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The History of Cosmology and its Many Surprises

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1. Introduction

I will tell you how the world began and how it will end, how life came to exist here on a little planet around an ordinary star in an ordinary galaxy, and how human beings came to know this amazing story. In the last century we have gone from ignorance and speculation to detailed knowledge, from verbal combat sport to a generally-accepted description and set of equations.

Now, looking back at this history, it's clear that our story has developed almost entirely from observations made with ever more powerful equipment. Now that the story is known, it is interesting to find the precursors, the wise ancients who already knew. But the main story is of advancing technology, often driven by societal demands for defense, communication, and entertainment. It's also the story of brilliant and intense personalities like Galileo, Newton, and Einstein. And then there is George Ellery Hale, who built in sequence the four then-most powerful telescopes in the world, starting with the Yerkes 40 inch refractor, and ending with the Palomar 200 inch reflector.

Hans Lipperhey in the Netherlands made a telescope in 1608 and tried to patent it; the patent application record still exists, but the patent was rejected. Soon the word was out and the already-famous Galileo Galilei started making and selling telescopes to the rich and powerful. And then, he pointed his best equipment at the Moon, at Jupiter, Venus, and Saturn, at the Sun, and at the Milky Way, and suddenly modern astronomy started off. Galileo had to improve the initial lens-making technology substantially to be able to make his discoveries and he kept the technical details secret.

Since then, lens technology improved, achromatic lenses were made to compensate for the colors found in images, Newton developed the reflecting telescope, and the race was on for bigger and better. Then came the photographic age and the electronic age and the space age, and observing speed continued to grow exponentially with time. The equivalent of Moore's law for telescopes shows that telescope power has grown about 8 orders of magnitude in 10 decades, for a doubling time of about 4 years. It's slower than for the semiconductor industry but it's still amazingly fast. The next steps are the James Webb Space telescope, which will be unfolded in space, and huge segmented telescopes on the ground with software to compensate for the turbulent atmosphere.

Martin Harwit wrote a lovely book about what makes new discoveries possible in astronomy. It's called "Cosmic Discovery" and it shows that a pretty large fraction of the major phenomena in astronomy were discovered by people who weren't looking for them, or who were using equipment designed for other purposes, especially military ones.

2. Looking back in time

Astronomers are the only scientists who really do look back in time. We do it by looking at distant objects, and we see them as they were when they emitted the light we are receiving; we don't see them as they are now. Geologists look at old rocks, paleontologists look at old bones, historians look at old records, but astronomers look at "old" light. So to know how far back in time we are looking, we only need to know distances, since we know the speed of light to great precision. (In fact, it is now a defined constant, since light is used to define both the scales of distance and of time.)

3. Measuring distance

So now we need to measure distances. The first and most fundamental way is the same method used by ancient Egyptian surveyors and thoroughly documented by Euclid: similar triangles (with the same angles) have sides in the same ratios. Because the Earth spins and moves, it is possible to measure the small angles of very long triangles to the nearest stars, and get their distances quite precisely. But for more distant objects, the angles are too small to measure directly. Then we are forced to rely on relative brightness: if we see two identical objects, and one is fainter than the other, then we conclude it is farther away, according to the inverse square law: (Brightness A/Brightness B) = (rB/rA)2. That works very well, except of course it's hard to know whether two objects that look "identical" really are. Quite a lot of the effort of astronomers for centuries has been devoted to this question.

4. Hubble discovers the universe

In the early part of the 20th century, the new 100-inch Hooker telescope (built by George Ellery Hale with Hooker's money) on Mount Wilson in California was the newest most powerful tool. For the first time, we had a telescope powerful enough to show (photographically) that there are individual stars in the Andromeda Nebula and other distant galaxies. Previously the galaxies were just milky fuzzy things that might have been glowing gas clouds (hence the name, from the Greek word for milk). Edwin Hubble was fortunate and determined enough to discover something even more surprising: some of the stars in the Andromeda Nebula change in brightness in a repeating cycle of a few days. He thought they were the same type of star found in the Milky Way with similar behavior, and hence was able to measure the distance to the great Andromeda Nebula. Suddenly, our Universe was immense, with galaxies millions of light years away, and not just our own Milky Way a few tens of thousands of light years across. So Hubble can be fairly said to have "discovered the Universe". It was a tremendously startling discovery, one which was really not expected at all.

5. Einstein invents Relativity

A little before Hubble did his work, Einstein "discovered" or maybe better "invented" relativity theory, both special and general. The first discovery, in 1905, was that space and time are unavoidably mixed together, not separate and absolute. This discovery was forced upon an unwilling community of physicists by the astounding discoveries that a) there is no ether to propagate light, and b) the speed of light can be predicted from Maxwell's equations based on measurements of electrical and magnetic properties taken with objects that do not move. The logical implication is that the speed of light must be independent of the rate of motion of a laboratory. And the mathematical implication of that statement is the Minkowski metric, with all the surprising implications of special relativity, including E = mc2. Einstein was right, and though generations of skeptics still try to prove him wrong, they have all failed.

In 1916 Einstein gave us a second conceptual breakthrough, one that was not yet required by measurements. The equivalence principle holds that the mass that is responsible for inertia is the same as the mass that is responsible for gravitation. Einstein showed that this idea is a natural consequence of a general picture in which gravitation operates by curving space and time, and so far Einstein's picture is still working perfectly, though new more serious generations still try to find holes in the theory.

Einstein applied his General Relativity to the universe as a whole, and saw that the gravitational forces would cause it to contract. So he added an optional constant of integration in the solution of the differential equations, which would be a kind of anti-gravity that could hold up the universe against the gravitational force. Now we call this the Lambda constant, Λ.

6. Arguing with Einstein

But other physicists argued with Einstein. It was pretty clear immediately that Einstein's neat balance was unstable. Russian mathematician Alexander Friedman showed in 1922 that the natural answer was one with a rapidly expanding space-time, but he died in 1925 without knowing he would be proven right. Belgian priest and mathematician Georges Lemaître got the same answer in 1927, and Einstein berated him as a bad physicist. Lemaître called his early universe the "primeval atom".

7. Doppler shift for velocities

To know the next bit of the story, we need to know how to measure velocities. Most astronomical objects do not move perceptibly across the sky, because they're too far away. But all of them move towards us or away from us, causing a Doppler shift of their wavelengths. An object moving towards us appears bluer and its spectrum is shifted to shorter wavelengths, while an object moving away is redder and has longer wavelengths. Fortunately Nature has given us the known standard wavelengths of chemical elements in the spectra of stars, so we know what the stars would look like if they weren't moving.

8. Hubble chart: (v ∞ r)

In 1929, Edwin Hubble succeeded in measuring enough velocities of distant galaxies to make a chart of velocities versus distance. The astonishing story is that almost all of them are moving away from us, with speeds about proportional to their distances. And if this trend is correct, then dividing the distance by the speed gives an apparent age of the universe, the time at which all the galaxies would have started together. Hubble got the wrong age though – his distances were wrong, because the standard pulsating stars that he saw in distant galaxies were not the same type as the standards he knew in the Milky Way with known distances from trigonometry. It took another few decades to find and correct the mistake. But at any rate, his discovery was headline news around the world, a remarkable thing to find the expanding universe in the same year that the worldwide economy collapsed.

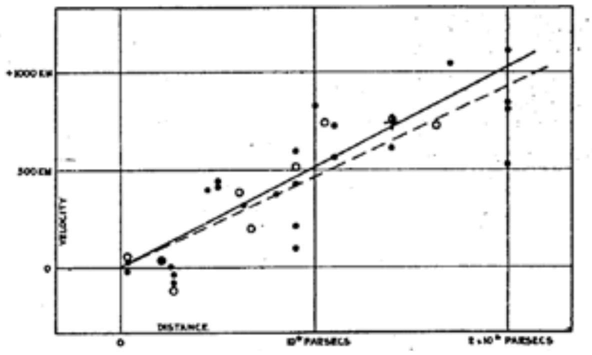

Figure 1. Hubble found that distant galaxies recede from us with a speed proportional to distance.

9. Predictions of the Big Bang – Gamow, Herman, and Alpher

Then came World War II, and scientists worldwide stopped what they were doing and joined the war. When it was over, US scientists had a big reservoir of new data about nuclear physics, from weapons work, and a huge stockpile of new capabilities in electronics, from radar work. Now it was possible to apply nuclear physics to the properties of the expanding universe. George Gamow at George Washington University in Washington, DC had brilliant ideas and started working out the details. He recruited Ralph Alpher and Robert Herman, and they found they could compute the temperature of the universe. The whole universe should be filled with microwave radiation that is the faint remnant of the primordial heat of the great explosion. The got a number of 5 K, fairly close to the modern number of 2.725 K considering the uncertainties they faced. They published their predictions but at the time nobody tried to measure the temperature. It was thought to be too difficult, and there were plenty of other experiments to try.

10. Your chin is made of exploded stars

By the way, one of the consequences of the Big Bang theory is that the early universe produced only hydrogen and helium, with traces of lithium and beryllium. That means that the chemical elements of life were not made in the Big Bang. So, how were they produced? We know now that they come from nuclear reactions inside stars that have since exploded and recycled their material back into outer space, and those same atoms have regrouped and formed planets like the Earth. So when you look in the mirror in the morning and you see your chin, you are looking at the interior of some star that exploded. It makes a person think a bit! This story wasn't so simple: it took many years to get the general picture right in the 1950's, and even now the details are not working out according to how we think stars explode. But there doesn't seem to be any doubt that we are made of exploded stars.

11. Penzias and Wilson and the Nobel Prize

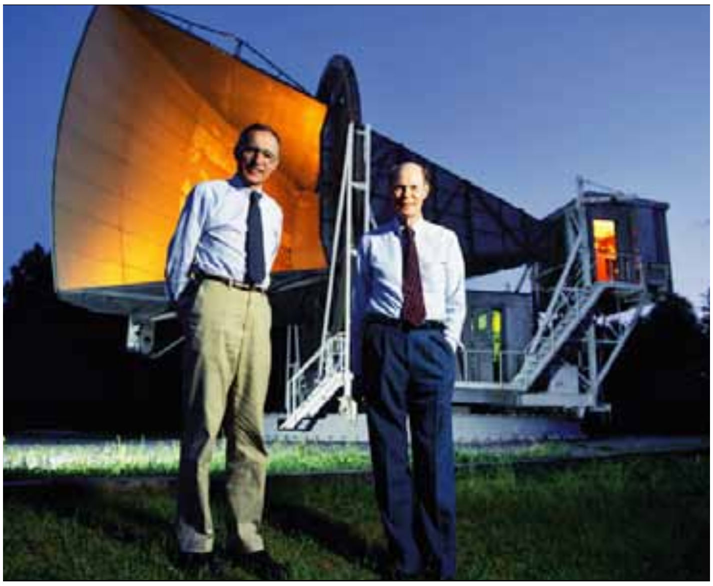

Figure 2. Penzias and Wilson with their horn antenna used to discover the microwave heat of the Big Bang.

Well, the cosmic microwave background radiation, the primordial heat, was finally discovered by accident, by Arno Penzias and Robert Wilson, using equipment designed for another purpose (see the Cosmic Discovery book by Harwit). At Bell Telephone Labs in New Jersey, they had built a giant horn-reflector antenna to do some early satellite communications experiments and some radio astronomy. But their equipment showed a little too much noise, and they were determined to find out why.They had shown that it came from outside the antenna and not from the Earth's atmosphere, and it was always the same brightness, so they were almost all the way to the cosmic interpretation. Then, they learned of a new experiment from a few miles down the road at Princeton, where a team was looking for the cosmic background radiation. Both teams published their papers in 1965. Penzias and Wilson were not convinced at first about the cosmic interpretation, until they saw it described on the front of the New York Times. The discovery confirmed the predictions of the Big Bang theory, but supporters of the Steady State theory didn't give up until much later. A huge rush of further measurements showed that the background radiation does indeed come almost equally from all directions, as it should if it is cosmic, and that it has about the right blackbody spectrum, as it should if it comes from the cosmic pressure cooker of the first moments of the expanding universe. The Nobel Prize was given for the discovery in 1978.

12. Theory of cosmic inflation


Figure 3. Alan Guth, creator of the first theory of cosmic inflation.

In 1980, there were still some big puzzles, which had existed for decades. What could possibly have made the cosmic background radiation so completely uniform? All tests had failed to find any hot or cold spots in it, except for a simple Doppler effect due to the Earth's motion in the cosmos. So it seemed that somehow the cosmos had gotten set up in an extremely puzzling way, with no physical process we could imagine that would make the cosmos so uniform. An answer was provided by Alan Guth in January 1980 and extended by many others: the idea of cosmic inflation. According to this story, the universe started off with an unstable state called a "false vacuum" and expanded exponentially, doubling in size about 100 times in the first 10-32 sec. This expansion supposedly took a small volume of space, smaller than the size of a softball, and made it much bigger, to become the whole expanding universe we see today. And according to hypothesis, the primordial softball existed long enough for equilibrium processes to make it uniform. When I heard this theory the first time I was pretty skeptical. But it fits neatly into other puzzles of high-energy physics, and is now extremely popular. It has even become possible to test some of its predictions.

So we can now illustrate the whole early history of the universe with a series of ovals. First, we have the primordial material, a few cm in size, doing whatever it does to start expanding. Second, we have quantum mechanical processes in that material, producing hot and cold spots in the heat radiation. Third, we have stars and galaxies forming from the primordial gases. And finally, we have the galaxies of today.

13. The COBE satellite

My own involvement with this story began in 1970 when I was a graduate student at Berkeley looking for a thesis project. The CMB had just been discovered 5 years before, and many attempts were being made to measure it, to find its spectrum and to verify its uniformity.

Charles Townes and Paul Richards and Mike Werner were already starting an experiment to make a mountain-top measurement and I said I wanted to join. That experiment worked but the results were not very precise. The next step was to fly a balloon-borne instrument that Richards designed. On the first flight the payload did not work, for at least three different reasons related to the cold conditions at an altitude of 130,000 feet. Nevertheless I was allowed to write a thesis, and afterwards I decided to try something else, since this kind of work was so difficult. I was fortunate to find a postdoctoral position with Pat Thaddeus at the Goddard Institute for Space Studies in New York City, and I started to learn radio astronomy. But a few months after I finished my thesis, NASA requested proposals for new satellite missions and I told Pat that my thesis experiment would have been a lot better if it could have been done in outer space. So we assembled a team and sent a proposal, and 15 years later the mission was launched. It was designed to measure the spectrum and anisotropy (nonuniformity) of the cosmic microwave radiation, and to hunt for the collected light of the first galaxies, even if they are too faint to be seen individually. I was the head NASA scientist for the mission, and was in charge of the instrument to measure the spectrum.

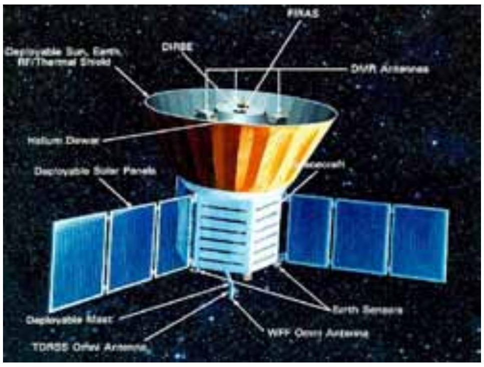

Figure 4. Cosmic Background Explorer (COBE) satellite, launched in 1989 to measure the cosmic microwave radiation of the Big Bang, and measure the combined light of the first galaxies.

14. CMB spectrum

Our first scientific result is the spectrum shown here, based on 9 good minutes of data taken in the first weeks of flight. The theoretical prediction is shown as the smooth curve, and the experimental results are the little boxes, which all lie nicely on the curve. When the chart was shown to the American Astronomical Society it received a standing ovation.

Not only is the result important and beautiful, it ended decades of concerns that maybe the spectrum was distorted and the whole big bang picture was wrong. Eventually the error bars were reduced to 50 parts per million by Dale Fixsen's amazing

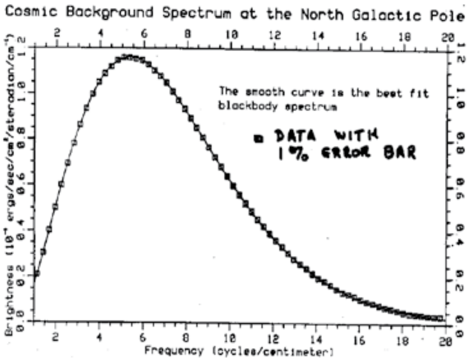

Figure 5. First measurements of the cosmic microwave background radiation spectrum from the COBE satellite. Observations (boxes) all fall precisely on the theoretical prediction (a blackbody curve), confirming the Big Bang theory.

calibration software, and the temperature is known to be 2.725 ± 0.001 K. When I first saw this spectrum, I was not surprised, and it didn't feel like a discovery – I had convinced myself that none of the theoretical predictions for anything else made any sense, so this had to be the answer. But of course, a good experimenter must try to be neutral, and not to let prejudice affect perception and measurement. I didn't fully appreciate how important it was until later, when really good theorists like Martin Rees told me they didn't expect it. The original doubts about the Big Bang are now erased but the CMB spectrum is still of interest; measurements at wavelengths longer than 1 cm are in progress by the ARCADE team led by Alan Kogut, and are showing some significant excesses possibly due to a new population of extragalactic objects.

15. The cosmic anisotropy

The next major discovery from the COBE team was that the cosmic background radiation really does have lumps and bumps, or as some more or less reverent people could say, the face of God has pimples. The blobs seen by the COBE satellite are about 7 angular degrees in size, because that's the resolution limit of the equipment, and on average they amount to about 30 μK, or a part in 100,000 of the total brightness. When Stephen Hawking saw the chart at the lower right, he said it was the most important scientific discovery of the century if not of all time. At first I thought that was nice but exaggerated. I think what it means is that if the bumps had not been found, we would not be able to understand how we exist. It now appears that the bumps are mostly caused by cosmic dark matter and that their gravitational fields caused the formation of galaxies and clusters of galaxies from the primordial gas. So the bumps are important to explain our history, as well as for the evidence they provide about the forces of nature in the most extreme conditions imaginable, in the Big Bang itself.

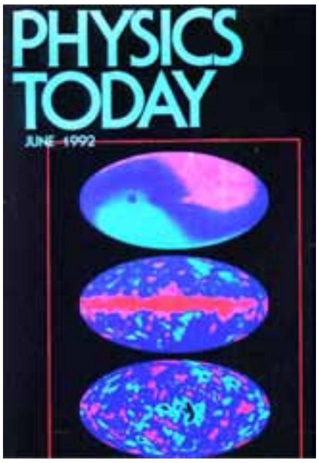

Figure 6. Maps of the microwave sky made with the COBE mission. Top oval is the whole sky, showing Doppler shift from motion of Earth relative to cosmos. Middle oval removes that effect and shows (in red) the radiation of the Milky Way galaxy. Bottom oval shows faint blobs, 7 degrees in size, in the cosmic background radiation from the Big Bang. Warm (red) areas are slightly less dense regions in the Big Bang and will develop into cosmic voids. Cool (aqua) areas are slightly denser and will develop into clusters of galaxies.

16. Surprises!

Surprises are part of what makes astronomy exciting, which is still primarily a measurement-driven science. The fact that the universe is accelerating (again) was not anticipated by most astronomers, who took the viewpoint that acceleration would be an unneeded complexity. But I took the viewpoint, as did some, that since there was no evidence against it, it might be possible. My view is that at least in astronomy, the more one looks,

Figure 7. (left to right:) Perlmutter, Riess, and Schmidt receive the Shaw Prize in 2006 for discovering the accelerating universe.

the more complex the universe appears, so Occam's Razor is a terrible guide to the truth. The cosmic acceleration began about 5 billion years ago and was detected using brightness measurements of distant supernovae of type Ia. These are almost standard candles, the same brightness wherever they are found, and the most distant ones are about 20% too faint to match the predictions without acceleration. So they are about 10% farther away, meaning that the universe is older and larger than had been thought just from the local rate of expansion today. The first team to discover this effect was the High-z Supernova Search Team team, led by Brian Schmidt, and the actual discovery was made by Adam Riess. It was soon confirmed by the Supernova Cosmology Project team led by Saul Perlmutter. Schmidt, Riess, and Perlmutter received the Shaw Prize, sometimes called the Asian Nobel Prize, in 2006 for their discovery.

17. WMAP image

The CMB results from the COBE mission were greatly improved by the successor mission, the Wilkinson Microwave Anisotropy Probe (WMAP). Built by Goddard Space Flight Center and Princeton University, and led by Chuck Bennett (then at Goddard) as Principal Investigator, the WMAP provided much better sensitivity and angular resolution than the COBE. Orbiting the Sun-Earth Lagrange point L2, the WMAP is well protected from interference from the Sun and the Earth, and its differential designs protected it from almost all types of internal problems. The WMAP showed that the now-standard model with dark matter and the cosmic acceleration term (ΛCDM) fits all the measurements extremely

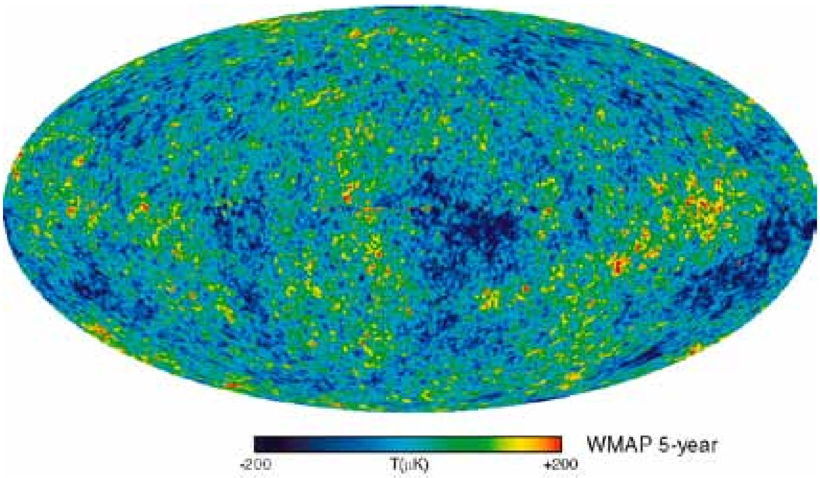

Figure 8. WMAP image of cosmic microwave background radiation temperature, from 5 years of data. Statistical properties of the speckles are used to determine densities of ordinary and dark matter and the cosmic dark energy to extraordinary precision.

well, and in that context allows determination of the cosmic parameters to an accuracy in the range of percents. The WMAP results are now the gold standard for textbooks and are among the most cited of all papers in science. And all from analyzing the statistical properties of little random-looking patches on a map!

18. Changing mix of mysteries

Among the major mysteries of the universe is the changing mix of various flavors of matter, radiation, and dark energy. In the early universe, electromagnetic radiation, ordinary matter, neutrinos, and dark matter all had comparable densities, the temperatures were high enough that matter particles had velocities near the speed of light, and the dark energy had negligible importance relative to the very high densities of matter and radiation. In the modern universe, electromagnetic radiation and neutrinos have cooled to low temperatures and have negligible gravitational effect, ordinary matter and dark matter combined add up to less than a quarter of the total stuff of the universe, and the balance is made of dark energy, whatever that may be.

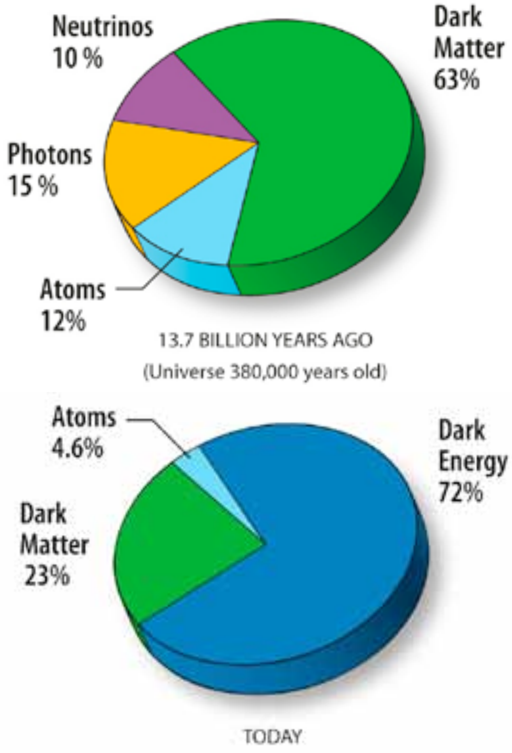

Figure 9. Left, mix of dark matter, atoms, photons, and neutrinos when univers was 380,000 years old. Right: Mix of atoms, dark matter, and dark energy now.

19. Future discoveries in cosmology

What discoveries are yet to come in cosmology? First, there is hope that the dark matter particles, whatever they may be, will be detected in laboratories. Either natural dark matter particles will react with ordinary matter in some detector, or dark matter particles will be recognized in the collision debris from an accelerator experiment at the Large Hadron Collider or some future successor. To the discoverer of dark matter particles will surely come fame and glory, and as of this writing there are already tantalizing hints of a discovery. Second, there is a possibility that the meaning of the cosmic dark energy will be understood on the basis of some new theory of quantum gravity or string theory. Measurements are in progress to characterize the dark energy, especially to determine whether it acts as an Einstein Λ constant, or is variable in time. Third, there is the prediction that the cosmic microwave background radiation may be polarized slightly, with a signature of the effects of gravitational waves in the hypothetical inflation period in the first sub-sub-nanoseconds the expansion. Measurements of this polarization are already being attempted and a firm discovery of the gravitational wave effects would be both a stunning experimental triumph, and a profoundly important guide to the correct theory of quantum gravity. The detection or understanding of these three areas could well lead to three Nobel Prizes, or more!

20. The James Webb Space Telescope

The Hubble Space Telescope (HST) was designed at a time when astronomy was still young, and electronic detectors were barely in their infancy. Nevertheless, owing to exponential progress in semiconductor technology, four servicing missions to the Hubble have dramatically increased its capabilities. It is as though we had a series of four telescopes, each ten times more powerful than the last. As a result, observations from the HST have enabled spectacularly surprising discoveries. To me the most interesting are the discovery of the cosmic dark energy and the first direct images of planets around other stars. The first was not even a subject of discussion when the HST was designed, and the second would have been thought hopelessly difficult.

Now that the HST is mature and has been upgraded for the last time, what will be the next frontier? A committee report, "HST and Beyond" by Alan Dressler et al., brilliantly laid out the opportunities afforded by an infrared telescope in space. Such an observatory would be able to observe the most distant universe (redshifted by the expansion), the first objects to form from the primordial material, the formation of stars near the Sun, and the most distant and ancient remnants of the formation of the Solar System. Studies for such a telescope were begun in October 1995, and launch is now planned for 2014.

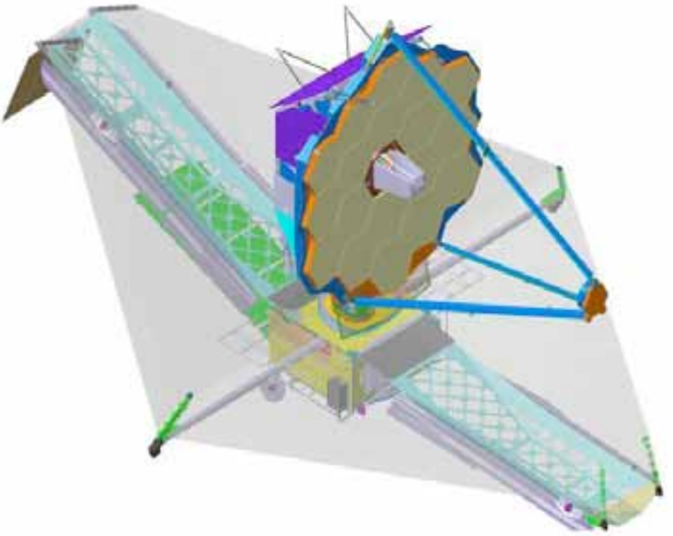

Figure 10. The James Webb Telescope, built by an international team of NASA, ESA, and CSA, will observe infrared wavelengths using a deployable telescope with an aperture of 6.5 m.

The new observatory was first called the "Next Generation Space Telescope" in honor of the fictional Star Trek, but was renamed the "James Webb Space Telescope" in honor of the real second administrator of NASA, the man who organized the United States to send a man to the Moon in just 8 years. It would take us more than 8 years today just to decide whether we could do such a mission!

The JWST is to be far larger than the HST (a 6.6 meter mirror versus 2.4 meters), and will observe at much longer wavelengths (from 0.6 to 28 micrometers versus HST's 0.1 to 1.7 micrometers). In fact the telescope is so large that it will not fit into any available rocket and must be folded

up for launch. It is being developed by an international partnership led by NASA with major contributions from the European and Canadian space agencies.
What will be the greatest and most important discoveries of the new telescope? Naturally nobody knows. But astronomers have found that when new equipment is capable of making an observation a hundred times faster or better than before, something remarkable always turns up. One can only guess, but some guesses might include:

- Discovery of early generations of stars that consume dark matter, strange matter, etc.,
- Discovery of the process that has placed a black hole at the center of almost every galaxy,
- Understanding, after generations of effort, what governs the formation of stars from gas and dust clouds, and what sets the masses and rotation rates,
- Understanding the formation of planets and the evolution of planetary systems.

The study of exoplanetary systems has become one of the most exciting topics of astronomy today, partly because as David Bennett likes to say, the theory of planetary formation is still awaiting its first successful prediction. In other words, almost everything we know about exoplanets has been a surprise derived from observations. We have planets orbiting so near their stars that they are called "roasters", reaching temperatures well above 1000 K. We have found planets of all sizes from super-Jupiters down to some only a little larger than the Earth. About 10% of stars like the Sun seem to harbor planets. And we already know something of the chemistry and physics of planetary atmospheres.

The famous Drake Equation lists the factors we would need to know to calculate the number of intelligent civilizations in the universe. Many of the factors are unlikely to be measurable, and are far outside astronomy: for instance, how long does an intelligent civilization persist after it develops? But many others are measurable by astronomical techniques: how many stars have planets, how many of them are the right size to be Earth-like, how many of them are at the right temperature to support life, and eventually, how many of them have oxygenated atmospheres from photosynthetic life? Perhaps the life sciences will tell us some of the other factors: how long does it take for life to arise on a hospitable planet? How long does it take for complex life to develop from primitive life? Is it necessary for life to have solid land as well as liquid water? Estimates from the Drake Equation have led some people to conclude that Earth may be unique. But even if intelligent life is relatively common, we do know that it will be difficult or impossible for us to find it with any techniques we can imagine. We already have the technology to communicate across our Milky Way galaxy, if we can match the sending and receiving equipment. But without the ability to know what equipment and codes the other party is using, the odds of discovery of such communications are microscopic. So in practical terms, we are very likely to be alone, receiving no signals from other intelligent civilizations. Nevertheless, just imagine the experience of discovery of:

- an Earth-like planet around a Sun-like star (likely in the next few years),
- an Earth-like planet with an oxygenated atmosphere (a sign of photosynthetic life),
- an Earth-like planet in a system resembling the Solar System, or
- an Earth-like planet with oceans and continents.

All of these discoveries are possible in the next few years and decades. The Kepler mission, launched by NASA in 2009, is designed to find Earth-like planets around Sun-like stars, and it is working well. One can imagine that perhaps it will be necessary to hold scientific meetings in sports arenas when this sort of discovery is announced!

Acknowledgements

This work is supported by NASA and the James Webb Space Telescope Project. I appreciate the gracious hospitality of the EURESIS at San Marino. The COBE science team of 19 people were part of the total COBE team of over 1500. The JWST team currently employs over 2000 people worldwide, and the JWST observatory will be used by thousands of astronomers in their search for the nature of the universe.

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