Physicists and astronomy – Will you join the dance?

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Twenty-five years ago when I was a graduate student in physics, I was drafted into the Army and sent to Eniwetok in the Marshall Islands. There was plenty of spare reading time for an army private on this tiny atoll, and I had taken along a paperback copy of Fred Hoyle's *Frontiers of Astronomy*. Hoyle made astronomy exciting and I began to wonder whether I might find a way to enter the field.

When I returned to graduate school a year later, I found that MIT required proficiency in a minor subject, and I quickly selected astronomy. Since MIT offered no courses in the subject, I enrolled at Harvard. I had never taken a course in astronomy, but decided on a graduate seminar that was to be conducted by several professors.

The first session was conducted by Cecilia Payne-Gaposchkin. She talked about variable stars, calling each star by name, recalling the peculiarities of its light curve, comparing and contrasting whole varieties of stellar characteristics seemingly without recourse to notes. I came reeling out of that lecture, convinced that I had made a bad mistake; astronomy was not for me—Hoyle's book must have been misleadingly simple.

Two of the Harvard students, Frank Drake and Nanilou Dieter, tried to console me, urging that I stick out a few more lectures: Thomas Gold was to start a professorship at Harvard the following week, and they thought his seminars would be more astrophysical and therefore more appealing to a physics student. I decided to give it a second try, and managed to survive the semester. I am still in astrophysics today.

In the late 1950s most physics students knew the names of at least a few physicists who had worked on astronomical problems. The best-known among these were theorists. Albert Einstein had formulated a physical approach to cosmology. Subrahmanyan Chandrasekhar, Lev Davidovich Landau and J. Robert Oppenheimer, respectively, had looked into the nature of degenerate matter in white dwarfs, neutron stars and the collapsing phases of black holes. Hans Bethe and Carl Friedrich von Weizsäcker had independently worried about the nuclear reactions that take place in the sun, and George Gamow had pondered the generation of chemical elements in the early, explosive phases of the universe. Many, like Enrico Fermi, or Evgeny M. Lifshitz, had worked on one or two problems of astronomical interest, but had remained largely in the field of physics; while others, like Hoyle or Hannes Alfvén, could be viewed as having made astrophysical problems their prime area of interest.

Experimentalists had become involved in the study of cosmic rays and in the then new field of radio astronomy; but their fields were slow to be recognized as important areas of astronomical study, and it would have been difficult to predict the exciting role that instrumentalists were to play in astronomy in the following decades (see figure 1).

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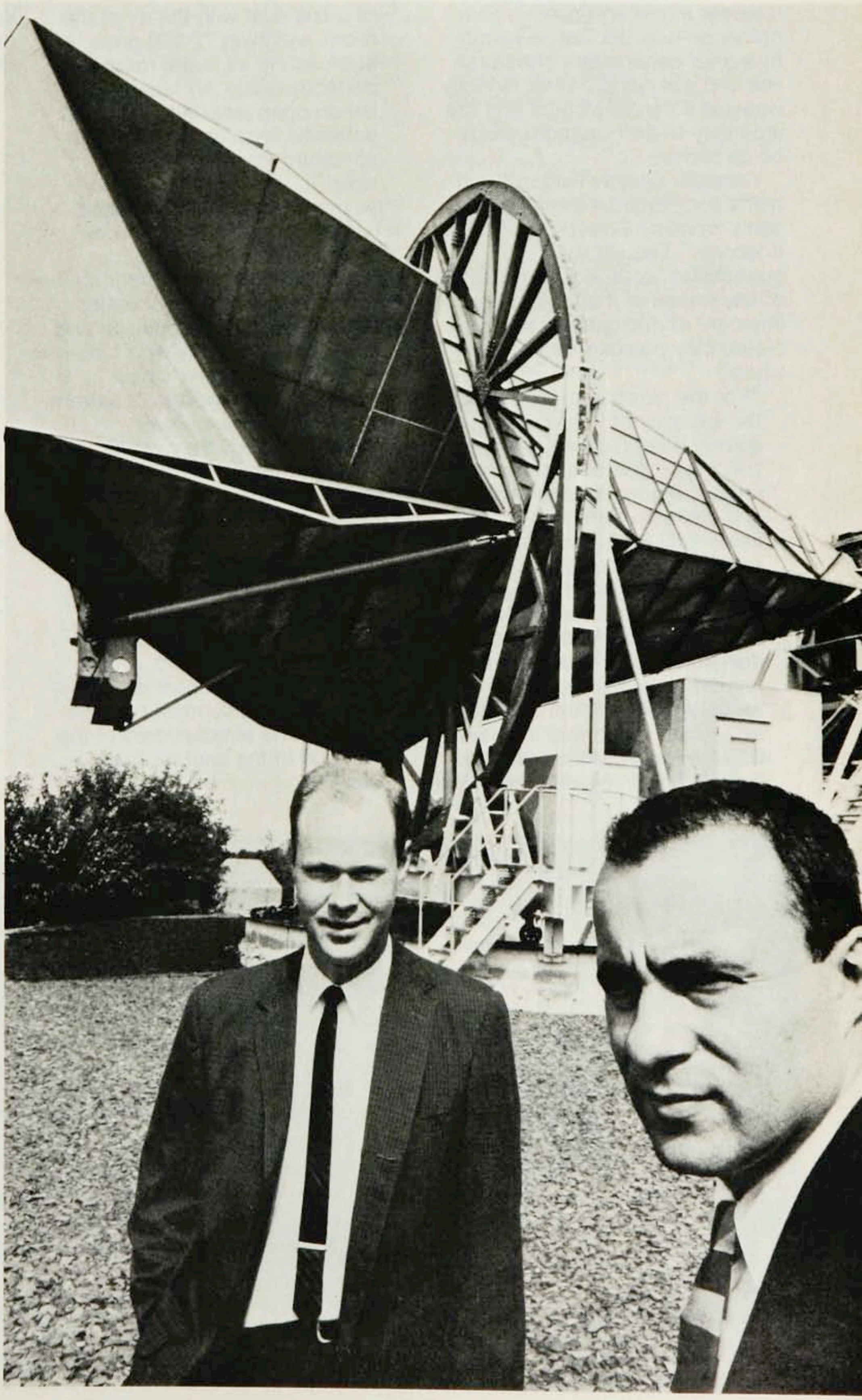
***Horn-shaped antenna** at Bell Telephone Laboratories in Holmdel, New Jersey. In 1965, Robert Wilson (left) and Arno Penzias (right) noted an excess noise temperature observed in the antenna system shown here.[11] Robert H. Dicke, P. James E. Peebles, Peter G. Roll and David T. Wilkinson at Princeton interpreted this observation as radiation remaining from an original cosmic explosion.[12] They were unaware that George Gamow,[13] Ralph A. Alpher and Robert C. Herman had predicted the remnant radiation more than a decade earlier. (Bell Labs photograph)* Figure 1



Today we know more about the part that physicists play in astronomy, but many young researchers captivated by the idea of working on larger cosmic problems, remain unsure of where they might best be able to make contributions to the field, or where their skills would be in greatest demand. This article focuses on past achievements of physicists in astronomy and attempts to shed a clearer light on astronomy as a career.

I begin with an account of the discovery of gaseous nebulae (figure 2) in the mid-nineteenth century—the first clear indication that gas clouds exist among the stars. In the next section I list seven commonly found features characterizing this and other observational discoveries. In succeeding sections I show how these traits suggest ways in which we can foster further discovery; how theory is related to observation in astrophysics; and where physicists make their greatest contributions to astronomy. Many of these results are new and have required detailed substantiation that cannot be reproduced in a short article. Further documentation on each can, however, be found in my recently published book *Cosmic Discovery*.[1]

Spectroscopes and gaseous nebulae

A close look at astronomical discovery reveals freshness of approach at each major turn throughout history—the twentieth century has by no means been unique. The elation we feel today when we uncover a new and curious phenomenon was felt just as keenly by earlier generations of naturalists and scientists. Their tenacity was just as great as ours and the ingenuity of their methods every bit as clever.

Consider Gustav Robert Kirchhoff's and Robert Wilhelm Bunsen's wonderful discovery of spectroscopy. Though their quantitative work required isolation of tiny traces of matter in an era innocent of microchemical technique, they persistently improvised:[2]

> "For the purpose of examining the intensity of the reaction, we quickly heated an aqueous solution of chloride of strontium, of a known degree of concentration, in a platinum dish over a large flame until the water was evaporated and the basin became red-hot. The salt then began to decrepitate, and was thrown in microscopic particles out of the dish in the form of a white cloud carried up into the air. On weighing the residual quantity of salt, it was found that in this way 0.077 grm. of chloride of strontium had been mixed in the form of a fine dust with the air of the room, weighing 77 000 grms. As soon as the air in the room was perfectly mixed, by rapidly moving an open umbrella, the characteristic lines of the strontium-spectrum were beautifully seen."

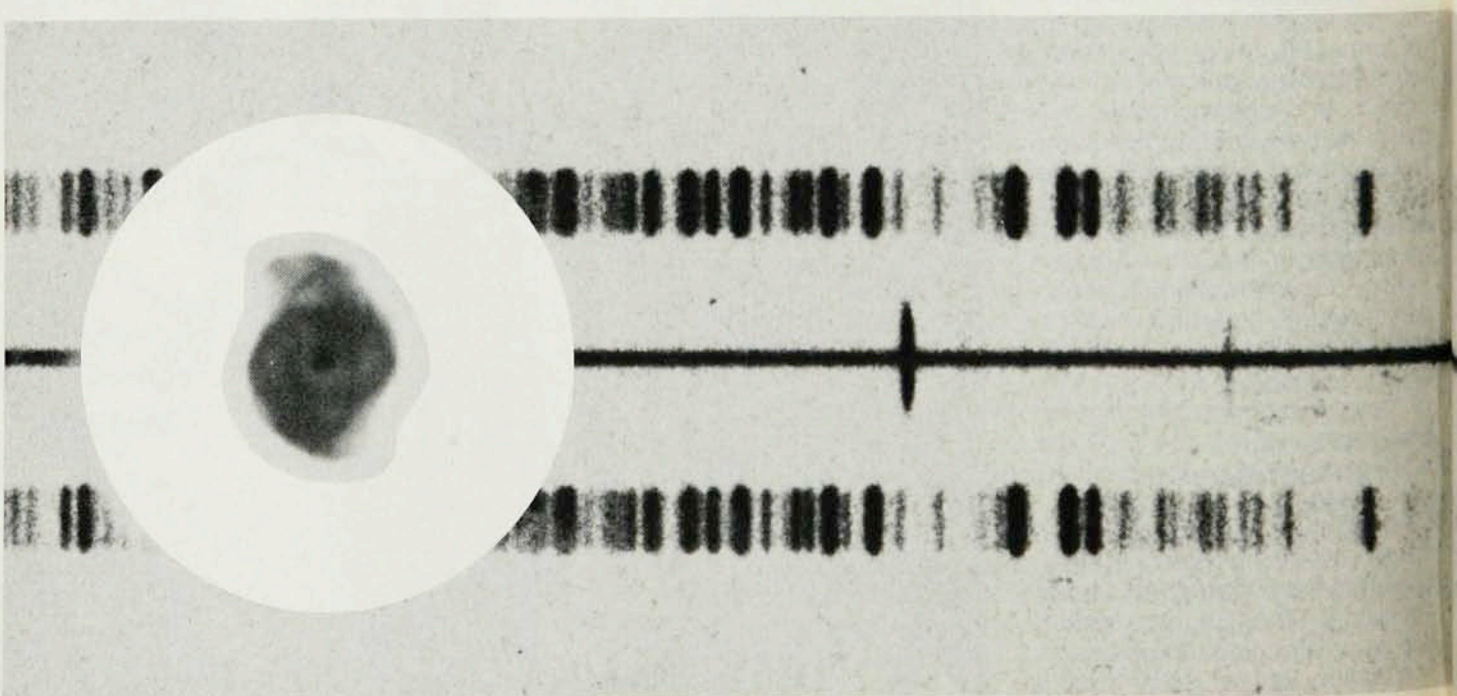
How many of us would consider an umbrella as the indispensible tool for the task?

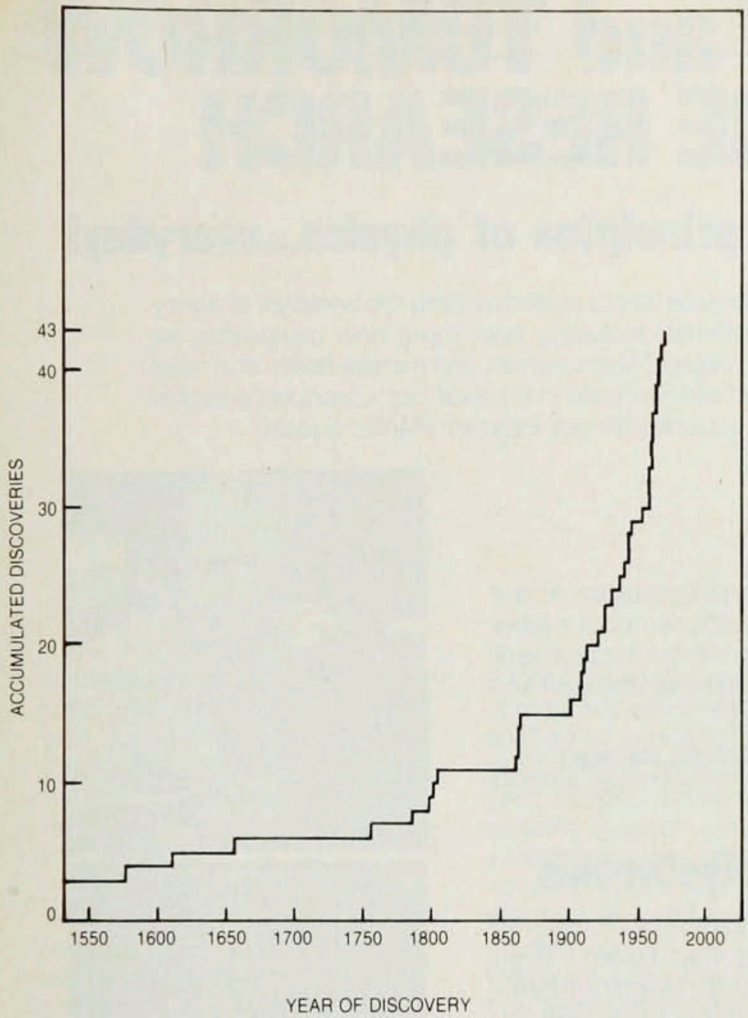
Kirchhoff and Bunsen not only established the correspondence between spectral line position and chemical identity, they also foresaw the revolutionary consequences of their findings to astronomy. In the *Philosophical Magazine* of 1860 they wrote:[2]

> ". . . the method of spectrum-analysis . . . opens out the investigation of an entirely untrodden field, stretching far beyond the limits of the earth, or even of our solar system. For, in order to examine the composition of luminous gas, we require, according to this method, only to see it; and it is evident that [this] mode of analysis must be applicable to the atmospheres of the sun and of the brighter fixed stars."

William Huggins, a young Englishman, reacted with animated excitement.[3]

> "It was just at this time, when a vague longing after newer methods of observations for attacking many of the problems of the heavenly bodies filled my mind, that the news reached me of Kirchhoff's great discovery of the true nature and the chemical constitution of the sun from his interpretation of the Fraunhofer lines.
>
> This news was to me like the coming upon a spring of water in a dry and thirsty land. Here at last presented itself the very order of work for which in an indefinite way I was looking—namely, to extend his novel methods of research upon the sun to the other heavenly bodies. A feeling as of inspiration seized me: I felt as if I had it now in my power to lift a veil which had never before been lifted; as if a key had been put into my hands which would unlock a door which had been regarded as for ever closed to man—the veil and door behind which lay the unknown mystery





***Cumulative graph** of the 43 prime cosmic discoveries listed in the table shows the increasing rate of discovery in recent years. Often, discoveries rapidly follow technological innovation in instrumentation.* *Figure 3*

Discovery dates for 43 cosmic phenomena

Antiquity	Stars
Antiquity	Planets
Antiquity	Novae
1577	Comets
1610	Moons
1655	Rings
1754	Galactic clusters
1785	Clusters of galaxies
1798	Interplanetary matter
1801	Asteroids
1803	Multiple stars
1861	Variable stars with nebulosity
1864	Planetary nebulae
1864	Globular clusters
1865	Ionized gas clouds
1903	Cold interstellar gas
1910	Giants/main sequence stars
1912	Cosmic rays
1912	Pulsating variables
1915	White dwarfs
1917	Galaxies
1929	Cosmic expansion
1930	Interstellar dust
1934	Novae/supernovae
1939	Galaxies with/without gas
1942	Supernova remnants
1946	Radio galaxies
1947	Magnetic variables
1949	Flare stars
1957	Interstellar magnetic fields
1962	X-ray stars
1962	X-ray background
1963	Quasars
1965	Microwave background
1965	Masers
1965	Infrared stars
1966	X-ray galaxies
1968	Pulsars
1968	Gamma ray background
1970	Infrared galaxies
1971	Superluminal sources
1973	Gamma ray bursts
1974	Unidentified radio sources

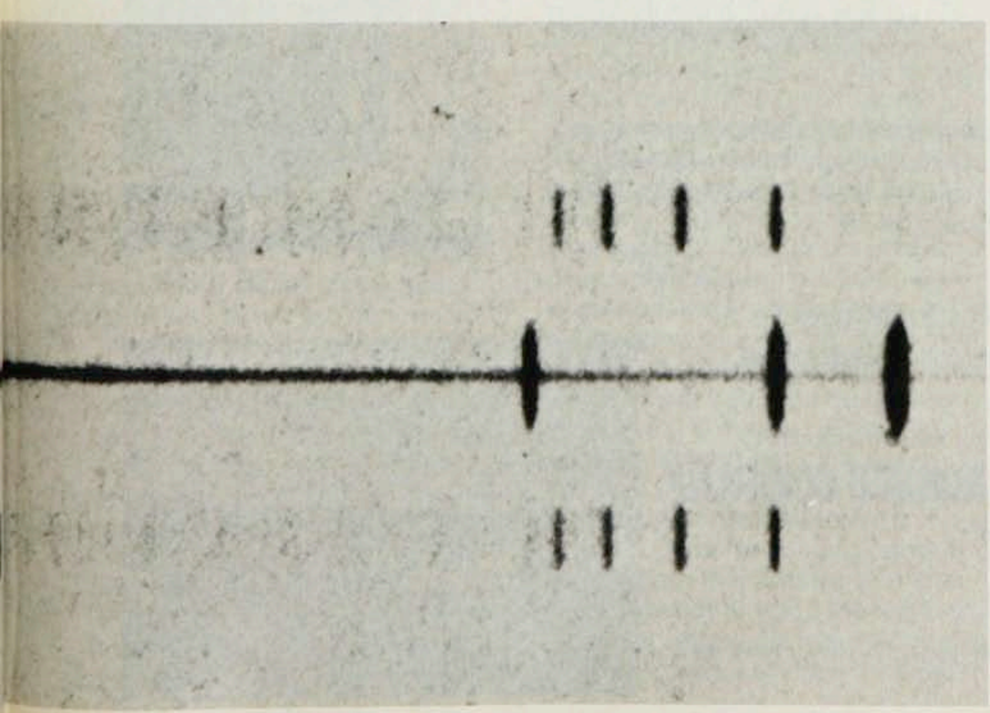


***Image and spectrum** of the planetary nebula NGC 6543. The entire picture is a negative, the darkest portions corresponding to the brightest features. At the top and bottom are laboratory reference spectra. The central trace shows four strong lines and a weaker one. From left to right the strong ones are the atomic hydrogen lines Hγ and Hβ, and two lines due to doubly ionized oxygen. One of the most decisive investigations in the astrophysics of nebulae was carried out in 1864 by William Huggins, a young Englishman of independent means. Huggins and W. Allen Miller devised a spectroscope for the telescope in Huggin's private observatory. When Huggins pointed the telescope at the nebula, he was taken aback at finding the light resolved into lines, a clear indication that the nebula was not a close grouping of stars but rather a gaseous complex. The spectrum shown here was obtained by C. Roger Lynds. The superposed picture of the nebula is a Kitt Peak National Observatory photograph.* *Figure 2*

of the true nature of the heavenly bodies. This was especially work for which I was to a great extent prepared from being already familiar with the chief methods of chemical and physical research.

It was just at this time that I happened to meet at a soirée of the Pharmaceutical Society, where spectroscopes were shown, my friend and neighbour, Dr. W. Allen Miller, Professor of Chemistry at King's College, who had already worked much on chemical spectroscopy. A sudden impulse seized me to suggest to him that we should return home together. On our way home I told him of what was in my mind, and asked him to join me in the attempt I was about to make, to apply Kirchhoff's methods to the stars."

Only four years later Huggins was looking at a bright planetary nebula in Draco, figure 2:[4]

"On August 29, 1864, I directed the telescope armed with the spectrum apparatus to this nebula. At first I suspected some derangement of the instrument had taken place; for no spectrum was seen, but only a short line of light perpendicular to the direction of dispersion. I then found that the light of this nebula, unlike any other ex-terrestrial light which had yet been subjected by me to prismatic analysis, was not composed of light of different refrangibilities, and therefore could not form a spectrum. A great part of the light from this nebula is monochromatic . . ."

Other nebulous sources showed a continuous spectrum much like the spectra of individual stars. As had been suspected for over a century, such nebulae consisted of large swarms of stars. Huggin's observation, however, showed with one decisive stroke that a completely different class of nebulosity exists as well—nebulosity consisting of luminous gas. Not only that, the chemical nature of the gas could clearly be determined through a study of the lines observed.

Observational discovery

The work of Kirchhoff and Bunsen, and Huggins and Miller shares important characteristics with a wide variety of observational discoveries that have taken place in astronomy during the four centuries since Tycho Brahe brought precise astronomical observations into vogue. The table shows the 43 prime astronomical phenomena recognized today and their dates of discovery; these are plotted in figure 3 to show the increasing rate of discovery of recent years.[5] Though there is no unique definition of a cosmic phenomenon, most astronomers would compile a list similar to that given in the table if asked to name the principal phenomena characterizing the universe. The phenomena named here are given prominence in most astronomical texts and standard reference works. Conferences and symposia concern themselves with individual phenomena on the list, and books or review articles frequently focus on one or another of these entries. The realization of a discovery sometimes dawns slowly. Where possible, however, we have taken the year of discovery to be the year in which the first unambiguous report of the discovery was published. Often, this date differs from an earlier year in which a source was detected but not recognized as anything unusual. The discovery date also tends to precede years during which the physical nature of a phenomenon becomes understood. At times a discovery involves the recognition that a previously known phenomenon actually comprises two quite distinct sources or classes of events. In the table such discoveries are indicated by a slash (/) in the designation of the two phenomena that were resolved.[5] I have examined each of the 43 discoveries in some depth, and have found several prevailing trends:[6]

▶ The most important observational discoveries result from substantial technological innovation.

Galileo's construction of a spyglass with a magnifying power of 20 permitted him to distinguish clearly four tiny specks of light whose motions he followed until he was certain he was seeing individual moons orbiting Jupiter. He also resolved the mountains on our own moon sufficiently well to conclude that the moon might well be made of the same kind of stuff as Earth. Three and a half centuries later Riccardo Giacconi and Bruno Rossi's group at the American Science and Engineering Corporation and Herbert Friedman's group at the Naval Research Laboratory constructed x-ray telescopes that similarly opened an entirely new world populated by astoundingly luminous x-ray stars and x-ray galaxies.

▶ Once a powerful new technique is applied the most profound discoveries follow with little delay.

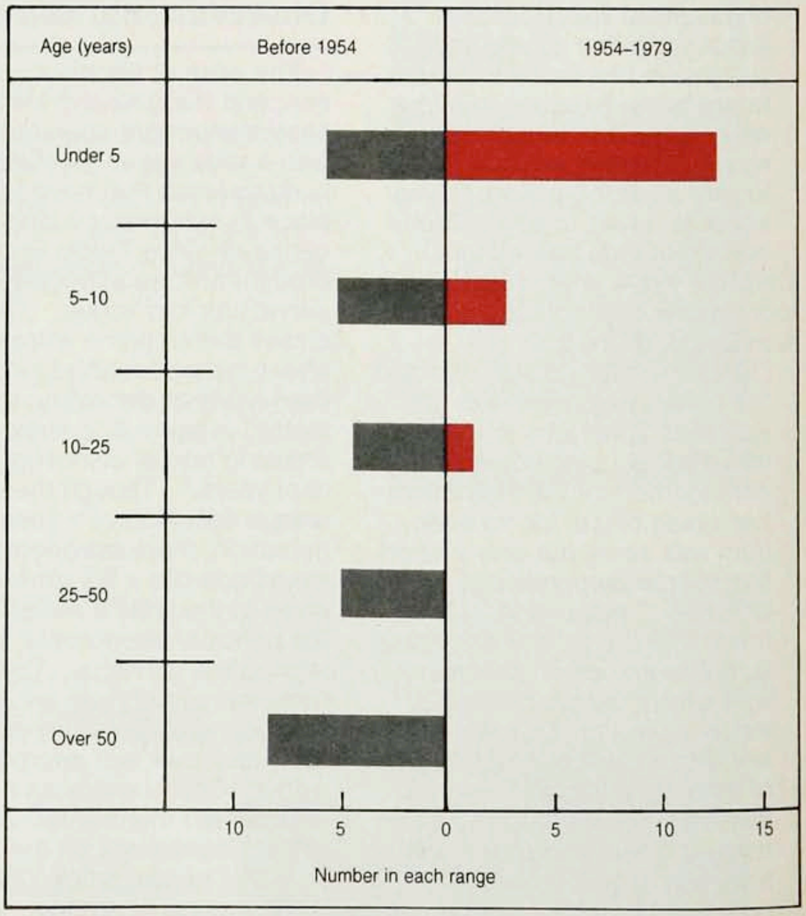
This conclusion is based on data graphically summarized in figure 4. The majority, by far, of all the discoveries made in the quarter century between 1954 and 1979 was made within five years of the introduction into astronomy of powerful new techniques without which the discovery could not have taken place. None of the discoveries made during that epoch was made with instruments more than 25 years old. And while the pace of research seems to have been somewhat slower in previous centuries, it is remarkable that Galileo's booklet *Sidereus Nuncius*, the tract in which he announced his earliest and most surprising results, appeared within 18 months of the first recorded description of a spyglass—at a time when the word "telescope" had not even been coined.

A corollary can be derived from the data exhibited in Figure 4.

▶ A novel instrument quickly exhausts its capacity for discovery.

The instrument by no means becomes useless; but its function changes as it joins the existing array of tools used in the astronomer's day-to-day analytical work, in which he seeks a closer understanding of known phenomena. To revitalize a technique in preparation for further discovery, instrumental sensitivity or resolving power usually must be increased by orders of magnitude. Thus the discovery of superluminal radio sources—sources that appear to be expanding at velocities exceeding the speed of light—only became possible when radio techniques had evolved to the point where angular separations amounting to milliseconds of arc could be reliably determined. The coarser second-of-arc angular resolution that had been instrumental in singling out the first quasars was just as powerless in dealing with superluminal sources as Karl Jansky's pre-War radio antenna would have been for detecting quasars.

▶ New cosmic phenomena frequently are discovered by physicists and engineers or by other researchers originally trained outside astronomy.



Age of required technology *at time of discovery for the 43 cosmic phenomena listed in the table. It is not surprising that a phenomenon cannot be discovered until technical means exist that make the discovery possible. An x-ray star cannot be discovered unless we construct telescopes sensitive to x-rays; bursts of gamma rays reaching us from the universe will not be noticed unless apparatus capable of sensing these rays is taken above the atmosphere to perform the observation. What is surprising, however, is the speed with which major discoveries follow innovation. This is particularly striking in recent times. For many of the discoveries the recognition of the new phenomenon occurred in a series of discrete steps. For these the age of the contributing technology was separately assessed for each step and weighed to keep the total at 43.* *Figure 4*

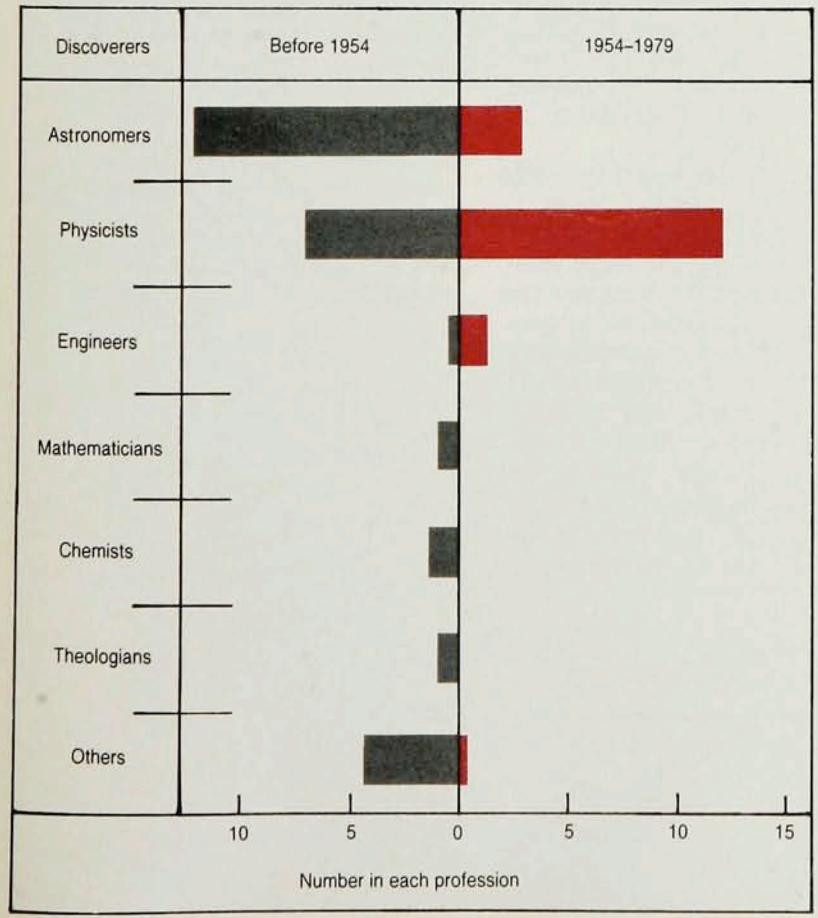
This is illustrated by the data shown in figure 5, again culled from the histories of the 43 discoveries listed in the table. The result was first suggested by the sociologists of science David O. Edge and Michael Mulkay who noted that all of the early radio-astronomers had been trained as physicists or engineers. But this finding is not restricted to radio-astronomy. We speak of "cosmic-ray physicists," and none of the early x-ray or gamma-ray astronomers appear to have had advanced degrees in astronomy. Most of them were trained as physicists.

▶ Many of the discoveries of new phenomena involve use of equipment originally designed for military use.

Shortly after World War II, a group led by James Stanley Hey, a young troubleshooter for the British radar network, discovered a curiously undulating cosmic radio signal emanating from what later was shown to be an extragalactic source and named Cygnus A—the brightest radio source in the constellation Cygnus. Radar equipment that had been developed for the war effort also made possible the rapid development of radio-astronomy after the War. Advances in infrared astronomy during the past twenty years have similarly benefited from military research on sensitive detectors. Cosmic gamma-ray bursts, bursts of gamma rays reaching Earth a few times a year from unknown regions in space and lasting only a few seconds at a time, similarly were discovered by the military's Vela satellite system designed to detect surreptitious detonations of nuclear bombs.

▶ The instruments used in the discovery of new phenomena often have been constructed by the observer and used exclusively by him.

Huggins and Miller in their discovery of gaseous nebulae, Anthony Hewish and Jocelyn Bell who discovered pulsars, and all the early x-ray, gamma-ray and infrared astronomers were individuals or small groups of researchers who developed their own instruments and maintained sole control. They were able to modify the apparatus, note its peculiarities and decide whether a puzzling result originated in an instrumental quirk or represented some new phenomenon never recognized



***Career Background** for the discoverers of the 43 cosmic phenomena listed in the table shows that most of the major cosmic phenomena were discovered by individuals prepared for careers other than astronomy—instrumentalists with novel techniques for looking at the sky. This educational background and early work experience outside astronomy is particularly apparent for the 25-year period between 1954 and 1979. Even prior to 1954, however, half of all discoveries were made by outsiders. Where several discoverers were involved, the contributions are weighted so that the number of careers also totals 43.* *Figure 5* before.

The discovery of the cosmic microwave background by Arno Penzias and Robert W. Wilson is another case in point. In 1961, E. A. Ohm at Bell Labs calibrated a horn-antenna, figure 1, at 11-cm wavelength and found a system noise temperature 2.1° higher than he could attribute to the several known sources of noise in his system.[9] Two years later, a system operating at 4 GHz, roughly 7-cm wavelength, gave an excess noise temperature 2.5 K above noise contributions from known sources.[10] Finally, in 1965, Penzias and Wilson established an excess temperature of roughly 3 K. In a letter they published in the *Astrophysical Journal* they wrote:[11]

> "... this excess temperature is within the limits of our observations, isotropic, unpolarized, and free from seasonal variations [July 1964–April 1965]. A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll and Wilkinson ... in a companion letter in this issue."

The interpretation of Robert Dicke and his coworkers was identical to a proposal George Gamow, Ralph A. Alpher and Robert C. Herman had advanced more than a decade earlier. It called for a microwave remnant of the explosive origin of the universe.[12,13,14]

Penzias and Wilson were sufficiently certain of their instrumental noise to seek an understanding, possibly in astrophysical terms, for the excess noise they measured. This type of familiarity marks most of the major observational discoveries. Current trends in astronomy, however, favor large shared facilities at national centers. Since guest observers at these observatories seldom have the chance to develop intimate acquaintance with equipment that is frequently updated, it is not clear that national observatories will be well-suited to observational discovery. Their strength may lie in more routine, though important, analytical work.

▶ Observational discoveries of new phenomena frequently occur by chance—they combine a measure of luck with the will to pursue and understand an unexpected finding.

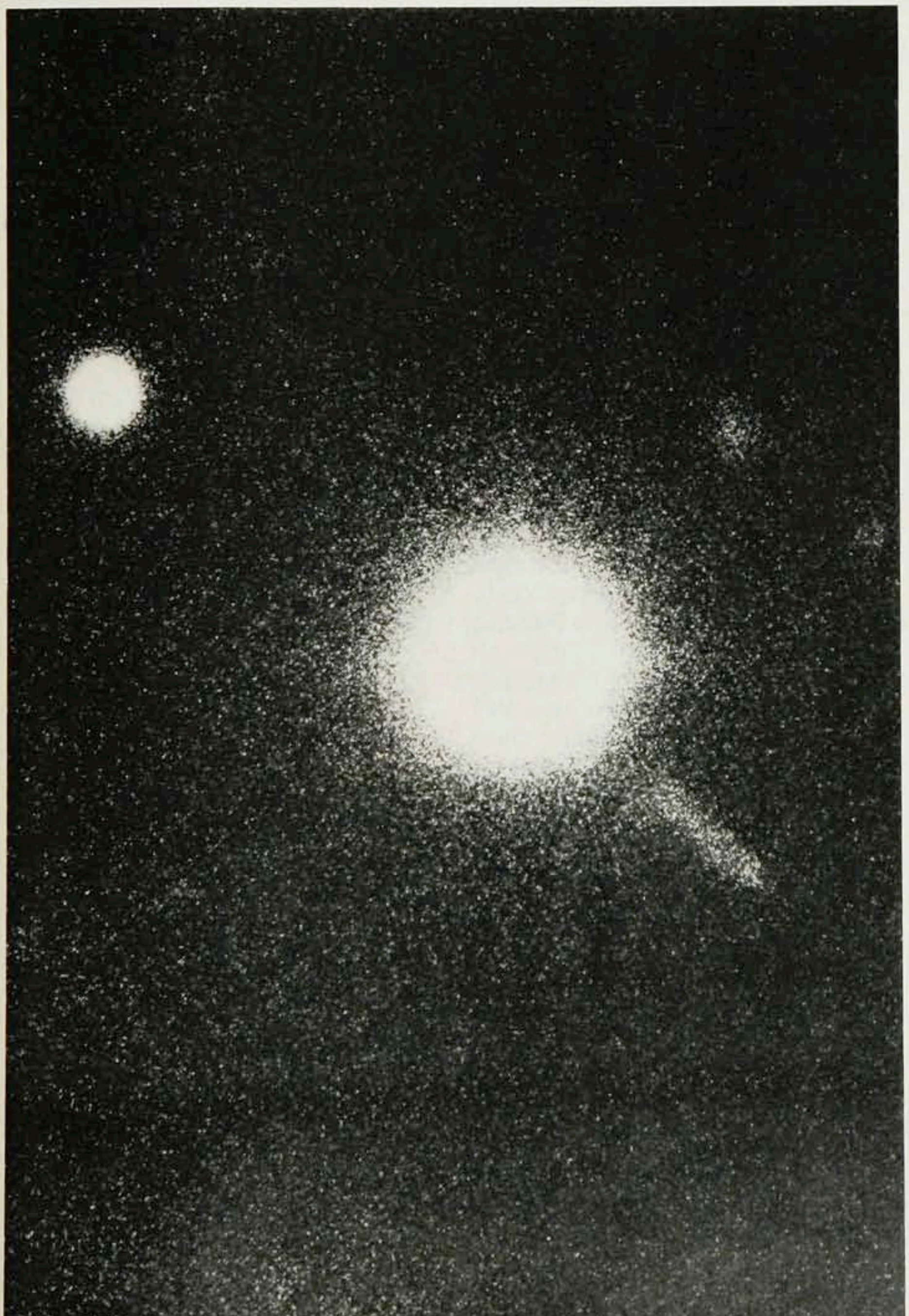
Karl Jansky discovered the radio emission from our Milky Way in 1931 while examining the nature of noise interfering with radio telephone transmission. Similarly, the Austrian scientist Viktor Hess was engaged in studies of atmospheric electricity when he discovered the existence of cosmic rays during a balloon ascent early on the morning of 7 August 1912. Indeed, not one of the many observers I have named clearly anticipated anything like the discovery he or she was to make.

Can we foster further discovery?

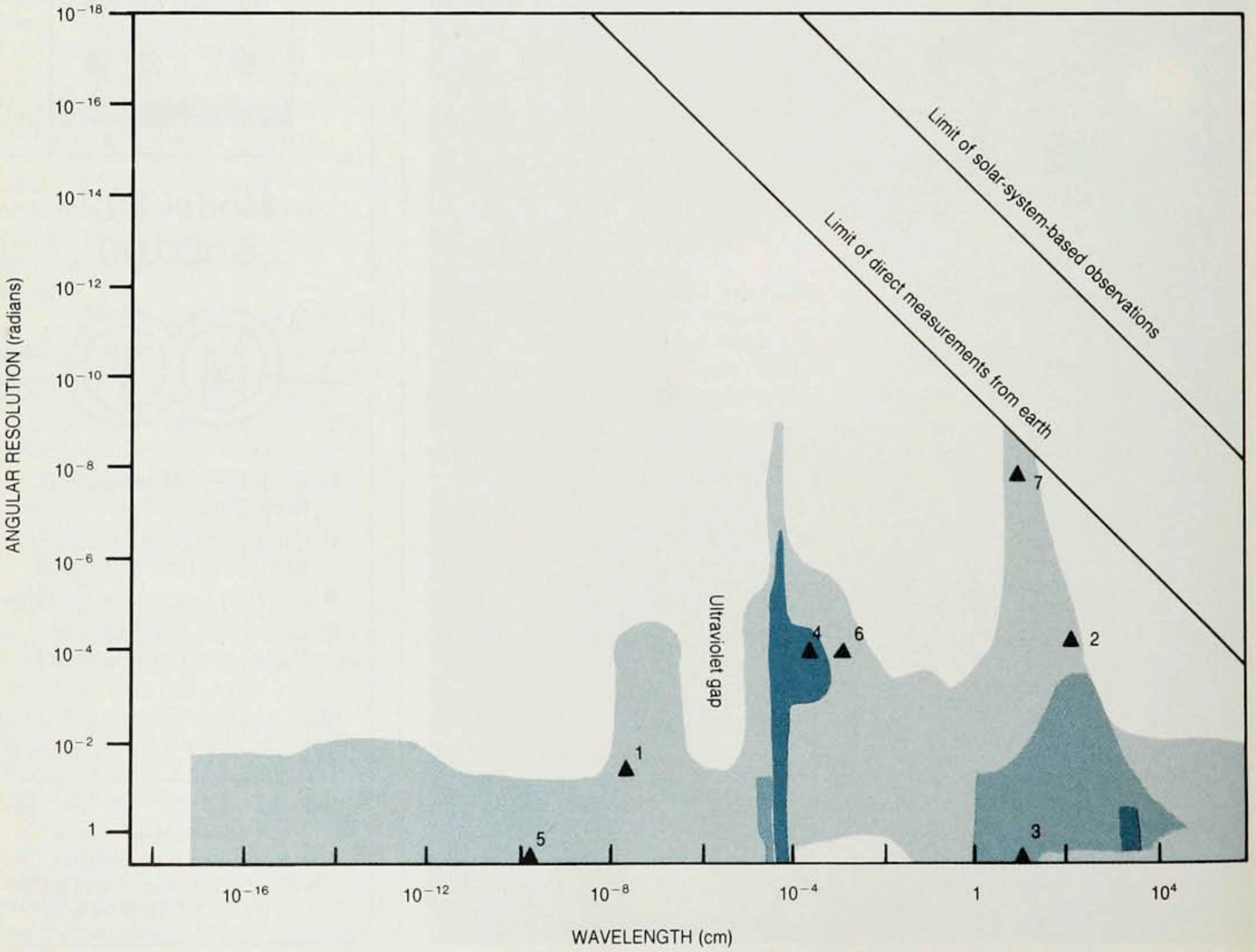
Let us consider a measurement carried out on the quasar 3C 273, which is shown in figure 6. The observation can be described in two parts:

We first characterize the appa-

The quasar 3C 273. *In 1962 the British radio astronomer Cyril Hazard and two colleagues began observations on the radio source 3C 273 from Australia. They observed occultations of the source by the moon and found two slightly separated components, which at optical wavelengths respectively have a stellar and jetlike appearance as seen in this photograph. An optical spectrum subsequently obtained by Maarten Schmidt at Mount Palomar showed a Doppler shift corresponding to a recession speed of 47 400 kilometers per second. 3C 273 also turns out to be a superluminal source; its nucleus contains components apparently flying apart at speeds exceeding the velocity of light. This activity, which occurs on a scale of milliseconds of arc, could not have been detected with the techniques available in the early 1960s; the discovery had to await further instrumental advances. Superluminal sources were discovered a decade later, in the early 1970s. (Palomar Observatory photograph.)* *Figure 6*



Angular resolution available *in various years. The graph[7] displays instrumental capabilities over a range of wavelengths stretching from the extreme gamma-ray end of the electromagnetic spectrum to long radio waves at the opposite extreme. Instrumental capabilities available in 1939 (shaded dark) deal mainly with the visible and near infrared parts of the spectrum, except for some early radio efforts. By 1959 (lighter shading) instrumental capabilities had stretched over considerable portions of the radio spectrum, and by 1979 (lightest shading) infrared, x-ray and gamma-ray observations had become possible. In the wake of instrumental advances, new cosmic phenomena crystalized (black triangles):* ***1*** *x-ray stars (1962) and x-ray galaxies (1966);* ***2*** *quasars (1963);* ***3*** *microwave background radiation (1965);* ***4*** *infrared stars (1965);* ***5*** *gamma-ray background radiation (1968);* ***6*** *infrared Galaxies (1970);* ***7*** *superluminal sources (1971). Most of the phenomena discovered in the 1960s and 1970s appear in areas outside the shaded portions representing the capabilities for 1959. Infrared stars, discovered in 1965, could have been found with the angular resolution available in 1939, but until well after World War II we lacked detectors that had sufficient sensitivity. Unshaded portions of the diagram represent current limitations on instrumental competence in detecting cosmic signals. Two diagonal lines show the limits for observations with instruments tied to the earth and with apparatus confined to the dimensions of the solar system. To improve on these capabilities, we would have to send instruments into interstellar space.* *Figure 7*



ratus used—an x-ray telescope sensitive in the wavelength range around 10 Å (about 1 kilovolt). It has a time resolution of 10 microseconds, an angular resolution of approximately 10 arc seconds, no discrimination for polarization, but is capable of achieving a spectral resolving power of 50 to 1000—roughly corresponding to the capabilities of the Earth-orbiting Einstein Observatory operating in the 1979–1980 era. Secondly, by specifying the intensity of radiation actually detected from the quasar by this apparatus, we complete the two-part description.

Whether we attempt to observe x-rays, cosmic-ray particles or gravitational waves, the instrumental description is the same: We specify energy or wavelength, spectral, time and spatial resolution, polarization discrimination and sensitivity. These traits define the set of information carriers observed—the photons or particles on which we depend for all our knowledge of the Universe.

We now ask, "How are advances in instrumentation related to major astronomical discoveries? What is the present state of astronomical instrumentation? Where are the new advances to be made?"

These questions are answered by plots of the kind presented in figure 7. For the electromagnetic domain, the left-hand boundary of the plot is the pair-production absorption limit, beyond which photons are so energetic that they are readily destroyed through collisions with photons from the 3 K cosmic microwave background, producing electron–positron pairs. Beyond the right-hand boundary of the graph—the interstellar absorption limit—radio waves are so strongly absorbed by the interstellar plasma that they cannot even cross the short distance to our nearest neighboring stars. Photons available for conveying astronomical information therefore lie roughly in the wavelength range from 10^{-19} cm to 10^{6} cm. Interstellar absorption by hydrogen atoms is strong in the "ultraviolet gap," the extreme ultraviolet portion of the spectrum, between 10^{-6} and 10^{-5} centimeters. The vertical axis ranges from isotropy (at the bottom of the graph) to the angle subtended by the Schwarzschild radius of a one-solar-mass black hole across the galaxy (at the top of the graph); the smallest observable source in distant parts of our galaxy might be such a black hole.

Figure 7 also shows the rapid expansion of technological capabilities in recent decades. Astronomical discoveries that accompanied these instrumental advances could not have taken place without apparatus whose wavelength response or resolving power differed by many orders of magnitude from earlier instrumental capabilities. The 1965 discovery of the microwave background radiation, by Penzias and Wilson, depended on a horn-shaped antenna, figure 1, capable of reliably measuring a totally isotropic flux. The discovery of quasars in the early 1960s was brought about by angular resolution capabilities that told of powerful radio sources subtending angles smaller than seconds of arc. A further thousandfold increase in angular resolving power revealed the existence of superluminal sources. Each of these three discoveries required radio instrumentation operating on entirely different orders of angular resolution.

The large unshaded areas in Figure 7 denote unavailable instrumentation. Here lie the opportunities for innovative physicists to advance astronomy. The history of past discoveries can leave no doubt that these blank regions hide major new phenomena awaiting discovery.

Surprises and the role of theory

I have mentioned the sense of astonishment that often accompanies the most significant observational discoveries. This element of surprise may be considered a measure of the discipline's immaturity.

The historian of science, Thomas Kuhn, has described progress in a mature science in terms of a series of successive revolutions. Each revolution is preceded by an impasse in which theory and observation clash in irreconcilable fashion. If that view is accepted, then astronomy, often called the most ancient of the sciences, must be quite immature. Astronomical theories seldom appear to clash with new observational discoveries. Instead, theory most often is mute. It does not anticipate the discovery; it offers little guidance; and when a new phenomenon is found, theorists offer a multitude of explanations where only one can be correct. The discovery of variable stars, supernovae, radio galaxies, quasars, x-ray stars and x-ray galaxies all illustrate this relation between theory and discovery.

Where then does theoretical astronomy make its contributions?

The answer is two-fold. Theory enters in astronomical analysis and in what might be called purely theoretical discovery.

Analytical work, as already mentioned, is the day-to-day work of the astronomer or astrophysicist. He studies the evolution of a supernova in terms of nuclear and particle physics and fluid dynamics, and he devises observations that test his theoretical models. This is painstaking work: Fundamentally different processes occurring deep within a source sometimes distinguish themselves only through minor differences at the surface. Refined techniques are then required to measure these distinctions. Alternatively, we may possess no theory capable of explaining accumulated data, and the analytical observer may employ some entirely new method for viewing the source in the hope of gaining new insight into the mechanisms at work. Similarly, a theorist engaged in analysis may recommend specific observations designed to distinguish unambiguously between rival models for an astronomical source.

Theoretical discoveries differ fundamentally from analytical work. They generally arise because a theoretical model is extended to exhibit its logical extremes. Discoveries of this kind include black holes, curved models of the universe, degenerate matter at the center of a white dwarf or in a neutron star and magnetohydrodynamic effects on a galactic scale.

Theoretical discoveries are curiously decoupled from observational discoveries. Their timing is quite different: The first white dwarf was discovered a couple of decades before a correct theoretical explanation could be offered. Neutron stars, on the other hand, were theoretically conceived four decades before the discovery of pulsars, which now are generally explained as rapidly rotating neutron stars. We still lack a good explanation for the quasar phenomenon almost twenty years after the original discovery of quasars, while at the same time no universally accepted black-hole candidate is yet known, four decades after Oppenheimer and Hartland S. Snyder first examined black-hole models in 1939. Nor are such long delays between theoretical prediction and observational verification, or alternatively, between observational discovery and theoretical explanation, merely a syndrome of modern astronomy. Copernicus expected the Earth's motion around the sun to produce an observable stellar parallax; but this idea had to wait three centuries for confirmation. Not until 1838 was Friedrich Wilhelm Bessel able to report his successful parallatic measurement of the distance to the nearby star 61 Cygni. The distance amounts to an astonishing 600 000 Earth orbital radii, a distance of ten light-years.

A role for physicists

We have seen that physicists have made sizeable contributions to the discovery of new observational phenomena, principally when they have come into astronomy with novel tools that exhibited strikingly powerful new capacities. The astronomical community appears substantially dependent on outsiders for this service.

While analytical work and theoretical contributions have not yet been studied in any reliable way, currently available data suggest that analytical work is largely carried out by researchers thoroughly trained in astronomy either by dint of formal education or through long-term work in the field. Theoretical discovery, in contrast, appears to be the domain of physicists working at boundaries to the unknown.

I would like to venture one generalizing speculation that I can only support by tenuous evidence. It is that physicists make their most important contributions to astronomy when they introduce new observational or theoretical tools that open domains inaccessible to traditionally trained astronomers. On entering such a domain, the physicist is not excessively handicapped by his lack of formal astronomical training. The domain, after all, is just as new to

the astronomer.

Astronomers have been slow to recognize their dependence on physicists for new instruments and fresh ideas. The prime US planning document for astronomy in the 1970s was a report commissioned by the National Academy of Sciences and prepared by a distinguished committee headed by Jesse L. Greenstein of the California Institute of Technology.[8] This committee's considerations of manpower problems in astronomy revolved largely around the number of new graduate students that might be trained in astronomy. The committee acknowledged contributions made by physicists but had no plan for attracting more of them. Although two-thirds of the major post-War discoveries in observational astronomy were being made by a pool of physicists numbering less than one-third of the astronomical work force, this important contribution had never been documented, and the committee probably was unaware of its actual magnitude. Despite the remarkable record that physicists have compiled, an individual physicist's entry into astronomy may therefore still pose problems.

Attitudes, however, change. Increasing numbers of universities conduct astrophysical research within their physics departments, and many institutions now have joint departments of physics and astronomy. Twenty-five years ago such arrangements were virtually unknown. Their full impact has only been felt within the last ten years.

The search for gravitational waves or for neutrinos of cosmic origin will almost certainly require major involvement of physicists. But even smaller advances within the more conventional electromagnetic or cosmic-ray domains may depend heavily on contributions by experimental and applied physicists. Recent advances have involved developments in laser techniques and heterodyne reception, the fabrication of multidetector and multichannel arrays, and improved sensitivity of radiation and particle detectors. Physicochemical techniques, similarly, have found increased application in the study of the early solar system through microchemical analyses of meteorites; and the past few years have seen great strides in our ability to discriminate not only between different chemical elements in the cosmic-ray flux incident on Earth, but also between distinct isotopes.

On the theoretical front, grand unified theories of physics may trace cosmic events further back in time toward the earliest moments of the universe when the apparent preponderance of matter over antimatter was decided, when galaxies were beginning to nucleate, and when the earliest cosmic magnetic fields may have come into being. For cosmologists all three of these topics remain unfathomed problems. The search for black holes may similarly advance as we improve our grasp of quantum field theoretical processes in strong gravitational fields.

Opportunities for physicists cluster at the frontiers of astronomy. Entry into the field may not be without difficulty, but any physicist with a powerful new instrumental or theoretical technique can quickly find himself making contributions at the forefront of astrophysics.

Will you, won't you, will you, won't you, won't you join the dance?[15]

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