Astronomy Bizarre
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Wheeler
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Review Sheet 5
Quantum Gravity, Strings, Branes, and Hyperspace

Conflict between Gravity and Quantum Theory – Need quantum gravity to understand the singularity at the birth of Big Bang and in black holes, worm hole time machines, and quantum foam.

Planck scale – the tiny scale (10^{-33} cm, 10^{-43} s, 10^{93} gm/cm^3) where Einstein's theory and quantum theory are predicted to collide, the implied "size" of the singularity. Strings are somewhat larger than this.

"Quantum Foam" – word description (in absence of quantitative mathematical theory) of the expected nature of space-time on the smallest level (Planck scale) where quantum effects compete with space-time curvature.

At the quantum foam level it is not just the position of an object in otherwise uniform space that is uncertain (the classic quantum view), but the nature of space itself must be quantum uncertain.

Carl Sagan's "Contact" - Catalyst of work on wormholes and time machines.

Exotic matter - like the tension in a rubber band only with an energy greater than the mass energy, mc^2. Rather than adding to the weight of gravity like ordinary pressure/energy, the "negative pressure" of exotic matter repels against gravity (related in principle to Dark Energy).

Worm holes - exotic matter could, in principle, be used to hold off the effects of gravity and maintain the opening of a worm hole to connect two distant places in the Universe.

Shape of a wormhole - a three dimensional worm hole is not a "tube" as it appears in its two-dimensional embedding diagram, but rather a spherical space that can be approached from any direction.

Travel through a worm hole - one would proceed "straight" along a radius toward the center of the spherical space, but eventually find oneself moving away from the center and out into normal space, without ever changing direction.

View inside a wormhole - one should be able to see through a worm hole looking along the radius toward the center of the spherical space, but if one looks "sideways," perpendicular to the radius, one would see light that traveled around the highly curved space and returned to its origin.

Time and Special Relativity - if two observers are in uniform motion, each will see the other aging more slowly.

The twin paradox - if one twin remains stationary, and the other is subjected to an acceleration, either by traveling out and back or by venturing in a stronger gravity, then the twin who has experienced the acceleration, not uniform motion, will be absolutely younger.

Time machines - if worm holes exist, then they can, in principle, be used to make a time machine through the twin paradox mechanism. After one end of the worm hole is accelerated and returned, it will thereafter be absolutely younger than the mouth of the worm hole that remained at rest or in uniform motion.

Grandfather paradox - the notion that since time machines can violate causality ("cause" before "effect") a situation, like traveling back in time to kill your Grandfather, can arise that can be neither true or not true.

Novikov consistency conjecture - the conjecture that physics must be self-consistent and simply does not allow paradoxes even if time travel exists.

The pool ball crisis - the idea that a simple mechanical example could be invented to show that time machines will always come with paradoxes. A pool ball rolling into one end of a worm hole can come out in the past and hit itself before it goes in, thereby preventing it from entering the worm hole in the first place.

Resolution of pool ball crisis - Novikov and Thorne and associates showed that the pool ball problem satisfies the consistency conjecture. No case was found that gave rise to a paradox. The past and future pool balls could just "kiss" with a slight deflection of the trajectory, but a "hard" collision with the first pool ball being knocked away from the worm hole, thus giving a paradox, simply did not and cannot arise.

Free will and time machines - if time machines exist and the consistency conjecture holds, then is everything pre-ordained, and there is no free will?

Changing the future - if the consistency conjecture is true, then the future cannot be "altered" by the acts of a time traveler who went back in time.

Vacuum energy and time machines - vacuum quantum energy could travel into the past, pile up, and create such a high gravity that any worm hole would be quickly sealed. This issue cannot be resolved without a complete theory of quantum gravity.

Classic quantum theory – particles are points (electrons) that also have quantum wave-like properties, or are made up of point particles (protons are made of three quarks). The notion of particles as strings changes that picture in a fundamental way.

String Theory – "particles" are actually strings in a space of 10 dimensions plus time. The theory "contains" Einstein's General Relativity and has been used to compute the entropy and temperature of a black hole from basic theory.

Fundamental forces – according to string theory all the basic forces, electricity, magnetism, strong force, weak force – are confined to regular three-dimensional space. Gravity – the creature of space-time – can "leak" into higher dimensions, if they exist.

Early history of string theory – recognition that equations that corresponded to the strong nuclear force also described entities, strings, that could stretch and wiggle.

Quantum View of Forces – the quantum theory views (mathematically) all forces as resulting from an exchange of particles, with different particles representing different forces (electromagnetic, weak, strong).

Strings and space – the shape of the wrapped-up spaces determine how the strings can vibrate and hence what particle they represent.

Extra dimensions – in the first version of string theory, all the extra dimensions were "wrapped up" on a scale comparable to the Plank Scale. Thought to be necessary so that gravity would have inverse-with-distance-squared behavior.

Calabi Yau – a space – special 6-dimensional geometry that could be the shape of the wrapped-up dimensions.

Finite extra dimensions – the realization, guided by string theory, that some of the extra dimensions could be "large." Experimental limits would not rule out one millimeter. Only gravity could go there.

Branes – surfaces or membranes in higher dimensional space suggested in string theory. Any 2D surface is a 2-brane in our 3D space. In higher dimensional spaces, higher dimenstional "slices" are possible, "P" is the dimension of the brane, hence P-brane.

Bulk – the large (not wrapped-up) *extra* dimension in which our 3D Universe is hypothesized to exist. There could be parallel 3D universes (3-branes) floating in the 4D bulk (with 6 wrapped-up dimensions at each point in those spaces).

Forces – the forces of standard quantum theory (electromagnetic, weak, strong), are stuck on branes (string loops with both footprints on the brane), hence within the 3-brane of our Universe.

Gravity is a creature of space, it can leak into the 4D bulk. This could make gravity seem weaker than the other forces.

Graviton – a "closed" loop of string that can leave our 3D brane and float in the 4D bulk.

Small leakage of gravity – just as gravity declines like r^{-2} in 3D space, it could decline like r^{-3} in 4D space (clearly wrong!). Recent realization that it could leak more slowly even if the 4D bulk existed brought a revolution in thinking about large extra dimensions.

Brane world – further work showed that even if one of the extra dimensions is very large, gravity might still be nearly confined to the 3-dimensional brane of our Universe. Our Universe could be a 3-D brane floating in a huge surrounding 4-D bulk. Our Universe might be expanding into this 4-D bulk.

Ekpyrotic Universe - the idea that another 3-D brane floating in the 4-D bulk collided with ours creating the huge, but finite, temperatures that launched the Big Bang without requiring any "singularity."

Brane-world theories – models of our Universe and cosmology exploring the possible existence and effects of a large extra dimension.

Tests of string theory – traces left over from Big Bang, evidence of extra dimensions, the bulk.

Newton had concept of "force" of gravity, Einstein's theory (which is mathematically the same as Newton's for weak gravity), had concept of gravity as curved space, string theory (which is mathematically the same as Einstein for safe distances from any singularity) has concept of gravity as a quantum force for which the messenger particles are gravitons propagating in 10 spatial dimensions.

String theory cannot yet tell us what the "singularity" is within black holes or at the beginning of the Big Bang. One idea, the singularity within a black hole represents the birth of a new Universe.

Dark Energy – the space-time fluctuations of the quantum foam might give an energy to empty space, but simple estimates give the wrong answer for the Dark Energy by a factor of 10^{120}. Recent theories explore whether the Dark Energy could be some manifestation of the 4D bulk, other 3D branes?

TERM-SPANNING THEMES

Quantum uncertainty – uncertainty pressure, vacuum energy, Hawking radiation, Dark Energy, quantum gravity

Stars to Cosmology – binary star evolution → white dwarfs → Type Ia supernovae → accelerating Universe → Dark Energy

Core collapse – thermal pressure, massive stars, supernovae, neutron stars, black holes, gamma-ray bursts, first stars, end of Dark Ages

Gravity – stellar evolution, curved space, black holes, singularities, worm holes, quantum gravity

Dimensions – zero, one, two, three, four, ten, embedding diagrams, curved space, hyperspace

Theories of Physics – Newton's gravity, Einstein's gravity, quantum theory, string theory, quantum gravity

Accretion disks – cataclysmic variables, dwarf novae, classical novae, x-ray transients, x-ray bursts, black hole x-ray novae, jets