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400 Years of Astronomical Discovery: The Accelerating Understanding of our Place in the Universe

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Abstract. This plenary talk is a fast-paced review of the four hundred years of astronomical discovery since Galileo's first use of the telescope.

In order to discuss "400 Years of Astronomical Discovery" I need to cover about 16 years per minute of speech. However, the scope of relevant material is by no means evenly divided over the years and so my subtitle is "The Accelerating Understanding of our Place in the Universe."

We are about 3/4 of the way through IYA, the International Year of Astronomy. It is thus timely to think about the successes of the year and, as this ASP annual meeting title indicates, forge a path to a future of continued public engagement in astronomy.

In this context of public understanding and appreciation of science, it is important to note the world view into which Galileo was born. The accepted cosmology was that there were two very separate realms: that of the Earth, consisting of soil/earth, air, fire, and water and on which all was transient, and that of the heavens or Heaven, consisting of a perfect regularity, remote from Earth's imperfections and eternal. It was Galileo's passion to understand these realms and the connection between them. In pursuing such questions, Galileo blazed the path to modern astronomy – and as we all know, got himself into a bit of trouble along the way. The scientific and political landscape is an important consideration when interpreting the progress of human knowledge.

Some ground work had already been laid by the time Galileo came of age. Specifically, the earlier Copernicun revolution (1543) took our cosmology from an Earth-centered to a Sun-centered system of perfect circles. Contemporary Kepler, while working with Tycho Brahe, determined (1605-1609) that planetary orbits are elliptical rather than circular. The stage was therefore set for Galileo to take humanity from the limited understanding enabled by naked-eye observations of the sky to that revealed by magnified observations through his use of the refracting telescope. He had heard of the 3x magnifier, which he duplicated in 1609, and quickly improved it to a 30x version.

By turning a spyglass into a telescope, Galileo taught us (1609-1612) that the Moon's surface is not a perfect sphere (but rather appears imperfect like the Earth, pockmarked with features), the Sun has blemishes (that rotate), Venus has phases, Jupiter has moons, and that there is much more to the universe than the 30 arcsec spatial resolution of the unaided eye can perceive – such as the non-pointlike or extended nature of the planets, the odd shape of Saturn (later understood as rings), that there are many more fainter stars within the Pleiades star cluster, and that the "Milky Way" is in fact a vast collection of stars, rather than a celestial fluid.

As evidenced from the above, and as we will see as we proceed through this brief history since Galileo, advances in astronomy (and many sciences) are driven by the interactions between three different ways of studying phenomena: invention and experiment, observation and analysis, hypothesis and theory. I invite you to witness their interleaving as we proceed.

At the time of Galileo, although the motions of the planets had been mapped, the *reason* they moved in the manner they did was not yet understood. Newton, who was born the same year Galileo died, brought explanation and understanding in the form of his universal law of gravitation. But possibly even more important for our story, he improved the telescope in two ways that remain fundamental today. First was his design (1669) of the reflecting telescope (using a mirror instead of a lens as the objective); this weight reduction per magnification factor allowed larger telescopes to be made, which led with each increase in aperture to ever new discoveries in the solar system, and beyond. Second was Newton's use of a prism to disperse received light in a spectrograph.

It is the spectrograph which has given us our greatest understanding of the nature of astronomical objects. Fraunhofer improved such a "spectroscope" (1814) both optically and through his novel design of a diffraction grating to supplant the prism. With the increase in spectral resolution, he found a forest of almost 600 dark lines interrupting the continuous emission spectrum from the Sun. He also found that the lines from several of the brightest night time stars in the sky are different from one another. Once these lines were explained several decades later by Kirchhoff and Bunsen as sequences formed by the interaction of light with particular atoms, we had a tool to measure what a distant celestial object is made of. However, it took developments some 100 years later to get this story right, as we will see shortly.

The brother and sister observing team of William and Caroline Herschel built huge telescopes and used them (1780-1834) to conduct a systematic survey of the sky. They identified stars, clusters, nebulae, what we now know as galaxies, etc. They were trying to understand the shape of the universe, really just the Milky Way at that time, through star counts. They also meticulously cataloged the nebulae (eventually resulting in the New General Catalog or NGC - the name by which many famous astronomical objects are still referred today). C. Herschel found many comets. W. Herschel discovered the planet Uranus, the first discovered with a telescope and also the first addition to the solar system since antiquity. He expanded our horizons in another important way: by experimenting with the temperature of different colors of light, he discovered that there is heat / light outside of the visible spectrum. Herschel is considered the father of infrared astronomy. Today, we have not only full-sky imaging surveys in the optical and infrared but also infrared space observatories, located above the atmosphere where the background noise is much lower than here on Earth – all carrying on the legacy of the Herschels.

Kapteyn took advantage of new techniques involving photographic astronomy, which had been developed by Draper, to collect information (1896-1922) on star counts, brightness, proper motion, parallax, spectral types and radial velocities. He estimated average distances to stars of different brightness, and developed the idea of the Galaxy as a flat disk of stars with radius $\sim$10 kilo-parsec and half-width $\sim$2 kilo-parsec (not too far off given that Kapteyn didn't appreciate interstellar extinction, as later pointed out by Trumpler), with the Sun located only 650 parsec from the center (pretty far off). This was known as "Kapteyn's Universe". He also measured but did not quite deduce from the two stellar proper motion streams he observed, that our Galaxy is rotating. Linblad and Oort in the mid-1900's clarified this situation for us.

By the late 1800's, the Newtonian view of gravitation began to hit some limits, particularly with respect to the orbit of the planet Mercury, which precesses at its closest approach to the Sun (perihelion) by 43 arcsec/century faster than predicted by Newton – even accounting for effects of other planets, the geometrical deformation of the Sun, and the Earth's frame of reference. Einstein followed up on his 1905 theory of special relativity to develop (1915-1919) general relativity, which posited that mass warps both space and time. This rectified the issue with Mercury's orbit, and also predicted that large masses such as stars could noticeably bend light. The famous eclipse observations by Eddington which located offsets in background starlight relative to when the Sun was located in another part of the sky, made Einstein a man of international public intrigue. Today, our understanding of these general relativistic effects enables us to study dark matter and the faintest, furthest objects in the universe through gravitational lensing (magnification) effects. Also, LIGO is poised to detect "gravity waves".

Back in the realm of stars, by 1910 Hertzsprung and Russell had each independently determined the relationship between absolute magnitude and color or spectral type of stars. This drove consideration of their *evolution* – a big change in thinking from the days of Galileo when the heavens were constant and perfect. They initially thought stellar evolution in what we now call the "HR diagram" occurred starting from the red giants, collapsing to become the early main sequence stars which gradually moved along the main sequence during their lifetimes, towards the red dwarfs; this picture is entirely wrong, but the philosophical advance of astronomical objects changing is far more important than the correct details, I would claim. Eddington, a theorist, provided important context for our understanding of HR diagrams based on thermodynamics and radiative transport considerations, concluding that stars are in fact static for most of their lives and the evolution is short-lived, consistent with our current understanding. Emden, Kelvin, Helmholtz, Jeans, Schuster, and Schwarzschild all made important theoretical contributions which connected observations to physical processes.

Building on the significant spectroscopic work of Huggins in the late 1800's and the in increasingly large stellar classification catalogs assembled by e.g. Canon, Fleming, Maury, and Pickering, Cecilia Payne Gaposchkin determined in the early 1920's that the stellar spectral classes (now OBAFGKMLTY) did not reflect the composition of the stars, but rather their temperatures. Through application of what are now known as the Saha (ionization states) and Boltzmann (electron level populations) equations, she showed that H and He are the dominant elements – even though they have very few lines which are typically weak. Gaposchkin's cracking of the stellar code is considered one of the greatest achievements in astrophysics.

Meanwhile, technology was not waiting for the universe to be physically understood. Hale had been busy building in sequence the largest telescopes of the day – a feat he set out to do *four* different times – from the Yerkes 40" completed in 1895 to the Mt. Palomar 200" dedicated in 1948, after his death. (A side note here: the recent fires in the Angeles National Forest were a serious threat to the historical Mt. Wilson site, though the valiant efforts of the fire fighting crews appear as of this presentation to have saved this still-working, and in fact state-of-the-art in some respects, observatory complex from destruction.) Hale was a solar observer, and is also responsible for our physical understanding of Sun spots and their 22-year cycle as driven by solar magnetic reversals.

Michelson (having already gained prominence for measuring the speed of light) was working on Hale's 100" at Mt. Wilson and developed (1919) with Pease the interferometer which was soon used to measure the diameters of Betelgeuse and several other stars. By the 1940's the technique of astronomical interferometry was routinely used at radio wavelengths. It was not until the 1970's, however, that the method became extendable to well-separated telescopes at optical wavelengths, and it is still being perfected today.

Henrietta Leavitt, much like Cecelia Payne-Gaposchkin, found patterns in observational data that led to a fundamental alteration of our understanding of the physics of the universe. She discovered that Cepheids, a specific type of variable star, pulsate more slowly if they are brighter (the so-called period-luminosity relation that has recently been re-named the Leavitt law). Because luminosity can be related through apparent brightness to distance squared, Leavitt's realization was critical for establishing the distance scale of the Milky Way, the Magellenic Clouds, and later of the larger universe.

Shapley, who was hired by Hale, was interested in using globular clusters to set the distance scale; he studied RR Lyrae stars as standard candles, calibrating a period-luminosity law for these fainter variables following Leavitt. He plotted the globular spatial distribution in three dimensions and found its center towards Sagittarius – at 13 kilo-parsec distance (much better than Kapteyn's 0.65 kilo-parsec estimate, but still not quite right). He also revised the scale of the Milky Way overall, increasing its radial size from Kapteyn's 10 to 50 kilo-parsec and estimated a distance to the Large Magellenic Cloud.

Meanwhile Hubble, who was also hired by Hale, and Humason were detecting (1924-1929) individual Cepheids in nearby galaxies again using the Mt Wilson 100". The 300 kilo-parsec value they derived using the same period-luminosity techniques put the spiral nebulae in which the Cepheids are located beyond the scale of the Milky Way. Further, when the data were combined with Slipher's earlier discovery of redshifted galaxy spectra, Hubble was able to determine a correlation between distance and recession velocity. The so-called "island universes" are not only just that: very distinct collections of stars apart from our own Milky Way, but they are moving apart from us and from one another. The universe appeared to be expanding, consistent with the Big Bang theory of its origin.

Baade in 1943 was able to make unprecedentedly clear observations of the nearby Andromeda galaxy and define two types of stellar populations: one in the spiral arms that is blue and young (PopI) and another in the central bulge that is red and old (PopII). The implication that there are also two types of Cepheids then led to recalculation of the size of the known universe and a more than doubling of Hubble's distance estimates (which were based on a calibration developed for one type of Cepheid but applied to the other type). There were also implications for the estimated age of the universe, bringing it into better alignment with the geologically determined age of 5 billion years for the Earth.

If Galileo is to be credited for advancing optical astronomy through instrumentation, Karl Jansky is our similar hero in radio astronomy. While both built on the insights and advances of those who came before, Jansky invented a new field whereas Galileo (and for that matter Herschel) merely improved theirs, albeit by revolutionizing. Jansky was studying static and interference in ship-to-shore communications at long wavelengths of light (14.6 meters) and had built a directional antenna and a "receiving apparatus" as well as data recording equipment. He identified local radio noise due to thunderstorms and that from the ionosphere, and he also postulated radio emission from the Sun. But his "Electric Disturbances of Apparently Extraterrestrial Origin" (1932) introduced us to a new window on the universe which (it was later learned) included not only stars and galaxies but new exotica such as the Galactic center region, pulsars, radio galaxies, etc.

Radio astronomy was further advanced by Reber who designed (1937) a telescope to improve on the antenna, and mapped the Galaxy. Ewen and Purcell were the first to observe (1951) neutral hydrogen (HI), which had been predicted earlier. This soon led to doppler measurements and thus velocity distances for the "stuff between the stars," tracing out the spiral structure of the Milky Way.

Returning to the optical, Zwicky, who is a well known character in astronomy, suggested many things including the connections between the supernovae he cataloged and neutron stars (which were yet to be discovered), as well as cosmic rays. He also speculated in the 1930's based on studies of the Coma galaxy cluster that there is "invisible matter," from consideration of mass-to-light ratios. In the 1970's, the existence of dark matter was incontrovertibly confirmed by the careful observations of galaxy rotation curves by Rubin. The nature of dark matter remains unexplaned, though there are many theories.

Picking up our stellar story, it took until the late 1950's for us to completely understand how stars are powered and the nucleosynthesis occurring in the cores of stars. The major players were theorists Bethe, Hoyle, Salpeter, G. Burbidge, M. Burbidge, Fowler, and Cameron who worked out various pieces of the relevant thermonuclear processes. Although many details were and still are to be accounted for before we could declare a complete theory, our rudimentary understanding of the basic physics of stars was essentially complete at this time.

Going not only extragalactic now, but towards the origin of the universe, Penzias and Wilson, continuing the serendipity of Jansky, were planning to use a radio antenna to look for interstellar molecular material (they were later indeed the first to observe interstellar CO), but decided to test their equipment at a frequency where no cosmic radiation was expected. They had an extra 3-4 degrees of unexplained "noise" in their experiment (1964), which turned out to be the relic radiation from the early universe - the afterglow of the Big Bang or the cosmic microwave background. The emission is caused by scattering of photons through the sea of electrons and nuclei (protons and neutrons), the only matter that existed before galaxies formed. This observation settled the Big-Bang-plus-expansion vs the Steady-State universe debate. More recently, COBE and WMAP have mapped the cosmic microwave background in great detail, particularly its 1:10^5 deviations from complete uniformity, with the results interpreted as detection of the earliest structure formation in the universe. The Planck experiment has recently launched and will tell us even more.

The 1960's also saw the discovery of several classes of "extreme" objects which continue to challenge our understanding even today. Schmidt used Hale's Palomar 200" to discover (1963) quasars, very luminous distant objects that are now appreciated as the accretion of material on to supermassive black holes and utilized as probes of very early galaxies and galactic environments. This discovery also opened our attention to astronomical objects in which relativistic physics is important, such as black holes, neutron stars, and pulsars. Pulsars, rotating neutron stars exhibiting pulses of radio and x-ray light as their beamed photons cross our line of sight, were discovered (1967) by Bell and Hewish. Taylor and Hulse (1973) discovered the first binary pulsar, which displays behavior that verifies predictions of general relativity such as the bending of radio waves.

However, while the well-developed fields of optical astronomy and radio astronomy were maturing and producing many discoveries, our eyes on the universe were not yet entirely open. The 1960's and 1970's saw the first exploration of the broad infrared and the x-ray windows, which required significant technology development including ground-based, jet/balloon/rocket, and satellite work. Pioneers such as Leighton and Neugebauer, Low and Johnson enabled infrared discoveries about the formation of stars, the content and structure of our Galaxy, and the enormous infrared luminosities of many distant galaxies. Giacconi developed X-ray astronomy, discovering (1966) the first x-ray source outside the solar system in Sco-X1. Subsequently developed x-ray facilities leading to the currently operating Chandra and XMM satellites have probed the physics of stellar coronae, accretion processes around young stars, various galactic exotica, and extragalactic black holes, as well as the intergalactic hot gas that surrounds many clusters of galaxies.

Satellites launched to detect gamma rays from nuclear explosions in the USSR discovered (1967) gamma ray bursts, occurring at a rate of about 1/day. This led to the astronomically oriented Bepposax satellite, which found that the bursts are uniformly distributed on the sky, and the first redshift from Keck (1997), which demonstrated the extragalactic nature of the gamma rays bursts and therefore their enormous luminosities. They are now connected with explosive events such as supernovae. Today, the SWIFT satellite plus an armada of ground based telescopes are better characterizing these objects and the puzzling physics they exhibit.

Further exploration across the EM spectrum has included rapidly paced developments in detectors and digitization. CCDs were developed in the late 1970s and 1980s, and flown in space on the Hubble Space Telescope. In the infrared, detectors were developed at near-infrared wavelengths also for Hubble but utilized extensively on the ground beginning in the 1990s. At longer mid-infrared wavelengths the detectors developed and finally flown on the Spitzer and Herschel telescopes in the 2000s have revolutionized discovery. Far-infrared and sub-millimeter detector arrays will finally mature in the future SOFIA and CCAT facilities. Many technologists have contributed to these efforts.

In the quest for ever more photons, though, efficient detectors and instrumentation is not enough. Pioneers in optical mirror design such as Roger Angel with the weight-reducing honeycomb and Jerry Nelson with his segmented mirror approach have resulted in the existence and the scientific productivity of the world's largest telescopes: GCT, Keck, SALT, HET, LBT, Subaru, VLT, Gemini, MMT, Magellan. We are now at a factor of a million increase in sensitivity over Galileo's equipment because of continued novel engineering designs. Another factor of 100 is coming in the next generation of large telescopes that is planned (TMT at 30m is comprised of 492 small segments compared to Keck's 36; GMT at 20m consists of 8 Gemini-like 8-m mirrors operating in sync).

For all we know about the distant universe, we are still – 400 years after Galileo – somewhat ignorant about our own backyard. It was only in 1992 that the first Kuiper Belt Object (since the 1930 discovery of Pluto) was found, following the postulation of such small bodies since the 1950's. Further mapping of the outer solar system led us to realize the extent of the population and to re-think some of the implications for the inner solar system. Wide-field mapping both in the recent past (2MASS, UKIDDS) and near future (WISE, Pan-STARRS) is cataloging the solar neighborhood for the first time in certain low luminosity regions of the HR diagram: white dwarfs on the blue side and brown dwarfs on the red side. Many observers are contributing to these efforts.

The most profound and awe-inspiring discovery, probably since the identification of the spiral nebulae as other galaxies - and maybe even since the Copernicun revolution itself - was the confirmation (1996) of the existence of planets around other Sun-like stars. As with other significant findings, there had been much ground work laid, including the previous announcement of planetary mass objects around pulsars and the discovery of low mass brown dwarfs. However, it was again a technological breakthrough that allowed the precise radial velocities needed to find planets – at first Jupiter-mass and recently close to Earth-mass – via the reflex motion of their central stars as they progress about their orbits. The Marcy et al., Mayor et al., and other planet search teams have found planets where we didn't expect them to be in many different phase spaces, starting from the very first discoveries. There are now hundreds of exoplanets, so many that popular culture has intervened to establish "top ten" lists. As the statistics accumulate, it seems clear that there are more smaller planets than larger ones, and there are more at Jupiter-like distances and beyond from their star than closer to their star. There are multiple planet systems of extreme diversity. And the question of the possibility for life elsewhere than our own Earth is closer to mainstream science than ever before. Very recently, direct images of objects that fall into the planetary mass regime have been taken, though we are still technologically quite a ways away from imaging an Earth analog.

The discovery of a supermassive (5 million solar masses) black hole in the center of our own Galaxy (1996) was another important step in our understanding of the relationship between us and the universe around us, in which such black holes had already been identified. Predicted in the 1960's, it took until the 1990's before sensitive enough instrumentation also having enough spatial resolution was available for the Ghez et al. and Genzel et al. teams to peer in the infrared through the intervening gas and dust so as to map the orbits of the stars around the Galactic center black hole and establish its mass.

Turning back to cosmology now, the expansion of the universe should be slowing down due to the attractive force of gravity. But it was demonstrated

(1998) from observations of Type Ia supernovae - first suggested by Baade as possible "standard candles" – that instead of deceleration there is actually acceleration of the expansion. Again, there were large teams involved in the discovery. The acceleration is driven by an unknown, dubbed dark energy, and we have a major undertaking before us to understand what it is.

During this past decade, at the fore of technology development has been adaptive optics (correcting for atmospheric blurring using either natural or artificial guide stars) and interferometry (interfering light collected by widely separated telescopes to achieve extremely high spatial resolution). Both techniques have been around for decades, but are only now achieving mainstream utility. More standard observational methods such as imaging and spectroscopy have become massively multiplexed over this same time period, and have launched us into an era of large surveys. Computing and databases are increasingly important to observers, and time domain science ranging from transiting planets to variable stars to high redshift transients is now routine. We are contemplating building new and ever-more capable observing machines. By historical precedent these will lead to innumerable discoveries which can not now be anticipated and for which they were not even intended.

We've come a long way in 400 years! But we are still building our understanding of our solar system, of our galactic neighborhood, the Milky Way Galaxy, the nearby universe, large scale structure, the epoch of galaxy formation, and our cosmology.

Any such review is necessarily incomplete. However, I hope to have hit many of the transformative highlights of the field since Galileo. I assert that the pace of discovery - as alluded to in my title - continues to accelerate. However, there are some common themes over the centuries which are worth pointing out. These include first and foremost the inspiration of other scientific discoveries and advances. We have returned again and again through the astronomical generations to cataloging the sky, to deciphering the physical nature of astronomical objects, to establishing empirical relations and patterns, to appreciating our place in the universe, and to utilizing our cleverness in the pursuit of the unknown.

From Galileo to today, and on in to the forseeable future, it is clear that advancement in astronomy is driven by the interaction between technology, observation, and interpretation. But there is another very important element.

Public appreciation of astronomy is currently on the rise. Galileo serves as a role model here as well. Remember that he wrote his "Starry Messenger" in 1610 in Italian, rather than the Latin preferred by academics of his day. His messages made it literally around the world as a consequence – because they could be understood. We are here to continue this legacy of public understanding and appreciation of astronomy. Astronomy is widely recognized as a gateway science, drawing the interest of those young people inclined to pursue diverse fields in science and technology, and so we should all be doing what we can to exploit this fact – for the good of all scientific inquiry and of general scientific literacy.

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