7 The Evolution of Science

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Analogies

I was asked to write about the 'Evolution of Science'. This is an enormous subject and would take a historian to do it justice. I am not a historian. I am a scientist with a smattering of knowledge about history. I prefer to write about things I know. Here, I tell stories rather than digging deep into the sources of historical truth. I write about astronomy, which is one little corner of science, and about recent events with which I am familiar. I use the recent history of astronomy to illustrate some evolutionary themes, which may or may not be valid when extended to earlier periods or to other areas of science.

My approach to evolution is based on analogies between biology, astronomy and history. I begin with biology. The chief agents of biological evolution are speciation and symbiosis. In the world of biology these words have a familiar meaning. Life has evolved by a process of successive refinement and subdivision of form and function; that is to say, by speciation, punctuated by a process of bringing together alien and genetically distant species into a single organism, i.e. symbiosis. As a result of the work of the biologist Lynn Margulis and other pioneers, the formerly heretical view, that symbiosis has been the mechanism for major steps in the evolution of life, has now become orthodox. When we view the evolution of life with an ecological rather than an anatomical perspective, the importance of symbiosis relative to speciation becomes even greater.

As a physical scientist, I am struck by the fact that the borrowing of concepts from biology into astronomy is valid on two levels. One can see in the sky many analogies between astronomical and biological processes, as I shall shortly demonstrate. And one can see similar analogies between intellectual and biological processes in the evolution and taxonomy of scientific disciplines. The evolution of the universe and the evolution of science can be described in the same language as the evolution of life.

Speciation in the sky

In the context of astronomy, speciation occurs by the process of phase transition. A phase transition is an abrupt change in the physical or chemical properties of matter, usually caused by heating or cooling. Familiar examples of phase transitions are the freezing of water, the magnetization of iron, the precipitation of snow from water vapour dissolved in air. In many of these, the warmer phase is a uniform disordered mixture while the cooler phase divides itself into two separate components with a more ordered structure. Such transitions are called order–disorder transitions, and humid air changing to cold dry air plus snowflakes is a typical example. Snowflakes are a new species, with a complex crystalline structure that was absent from the humid air out of which they arose. Also, by the action of the earth's gravity, snowflakes spontaneously separate themselves from air and fall to the ground. At all stages in the evolution of the universe we see order–disorder transitions with the same two characteristic features: first, the sudden appearance of structures that did not exist before; and, second, the physical separation of newborn structures into different regions of space.

Another name for the process of phase transition from disorder to order is symmetry-breaking. From a mathematical point of view, a disordered phase has a higher degree of symmetry than an ordered phase. For example, the environment of a molecule of water in humid air is the same in all directions, while the environment of the same molecule after it is precipitated into a snowflake is a regular crystal with crystalline axes oriented along particular directions. The molecule sees its environment change from the greater symmetry of a sphere to the lesser symmetry of a hexagonal prism. The change in the environment from disorder to order is associated with a loss of symmetry. Sudden loss of symmetry is seen in many of the most important phase transitions as the universe evolves.

In the earliest stages of its history, the universe was hot and dense and rapidly expanding. Matter and radiation were then totally disordered and uniformly mixed. One of the greatest symmetry-breakings was the separation of the universe into two phases: one contained most of the matter and was destined to condense later into galaxies and stars; the other contained most of the radiation and was destined to become the intergalactic void. The separation happened as soon as the universe became transparent enough, so that large lumps of matter pulled together by their own gravitation could radiate away their gravitational energy into the surrounding void. As a result of this transition, the universe lost its original spatial symmetry. Before the transition, it had the symmetry of uniform space. After the transition, it became a collection of irregular lumps. The same process of symmetry-breaking was then repeated successively on smaller and smaller scales. A single lump of the first generation was a huge mass of gas, locally uniform and locally symmetrical. The local uniformity of the gas was then broken when it condensed into the second-generation lumps which we call galaxies. The gas in a local region of a galaxy cooled further until it condensed into the third-generation lumps which we call giant molecular clouds. Finally, the gas and dust in a local region of a molecular cloud condensed into the fourth-generation lumps which we call stars and planets. The universe in this way became a hierarchical assortment of lumps of various shapes and sizes. The formation of lumps was at each stage driven by gravity and assisted by phase transitions allowing the physical separation of matter into different phases.

The processes of astronomical speciation did not stop after the stars and planets were formed. After the earth had condensed out of the interstellar dust, a new world of opportunities opened for separation of phases and growth of structures. First came the separation of the interior of the earth into its main components: core, mantle and crust. Next came the separation of the earth's surface into land, ocean and atmosphere. This is a continuing process, with water constantly circulating from the ocean into the atmosphere, onto the land and back to the ocean. The third process transforming the earth is the division of the crust into plates and the formation and destruction of the crust at the plate boundaries, the process known as plate tectonics; plate tectonics is a powerful force, constantly giving the earth new structures. The fourth process creating structure and order on earth is the most powerful of all. The fourth process is life. Life appeared here between three and four billion years ago and gave the concept of speciation a new meaning.

The transition from dead to living was a phase transition of a new type. It was a transition from disorder to order, in which the ordered phase acquired the ability to perpetuate itself after the conditions that caused it to appear had changed. There are many theories of the origin of life, and there is no direct evidence to decide which theory is true. All that we know for sure is that a complicated mixture of organic chemicals made the transition to an ordered phase that could grow and reproduce itself and feed on its surroundings. And then, after the ordered phase was once established, it possessed the flexibility to mutate and evolve into a million different species. Life has given to our planet a richness of structure that we see nowhere else in the universe. But the diversification of new forms of life on the earth is in many respects similar to the diversification of new celestial species, galaxies and dust clouds, and stars and planets, in the universe as it was before life appeared. The evolution of life fits logically into the evolution of the universe. Both in the non-living universe and on the living earth, evolution alternates between long periods of metastability and short periods of rapid change. During the periods of rapid change, old structures become unstable and divide into new structures. During the periods of metastability, the new structures are consolidated and fine-tuned while the environment to which they are adapted seems eternal. Then the environment crosses some threshold that plunges the existing structures into a new instability, and the cycle of speciation starts again.

Symbiosis

Phase transitions are one of the two driving forces of evolution. The other is symbiosis. Symbiosis is the reattachment of two structures, after they have been detached from each other and have evolved along separate paths for a long time, so as to form a combined structure with behaviour not seen in the separate components. Symbiosis played a fundamental role in the evolution of eukaryotic cells from prokaryotes. The mitochondria and chloroplasts that are essential components of modern cells were once independent free-living creatures. They first invaded the ancestral eukaryotic cell from the outside and then became adapted to living inside. The symbiotic cell acquired a complexity of structure and function that neither component could have evolved separately. In this way symbiosis allows evolution to proceed in giant steps. A symbiotic creature can jump from simple to complicated structures much more rapidly than a creature evolving by the normal processes of mutation and speciation.

Symbiosis is as prevalent in the sky as it is in biology. Astronomers are accustomed to talking about symbiotic stars. The basic reason why symbiosis is important in astronomy is the double mode of action of gravitational forces. When gravity acts upon a uniform distribution of matter occupying a large volume of space, the first effect of gravity is to concentrate the matter into lumps separated by voids. The separated lumps differentiate and evolve separately. They become distinct species. Then, after a period of separate existence, gravity acts in a second way to bring lumps together and bind them into pairs. The binding into pairs is a sporadic process depending on chance encounters. It usually takes a long time for two lumps to be bound into a pair. But the universe has plenty of time. After a few billion years, a large fraction of objects of all sizes become bound in symbiotic systems, either in pairs or in clusters. Once they are bound together by gravity, dissipative processes bring them closer together. As they come closer together, they interact with one another more strongly and the effects of symbiosis become more striking.

Examples of astronomical symbiosis are to be seen wherever one looks in the sky. On the largest scale, symbiotic pairs and clusters of galaxies are common. When galaxies come into contact, their internal evolution is often profoundly modified. A common sign of symbiotic activity is an active galactic nucleus. An active nucleus is seen in the sky as an intensely bright source of light at the centre of a galaxy. The probable cause of the intense light is gas falling into a black hole at the centre of one galaxy as a result of gravitational perturbations by another galaxy. It happens frequently that big galaxies swallow small galaxies. Nuclei of swallowed galaxies are observed inside the swallower, like mouse-bones in the stomach of a snake. This form of symbiosis is known as galactic cannibalism.

On the scale of stars, we can distinguish many types of symbiosis, because there are many types of star and many stages of evolution for each of the stars in a symbiotic pair. The most conspicuous symbiotic pairs have one component that is highly condensed (a white dwarf, a neutron star or a black hole) and the other component a normal star. If the two stars are orbiting around each other at a small distance, gas spills over from the normal star into the deep gravitational field of the condensed star. The gas falling into the deep gravitational well becomes intensely hot and produces a variety of unusual effects, recurrent nova outbursts, intense bursts of X-rays and rapidly flickering light variations. The more common and less spectacular symbiotic pairs consist of normal stars orbiting around each other close enough so that the mass is exchanged between them.

The rarest type of symbiotic pair consists of two condensed stars. These can be seen with radiotelescopes if one component of the pair is a pulsar, a neutron star emitting radio pulses as it rotates. One such pair, a symbiosis of two neutron stars, was discovered by the radio-astronomers Joseph Taylor and Russell

Hulse who received the Nobel Prize for Physics in 1993 for the discovery. This symbiotic pair of neutron stars is scientifically important because it gave us the first clear evidence for the existence of gravitational waves. The drag produced by gravitational waves brings them steadily closer together as time goes on. Ultimately they will be brought so close together that they become dynamically unstable and fall together into a single star with a splash of spiral arms carrying away their angular momentum. The process of collapse takes only a few thousandths of a second and must result in a huge burst of outgoing radiation. The details of the collapse have been calculated by Fred Rasio, a young astronomer now at the Massachusetts Institute of Technology. The collapse of symbiotic neutron stars may explain the mysterious bursts of gamma-rays that are seen coming from random directions in the sky at a rate of about one per day. I will have more to say later about the way gamma-ray bursts were discovered. If Fred Rasio's explanation of the gamma-ray bursts is correct, they are the most violent events in the whole universe, even more violent than the supernova explosions that occur when neutron stars are born. A symbiotic pair of neutron stars can deliver a stronger punch than any single star by itself. Symbiosis becomes more and more central as the universe evolves.

From our human point of view, the most important example of astronomical symbiosis is the symbiosis of the earth and the sun. The system of sun and planets and satellites is a typical example of astronomical symbiosis. At the beginning, when the solar system was formed, the sun and the earth were born with different chemical compositions and physical properties. The sun was made mainly of hydrogen and helium; the earth was made of heavier elements. The sun was physically simple, a sphere of gas heated by the burning of hydrogen and shining steadily for billions of years. The earth was physically complicated, partly liquid and partly solid, its surface frequently transformed by phase transitions. The symbiosis of these two contrasting worlds made life possible. The earth provided chemical and environmental diversity for life to explore. The sun provided physical stability, a steady input of energy on which life could rely. The combination of the earth's variability with the sun's constancy provided the conditions in which life could evolve and prosper.

Tools and concepts

I now move from astronomy to history, from the evolution of the universe to the evolution of science. The major events in the history of science are called scientific revolutions, and of these there are two kinds – those driven by new concepts and those driven by new tools. They are analogous to biological revolutions driven by speciation and by symbiosis, or to astronomical revolutions driven by phase transition and by gravitational binding. When a field of science is overturned by a new concept, the revolution starts from the inside, from an internal inconsistency or contradiction within the science, and results in a phase transition to a new way of thinking. When a field of science is overturned by new tools, the revolution starts from the outside, from tools imported from another discipline, and results in a symbiosis of the two disciplines. In both types of revolution, the final outcome is a new subdiscipline of science and a new species of scientist, specialized in the new ideas or in the new tools as the case may be.

Thomas Kuhn, in his famous book *The Structure of Scientific Revolutions* (1962), talked almost exclusively about concepts and hardly at all about tools. His idea of a scientific revolution is based on a single example, the revolution in theoretical physics that occurred in the 1920s with the advent of quantum mechanics. This was a prime example of a concept-driven revolution. Kuhn's book was so brilliantly written that it became an instant classic. It misled a whole generation of students and historians of science into believing that all scientific revolutions are concept driven. The concept-driven revolutions are the ones that attract the most attention and have the greatest impact on the public awareness of science, but in fact they are comparatively rare. In the last 500 years we have had five major concept-driven revolutions, associated with the names of Copernicus, Newton, Darwin, Einstein and Freud, besides the quantum-mechanical revolution that Kuhn took as his model. During the same period there have been about twenty tool-driven revolutions, not so impressive to the general public but of equal importance to the progress of science. I will not attempt to make a complete list of tool-driven revolutions. Two prime examples are the Galilean revolution resulting from the use of the telescope in astronomy, and the Watson–Crick revolution resulting from the use of X-ray diffraction to determine the structure of big molecules in biology. Galileo brought into astronomy tools borrowed from the emerging technology of eyeglasses. James Watson and Francis Crick brought into biology tools borrowed from physics. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained. In astronomy there has been a preponderance of tool-

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driven revolutions. We have been more successful in discovering new things than in explaining old ones.

Up to this point I have been discussing generalities; now I turn to the details, as I happen to be more interested in the details of particular scientific revolutions than in the general rules that they may or may not exemplify. The details are real. The general rules are at best an approximation to reality, at worst a delusion. Several tool-driven astronomical revolutions happened in the nineteenth century. One was the introduction of high-resolution spectroscopy by Joseph von Fraunhofer, allowing astronomers to study the chemical composition of the sun and the stars. Another was the development of astronomical photography by Henry Draper and James Keeler, allowing astronomers to study with long exposures objects a thousand times fainter than the human eye could see. In each case, the old community of sky-watchers absorbed by symbiosis an alien technology with different traditions. Fraunhofer belonged to the world of commercial glass manufacture. Photography brought into the observatories experts trained in the craft of studio portraiture. The symbiosis of sky-watchers with these two alien cultures resulted in the emergence of a new science with the name 'astrophysics', the science that tries to describe quantitatively the physical processes going on in stars and other celestial bodies. I pass briefly over the nineteenth century because I want to have some time left for the twentieth.

Bernhard Schmidt and Fritz Zwicky

Let us examine in detail three twentieth-century revolutions. The first is associated with the names of Bernhard Schmidt and Fritz Zwicky. Schmidt invented a new kind of telescope and Zwicky understood how to use it. Schmidt and Zwicky were both highly unorthodox characters. Schmidt was an optical technician who grew up on a small island in the Baltic, experimented as a boy with home-made explosives, blew off his right hand at the age of twelve and then taught himself the art of making telescopes with his left hand. He supported himself by selling mirrors of superlative quality to amateur astronomers and professional observatories all over Europe. In 1932 he built at Hamburg the first telescope of the new type now known simply as a 'Schmidt'. The Schmidt was a revolutionary instrument. By throwing overboard the customary way of designing optical systems, Schmidt obtained images in sharp focus over a field of view a hundred times larger than the field of view of conventional telescopes.

This meant that it was possible for the first time to produce sharp photographs of large areas of sky quickly and conveniently. For the first time it was possible to scan the entire sky photographically in a reasonable time and at reasonable cost. Schmidt was a man of few words. His collected works fill three pages.

Fritz Zwicky was a young Swiss physicist, working at the California Institute of Technology, when Schmidt invented his telescope. Zwicky was interested in supernovae, the new stars that occasionally shine in the sky for a few weeks with extraordinary brilliance. Until that time very few supernovae had been identified. One had been seen by Tycho Brahe and another by Kepler, before the days of telescopes, but it was not clearly established that they were different from ordinary novae. Zwicky was one of the few people who took supernovae seriously. He understood, before this became accepted dogma, that supernovae were cataclysmic events on a totally different scale from ordinary novae. He understood that a supernova was an event of extreme violence, probably resulting in the disruption of an entire star. He saw that the key to the understanding of supernovae was to observe a substantial number of them rather than one or two. And he saw that the Schmidt telescope was the tool he needed, the tool that would make it possible to find supernovae in reasonable numbers and to study them systematically.

About thirty years later, Zwicky wrote an autobiography with the title *Discovery, Invention, Research through the Morphological Approach.* He believed passionately in a private theory of everything, a theory that he called the morphological method. The idea of the morphological method is that you write down a complete list of all the conceivable ways of solving a problem before you choose the way that actually solves the problem. If you judge the method by the number of important things that Zwicky discovered, you have to conclude that it is highly effective. The disadvantage of the method is that it does not seem to work so well if your name is not Zwicky.

Here is Zwicky's description, recorded in his autobiography, of how he used the morphological approach to study supernovae.

> I wish to caution all hotheads that it is not advisable to try to do everything at the same time, a mistake which is often committed by individuals and by institutions whose funds are limited. For instance, the construction of multipurpose telescopes is in general not to be recommended. It is better to concentrate one's attention on specific problems and to build instruments best adapted for their solution. One often discovers subsequently that such instruments can also be used effectively for other purposes. As an example I mention

> the eighteen-inch Schmidt telescope on Palomar Mountain, whose construction I promoted in 1935 for the specific task of supernovae . . . I put this instrument into operation on the night of September 5, 1936, and immediately started a systematic survey of several thousand galaxies.
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> (*Ibid.*, p. 91)

As soon as Zwicky heard about Schmidt's invention, he moved fast, with the enthusiastic help of George Hale, to acquire an 18-inch Schmidt and install it in a small dome on the Palomar site that was to be the future home of the 200-inch telescope. Zwicky's little Schmidt was the first telescope on Palomar Mountain. It was the first Schmidt telescope to be installed anywhere in the world in a place with clear skies and good seeing. It is still there today, and still doing important science. Zwicky had it all to himself, a situation that he regarded as essential for doing serious work in astronomy. He had a single assistant who was paid to work for him full-time. He ran a programme that became a prototype for all the later sky surveys carried out with bigger instruments and bigger budgets. He understood that in order to detect rare and transient events it was necessary to scan the whole sky repeatedly, over and over again. For five years he and his assistant Johnson took pictures of huge areas of sky, night after night, covering the northern sky as often as they could. They compiled a catalogue of 50 000 galaxies and 10 000 clusters of galaxies that they kept under observation. About once every three months, comparing an image of one of these galaxies with an earlier image of the same galaxy, they found a newly bright feature that they could identify as a supernova. Supernova candidates were then studied in detail and their spectra analysed with bigger telescopes. Working in this way for five years, between 1936 and 1941, Zwicky and Johnson discovered twenty supernovae. On the basis of this sample, Zwicky could measure roughly the frequency of occurrence of supernovae in the universe and their absolute optical brightness. He identified the two main types of supernova. Supernovae were moved suddenly from the shadowy edge of astronomy to the well-observed centre.

The Schmidt–Zwicky revolution had consequences extending far beyond the initial discoveries. It caused a major shift in our perception of the universe as a whole. The old Aristotelian view of the celestial sphere as a place of perfect peace and harmony had survived intact the intellectual revolutions associated with the names of Copernicus, Newton and Einstein. The Aristotelian view still dominated the practice of astronomy until 1935. Zwicky was the first astronomer who imagined a violent universe. He chose to study supernovae because they provided the most direct evidence of violent processes occurring on a universal scale. After 1935, the idea of a universe dominated by violent events gradually spread, until it was confirmed by the spectacular discoveries of radio-astronomers and X-ray astronomers thirty years later. Now we all take it for granted that we live in a violent universe. But this awareness only began in 1935 with the little Schmidt telescope on Palomar Mountain.

Vela Hotel

Twenty years after the Schmidt–Zwicky revolution came two more tool-driven revolutions, two symbiotic invasions of traditional astronomy by borrowed technologies, first by radiotelescopes and then by X-ray telescopes. I skip over the radio-astronomy and X-ray revolutions, because their history is well known and I have nothing new to say about them. I consider instead another revolution, the gamma-ray revolution, which led thirty years later to the launching of the Compton Gamma-Ray Observatory now orbiting over our heads.

A few years before the gamma-ray revolution, Zwicky had stated his rule: do not build multipurpose telescopes but concentrate your attention on specific problems and build instruments best adapted for their solution. Zwicky said it would often happen that a single-purpose instrument would afterwards find other unexpected applications. The gamma-ray revolution was a fine example confirming Zwicky's rule. It began in the Los Alamos National Laboratory with a project called Vela Hotel, designed to verify compliance with the 1963 Limited Test Ban Treaty. Vela Hotel deployed satellites in orbits far beyond geosynchronous, carrying among other things gamma-ray detectors that would respond sensitively to nuclear explosions in space or in the upper regions of the earth's atmosphere. The gamma-ray detectors never detected any bomb tests. As Zwicky had surmised, they turned out to be ideally suited to detect natural events of an unexpected kind. They detected bursts of gamma-rays arriving mysteriously from unknown sources, unconnected with any human activity or with any known astronomical object. As a result, a part of the weapons-dominated culture of Los Alamos was symbiotically absorbed into the peaceful culture of astronomy.

The first discovery of gamma-ray bursts was published in 1973 by the Los Alamos physicists R. W. Klebesadel, I. B. Strong and R. A. Olson. After describing the Vela Hotel detectors, they say, 'This capability provides continuous

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coverage in time which, combined with isotropic response, is unique in observational astronomy.' A proud claim and a true one. It was true that no astronomical instrument up to that time had ever been capable of detecting signals for twenty-four hours a day over the entire sky. The Vela Hotel detectors had three additional advantages that distinguished them from earlier instruments. They recorded events with high time-resolution, with accurate absolute timing, and with four independent detectors at points widely separated in space. As a consequence of the good timing and wide separation, most of the observed events could be located on the sky with reasonable precision. The superior capabilities of the Vela Hotel instruments arose naturally out of the requirements of the nuclear weapons culture. The astronomical culture, before Vela Hotel, had never seen a need for such capabilities.

I have vivid memories of a visit to Los Alamos when Ian Strong talked to me about the early evidence for gamma-ray bursts. This was after the first Vela Hotel discoveries but before the first publication. Strong was reluctant to publish, not because the data were secret but because they seemed too weird to be credible. The Los Alamos team delayed their publication for four years after the first bursts were seen. The four-year delay is a measure of how revolutionary the discovery of gamma-ray bursts was felt to be. The discoverers thought their data would be more credible if they could identify a few of the gamma-ray burst sources with unusual objects visible in optical or radio wavelengths. In spite of strenuous efforts, they failed for ten years to find convincing identifications. As usually happens when a new window into the universe is opened, the view was so strange that it took considerable courage to publish it.

It was a happy accident that the Vela Hotel satellites combined so many features that were well matched to the gamma-ray burst phenomenon. They had high orbits, continuous all-sky sensitivity and multiple detectors widely separated in space. Unfortunately, because of the constraints imposed by the use of the Space Shuttle as a launch vehicle, the Compton Gamma-Ray Observatory was forced to abandon every one of these advantages. It has a low orbit, with almost half of its view of the sky obscured by the earth, and no ability to measure direction of a source by differential timing at the ends of a long base-line. It was designed, in violation of Zwicky's rule, as a general-purpose observatory. We may hope that future generations of gamma-ray burst detectors will be special-purpose instruments and will fully exploit the advantages of the Vela Hotel architecture. The Vela Hotel revolution will not be complete until it is extended to the study of transient events in other parts of the electromagnetic spectrum besides gamma-rays. We should use the Vela Hotel architecture to search for transient events with detectors of visible light, infra-red, ultra-violet and X-rays, deployed on multiple small satellites in high orbits with long base-lines. And the satellites should be complemented with ground-based detectors searching for transient events in other channels, such as radiowaves, neutrinos and gravitational waves. The Vela Hotel revolution still has a long way to go.

Digital astronomy

The next revolution after Vela Hotel is the digital astronomy revolution. It belongs to the present rather than to the past. We are living in the midst of it. It is driven by another new tool of observation, the charge-coupled device, popularly known as the CCD. This revolution was predicted by Fritz Zwicky, long before the CCD was invented. I quote from the Halley Lecture given by Zwicky in 1948 at Oxford University, with the title 'Morphological Astronomy' (pp. 126–7). To save space I have omitted some phrases and sentences, but I have not added a single word.

> The photo-electronic telescope introduces the following new features. (1) Electrons can be accelerated from the image surface to the recording surface and power can be fed into the telescope to increase the intensity of the signals . . . (2) Uniform background of light . . . may be eliminated by electric compensation . . . The sky background . . . may thus be scanned away . . . (3) Although the original image may move, dance or scintillate . . . because of the unsteadiness of the atmosphere, the refocused image on the recording surface can . . . be steadied . . . Zworykin has actually built such an image stabilizer . . . (4) Automatic guiding of a telescope may be accomplished . . . (5) Images from photo-electronic telescopes can be televised, and the search for novae, supernovae, variable stars, comets, meteors, etc., can be put on a mass production scale.

Zwicky was hoping in 1948 that all these good things could be achieved by a television camera system that he had been working on with his friend Vladimir Zworykin at the Radio Corporation of America (RCA). Zworykin was my nextdoor neighbour in Princeton, a great engineer and a cantankerous character, almost as eccentric as Zwicky. The RCA camera did not fulfil Zwicky's hopes. Now the CCD does everything that he wanted. The main reason why the RCA system failed was that it still depended on photographic plates for recording images. The main reason why the CCD succeeds is that it is coupled to a digital memory instead of to a chemical image on a plate. The digital astronomy revolution had to wait until the technology of image-processing had matured, with powerful microprocessors and digital memories to match the abundance of data that the CCD could supply.

The digital astronomy revolution is now in full swing. Astronomy is now an intimate symbiosis of three cultures, the old culture of optical telescopes, the newer culture of electronics and the newest culture of software engineering. One of the results of this symbiosis is the Sloan Digital Sky Survey (SDSS), a project in which many of my colleagues at Princeton are actively engaged. The SDSS is a modern version of the Palomar Sky Survey, the photographic survey of the northern sky which was finished in 1956 and supplied the astronomers of the world with their first accurate large-scale map of the universe. The Palomar Sky Survey plates have been enormously useful but are now about to be superseded by something better. The output of the SDSS will be a photometrically precise map of the sky in five colours, plus a collection of spectra providing red-shifts of about a million galaxies and other interesting objects. One by-product of this output will be a three-dimensional view of the large-scale structure of the universe over a volume 100 times as large as the volume covered by existing surveys. Another by-product will be a catalogue of about 100 000 quasars, gravitational lenses, brown dwarfs and other peculiar objects, giving a complete count of objects in each category down to some faint limiting magnitude. The entire output of the survey will be transmitted at electronic speed to any astronomical centre possessing a digital memory large enough to swallow it. The size of memory required will be measured in tens of terabytes, a terabyte being a million megabytes. For customers lacking such a gargantuan memory, various predigested versions of the output will be provided, with the photometric data compressed into star catalogues and galaxy catalogues supplemented by images of particularly interesting local areas. The essential difference between the SDSS and all previous surveys is that the output will be linear, consisting of directly measured light intensities instead of measured marks on a photographic plate. The output will be packaged so that all the tricks of modern data-processing can be immediately applied to it.

The Sloan Digital Sky Survey is a collaborative project in which Princeton is one of seven partners. It uses a new 2.5-metre wide-field telescope, built in New Mexico and dedicated to the project for five years. With luck, the survey will be finished by the year 2002. A large array of CCD detectors sits in the focal plane of the telescope. The hardware components of the project do not stretch the state of the art in telescope or detector design. The main novelty of the project lies in the software, which has to control the sequence of operations, calibrate the CCD detectors, monitor the sky quality and apply several levels of data-compression to the output before distributing it to the users. The major share of the cost of the project is paid by the Sloan Foundation, following the good example of the National Geographical Society, which funded the Palomar Sky Survey fifty years earlier. The total cost is estimated to be $50 million, including the capital cost of the telescope. This is about a half of the cost of a major ground-based observatory, and about a thirtieth of the cost of the Hubble Space Telescope.

After our little Digital Sky Survey is finished, there will be other surveys putting into digital memory larger and deeper maps of the universe. There are many directions for future surveys to explore. One survey may push towards fainter and more distant objects, another towards higher angular resolution, another into a wider choice of wavelengths, another into higher spectral resolution. The power and speed of digital data-processing will continue to increase. The digital astronomy revolution will continue to give us clearer and more extended views of the large-scale structure of the universe. There will be no natural limit to the growth of digital surveys, until every photon coming down from the sky is separately processed and its precise direction and wavelength and polarization recorded.

Finally, I want to touch on space science. Here, even more than in ground-based astronomy, the digital revolution has created enormous opportunities which have not been fully exploited. Space missions on a grand scale, such as the Voyager explorations of the outer planets and the Hubble Space Telescope explorations of distant galaxies, have sent back to earth a wealth of scientific knowledge. But the cost of such missions is out of proportion to their scientific value. From a purely scientific point of view, neither Voyager nor Hubble was cost-effective. Both missions were launched in a political climate which valued them as symbols of nationalistic glory rather than as scientific tools. Now the winds of political change are blowing hard. Space scientists are keenly aware that times are changing. Billion-dollar missions are no longer in style. Funding in the future will be chancy. The best chances of flying will go to missions that are small and cheap.

In 1995 I spent some weeks at the Jet Propulsion Laboratory (JPL) in California. JPL built and operated the Voyager missions. It is the most independent and the most imaginative part of NASA. I was particularly interested in two proposals for planetary missions that JPL wished to fly, the Pluto Fast Fly-by and the Kuiper Express. Both missions existed as ideas in the minds of JPL designers. The Pluto Fast Fly-by would complete the Voyager exploration of the outer planets by taking high-resolution pictures of Pluto and its satellite Charon. The Kuiper Express would similarly explore the Kuiper Belt of newly discovered planetary objects orbiting the sun beyond the orbit of Pluto. Both missions are based on a radical shrinkage of the instruments that were carried by Voyager. The digital revolution has made radical shrinkage possible. I held in my hands the prototype package of instruments for the new missions. The package weighs seven kilograms. It does the same job as the Voyager instruments, which weighed half a ton. All the hardware components, optical, mechanical, structural and electronic, have been drastically reduced in size and weight without sacrifice of performance.

Daniel Goldin, the Administrator of NASA, encouraged JPL to design these new missions, to carry on the exploration of the outer solar system with spacecraft radically cheaper than Voyager. Each Voyager mission cost about a billion dollars. The JPL designers came back to Goldin with their design for the Pluto Fast Fly-by. Their estimated cost for the mission was 700 million dollars. According to hearsay, Goldin said, 'Sorry, but that is not what I had in mind'. The mission was not approved. The Pluto Fast Fly-by missed its chance for a quick start. It failed because it did not depart radically enough from the design of Voyager. It still carried for its electrical power supply the heavy Voyager thermo-electric generator using the radioactivity of plutonium-238 as the source of energy. It still relied on massive chemical rockets to give it speed for the long haul from here to Pluto. It was new wine in an old bottle, new instruments riding on an old propulsion system. The instruments were radically shrunk, but the rest of the spacecraft was not shrunk in proportion.

Meanwhile, a new design with the name Pluto Express has been cobbled together by combining pieces of the old Pluto Fast Fly-by and Kuiper Express. The Pluto Express is new wine in a new bottle. It is the first radically new planetary spacecraft since the early Pioneers went to Venus. The Pluto Express uses solar-electric propulsion to give it high speed. The propellant is xenon, which can be conveniently carried as a supercritical liquid as dense as water without refrigeration. The prototype xenon-ion engine was undergoing endurance tests in a tank at JPL when I visited. It must run reliably for eighteen months without loss of performance before it can be seriously considered for an operational mission. The power source for the mission is a pair of large and extremely light solar panels. The panels are large enough to provide power for instruments and for communication with earth as far away from the sun as the Kuiper Belt. No plutonium generator is needed. The Pluto Express has finally jettisoned the last heavy piece of Voyager hardware, so that it can fly fast and free.

The Pluto Express is a daring venture, breaking new ground in many directions. It demands new technology and a new style of management. It may fail, like the Pluto Fast Fly-by, because its designers make too many compromises. Its designers may not dare enough. But solar-electric propulsion has opened the door to a new generation of cost-effective small spacecraft, taking full advantage of the digital revolution. If the Pluto Express fails to fly, some other more daring mission will succeed. The use of solar-electric propulsion will change the nature and style of planetary missions. Spacecraft using solar-electric propulsion may wander around the solar system, changing their trajectories from time to time to follow the changing needs of science. Solar-electric propulsion will make them adaptable as well as small and cheap. The new generation of spacecraft will evolve from Voyager as birds evolved from dinosaurs. In space science, just as in evolutionary biology or in international politics, the collapse of the old order opens new opportunities for adventurous spirits.

FURTHER READING

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