25 November 1983, Volume 222, Number 4626 SCIENCE

The 1983 Nobel Prize in Physics

The 1983 Nobel Prize in Physics was awarded equally to two astrophysicists: Subrahmanyan Chandrasekhar of the University of Chicago, for his theoretical studies of the physical processes of importance in the structure and evolution of stars, and William A. Fowler of the California Institute of Technology, for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe.

The name of William Fowler is almost synonymous with nuclear astrophysics, the study of the nuclear phenomena occurring in stars. This is the way in which stars produce their energy, but it is also fundamental to the evolution of stars and the origin of the chemical elements. Fowler has made the Kellogg Radiation Laboratory at the California Institute of Technology the world center for research in nuclear astrophysics. He has greatly influenced the field by his published papers and his ideas, but also by being the leader of the group in the Kellogg Laboratory. Almost everyone currently active in the field of nuclear astrophysics has spent some part of his career as a graduate student, as a member of the team, or as a visitor at Kellogg being inspired by Fowler.

Fowler's work on the nuclear reactions in stars started about 1950 with an experimental investigation of the carbon-nitrogen cycle, the sequence of reactions that builds up helium from hydrogen and is responsible for energy production in the more massive stars in the main sequence. Fowler was well prepared for this because for more than 15 years he had worked on nuclear reactions with Charles Lauritsen and others. They had developed the electrostatic generator into a tool of high precision that gave accurately defined energies, and they had developed detection equipment of similar precision. Using these tools, they had investigated the capture of protons by light elements and discovered that most of these captures take place in very sharp resonances. This was just the right basis for investigating the reactions in the carbon cycle, the most important of which are proton captures with the emission of gamma rays. Fowler and his collaborators found that the rates of reactions in the carbon-nitrogen cycle were adequate to explain the energy production for the heavier stars in the main sequence.

From the reaction rates, they could determine the ratio of the isotopes involved in the cycle, in equilibrium in a star. These isotope ratios are not the same as those found on the earth. Most strikingly, the abundance of ^{14}N should be vastly greater than that of carbon or oxygen, in contrast to the abundances found on the earth or on stellar surfaces. The conclusion is that there is no substantial mixing between the hot material at the center of a star and the much cooler surface. This finding is consistent with the fact that lithium—an element that could not survive at the high temperatures in the interior of the sun—is found on the solar surface.

Fowler likes to speak of the CNO bicycle, because ^{17}O (which is formed from ^{16}O by proton capture and positron emission) undergoes the reaction

$$^{17}O + H = {}^{14}N + {}^{4}He \qquad (1)$$

It is for this reason that oxygen, as well as carbon, is largely converted into nitrogen in any stars in which the temperature is high enough to make the CNO bicycle take place. This is important for the building up of elements, as I will discuss later.

A very important activity of Fowler and his collaborators has been to make accurate tables of the rates of the important nuclear reactions, based on experiment, which greatly facilitate the work of others in the field.

In the sun, the temperature is not hot enough to make the CNO bicycle the dominant source of energy. The most important energy production comes from the proton-proton reaction

$$H + H = D + e^+ + \nu \qquad (2)$$

Fowler showed conclusively that this is the case. On the basis of his reaction rates, the temperature at the center of the sun is now calculated to be about 14 million degrees. (Eddington, in his original theory of the internal structure of stars, had estimated 40 million degrees.)

Fowler and his group then investigated how reaction 2 is completed. They found that the dominant chain of reactions is

$$D + H = {}^{3}He + \gamma$$
$$^{3}He + {}^{3}He = {}^{4}He + H + H \qquad (3)$$

But in a small percentage of cases a different chain occurs, namely

$$^{4}He + {}^{3}He = {}^{7}Be + \gamma$$
$$^{7}Be + e^- = {}^{7}Li + \nu \qquad (4)$$

and, more rarely still,

$$^{7}Be + H = {}^{8}B + \gamma$$
$$^{8}B \rightarrow 2\,{}^{4}He + e^+ + \nu \qquad (5)$$

The cross sections for all these reactions were measured by Fowler and collaborators.

Especially in the beta decay (reaction 5), very energetic neutrinos are emitted. Fowler suggested that these neutrinos from the sun could be sufficiently abundant and energetic to cause observable reactions on the earth. For nearly 20 years, R. Davis at Brookhaven has been engaged in an effort to observe these neutrinos. For this purpose he uses a boxcar full of CCl_4; the neutrinos convert (with a very small cross section) the ^{37}Cl into ^{37}Ar, which can then be flushed out of the CCl_4, put into a counter, and its electron captures counted. At first, Davis's experiments gave inconclusive results because the background was too large, even though the cosmic-ray back-

William Fowler holding a shirt presented to him by his colleagues at a conference he was attending at the Yerkes Observatory on the day of the announcement of his Nobel Prize. [California Institute of Technology]

ground was avoided by doing the experiment in the Homestake mine 5000 feet underground. By careful suppression of the background from radioactivity in the walls of the mine, Davis has in the past 10 years obtained positive results, but they are only about one-fourth of the number of neutrino effects expected.

Because of these results, Fowler, Bahcall, and others completely revised the calculations of the internal distribution of density and temperature in the sun. While these revisions produced some changes, the discrepancy remained. It was tempting to blame the discrepancy on the measurements of reaction 4. Indeed, a group under C. Rolfs in Münster claimed to have found that this reaction has only half the cross section previously found by Fowler's group. This would reduce the discrepancy from a factor of 4 to a factor of 2. However, Fowler's group repeated their own measurements with much improved control of energy and detection and essentially confirmed their old result. So the discrepancy persists.

Fowler, who had stimulated and encouraged Davis's experiment, has been much concerned by this disagreement. It is very unlikely that anything happens to the neutrinos on their way from the sun to the earth. At one time, Fowler proposed what he called the "desperate theory": we might find ourselves in a period of abnormally low energy production in the sun. The light we see from the sun comes from energy that was produced 10 million years ago (the length of time it takes light to bounce its way from the center of the sun to the surface); only the neutrinos, which pass unhindered, indicate the present production. Could it be that the low neutrino emission indicates that in a few million years the sun will give out much less light than it does today? It would return to normal after another few million years, but a heat output of only one-fourth of the present one for some million years would surely have very unpleasant consequences for life on the earth. It is more likely that the calculated temperature at the center of the sun is still too high for some reason.

The best way to check this would be to observe the interaction of neutrinos with gallium, which could also capture the neutrinos from the primary reaction 2 and should therefore give effects directly proportional to the present energy production. Unfortunately, gallium is a very expensive substance, and the government has so far not approved the spending of $10 million for this crucial experiment.

Since there is little mixing of material inside a star, the hot center will consume its hydrogen quickly. Theoretical astrophysicists have calculated that the star will thereby change into a red giant. New nuclear reactions will occur, mostly involving ^{4}He and then later ^{12}C, ^{16}O, and other nuclei. Fowler set out systematically to measure the rates of these reactions. He paid special attention to the reactions of ^{28}Si, which finally lead to ^{56}Fe. Knowledge of these reaction rates, together with intricate computer calculations, has led to a detailed understanding of the evolution of red giant stars. This understanding is one of the best proofs that the general theory of nuclear energy generation in stars, and of the internal distribution of temperature, is correct.

In these reactions in giant stars, elements up to iron are built up. In 1955 Fowler proposed, together with Fred Hoyle, E. M. Burbidge, and G. R. Burbidge, that this is, in fact, the way in which elements heavier than helium are made. At the end of the evolution of a heavy star, the elements produced in it are expelled in a supernova explosion. This theory is rather generally accepted.

Elements heavier than iron are made by successive neutron capture, also in heavy stars, either before or during the supernova event. In order to make neutrons available, it is essential that during the main sequence phase of the star its carbon, nitrogen, and oxygen were all converted into ^{14}N. Then in the early red giant phase, the ^{14}N undergoes the reaction

$$\begin{aligned} {}^{14}\mathrm{N} + {}^{4}\mathrm{He} &= {}^{18}\mathrm{F} + \gamma \\ {}^{18}\mathrm{F} &\rightarrow {}^{18}\mathrm{O} + e^+ + \nu \qquad (6) \end{aligned}$$

The resulting ^{18}O has two neutrons beyond its alpha particles. These neutrons can be released in later stages by the high temperature which then prevails in the interior of the star, simply by statistical equilibrium. The neutrons preferentially attach themselves to heavy elements, which have a much greater cross section for such capture than the lighter elements. Fowler stimulated a great deal of work at Oak Ridge National Laboratory to determine the cross section for capture of neutrons at kilovolt energies. In his theoretical papers, he defined slow and rapid neutron capture processes (*s* and *r* processes) by which elements can be built up. The fundamental paper on this was published by Fowler, Hoyle, Burbidge, and Burbidge in 1957.

The result of this buildup was then checked by calculating the ratio of the abundances of various rare earth elements and isotopes, which should be inversely proportional to their neutron capture cross sections. The result agreed very well with the observed ratios of the rare earths.

Fowler then investigated whether chemical elements could be produced in the initial Big Bang. He concluded that no element heavier than helium could be produced under these circumstances with abundances anywhere near those presently observed in the universe. Helium-4 could be synthesized in a universal fireball with a mass fraction in the neighborhood of 25 percent, which is close to that observed. Deuterium, helium-3, and lithium-7 could be produced in mass fractions comparable to those in the solar system, although it is not clear that such cosmologically produced nuclides could escape thermonuclear destruction later in the history of the universe.

The finding that elements heavier than helium could not be formed in the initial Big Bang meant that they must be formed in stars, and thus made the theory of Fowler *et al.* on their formation in stars a necessary counterpart.

The universe contains some very old stars, generally referred to as Population II. Globular cluster stars are particularly good examples because these clusters consist of stars of nearly the same old age. The spectra of these Population II stars are very poor in elements heavier than helium. Moreover, because of their old age, many of them have entered the red giant stage, and the evolution in this stage looks different for stars deficient in heavier elements because they have less opacity. The evolution of these red giants and globular clusters confirms very well the theory that they are poor in "metals"—that is, elements heavier than helium.

Recently, it has become possible to measure gradients of "metallicity" across an individual galaxy: The metal abundance is largest where star formation was most prolific, illustrating even more dramatically that the medium-heavy elements were indeed produced in stars.

On the basis of nuclear reactions, Fowler was able to establish a chronology of the cosmos. In particular, he showed that the observed isotope ratios of uranium and thorium are consistent with a synthesis of these materials extending over a period of about 7 billion years and could not easily be accounted for by a more abrupt process. Including the measured age of the solar system, he estimated an age for the galaxy of about 20 billion years, an estimate which he has recently lowered somewhat. This result is in good agreement with estimates based on other evidence.

Lunar samples appear to have terrestrial U/Th ratios, confirming Fowler's deduction that these quantities must be universal for the solar system. On the other hand, G. Wasserburg has found that some samples of meteorites have isotopic ratios of such elements as silver totally different from those on the earth. It is suggested that these were injections into the solar system from a supernova that occurred just about at the time when the solar system was formed. Recently, Fowler has worked on the details of this theory.

In 1963 Fowler realized, together with Hoyle, that one must not confine oneself to considering stellar objects below 100 solar masses; stars probably can exist with masses up to 10^8 times that of the sun, and such "supermassive stars" could be the driving force behind the explosions in galactic nuclei which create strong radio sources. Some months after this proposal quasars were discovered, and supermassive stars immediately became an attractive explanation. Although no fully viable model for the energy source of quasars yet exists, supermassive stars remain a contender.

Much of Willy Fowler's theoretical work was done jointly with Fred Hoyle of the University of Cambridge, England. Fowler spent two sabbatic leaves there (1954–1955 and 1961–1962) and various summer visits between 1967 and 1972. Hoyle was a frequent guest at Caltech. More than 25 papers, of the more than 200 published by Fowler, were written jointly with Hoyle.

Fowler has done a great deal of public service. During World War II he was associated with the National Defense Research Council and contributed to the research and development on proximity fuses, rockets, and atomic weapons. He was an assistant director of research of one section of the NDRC, and a technical observer for the new developments division of the War Department, in the South Pacific and Southwest Pacific territories. Most important was his activity as scientific director of the VISTA project of the Department of Defense in 1951–1952. This project considered the feasibility of using nuclear weapons in tactical warfare in Europe and was partly intended to reduce Air Force enthusiasm for the bombing of cities with large nuclear bombs. Fowler was a member of the National Science Board, the main directing body of the National Science Foundation, from 1968 to 1974, and was a member of the Nuclear Science Advisory Committee of the NSF beginning in 1977. He was a member of the Space Science Board of the National Academy of Sciences from 1970 to 1973 and from 1977 to 1980, and of the Space Program Advisory Committee of NASA from 1971 to 1974. For his work during the war he received the Presidential Medal for Merit in 1948. Of course, he also has received a spate of other awards, prizes, and honorary degrees.

The most outstanding characteristic of Willy Fowler is that he loves people. He is full of humor and cheerfulness and his example is infectious. It is his ebullience together with his mastery of experimental physics and theoretical ideas which has made him so successful as a leader of a large group of scientists in the Kellogg Laboratory and the world over.

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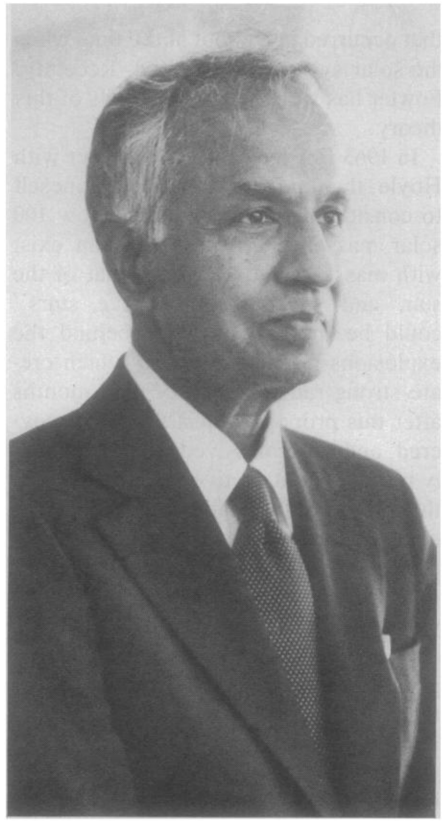
When describing theoretical physicists, a clear distinction is sometimes made between two types. The first type is the speculative innovator, thinking brave thoughts in qualitative fashion, guided by inspiration. One might expect the person who first discussed the formation of black holes to be a prime example of this type. The second is the "theorist's theorist," who specializes in detailed calculation with meticulous attention to mathematical rigor and without shortcuts or appeal to plausibility arguments. Applying relativistic quantum mechanics to a study of the equation of state (the relation between the density and pressure of matter) is certainly a fertile field for the second type. Subrahmanyan Chandrasekhar of the University of Chicago, who shares the 1983 Nobel Prize in Physics with Willy Fowler, presents us with a number of contrasts and paradoxes. His research style fits in perfectly with the second type of theorist, yet he is credited with "having made black holes possible."

Nobel, the man, and the Nobel Prize Committee have sometimes been accused of having a detrimental effect on science by overemphasizing a recent spectacular discovery, rewarding a single episode rather than a lifetime of solid scientific achievement. Chandrasekhar wrote one paper that fits in the spectacular discovery category, but that was published 52 years ago; furthermore, the Nobel Prize citation does not single out this one piece of work but emphasizes the overall achievement: "his theoretical studies of the physical processes of importance to the structure and evolution of the stars." Emphasis on spectacular discoveries is supposed to lead to overemphasis on superstars; however, the superstar in this story is neither the inventor Nobel nor the theorist Chandrasekhar, but a third party, Sir Arthur Eddington.

Subrahmanyan Chandrasekhar, born

in Lahore, India, on 19 October 1910, studied physics at Presidency College, Madras, India, where he met his future wife, Lalitha, a fellow student of physics. After receiving his bachelor's degree there in 1930 he became a graduate student at Cambridge University to work in theoretical astrophysics, more specifically in the theory of stellar structure. This field was dominated then and for some time, in Cambridge as elsewhere, by Arthur Eddington, who was a master both of ideas and of mathematical technique. Another mentor at Cambridge, R. H. Fowler, had also made a major contribution to the theory of stellar structure by applying quantum statistical mechanics to the dense matter inside white dwarf stars (the companion of Sirius was already known to have a density of the order of 10^6 g cm^{-3}). This first "practical application" of Fermi-Dirac quantum statistics came in the same year as the enunciation of this statistics (1926, even before the application to the theory of metals). This work had already led to a first qualitative understanding of the structure of white dwarfs, but a quantitative theory was still needed and required great mathematical skill. The young Chandrasekhar proceeded to do just that, with care and precision. To appreciate the hornet's nest stirred up by this quiet, painstaking work we need a technical digression on the equation of state for ionized matter.

The ratio of pressure P to the number density, n, of the electrons in the matter is of the same order as the mean kinetic energy per electron. Without quantum mechanics this energy is purely thermal, $\sim kT$, where k is a constant and T is the temperature, quite independent of density. With Fermi-Dirac quantum statistical mechanics, when the density is very large and the temperature relatively low, this kinetic energy is of the order of the Fermi energy, E_F, of the electrons, instead of kT. In turn, E_F is a function of n, but what that function is depends on the dynamic relation between kinetic energy E and momentum p: if $E \propto p^{\nu}$ then one finds that $P/n \sim E_F \propto n^{\nu/3}$. At sufficiently low n the electrons are nonrelativistic; $E = p^2/2m$ and $\nu = 2$. This limit is uncontroversial and was already known to R. H. Fowler. However, when the density is extremely high the electrons are extremely relativistic; according to special relativity $E = pc$ and in this limit $\nu = 1$. Changing an exponent in the equation of state by a factor of 2 may not sound like an emotional issue, but in fact it makes a profound difference for the structure and evolution of old stars (which have no nuclear fuel left): if the



Subrahmanyan Chandrasekhar [University of Chicago]

stellar mass, M, is sufficiently small, the electrons are always nonrelativistic, $\nu = 2$, and the quantum mechanical outward pressure can be made to balance the inward gravitational force. This means that the final evolution of an old star is a quiet, serene death—it slowly cools off to a final state of zero temperature at constant radius, density, and quantum mechanical pressure. However, Chandrasekhar showed that, for sufficiently large M, special relativity comes in eventually and, with $\nu = 1$, quantum mechanical pressure cannot compete with gravity nor with the classical thermal pressure. In this limit a star will keep on contracting as it radiates away energy and (unless it loses mass first) will eventually suffer a fate worse than death—invisibility. General relativity had preceded quantum mechanics and it was already known that no radiation could escape from a star if it contracted to less than its "Schwarzschild radius." Such a state of invisibility is what we nowadays call a black hole.

Chandrasekhar had already obtained the most startling result of his calculations in his first year in Cambridge: the fact that there is a finite maximum mass for an ideal white dwarf star. This mass is now known as the Chandrasekhar limiting mass, M_{Ch}, and is slightly larger than one solar mass, $M_{\odot}$. This result, too startling for his British mentors, was published in a short paper in the *Astrophysical Journal* (*1*). This journal, then published by the University of Chicago, in 1931 was considered a somewhat obscure journal by many authors (but not by all—the preceding paper in the same issue of the journal describes the Hubble expansion of extragalactic nebulae). Chandrasekhar continued his quantitative development of stellar structure theory in a long and masterful series of mathematical papers over 5 or 6 years, followed by a book in 1939, which is still considered a definitive text today. The embedding of the possibility of black hole formation in a more and more quantitative framework seems to have infuriated Eddington (and some of his colleagues) more and more. At a famous meeting of the Royal Astronomical Society on 11 January 1935 (*2*) Eddington attacked black holes and ridiculed Chandrasekhar, for whom this meeting was the most traumatic experience of his career. An interesting document for the modern reader is a quantitative paper by Eddington (*3*) in which he attempts to disprove Chandrasekhar's theory; although this cannot detract from Eddington's greatness, this paper is not only wrong but is sheer nonsense in mathematical guise.

In 1937 Chandrasekhar left Cambridge, and he has been associated with the University of Chicago, and partly with Lick Observatory, ever since. Even apart from his earlier Cambridge work, he has had and continues to have an amazingly productive career. A fascinating aspect of this career, which has enhanced his achievements even further, is a certain incongruity in his working style. He changes fields radically every 5 or 10 years, which one expects of a speculative, qualitative person, but he attacks each problem as a superb mathematician without intuitive shortcuts. In each new field he likes to mingle with the graduate students (who all call him Chandra), rather than the "big shots," but his impeccable dark suit and equally impeccable speech single him out. Perhaps it is an effort to use Eddington, who could "put down" young people by remaining a "super expert" in his constant field, as an "anti–role model"—to follow instead Lord Rayleigh's advice that old men should continue working but should not contradict young people. Chandra prides himself on attacking problems which are important in the long run but are not spectacular, and in an interview last year he explained that his working style is the least likely to lead to a Nobel Prize.

In each of a number of fields Chandra would first write a long, systematic series of mathematically powerful papers (mostly for the *Astrophysical Journal*) and then "wrap it up" with a definitive textbook. Each field was connected with the structure and/or evolution of stars and/or stellar systems, a few of them also with black holes. The first post-Cambridge series of papers dealt with the dynamics of star clusters and especially with "dynamical friction," which controls the secular evolution of such a cluster. In a delightful paper in 1940 Lyman Spitzer had already given an approximate treatment of mass segregation and evaporation from a cluster with just enough accuracy for practical applications. In 1941 Chandra developed a more rigorous and general treatment of this subject. Quasars and active galactic nuclei were not known then, but dynamical friction is likely to be a key ingredient; these objects may well be powered by massive black holes formed from the shrinking cores of a star cluster. Next came radiative transfer theory, which is important for atmospheres, stellar luminosity, and spectral line formation. Chandra treated various topics of equilibrium and stability (or the lack thereof) and most recently returned to the mathematical theory of black holes.

The expression for the Chandrasekhar limiting mass is of the form $M_{\mathrm{Ch}} \sim (hc/G)^{3/2}\ m_{\mathrm{n}}^{-2}$, where h is the Planck constant, c the speed of light, G the gravitational constant, and m_{n} the nuclear mass per electron. Although the electrons play a key role in providing the pressure, the mass of the electron itself does not occur in this expression. For a star made up of pure neutrons (instead of electrons and positive nuclei), m_{n} has a similar value and the theory of neutron stars is close to the theory of white dwarfs. These two theories become intertwined in describing a supernova outburst; a stellar core more massive than M_{Ch} starts to collapse but, before it reaches the black hole state, its outer layers explode while its inner layers form a stable neutron star. The careers of the two 1983 Nobel laureates are also intertwined at this point—supernovae produce most of the heavy elements in the galaxy, as Willy Fowler has demonstrated so convincingly.

Chandra's books are so clearly written and so widely reprinted that few young scientists today have read his original papers in the *Astrophysical Journal*, but he has had a profound and lasting effect on this journal. He was the sole editor for almost 20 years, starting in 1952, maintaining the highest standards for all manuscripts and refereeing all contributions for the Letters section himself. Although many authors grumbled at his strictness, he made his journal foremost in the world. This strictness was occasionally tempered by a sense of humor, such as his condoning a spoof on his own dry style of writing papers in the form of a dry paper by a nonexisting S. Candlestickmaker.

Chandra's career has emphasized the importance of beauty in theoretical physics and of brooking no shortcuts or expediency in one's work. His love for mathematical beauty is shared by many pure mathematicians, but he expresses it more exuberantly (possibly because experimental physics is a reassuring background, even if not used by him explicitly). One year a class of his consisted of only two students but he made no shortcuts in his teaching. This strict maintenance of standards paid off when the whole class won the Nobel Prize (T. D. Lee and Frank Yang in 1957). Chandra's temperament will also prevent any detrimental effects of his own winning of the prize. The institution of Nobel Prizes has been likened to the ancient ritual described in "The King Must Die": There, a young man was given honors for one year and then sacrificed to help renew agriculture. Here, the attention given to any recent Nobel Prize winner, and the many pronouncements he is expected to make, bring publicity (and presumably public funds) to the scientific profession but may lessen the individual's future research output. This will certainly not happen to Chandra—he will quietly and thoroughly continue to move into new fields, so that the young men and women in the field should be (at first) greater experts than he.—E. E. SALPETER

References

1. S. Chandrasekhar, *Astrophys. J.* **74**, 81 (1931).
2. A. Eddington, *Observatory* **58**, 37 (1935).
3. ——, *Mon. Not. R. Astron. Soc.* **95**, 194 (1935).

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