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The Nineteenth Century's Last Five Years

In the fall of 1895, the 16-year-old Albert Einstein traveled to Zürich to seek admission to the engineering division of the Eidgenössische Polytechnikum. He had prepared for the entrance examinations on his own, in Italy, where his family had recently moved. Most students took these exams at age 18, and the Polytechnikum's Rector, instead of admitting the youngster straight away, recommended him to the Swiss canton school in Aarau, from which Einstein graduated the following year.

Graduation in Aarau led to acceptance at the Polytechnikum without further examinations. Albert began his studies there in October 1896 and graduated in late July 1900. Only, instead of pursuing engineering, he registered for studies in mathematics and physics.

Looking back at those five student years between the fall of 1895 and the summer of 1900, one can hardly imagine a more exciting era in science.

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Late on the afternoon of Friday, November 8, 1895, Wilhelm Conrad Röntgen, professor of physics at Würzburg, noticed an odd shimmer. He had for some weeks been studying the emanations of different electrical discharge tubes, and had previously noted that a small piece of cardboard painted with barium platinocyanide fluoresced when brought up to one of these tubes. To understand better the cause of the fluorescence, he had now shrouded the tube with black cardboard so no light could escape. In the darkened room, he checked the opacity of the shroud. It looked sound, but there was a strange shimmer accompanying each discharge. Striking a match in the dark, he found the shimmer to come from the barium platinocyanide–coated cardboard he had set aside to use next.

Over the weekend, he repeated the procedure. Some novel effect appeared to be at work. In the weeks to follow he conducted a wide variety of experiments to study more closely the cause of the fluorescence. He found that whatever emanation was passing through the blackened cardboard shroud also darkened photographic plates.

The emanation was absorbed most strongly by lead. Unlike the electric discharge in the tube, it could not be deflected by a magnet. It traveled along straight lines but, unlike *ultraviolet radiation*, it was not reflected by metals. Not knowing precisely what to call these rays, he chose the nonprejudicial designation, *X-rays*.

On December 28, his first paper on his findings, titled 'Über Eine Neu Art von Strahlen' (On a New Kind of Rays) was published in the *Sitzungsberichte der Würzburger Physikalisch-Medizinischen Gesellschaft*. Six days earlier, Röntgen had asked his wife to place her hand over a photographic plate. His paper included the resulting picture, shown here as Figure 1.1. It caused an immediate sensation and may still be the most iconic scientific image of all time, showing the skeletal structure of her hand and, even more clearly, the ring she was wearing. At one glance it revealed both the discovery of a new, penetrating imaging technique, and clear indications of its vast promise for medical science and countless other investigations. In Britain, the journal *Nature* published

Figure 1.1. This image was included in the original paper Röntgen published, albeit without the stamp of the Physics Department of the University of Würzburg. An intensely private man, Röntgen captioned the published image simply 'Photograph of the bones in the fingers of a living human hand. The third finger has a ring upon it.' It was not in Röntgen's nature to publicize that the hand was his wife's. The German caption on the image reproduced here denotes even more sparingly 'Hand with rings.' (*Courtesy of the University of Würzburg*).

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Martin Harwit
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an English translation of the paper on January 23, 1896.[1] This, and the newspaper articles that had preceded it, led to instant world-wide attention. More than 1000 publications on X-rays, including books and pamphlets, appeared that same year, 1896.[2]

Röntgen was not sure precisely what kind of radiation he had discovered. He thought it was light-like or some variant of light. He knew about the medical applications X-rays would have and refused to take out a patent, insisting that all mankind should benefit from his work. But he could never have anticipated that a century later, Earth-circling X-ray telescopes would be studying signals emanating from cosmic *black holes* far out in the expanding Universe. Even uttering this last sentence would have made no sense; it conveys concepts unimaginable at the time!

* * *

The news of Röntgen's discovery spurred Antoine Henri Becquerel, professor of physics at the Polytechnic in Paris, to see whether all phosphorescent materials emitted similar rays. They did not. But Becquerel encountered another unexpected phenomenon, a spontaneous emission of radiation from uranium salts, which he announced in 1896.

The following year, 1897, Joseph John Thomson, Cavendish Professor of Physics at Cambridge, revealed the origin of the energetic cathode rays that had given rise to Röntgen's X-rays. The cathode rays, Thomson found, were streams of negatively charged particles. The magnitude of their charge was identical to that of the positively charged hydrogen atom in the electrolysis of dilute solutions. The mass of the particles he judged to be only 1/1700 of the mass of a charged hydrogen atom.[a] The careful measurements, and the completeness of Thomson's arguments led to the swift acceptance of the new particles we now call *electrons*.

By 1898, Becquerel's investigations had been pursued further by Pierre Curie, professor of physics at the Sorbonne in Paris, and by his young Polish wife, Marie Skłodowska Curie, who coined the word *radioactivity* for the phenomenon Becquerel had discovered. Among the many experiments they conducted, the Curies isolated two new radioactive materials from the uranium-containing ore *pitchblende*. Each was millions of times more radioactive than uranium. Both were previously unknown elements. The first, Marie Curie called *polonium*; the second, *radium*.

By late 1898, the Scottish chemist William Ramsay and co-workers in his laboratory had also isolated the inert elements helium, argon, neon, krypton, and xenon, in a succession of ingenious experiments conducted over the previous several years.

[a] Thomson's ratio of the mass of the *electron* to that of the *proton*, the nucleus of the hydrogen atom which Thomson called "the charged hydrogen atom," was remarkably close to today's accepted ratio $\sim 1/1836$.

As the nineteenth century was drawing to a close, physicists and chemists were beginning to understand the nature of the chemical elements. The periodic table the Russian chemist Dmitri Ivanovich Mendeleev of St. Petersburg had published in 1869 was serving as a roadmap whose details were emerging with increasing clarity. Full of confidence in the table he had devised, Mendeleev had provocatively left blank spaces in it. Now, chemists were rapidly isolating the new elements whose existence he had predicted and finding them to fall in line. Ramsay's new elements fit neatly into a new column added to the table, just as Marie Curie's new elements filled two of its previously blank spaces. Chemists were increasingly feeling they were on the right track.[3]

The atomic nature of the elements was gaining acceptance. Molecules were recognized as invariably composed of atoms. The structure of atoms was not yet known, but J. J. Thomson's experiments showed them to contain electrons, which could be removed from any number of different substances by strong electric fields.

In the course of the century, the nature of electricity and magnetism had become established through many experiments, particularly those that Michael Faraday had conducted in England. By 1865, James Clerk Maxwell in Scotland had extended Faraday's work and developed the electromagnetic theory of radiation as we know it today. This indicated that light was a wave oscillating transverse to its direction of propagation, transporting equal parts of electric and magnetic energy across space.[4] This prediction had been confirmed experimentally with radio frequency waves, by Heinrich Hertz in Germany in 1888.[5,6] Following Hertz's lead, the Italian inventor Guglielmo Marconi, by 1899, was demonstrating that radio waves could even be transmitted across the English Channel.[7]

* * *

For astronomers many of these results remained too new to find immediate application. Astrophysics was still too young a discipline. The first issue of the *Astrophysical Journal* had appeared only on January 1, 1895, and then was largely devoted to *spectroscopy*. Spectra of the Sun, stars, and laboratory sources were being pursued with vigor to discern parallels between chemical constituents found on Earth and those that might compose the atmospheres of planets, stars, and astronomical nebulae.

Although spectroscopic work was still largely devoted to gathering data and classification of stellar spectra, high-resolution spectroscopy was beginning to yield line-of-sight velocities of stars through observation of their *Doppler-shifted* – that is, velocity-shifted – spectra.[b] By the 1890s, Hermann Carl Vogel and Julius Scheiner at the Astrophysical Observatory at Potsdam had advanced spectroscopic techniques sufficiently to permit reliable determination of the line-of-sight velocities of stars

[b] The spectroscopic shift had been predicted half a century earlier, in 1842, by the mathematician Christian Doppler in Prague.[8]

relative to Earth and to provide a direct measurement of Earth's velocity during its annual orbit about the Sun.

By observing the Doppler shift of *spectral lines* over periods of months or years, the speeds at which close binary stars orbit each other could also be determined precisely, provided they happened to *eclipse* each other. Once their orbital velocities and periods were determined, Newton's laws of motion could be applied to derive the stars' masses.[9]

On several crucially important points, however, astronomy remained mute: We knew nothing about the size of the Universe. We knew nothing of its age – or whether it might be ageless, as most people believed. And how the Sun might have kept shining for as long as Earth appeared to have been warmed by sunlight also was quite uncertain.

The rate of erosion of terrestrial rocks by winds and rain, and the resulting salinity of the oceans into which the eroded matter was being swept, implied that Earth had been warmed by the Sun for hundreds of millions of years. The depth of stratigraphic deposits containing fossilized fauna led to similar conclusions. But how the Sun could have kept shining so long, nobody could explain. The required energy far exceeded any conceivable supplies!

The twentieth century would gradually answer this question.

Notes

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3. Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente, D. Mendelejeff, *Zeitschrift für Chemie*, *12*, 405–406, 1869.
4. A Dynamical Theory of the Electromagnetic Field, James Clerk Maxwell, *Philosophical Transactions of the Royal Society of London*, *155*, 459–502, 1865.
5. Über die Entwicklung einer geradlinigen elektrischen Schwingung auf eine benachbarte Strombahn, H. Hertz, *Annalen der Physik*, *270*, 155–70, 1888.
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8. Ueber das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels, Christian Doppler, *Abhandlungen der königlich böhmischen Gesellschaft der Wissenschaften zu Prag*, Folge V, 2, 3–18, 1842.
9. *A History of Astronomy*, Anton Pannekoek, p. 451. London: George Allen & Unwin, 1961. Reprinted in Mineola, NY: Dover Publications, 1989.

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Part I The Import of Theoretical Tools

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An Overview

The Universe We See Today

Twentieth century astrophysics has taught us that the origin and evolution of everyday matter, of the stars we see at night and the Universe we inhabit, share a coherent history dating back *billions* of years. Our knowledge remains fragmentary, but progress has been rapid and provides hope that our search will someday be complete, perhaps not in the sense that we will be all-knowing, but that we may have uncovered all that science can reveal.

One helpful feature in our search is that, as far back in time as we are able to probe, we find the known laws of physics holding firm. The *speed of light*, the properties of atoms, their constituent electrons and nuclei, and the mutual interactions of all these particles and radiation, appear unchanged ever since the first few seconds in the life of the Cosmos.

Also helpful has been that the Universe is expanding and that light, despite its high velocity, requires eons to cross cosmic distances. Using our most powerful telescopes we are able to directly view remote stars and galaxies, which emitted their light billions of years ago. We can compare how they appeared then and how stars and galaxies nearer to us in space appear now. And, as the Universe expands, light waves crisscrossing space expand with it. Short-wavelength light emitted by a distant galaxy reaches us with a longer *wavelength*; blue light is shifted toward the red. This *redshift* increases with the distance traversed and the time since the light was emitted. A galaxy's redshift then dates the epoch at which the galaxy emitted the light we observe.[a]

[a] We tend to think of telescopes as devices we use to look far out into space; but, in cosmology, they actually serve to look back in time. Galaxies coming into view today from the most remote early epochs are those that also are most distant. Time has been needed for their light to reach us. The nearest galaxies we see today can be seen only as they appeared just a few million years ago. We never will observe these as they might have appeared billions of years earlier. Light they emitted then bypassed us far too long ago.

Powerful telescopes can map a galaxy's appearance, discern its structure, and spectroscopically detect its internal motions and chemical constituents to determine the physical processes at work: Is the galaxy forming new stars? Just how much radiation is it emitting? Is it isolated, or possibly interacting with a neighboring galaxy?

As we probe ever more deeply in space and further back in time, large surveys provide a panoramic history of cosmic evolution. We see small galaxies shortly after their birth; we note their merging to form larger galaxies in an epoch during which the galaxies' nuclei everywhere briefly blazed more brightly than ever before or after. The early Universe appears almost devoid of chemical elements more massive than hydrogen and helium; at later times, we see the abundance of heavier chemical elements steadily rising.

The most difficult epochs to probe are the very earliest times. During the first few hundred thousand years after the birth of the Cosmos, a dense fog of electrons, *nucleons*, radiation, and *neutrinos* permeated space, degrading all data that visible light, radio waves, X-rays, or any other electromagnetic radiation could have transmitted about the birth of the Universe. We cannot yet tell precisely how much information about its creation the Universe may have eradicated this way. But we make up for this loss, with some success, by seeking other clues to cosmic history at early times.

One of these is provided by the ratio of hydrogen to helium atoms. The other is the temperature of a pervasive *microwave background radiation* bath that we now detect dating back to a time just after the initial fog had cleared. Between them these two features tell us how dense and extremely hot the Universe must have been when it was only a few minutes old, as primordial protons, *neutrons*, and electrons repeatedly collided to form the abundance of helium atoms that remain a major cosmic constituent to this day.

Further clues, which we do not yet know how to interpret, may be the high abundances of electrons and protons in the Universe and the virtually complete absence of their *antiparticles*, the *positrons* and *antiprotons*. At the high temperatures that existed at earliest times, collisions among particles and radiation should have formed protons and antiprotons, and electrons and positrons, in equal numbers. Could the laws of physics as we currently understand them have differed at those earliest epochs, after all? Or is our current knowledge of physics at extremely high energies merely incomplete? If so, experiments conducted at high-energy accelerators, or observations of high-energy *cosmic rays* naturally impinging on Earth from outer space, may some day tell us how these laws should be augmented.

Our search continues.

Discovery and Insight

Our understanding of the Cosmos is based on a confluence of discovery and insight. The two words can have many meanings. Here, I will consider *discovery* to be the recognition that a confirmed finding does not fit prevailing expectations. Observations, experiments, and exploration, can all lead to discovery. *Insight* enables us to place the discovery into a pattern shaped by everything else we believe we know. It is as though the discovery was a strangely shaped piece to be fitted into a larger jigsaw puzzle. To make the discovery fit, the shape of the puzzle may have to yield, or the entire puzzle may have to be disassembled and reconfigured through novel insight before the new piece can be accommodated.

The growth of understanding involves successive cycles of discovery and insight. But, unlike more orderly cyclic processes, discovery and insight generally do not follow neat periodic patterns. The sequence may be better described as times of accumulating discoveries, uncertainty, and doubt, followed by recognition that we will find clarity only by abandoning previously held views in favor of new perspectives.

Verification of the new perspectives, however, may require novel sets of tools. For astronomers this may mean construction and use of new kinds of telescopes and instrumentation. For theorists it may be the use of specially invented analytical approaches or mathematical concepts. For both, a lack of laboratory data may be a roadblock to be removed with yet a third set of tools. The proper tools are indispensable.

Due diligence alone cannot make up for a lack of tools. But the availability of the required tools, or even a knowledge of what those tools might be, often may be lacking. For decades, no astronomer could conceive that tools for detecting X-rays could revolutionize the field.

As we shall see later, when Einstein had struggled several years to understand the nature of space, time, and gravitation, he had to turn for help to his friend and former fellow-student, the mathematician Marcel Grossmann, who introduced him to an arcane differential geometry that the mathematician Bernhard Riemann and his successors had explored late in the nineteenth century. Advances are possible only when the right tools come to hand.

At times, theoretical tools abound and then astrophysical theory outstrips observations until theory threatens to detach from reality. At other times, observations are readily obtained, and our knowledge of the Universe becomes phenomenological. We may know what transpires, but cannot account for it with overarching principles that relate different phenomena to each other. Astronomers are most satisfied when their theories roughly match observations, both in depth and in the range of topics they cover. Such balance enables steady progress along a broad front where new problems can be tackled both with available observational and theoretical tools.

Ultimately, however, even discovery, insight, and the tools they require are not enough to ensure progress. Each astronomical advance leading to a new level of understanding must first become accepted before a succeeding advance can follow. For this, the persuasion of fellow astronomers is critical. Acceptance entails the consent of the community. An individual scientist may make a discovery, gain new insight, and find a journal willing to publish the findings – though even this is not assured if the finding does not find favor with the journal's editors and referees. But publication alone does not automatically lead to acceptance. Most published articles, particularly those announcing a novel advance, are largely ignored by the community, which prefers to deal with accepted knowledge rather than novelties. Unless a scientist can persuade critics that he or she has made a valuable contribution, the advance will remain buried in some publication – if it even gets that far. Most astronomers will tell you that it is easier to find acceptance for a finding that independently verifies a well-known truth than to persuade colleagues of the importance of an exceptional observation or a particularly daring insight.

Persuasion is so difficult because it normally proceeds not through a single advance but through an expanding list of convincing instances of how a new insight or novel discovery brings harmony to disparate findings that prevailing views fail to explain.

To perceive how our understanding of the Universe advances, the importance of each of the ingredients – discovery, insight, the existence of requisite tools, and persuasion of the astronomical community – must all be recognized. If we neglect or minimize the significance of any of these four, the growth in understanding becomes unfathomable and seemingly haphazard.

The Growth of Understanding

How new discoveries come about and lead to greater understanding of the Universe can depend on many factors. *Quasars* and *pulsars* were both discovered in the 1960s. But, whereas it took nearly 30 years to recognize fully what quasars are, the physical processes that account for pulsars were understood almost at once.

The first sign that quasars were quite unusual was that they emitted powerful radio signals from what appeared to be point-like sources in which even the largest radio telescopes could not resolve observable structure. Added to this, observations with optical telescopes showed that the radiation was strongly redshifted. All this was known by 1963. Wanting a crisp name to identify these newly found sources, but not wishing to prejudice the interpretation of what they entailed, we called them *quasars*, a contraction of *quasi-stellar* sources – a reference to their point-like appearance.

Einstein's general relativity offered two quite distinct interpretations of what we might be seeing. One potential explanation for the high redshift was that the quasars were at extreme distances where the Universe was expanding at ever greater speeds. An alternative possibility was that quasars were highly compact and massive, and that the observed redshift was due to the quasar's strong gravitational pull on light escaping its surface. Einstein's general theory of relativity