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Professor Trimble has published more than 450 papers, reviews, and book chapters and is currently an Associate Editor of *Reviews of Modern Physics*. She was a Sloan Fellow (1972–1974), Maryland Academy of Sciences Outstanding Young Scientist (1976), and recipient of the National Academy of Sciences T. Murray Luck Award (1986). Dr. Trimble was White Lecturer (Otterbein College, 1995), Dean Lecturer (California Academy of Science, 1996), and John Schop Memorial Lecturer (San Diego State University, 1999).

Dr. Trimble is a Fellow of the Royal Astronomical Society, American Association for the Advancement of Science, and American Physical Society (APS). She also serves as President, Division VIII (Galaxies and the Universe), International Astronomical Union (2000–2003); Chair, Historical Astronomy Division, American Astronomical Society (1999–2001); Councilor and member of the Executive Board, APS (1998–2000); and Chair, Division of Astrophysics, APS (2000–2001).

Professor Trimble is the widow of Joseph Weber, the pioneer of gravitational radiation detectors.



Professor Trimble spoke at the Millennial Challenges Colloquium series on 10 November 2000. The text of “Astrophysics Faces the Millennium” follows.



Astrophysics Faces the Millennium

Virginia Trimble

About 750 years ago, the Dominican Saint Thomas Aquinas attempted to reconcile and merge Catholic Church doctrine with the Aristotelian philosophy that Europe was then just rediscovering. This worked rather better than you might have expected, with G.d as the prime mover of the celestial spheres and so forth, and provided the background against which the next four or five centuries of science arose and often struggled. Indeed, it is possible to describe many of the most important astronomical discoveries from about 1500 right down to the present in terms of how they violated Thomistic principles. Probably one could describe them all that way, but not in 3500 words or fewer.

Most discussions of the century or millennium in science seem to pick a “top 10.” I have selected seven here, a magic number more in keeping with the spirit we will be violating later (see #6). They are arranged chronologically, in the order in which we now (with 20-20 hindsight) perceive the contradiction of observational data with doctrine to have become inescapable.



Saint Thomas Aquinas

#1 THE IMMUTABILITY OF THE HEAVENS

The word “secular,” with its dual meanings of “changing monotonically with time” and “not religious,” preserves the core of this principle of immutability. Only cyclical, periodic changes were expected in the heavenly realms beyond the lunar sphere. Accordingly, lightning, aurorae, meteors, and comets were all regarded as atmospheric phenomena, and rightly so in three of the four cases. Three things came together to push change out beyond the orbit of the Moon: the nova stella (“new star”) of 1572, the comet of 1577, and the extraordinarily careful and precise measurements of positions in the sky by Tycho Brahe. He looked for apparent shifts of position of the nova and comet when the rotation of the Earth carried him a few thousand miles through space. That shift had already been measured for the Moon. It was undetectable



Tycho Brahe

for the nova (now known to have been a supernova) and comet. They were truly mutable heavenly bodies.

Since then, it has gradually become evident that all astronomical objects change on every timescale permitted by the laws of physics, including some very rapid cases where you have to think hard

about exactly what special and general relativity mean. Many of those changes are well understood. The classic example is the evolution (changes of individuals, not populations) of stars, so that we can predict what our Sun will be doing 1, 5, or 10 billion years in the future, including, sadly, frying the Earth about 5 billion years down stream.

Other changes are not at all well understood. The most important is the process by which an extremely homogeneous and isotropic universe, whose smoothness we can still trace with the cosmic microwave background radiation, gave way to the extremely lumpy structures called galaxies, clusters of galaxies, stars, planets, and people. How the matter clumped to make these without rucking up the radiation is arguably the single largest unsolved problem in modern astrophysics. Hints of its solution are beginning to come to us from modern particle physics, and one vital step to be taken, perhaps quite soon, will be figuring out what (or what all) the notorious dark matter (see #7) is made of.

#2 THE PERFECTION OF CELESTIAL BODIES

The key word here is “immaculate” or unspotted, and perfection often also implied “perfectly circular or spherical” for the paths and shapes of the Sun and planets. The Moon, being on the edge between the divine and celestial regimes, quite naturally had light and dark areas on its surface. Sunspots had been seen in both ancient and medieval times, but were always attributed to relatively dark bodies, including Mercury and Venus, passing across the line of sight. Recognition of stains, spots, and asphericity came with the advent of the telescope. Galileo was among the first to report shadows cast by mountains on the Moon and to follow sunspots carefully enough to recognize that they belonged to the Sun itself and demonstrated its rotation. In the same decade, the 1610s, came Johannes Kepler’s

elliptical orbits for the planets, although Kepler initially used only pre-telescope data from Tycho, whose successor he had been at Prague.

Many issues in current astronomy are closely associated with these imperfections. After many decades of squabble, we recognize that mountains on the Moon result from impacts of comets and asteroids (and rightly worry about similar things happening on Earth), while what produced the topographies we see of Venus and Mars is still under discussion. Various surface irregularities have been variously attributed to flowing water, impacts, vulcanism, and perhaps to processes rather different from terrestrial ones.

Sunspots and associated flares are the sources of streams of fast-moving particles that hit our upper atmosphere, causing aurorae, but also shortwave radio and radar fade-outs, interruption of satellite communications, crashes of electrical power grids, and much else. Better ways of forecasting these events are urgently needed and being sought during the current period of maximum solar activity.

And, if you wish to descend to the profound, sunspots, flares, and all the rest exist because the Sun has a magnetic field. It is normally attributed to a dynamo (i.e., “I could do it in the lab if I had a big enough lab”), but the large-scale magnetism of galaxies and intergalactic space is more difficult to explain: perhaps giant dynamos, or lots of little ones merging, or, perhaps, what are called “primordial fields” (i.e., “I don’t know where it came from, but it’s been there a long time”). This is another area where “more work is needed.”



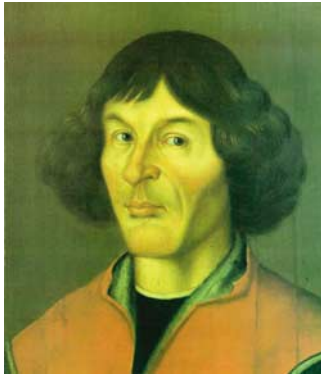
Galileo



Johannes Kepler

#3 GEOCENTRISM AND UNIQUENESS

Various Greek philosophers had played with Sun-centered, infinite homogeneous, and other universes now more to our taste. But Aristotle and Aquinas settled on Earth-centered, with heaven above and hell below, and nothing else like the Earth anywhere. The most thorough, early-modern working out of the

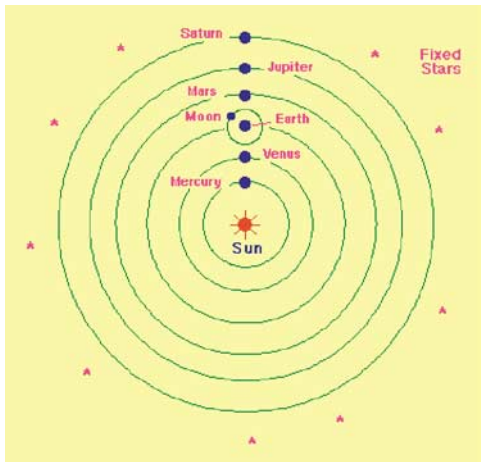


Copernicus

Sun-centered hypothesis and how the motions of the Sun, Moon, and planets in the sky might thereby be predicted was done by Nicolaus Copernicus, who sensibly arranged for his *De Revolutionibus* to be published just as he was dying, in 1543. Most of his contemporaries and immediate successors embraced his emphasis on

uniform circular motion but ignored his heliocentrism, the teaching of which was part of what brought Giordano Bruno to the stake in 1600.

Indeed observations did not then yet rule out a geocentric system. A big step came, again, from Galileo. First were the moons of Jupiter. Anybody could see that they went around Jupiter, not the Earth. The universe was not, anyhow, single-centered. Second, the trickier to interpret, were the phases of Venus, which, in Galileo's own cryptogram, imitate those of the Moon, from crescent to full and back again. Only a Cytherean orbit around the Sun makes this possible. The most direct evidence that we go around the Sun is parallax, the apparent shift in stellar positions as we move around



The Copernican universe

a circle of nearly 200 million miles in diameter each year. By the time parallaxes were first measured in 1838 (essentially simultaneously by three widely separated people), no one capable of understanding the issue was still in doubt.

Well, not geocentric then. But most astronomers concluded that the solar system must be quite close to the center of the system of stars called the Milky Way or Galaxy. Much of the problem was that they had not allowed for starlight being scattered and absorbed by

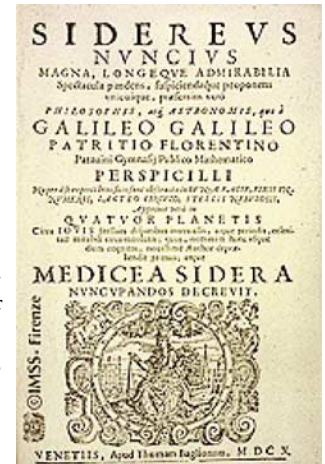
dust in interstellar space. (Where would you think the edges of the Earth were if you had never seen anything but a smoggy Los Angeles or Foggy Bottom day!!) And it was not until 1918–1920 that Harlow Shapley of Mt. Wilson Observatory showed that the galactic center was something like 20,000 times as far from us as the nearest stars. The recognition that space teems with galaxies and the Milky Way is pretty average, followed soon in work by Edwin Hubble, also of Mt. Wilson (and best known for the 1929 discovery that we live in an expanding universe, another tie to #1).



The Milky Way

Other planetary systems also exist. Observations of motions of stars along their directions toward and away from us started revealing little wiggles (due to mutual orbiting with planetary companions) in the 1990s as technology advanced to being able to measure them. First was the companion of 51 Peg in 1995. There are now a few dozen, including at least one case of three planets belonging to a single star, Upsilon Andromedae. All are “hot Jupiters,” with masses like the giants of the solar system, but at small distances from their stars. Indeed, no others could yet have been seen.

The outstanding questions are perhaps too obvious to mention. Does the existence of these hot Jupiters around 5% of nearby stars make the existence of Earth-like planets around the others more or less likely? What sorts of atmospheres and hydro-spheres will they have? And does anybody live there? We know how to make progress on all three issues, although interferometers in space will almost certainly be required.



Galileo's *Sidereus Nuncius*, in which he announced the satellites of Jupiter

#4 THE FINITE SPEED OF LIGHT

Curious that anyone should care about this, but Aristotle's theory of vision, and indeed Descartes', required that we perceive things instantaneously as they are. Galileo (yet again) was the first to record an attempt to show whether light took time to travel. He and a co-investigator, each carrying a lantern, stood on adjacent mountaintops. Galileo uncovered his lantern, the co-I uncovered his as soon as he saw the flash, and Galileo timed the interval until he saw the return flash.



Instrument derived from studies of Galileo to determine the orbits and periods of satellites of Jupiter

It was essentially human reaction time, and he concluded that light was, anyhow, very fast.

The first number for c came in the 1670s from Ole Römer of Paris and Copenhagen (the inventor of the Fahrenheit thermometer and much else). He timed eclipses of the Galilean moons of Jupiter and found them coming early or late relative to the average, depending on whether our distance from Jupiter was larger or smaller than average. Looking back at the numbers he reported, you discover that his c would have been good to about 15% if his generation had known the size

of the solar system well enough. Cartesians were not impressed.

The final word on the issue came from James Bradley, who, looking for parallax (but not yet finding it) in 1729 did find the so-called aberration of starlight. This is the equivalent of tipping your umbrella forward as you walk into the rain. The Earth goes around the Sun at about 30 kilometers per second, and Bradley had to tip his telescope forward about 20 arcseconds to catch the rain of photons from stars, meaning that the speed of light is larger than the speed of the Earth by a factor of 10,000. Because the aberration effect is the same for distant quasars as for nearby stars, we can say that the speed of light cannot vary significantly over the volume or age of the observable universe.

Today, we use our telescopes as time machines, using the finite speed of light to look back to nearly 90% of that age, to watch the tail end of the processes by which small galaxies merge to make large ones, form quasars at their cores, and gradually turn their gas and dust into successive generations of stars. Decoding what we see to figure out the actual time history of star formation is another area of active research, using data gathered at every wavelength, from radio and submillimeter to X rays and gamma rays.

#5 FIRST CAUSES AND THE UNIFORMITY OF NATURE

The discoveries that if you stop pulling your sled it stops moving and if you let go of your banana it falls were probably made by a Zinjanthropian named Og.

The celestial spheres, in contrast, had already been turning for a long time, and no planets had fallen lately when Aristotle and Aquinas wrote. It was, therefore, necessary to postulate heavenly natural principles different from terrestrial ones and/or angelic hosts, whose job was to keep the spheres in place and moving. Doubts about just how different “celestial” was from “terrestrial” clearly trace back to Galileo and before, but the undoubted culture hero in this area is Isaac Newton, whose 1687 work, *Principia Mathematica*, contained, among much else of importance, a demonstration that the orbit of the Moon can be described by the same equations that govern the motion of projectiles (and apples) on Earth.

Within the 20th century this concept of “same physics everywhere” has been observationally extended to the force of electromagnetics and nuclear interactions as well as beyond Newtonian gravity to general relativity. For instance, the strength of the electromagnetic force cannot have changed by as much as 1 part in 10 trillion per year since the quasars were young, 10 billions years ago. Nuclear reactions when the universe was hot and young had the same reaction rates and products as in our laboratories. And orbits of binary pulsars are better described by Einstein’s equations than by anything else anybody has been able to think of.

Recently we have moved beyond looking at the four (and only four!) forces, one by one, to attempts to unify them in somewhat the same way James C. Maxwell unified the phenomena of electricity and magnetism into his theory of electromagnetic forces and fields. The evidence probably lurks in processes that can occur only at very high energies, perhaps on the edge of what can be achieved in laboratory accelerators, perhaps beyond it. Thus the universe is once again our particle physics laboratory, being searched for the new kinds of particles and fluctuations in the microwave background that should be the signatures of grand and super unification, as it was in the 1930s, when the positron and other new particles were discovered in cosmic rays.

#6 IS THERE ANYTHING NEW UNDER THE SUN?

Seven was obviously exactly right for the number of “planets” (wanderers) in the Greek and medieval skies.



Isaac Newton

They were, of course, the Sun, Moon, Mercury, Venus, Mars, Jupiter, and Saturn, corresponding to the seven days of the week, the seven archangels, the seven deadly sins, and so forth. Even Bruno, when he pinned the Sun down at the middle, felt a need to keep seven planets, and so counted the Moon along with the Earth and the traditional five.

The 1781 accidental discovery of Uranus by William Herschel was thus a major surprise, as much to its discoverer as anyone else.

The first two asteroids turned up in 1801 and fitted into a gap in Bode's Law (not a law and not due to Bode) by the time analysis of irregularities in the motion of Uranus led to the discovery of Neptune by Gottfried Galle in Berlin in 1844: and no, I am not prepared either to adjudicate between James C. Adams and Urbain J. J. Le Verrier about who did the arithmetic of the prediction first or to pontificate on whether Pluto is "really" a planet.

From that day to this, every time we have opened up a new window, we have seen not just new astronomical objects but new kinds of objects. Radio astronomy brought us the quasars and (with the addition of precise time resolution) the pulsars, and X-ray astronomy the first clear-cut examples of real black holes. Gamma rays carry direct evidence for the production of heavy elements from light ones in supernovae and (again with time resolution of milliseconds or better) the gamma-ray bursters, which are perhaps signatures for the formation of black holes from very massive stars or from pairs of neutron stars.

"Windows" that need opening include not just new wavelength bands and better timing, but also sharper images (think of all that Hubble Space Telescope publicity), better wavelength resolution (i.e., better velocity measurements and composition analysis), and more sensitive detectors. Work is in hand in all these areas. The least explored wavelength bands include very long radio waves (you need a really big antenna outside the Earth's magnetosphere), the longer infrared wavelengths (for which our atmosphere is both an absorber and a noise source), and the hardest X rays (for which we still have no all-sky survey). Interferometry and adaptive optics are buzz words that go with attempts, now beginning to succeed, to fool Mother Nature into allowing us sharper images than the limits set by atmospheric blurring. And devices pioneered by our colleagues in condensed matter physics, like superconducting tunnel junctions, are just beginning to find a



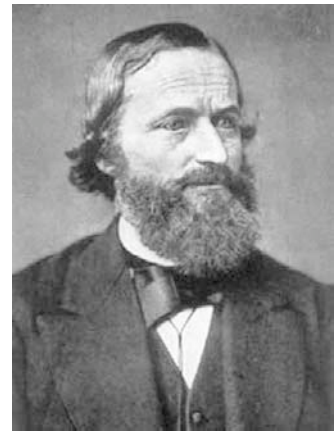
William Herschel

place as detectors that can record simultaneously the time of arrival of a photon, where it came from on the sky, and its energy.

On beyond lie the frontiers of neutrino and gravitational radiation astronomy. There is probably a Nobel Prize waiting for the woman who figures out how to measure the cosmic neutrino background, corresponding to the 3 K microwave one, because it probes much further back into the history of the universe. If you feel that LIGO and VIRGO (very expensive American and European projects aimed at the detection of gravitational radiation from merging pairs of neutron stars and such) ought to be mentioned here, consider them mentioned.

#7 THE FALL AND RISE OF QUINTESSENCE

An ancient Greek periodic table would have included four elements—earth, air, fire, and water—responsible for terrestrial phenomena and, stuck out to one side, the fifth element or quintessence responsible for the celestial ones. Copernicus, Tycho, Kepler, Galileo, and Newton all contributed to making the heavens seem more Earth-like. The *coup de grace* came in 1859 from spectroscopists Robert Bunsen and Gustave Kirchhoff, who saw in the light of the Sun features identical with ones produced by sodium and iron vapor in the laboratory. For the next 120 years or so, the stars were made of people stuff, as well as people of star stuff. This remains true for every bit of every star, galaxy, quasar, planet, or gas cloud from which we receive any form of electromagnetic radiation.



Gustave Kirchhoff

But there is also stuff in the universe that neither emits nor absorbs such radiation at any detectable level. This is the notorious dark matter. We know, beyond reasonable doubt, that it makes up 90% or more of the matter exerting gravitational forces that kept the stars together in their galaxies and the galaxies in their clusters. Fritz Zwicky, Jan Oort, and others who found early evidence for it, before the radio and X-ray windows had been opened, naturally assumed that the dark stuff was all small stars, gas clouds, and giant galaxies. These can now be excluded. We see small stars, gas clouds, and faint galaxies. They exist, but do not dominate anywhere, at least in majority opinion.

What else might be out there? The standard phrase is nonbaryonic (something other than matter made of atoms with protons and neutrons—baryons—in their nuclei) dark matter (no electromagnetic radiation) candidates (meaning that the evidence for any one is not unambiguous). A complete table runs to a couple of single-spaced pages, and always gets a laugh when shown in colloquia. Particularly promising entries include neutrinos with just a tiny bit of mass (for which there is independent evidence from studies of neutrinos produced in the Sun and by cosmic rays) and particles predicted by attempts to unify the forces (see #5), and given names like WIMPs (weakly interacting massive particles), “inos,” and LSPs (lowest-mass supersymmetric particles). Some kinds of black holes and Einstein’s infamous cosmological constant (with again some independent evidence based on the brightness of distant supernova explosions) also live on the list, as do a couple of theories of gravity that differ enough from general

relativity to let the observed baryonic masses be sufficient to bind the heavens.

With remarkable self-control, physicists refrained for almost 30 years from calling any of these quintessence. The word has, however, been revived in the late 1990s to label one of the strangest dark matter candidates—stuff that exerts negative pressure. It’s a little difficult to imagine, but suppose you had a balloon blown up with some combination of baryons (gas and quintessence). If you let a bit of the gas out, the balloon shrinks; let a bit of quintessence out and the balloon expands. Don’t try to breathe it!

How am I betting on all these candidates? If, in addition to dark baryons, you allow some neutrinos with rest mass, one of the WIMP or LSP items, and either a cosmological constant or quintessence, the mix does a good job of fitting most of the observations of the large-scale structure and evolution of the universe and, in addition, may provide part of the answer to how galaxies form (see #1), bringing us back to where we started.