# The Exploration of the Unknown


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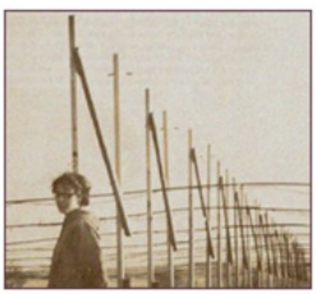

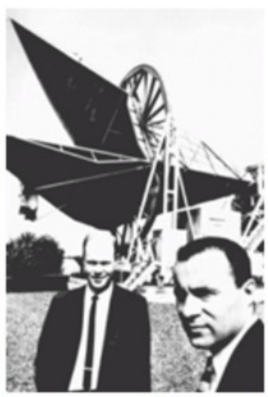

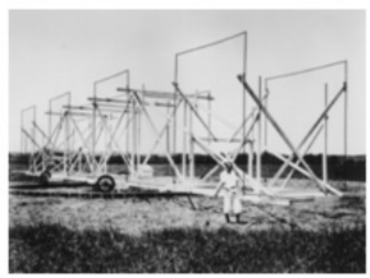

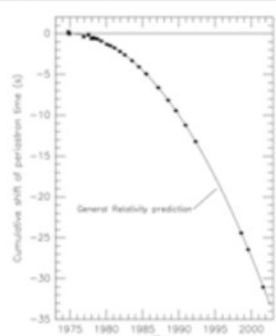



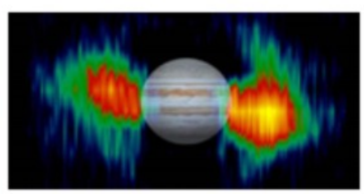

*The excitement of the next generation of astronomical facilities is not in the old questions which will be answered, but in the new questions that they will raise.*

# The Exploration of the Unknown

*"Fortune brings in some boats that are not steered" (William Shakespeare).*

## Where are the New Roads to Understanding the Universe and its Contents?

Astrophysics is an observational science. Unlike most scientists, astronomers do not do experiments, but can only observe the sky with open "eyes." We are dependent on a variety of emission processes complicated by a variety of absorption mechanisms, but we try to observe and understand. Since Galileo's observations of sunspots, craters on the moon, the phases of Venus, the satellites of Jupiter, and the rings of Saturn, astronomers, using instruments of ever increasing sophistication (and cost) have made a series of remarkable discoveries, only a few of which have resulted from attempts to test theoretical predictions. The existence of other galaxies, novae, and supernovae, dark matter, and dark energy were all first recognized from their observational discovery. Arguably, the most remarkable changes in the astronomical landscape began only in the 20$^{th}$ century, many as a result of observations made at radio wavelengths, as well as others that were unanticipated, such as the accelerating Universe.

For more than three centuries after Galileo's discoveries, astronomical observations were confined to the narrow octave window closely corresponding to the sensitivity of the human eye. With the extension, some 75 years ago, to the broad radio spectrum covering more than 8 decades of wavelength and later the expansion to space based facilities to access the IR, UV, X and $\gamma$-ray parts of the electromagnetic spectrum, modern astrophysical research currently deals with questions and phenomena undreamed of even a few decades ago. While it is important to delineate the questions and problems to be addressed by the next generation of astronomical facilities which will lead to a better understanding of these recently discovered phenomena, it is equally important to design the new facilities to optimize their potential for the discoveries which will raise new questions and new problems.

## The Lessons of History: Astronomical Discoveries

Planning for the unexpected can be challenging, but there is perhaps something to be learned from understanding the circumstances leading to past discoveries and how they have changed our perception of the large scale properties of the Universe and the nature of its constituents.

Because radio astronomy was the first of the new astronomies to explore the rich region beyond the classical optical/NIR spectrum, observations at radio wavelengths have been particularly rewarding in disclosing new previously unknown cosmic phenomena. Later, space borne facilities opened up the rich high energy sky. Most of these discoveries serendipitously resulted from investigations targeted at other astronomical problems, but some were the result of applied communications research, testing of new equipment, or even as the by-product of military weapons surveillance. We concentrate here on radio wavelength observations, since they were the first to reach out beyond the traditional optical window, but there are more examples from other areas as well.

***Communications research*:** In the course of trying to identify the source of interference to trans-Atlantic telephone communications, Karl Jansky discovered cosmic radio emission in 1933. Jansky had no formal training in astronomy, and once he had determined that the interference was "of extraterrestrial origin," there was little support from his superiors at the Bell Telephone laboratory to further pin down the location in space. But Jansky learned about celestial coordinates and located the radio emission as coming from the Galactic Center. Follow-up studies by Jansky and later Grote Reber showed that the Galactic radio emission, unlike all previously recognized cosmic radiation, must have a non-thermal origin, and later observations especially in Australia and the UK by former WWII radar scientists, found many discrete radio sources which were soon recognized as radio galaxies having unprecedented energy requirements.

Some thirty years later, in the same BTL laboratory, Arno Penzias and Bob Wilson discovered the three degree cosmic microwave background while trying to understand the apparent loses in a radio antenna also designed to support trans-Atlantic telephone communication, this time by satellite relay. The detection of the CMB has led to a whole new industry of observations of the CMB, the rise of precision cosmology, and four Nobel Prize winners.

***Military Spinoffs:*** In February 1943, two German battleships were able to safely pass through the English Channel, unnoticed, due to apparent jamming of the British radar defense. Over subsequent weeks, the interference to British radar stations continued, but only in the daytime! J.S. Hey was assigned to locate the source of the radio transmissions which were compromising the defense of Britain from German attack. Hey recognized that the most intense periods of jamming occurred during times of unusually large sunspot activity and correctly concluded that the active sun was sending out intense meter wavelength radio emission. Coincidently, a few months later George Southworth, working at Bell Laboratories on the development of centimeter radar systems, independently observed solar radar bursts. Due to military secrecy, neither Hey nor Southworth were allowed to publish their remarkable discovery. It remained for Grote Reber to be the first to report the existence of solar radio bursts, when his chart recorder went off scale while demonstrating his radio telescope to potential buyers from the US Navy.

An even more dramatic and accidental astronomical discovery from a military activity came from the four Vela spacecraft which were deployed to identify γ-ray emission from possible banned Soviet testing of atomic weapons, and which instead discovered cosmic Gamma Ray Bursts. GRB's are now recognized as the most powerful events in the universe and are at the core of a whole new field of research in high energy astrophysics. Several subsequent purpose built spacecraft, Compton, GRO, AGILE, Integral and Fermi, have been built to study the GRB's that came to be known to the astrophysical community through their accidental detection by military space craft.

***Radio Galaxies and Quasars*:** The mystery of understanding the immense source of energy needed to power the radio galaxies was unlocked with the discovery of the very small but distant and powerful quasars. Most extragalactic radio sources were identified with Elliptical galaxies or peculiar nebulae. Lunar occultation observations of the bright, but previously unidentified source 3C 273 showed the source to lie near a bright 13 magnitude star and a nearby "nebular wisp or jet." Based on his previous understanding of radio source identifications, Maarten Schmidt assumed that the proper counterpart to the radio source must be the 'thin wisp,' but on a hunch he decided to first take a spectrum of the star as it was much brighter and an easier spectroscopic target. The "star" turned out to have a redshift of 0.15 implying unprecedented luminosity from a very small volume *(Schmidt 1963, Nature 197, 1040)*. These *quasars,* as they were later called, could be explained only as the result of infall onto a supermassive black hole (*Lynden-Bell, 1969, Nature 223, 690*). Some quarter of a century later VLBA measurements of the water maser in the nucleus of NGC 4278 gave the first direct evidence for a supermassive black hole ~ $10^8$ solar masses *(Miyoshi et al., 1995, Nature 373, 127),* and at the same time what is still the best direct geometric measure of the distance to a galaxy *(Hernstein et al., 1999, Nature 400, 539).* The idea of black holes had been developed much earlier by Einstein and Schwarzchild, but when he discovered quasars, Martin Schmidt wasn't looking for black holes, or trying to improve on the value of the Hubble constant. In 2008, Schmidt and Lynden-Bell were awarded the first Kavli Prize for the discovery and understanding of quasars.

***Interplanetary Scintillations***: In the summer of 1962 and 1963, Cambridge University graduate student, Margaret Clark was using a radio telescope to determine accurate radio positions with the goal of identifying more quasars. But, her data for several sources proved difficult to interpret due to rapidly fluctuating signal strength especially when the sources were observed in close proximity to the sun *(Clark, 1964 PhD Thesis, Cambridge University).* Because her telescope had a shorter response time (time constant) than normal, she was able discern the 1 to 2 sec fluctuations that might have been smoothed over with other radio telescopes. Also, she connected the strange behavior of the scintillating sources with the unusual shape of their radio spectra which were characteristic of self-absorption, and she realized that they had to have very small angular dimensions. Despite criticism from senior associates that her equipment was faulty, she had the conviction, curiosity, and perseverance to convince others that the scintillations were real and not due an instrumental malfunction. Tony Hewish et al. *(1964 Nature, 203, 1214)* later interpreted this newly discovered phenomena as due to moving inhomogeneities in the interplanetary medium or Interplanetary Scintillations (IPS).

***Pulsars and Neutron Stars:*** In order to better study the structure of compact radio sources, to locate the position of quasars, and to study the interplanetary medium, Hewish raised funds for and designed a new radio telescope with a large collecting area using an even shorter time constant to study the newly discovered IPS phenomena. Graduate student, Jocelyn Bell, was assigned to build the telescope to and to write her PhD dissertation on IPS. But, after going through literally miles of chart recordings by hand, Bell noticed a strange, "scruff" on the record which repeated each day, but at the same sidereal not the same solar time. With determined curiosity, in spite of pressures from her supervisor to concentrate on her dissertation work, she soon realized that she was dealing with a previously unknown phenomenon, radio sources that pulsed with periods of the order of one second, and later named *pulsars (Hewish et al, 1968 Nature 217, 709).* After dismissing an interpretation in terms of "Little Green Men," pulsars were soon understood to be rapidly rotating neutron stars (*Gold, 1968, Nature 218, 73*). The possible existence of stars composed completely of neutrons had been discussed much earlier, only a year after the discovery of neutrons by Baade & Zwicky *(1933, Phys Rev 46, 76*) but this paper was unknown to Bell and Hewish, and it played no role in the discovery of pulsars. "For his decisive role in the discovery of pulsars," Tony Hewish shared the 1974 Nobel Prize with Martin Ryle. As it later turned out, around the same time, Air Force Officer Charles Schisler *(2008, in 40 years of Pulsars, pg. 642, AIP),* had independently discovered ten pulsars, including the Crab Nebula pulsar, during a tour of duty in Alaska at the Ballistic Missile Early Warning

Site. But, only after the recent deactivation of the radar system, was this work declassified and released to the public.

***Gravitational Radiation****:* Following the discovery of pulsars, many astronomers set out to make accurate timing measurements in order to better understand their energetics, spin-down rates, etc. From careful timing measurements at Arecibo, it was realized that the pulsar PSR 1913+16, was part of a binary system. Continued observations to determine the orbital characteristics led to realization by Joe Taylor and his graduate student Russ Hulse that the orbit was decaying within 0.1 percent of that predicted by the loss of energy due to gravitational radiation. Hulse and Taylor later shared the 1993 Nobel Prize for their role finding the first experimental evidence for gravitational radiation.

***Extra-solar Planets****:* Precision timing observations of the millisecond pulsar PSR 1257+12 led to Alex Wolszczan and Dale Frail *(I993, Nature 355, 145),* to realize that small perturbations in the orbit were due to at least two planet-sized bodies orbiting the pulsar. Although followed by other detections of extra solar planets, for many years 1257+12 remained the only known extrasolar planetary system, and the only earth-sized planets known.

***Ignored Predictions****:* Although the existence of the CMB was predicted, and even earlier observed, but unrecognized, the theoretical prediction played no role in the discovery by Pennzias and Wilson (*1965, ApJ 142, 419)* at the Bell Telephone Laboratories in Holmdel, NJ. As is well known, Penzias and Wilson were trying to find the source of noise in the 20-m horn parabola which was intended as the ground link for the Echo balloon relay satellite. After painstaking troubleshooting and eliminating all possible instrumental sources, it was realized that their excess noise was from what was later named the cosmic microwave background (CMB). Meanwhile, not far away in Princeton, Robert Dicke and his colleagues were building a radiometer to follow up on Dicke's prediction that it might be possible to detect the remnants of the big bang. But they were beaten out by Penzias and Wilson for the Nobel Prize, although all that Penzias and Wilson were trying to do was to understand their antenna. In fact as Dave Wilkinson (*1983, in Serendipitous Discoveries in Radio Astronomy, p. 176*) has commented, using a simple system he had built to measure atmospheric water vapor, Dicke could have detected the CMB back in 1946 around the time that Gamov (*1946, Phys. Rev. 70, 572*) predicted its existence. But by 1965, everyone had forgotten Gamov's prediction. Everyone, that is, except the Russian scientists, A. G. Doroshkevich and Igor Novikov, who were more familiar than the Americans with a 1961 paper by E. A. Ohm *(Bell System Technical Journal, pg. 1065)* that reported an excess antenna temperature. The Russians were looking for experimental evidence of what they called "the relict radiation," but they mistranslated Ohm's paper and incorrectly concluded that the excess temperature observed by Ohm was due to atmospheric radiation. As it later turned out, the CMB had been detected much earlier by Andrew McKellar who noted that interstellar CN had an excitation temperature of 2.3 K. Although no process was then known to produce this level of excitation (*1941 Publ. Dom. Astrophys. Obs. 7, 251*), and although this was a long standing puzzle in astrophysics, no one made the connection with Gamov's prediction until after the Bell Labs detection.

***Beware of Theoreticians****:* In 1968, a proposal to NRAO to search for $H_2O$ emission with the 140-ft radio telescope was rejected because theoretical arguments suggested that the water molecule would be too weak to detect. However, subsequent observations by Cheung et al. (*1969, Nature 221, 626*) with only a 6-m antenna observed remarkably strong $H_2O$ due to maser action. With hindsight, $H_2O$ masers could probably also have been detected even before the HI line with the simple 1.3 cm radiometer and 18 inch dish used more than 20 years earlier by Dicke & Beringer *(1946, ApJ 103, 375*) to measure atmospheric water vapor.

***Close to Home in the Solar System****:* Even with the solar system, there have been many surprises. Stefan's Law predicts the expected surface temperature of each planet depending only on the solar constant, the distance from the sun and the albedo. Passive radio studies simply intended to detect the thermal emission from each planet and confirmation of the expected surface temperature turned up surprises with every planet except Mars.

Ever since Giovanni Schiaparelli thought he repeatedly saw the same markings on the surface of Mercury, it was widely accepted that Mercury rotated every 88 days in synchronism with its orbital motion, and so it was expected that the daytime side must be very hot, and the eternally unheated night side incredibly cold. But 10 cm radio measurements showed both the day and night side to both be close to room temperature *(Kellermann, 1965, Nature 205, 109),* and radar observations showed directly that Mercury rotates with a 59 day period in 2/3 synchronism with the revolution (*1965, Pettengill & Dyce, Nature 206, 1240*). So for every two revolutions of Mercury around the sun, there are three full rotations about its axis, and thus for every other perihelion passage the same face is visible from the Earth and for more than a hundred years astronomers had apparently ignored half of their admittedly difficult observations of the sparse surface markings. Retroactive "*predictions"* quickly showed, in fact, that an 88 day period would not be stable, and that a 59 day period was required as a result of Mercury's very eccentric orbit (*1965, Peale & Gold, Nature 203, 1241*).

In the late 1950's and early 1960s Russian, British, and American radar scientists were competing to be the first to detect radar echoes from Venus. There was no particular scientific motivation, other than to be first, and to demonstrate the effectiveness of their sensitive receivers, powerful transmitters, and newly devised high speed digital recording and sophisticated signal analysis techniques. However, the echoes from Venus showed that it unexpectedly rotated in the retrograde direction and gave a new value for its distance and thus the AU, more accurate by about a factor of 100 than the previously accepted value. Passive radio observations showed that the surface of Venus was incredibly hot, near 600 C, later explained as due to a greenhouse effect, a phenomenon subsequently applied to global warming on the Earth.

Unrealistically high temperatures were also measured for Jupiter, but the apparent temperature increased with wavelength, suggesting a non thermal origin *(Drake & Hvatum, 1959, AJ 64,* 329). Speculation that the non thermal radiation from Jupiter might be due to a powerful analogue of the Earth's Van Allen Belts, was later confirmed with direct radio interfeometric imaging of Jupiter's radiation belts *(Radhakrishnan & Roberts, 1960, AJ 65, 498).* Even earlier, Burke and Franklin *(1955, JGR 60(2), 218)* had detected intense dekametric busts from Jupiter while setting up their new antenna to observe the Crab nebula which fortuitously happened to be close to the same declination and passed through their beam every night. Multi-wavelength radiometric observations of Saturn, Uranus, and Neptune, later indicated temperatures well in excess of that expected from heating by the sun, giving the first suggestions of an internal source of heat due to radioactive decay.

## The Lessons of History: The Design of New Facilities

Although they were quite independent, it is perhaps no coincidence that the first detections of cosmic radio noise, solar radio bursts, and the CMB, were all made at the same industrial laboratory– the Bell Telephone Laboratories with its rich heritage of independent research and concentration of scientists and engineers such as Bruce, Southworth, Shannon, Townes, Nyquist, Shockley, and Bardeen with their wide range of expertise that could be applied to any problem.

Theoretical calculations can be dangerous in the planning and design of new instruments as well as for predicting new discoveries. The Jodrell Bank 250-ft radio telescope was designed to detect radio echoes from cosmic ray air showers which P. M. S. Blackett and A. C. B. Lovell (*1941 Proc. Roy. Soc. A177, 183*) calculated would be possible with a large antenna. Although it was later pointed out to Lovell that recombination in the ionized cosmic ray trail greatly suppresses the echo below detectability, Lovell claimed to have forgotten or not paid attention to the correct calculations and built the 250-ft reflector anyway.

The Arecibo 1000-ft dish was designed by Bill Gordon in the 1950's for ionospheric backscatter experiments, not for radio astronomy. It later became apparent that Gordon had overestimated the spectral width of the returned echoes in calculating the dish size needed to detect echoes from the ionosphere, and that a much smaller (and very much cheaper) dish would be sufficient for the ionosphere experiments. However, by then enthusiasm for a 1000-ft dish had grown, and Gordon was able to obtain construction funds from the military who were obsessed with anything that they might learn about the ionosphere in order to detect incoming Russian missiles (*2008, M. Cohen, private communication*) and the Arecibo telecope was built as designed.

Interestingly, although the theoretical arguments leading to the Jodrell Bank and Arecibo telescopes were wrong, the telescopes were built based on these wrong arguments, and they have had nearly a 50 year record of successes in ways that the original advocates could not have possibly imagined, including the detection of the effects of gravitational radiation, the discovery of the first extra-solar planetary system, the surprising measurement of the rotation period of Mercury, and the return of the fist photographs from the backside of the moon..

## The Human Factors

Arguably, "luck," plays as much a role in scientific discovery, as careful planning. But, as wisely commented by Louis Pasteur, *"In the field of observation, chance favors the prepared mind,"* or from Gary Player's approach to golf, "*The harder I practice the luckier I get."* Scientific discoveries come from the right person, in the right place, doing the right thing, using the right instruments.

While the potential for new astronomical discoveries will be heavily dependent on the application of innovative new technologies to the next generation of astronomical instruments, a lot will also depend on the quality of the scientists with good understanding of their instrument and an ability and willingness to explore and accept new ideas and not to sweep seemingly anomalous results under the rug as due to "instrumental effects." It will be equally important for those who are in a position to filter research ideas, either as grant or observing time referees, as managers of facilities, or as mentors to young scientists, not to dismiss as "butterfly collecting," proposed investigations which explore new areas of phase space *without having predefined the result they are looking for.*

However, the impact of the next generation of astronomical facilities will not only depend on the cleverness of the scientists who use them, but also on the cleverness of their designers to obtain better sensitivity, image quality, resolution, field of view, time domain coverage, or the opportunity to explore new parts of electromagnetic and non electromagnetic spectrum (e.g., gravity). Equally important, will be the training of the next generation of scientists so that they understand the instruments they use. So, like Jansky, Bell, Penzias, and Wilson, they are able to explore unanticipated results for more than their immediate intended purpose.

## Future Discoveries

Three very important astronomical discoveries which defined the path for future research were Jansky's detection of extraterrestrial radio emission, the detection of the cosmic microwave background by Penzias and Wilson, and the accidental detection of solar radio bursts by Southworth, all occurred at the same Bell Telephone Laboratories. These Bell Labs discoveries, as well as the Los Alamos discovery of GRBs were not made by people trained in astronomy or even as a result of a basic research investigation, but by physicists trying to solve important applied problems.

Most of the phenomena studied by modern telescopes were unknown even 50 years ago, and many were discovered from observations made at radio wavelengths by using increasingly more powerful instruments, and often motivated by solving other problems or just following their curiosity. The discovery of new phenomena has been and will continue to be more transformational than the explanation of old questions posed by previous discoveries. The history of astronomy suggests that the opportunities for the discovery of new phenomena are optimized when new facilities have at least an order of magnitude improvement in capability in sensitivity, resolution or image quality, temporal extent and resolution, or spectral coverage and resolution. But, it will be equally important that scientists understand their instruments and their data, and that they are given the opportunity to follow their curiosity.

While it is fashionable to consider that all research follows the textbook picture whereby theories are first formulated and then followed by experimental or observational tests, real progress in science must allow for new discoveries as well as for the explanation of old discoveries.

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