed how motion could be plotted and studied quantitatively. Part singing was coming into practice and musicians needed a way of staying together. Music notation shows how pitch, indicated by the vertical position of notes, varied in time, indicated by horizontal position. Geza Szamosi, a former colleague of mine specializing in relativity in the Physics Department at the University of Windsor, authored a popular McGraw-Hill book in 1986, **The Twin Dimensions: Inventing Time and Space**, pointing out the likely role that music notation had on physicists' analysis of motion by plotting position as a function of time, and recognizing time as a "twin dimension" to space.

Speed of Light

[slide 6] Newton experimented with light and discovered that a prism could spread white light into a rainbow of colours. He thought of light as a stream of tiny particles, but his contemporary Christian Huygens argued in 1678 that light was a wave that transmits vibrations. As a wave of vibration, light must have a medium to vibrate. Sound in air pushes and pulls on air molecules as it is transmitted, creating waves of density fluctuations. Light must vibrate something in space, even in space that seemed empty. The medium that light would vibrate was called *aether.*

The speed of light *c* was obviously much faster than any common speed known at that time, but Galileo's discovery [slide 6] of the moons of Jupiter in 1610 led the way for the Danish astronomer Ole Rømer to get a value from the timing of eclipses [slide 7] of Jupiter's Galilean moons as seen on Earth from different distances. (Galileo might have completed his measurements of eclipses and found the speed of light more accurately and earlier had not his work been impeded by the Church's objection to his astronomical observations that were inconsistent with the Ptolemaic and biblical system with Earth fixed at the centre of the solar system.

Now if light is a vibration of aether, its speed with respect to this medium would be fixed. The speed of light relative to Earth would then change as Earth moved in its orbit around the Sun. [slide 8] It was known by then that Earth was about 150 million km from the sun, and in order to complete its orbit in one year, it must have a speed of 30 km/s = 108,000 km/hr = 10^{-4} *c* in its motion about the Sun. Measurements to test this, made by Michelson and Morley using interferometry in 1877, failed to find any change in the speed of light. Further experiments followed only to confirm the surprising conclusion: light always moves in space at the same speed of about $3x10^8$ m/s relative to the observer, no matter how fast or in what direction the observer is moving. There is no place for a fixed aether in this. NB, the speed of light is now *defined* as 299,792,558 m/s, as this constant is used to measure length by defining the meter in terms of the time.

Time Dilation and the Spacetime Continuum

The speed of light is a limiting velocity of material objects for every nonaccelerated observer. Nothing can go faster. Time therefore cannot be universal. Light moves through empty space as a vibrating electromagnetic field, always at the same speed *c.* Time must depend on the motion of the observer. Albert Einstein sought to understand this by a thought experiment using clocks based on the constancy of the speed of light. A light pulse would bounce back and forth between mirrors and every cycle of the light would give one tick of the clock. [slide 9] Motion of the clock as shown would stretch the light path and thus *slow* the clock. This is time dilation. Time on the moving clock is slow or "dilated." An astronaut on a rapid space trip to the alpha centuari system and back, some 4.3 ly distant, for example, might be away for 10 Earth years but age only 8 years during the trip. She would be younger by years than her twin brother when she returned. [slide 10] This is called the twin "paradox", but it is factual, not a paradox but part of Einstein's teory of relativity! (Our picture illustrates an Interstellar rocket with a transverse light clock. A longitudinal clock is also possible and would illustrate desynchronization of time, even different time ordering for spatially separated events. It is responsible for de Broglie waves with *phases*--NOT matter--that travel from back to front faster than *c*.)

The one dimension of time combines with three dimensions of physical space to form a *spacetime continuum*. Time and space dimensions are different, but they are simply represented by a mathematical model. Velocity changes are "rotations" in a spacetime plane formed from one dimension in space and one in time. A century ago, Einstein successfully described *gravity* as distortions of spacetime, and this led to predictions of black holes and the "big bang" origin of the Universe.

Just in case you are thinking that relativity has little practical meaning unless you are near a blackhole or moving close to the speed of light, consider GPS, our global positioning system. GPS uses 32 satellites at 26,600 km (from Earth centre) circling every 12 hours, thus moving ~ 14,000 km/hr. Clocks on these GPS satellites, are dilated by 7.2 microsec every day, and this together with gravitational effects, must be accurately taken into account for the system to work, find locations, and provide directions. Cosmic rays also provide a demonstration of time dilation: they create muons (heavy electrons) at the top of the atmosphere, about 100 km high. These decay with a half-life of 2.2 microseconds and even traveling at the speed of light, they would decay in less than one kilometer. But thanks to time dilation, many make the full 100 km trip to the surface of the Earth.

Models vs. Reality

Mathematics is an extension of symbolic logic and an important tool in discovering how Nature works. Galileo called it the language of science. Our current mathematical model works so well, it is tempting to take the model not only as representing reality but *being* it! Some caution is needed because more than one mathematical model may represent the same incomplete set of data. Simpler, more "beautiful" models have generally proven best and are favoured by theoretical physicists, but no mathematical model should be assumed to give *the true physical description* of Nature. As experimental data becomes more accurate and complete, the current model must be tested, refined if possible, and replaced if necessary.

The Ptolemaic model of the solar system was improved with epicycles and several other additions. With these improvements, it was able to make accurate predictions of most observations, but its refinements became cumbersome, and once Galileo observed the heavens with his telescope, the Ptolemaic was no longer tenable. Even the strong backing of the Church was insufficient to maintain it against the simpler Copernican model, although this model itself needed some refinements, such as replacing circular planetary orbits with elliptical ones.

Evolution of the Cosmos

Our current models have been validated and extended by impressive astronomical observations and laboratory experiments. [slide 11] We can trace the evolution of the Universe back to an explosive origin almost 14 billion years ago. Hydrogen atoms were formed about 380,000 years after the big bang, these collected into stars and billions of stars formed galaxies. Stars manufactured light elements from the hydrogen, producing energy and light in the process. Supernovae made heavier elements and produced neutron stars and black holes. Collisions of neutron stars produced massive amounts of gold, platinum, and other really heavy elements, as we saw in a break-through observation of both electromagnetic and gravitational waves in 2017. All this material formed third (and higher) generation stars and their planets and provided the conditions for life.

To tie this all together and relate cosmic evolution to time, the hyperinflationary period initiated by the big bang created not only space, but spacetime: both space and time! There may have been no time before the big bang! Such ideas are still being fleshed out by theoretical astrophysicists.

We celebrate not only this amazing evolution, but also the creation of thinking life that could work out how this all happened. As we discover more about Nature, new puzzles arise. The critical problems of current physics involving dark matter and energy as well as problems unifying Einstein's gravity and quantum theory, may indicate an approaching paradigm shift in parts of our models of reality.

[slide 12] May humanity celebrate this revelation by preserving a continuing evolution of understanding and compassionate life!