Nobel prize to Chandrasekhar and Fowler for astrophysics

The 1983 Nobel prize in physics has been awarded to Subrahmanyan Chandrasekhar (University of Chicago) "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars" and to William A. Fowler (Caltech) "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the Universe." The two men shared the prize (worth about \$190 000 this year) equally.

Chandrasekhar. The announcement from the Swedish Academy says that "Chandrasekhar's work deals with a large number of features in stellar evolution. A major contribution is the study of the stability problem in different phases of the evolution. In recent years he has studied relativistic effects, which become of importance because of the extreme conditions arising during the later stages of stellar evolution. Chandrasekhar's possibly best-known achievement, accomplished when he was in his 20s, is the study of the structure of white dwarfs. Although many of these investigations are of older dates, they have through the great progress of astronomy and space research in recent years gained renewed interest."

When it was realized in the early 1920s that white-dwarf stars had mean densities in the range 10^5–10^6 gm/cm^3, Eddington pointed out a curious paradox concerning matter at high temperature attaining such densities. The paradox, as Ralph Howard Fowler formulated it in 1926, is this:

> The stellar material, in the white-dwarf state, will have radiated so much energy that it has less energy than the same matter in normal atoms expanded at the absolute zero of temperature. If part of it were removed from the star and the pressure taken off, what could it do?

In 1926 Fowler resolved the paradox in terms of the Fermi–Dirac statistics that had been discovered a few months earlier, Chandrasekhar explained to us. Fowler's resolution of Eddington's paradox consisted in showing that the matter in the interior of white-dwarf stars must be highly degenerate in the sense that all the available parts of the phase space, with momenta p less than a certain "threshold" value p_0—the Fermi threshold—are occupied consistently with the Pauli exclusion principle, that is, with two electrons per "cell" of volume h^3 of the six-dimensional phase space. On this assumption Fowler showed that the kinetic energy per unit volume associated with the degenerate electron gas must vary with the density ρ as $\rho^{5/3}$, and that this kinetic energy is much greater than the electrostatic energy, E_v, per unit volume of an assembly of atoms, ionized down to bare nuclei.

On Fowler's premises, Chandrasekhar told us, he showed in 1931 that the white-dwarf configurations must be polytropes of index $3/2$ (a polytrope is stellar material in equilibrium under its own gravity, obeying a general equation of state $P = K\rho^{1+1/n}$ where P is pressure and n is the polytropic index); because of this behavior, one has the relation

$$\log_{10}(R/R_\odot) = -\tfrac{1}{3}\log_{10}(M/M_\odot) - \tfrac{5}{3}\log_{10}\mu_e - 1.397$$

where $R_\odot$ and $M_\odot$ denote the radius and mass of the Sun and μ_e the mean molecular weight per electron.

For a mass equal to the solar mass and $\mu_e = 2$, this relation predicts $R = 1.26 \times 10^{-2} R_\odot$ and a mean density of 7.0×10^5 gm/cm^3, Chandrasekhar told us. These values are precisely of the order of the radii and mean densities encountered in white-dwarf stars. According to the display equation above, the radius of the white-dwarf star is inversely proportional to the cube-root of the mass. Because of this relation, finite equilibrium configurations are predicted for all masses.

Chandrasekhar then noted that the simple theory just described, based on Fowler's premises, required modifications because the electrons at their threshold energies, at the centers of the degenerate stars, begin to have velocities comparable to that of light as the mass increases. Thus, even for a degenerate star of solar mass (with $\mu_e = 2$) the central density (which is about six times the mean density) is 4.19×10^6 gm/cm^3; this density corresponds to a threshold momentum $p_0 = 1.29\ mc$ and a velocity that is 0.63c. Consequently, the equation of state must be modified to take into account the effects of special relativity. And when the effects of special relativity are taken into account, he showed that, in the extreme relativistic limit, the pressure varies at $\rho^{4/3}$. While the modification of the equation of state required by the special theory of relativity appears harmless enough, Chandrasekhar explained, it has a dramatic effect on the predicted mass–radius relation for degenerate configurations: There is an upper limit to the mass (1.4 $M_\odot$ for $\mu_e = 2$) that can be supported by electron pressure.

Chandrasekhar obtained these results in the summer of 1930 during his voyage to England to begin graduate work at Trinity College, Cambridge; the results were published in 1931.[1,2] (He received his bachelor's degree in 1930 from Presidency College, Madras University, and his PhD from Cambridge in 1933.) In 1934 he gave a complete theory establishing the same results in terms of an exact theory. Eddington immediately realized that the existence of this upper limit to the mass of the white dwarfs implied that "unless accidents intervene to save the stars," black holes, as we now call them, must form. In fact, at the meeting of the Royal Astronomical Society in January 1935, after the presentation of Chandrasekhar's paper, Eddington stated

> The star has to go on radiating and radiating, and contracting and contracting until, I suppose, it gets down to a few km radius, when gravity becomes strong enough to hold in the radiation, and the star can at last find peace.

But he added,

> . . . I felt driven to the conclusion that this was almost a *reductio ad absurdum* of the relativistic degeneracy formula. Various accidents may intervene to save the star, but I want more protection than that.

0031-9228 / 84 / 0100 17-06 / \$01.00

> I think there should be a law of nature to prevent a star from behaving in this absurd way!

Because of Eddington's supreme authority, the astronomical community was slow in accepting Chandrasekhar's principal conclusion (as he stated it in 1934):

> The life history of a star of small mass must be essentially different from the life history of a star of large mass. For a star of small mass the natural white-dwarf stage is an initial step towards complete extinction. A star of large mass cannot pass into the white-dwarf stage and one is left speculating on other possibilities.

Last year Chandrasekhar summarized his controversy with Eddington in one of the Eddington Centenary Lectures that he gave in Cambridge:

> . . . It is pertinent to ask what the present status of Eddington's convictions with regard to this matter are. The simple and direct answer is that they are not accepted. This is not the occasion and there is not the time either to describe how the existence of the limiting mass is inextricably woven into the present fabric of astronomical tapestry with its complex designs of stellar evolution, of nuclear burning in the high-density cores of certain stars, and gravitational collapse leading to the supernova phenomenon and the formation of neutron stars of nearly the same mass and of black holes. All these are discernible even to the most casual observer. For my part I shall only say that I find it hard to understand why Eddington, who was one of the earliest and staunchest supporters of the general theory of relativity, should have found the conclusion that black holes may form during the natural course of the evolution of the stars, so unacceptable.

Chandrasekhar told us that in the citation for the Nobel award, the reference to his recent "studies on relativistic effects which become of importance because of extreme conditions arising during the later stages of stellar evolution" is to his discovery of two types of instabilities (in 1964 and 1970) that arise from the effects of general relativity, and which have no counterparts in the Newtonian framework. They are

▶ *vibrational instabilities* of spherical stars that arise even when the Newtonian criterion for stability is satisfied, provided the radius of the star is less than a certain determinate multiple of the Schwarzschild radius of the star,[3]

▶ *secular instabilities* of rotating stars derived from the emission of gravitational radiation by non-axisymmetric modes of oscillation.[4] The first of these effects intervenes in the evolution of very massive stars even when the radii are 1000 or more times the Schwarzschild radius, and the second of these effects seems to limit the periods of rotation of pulsars, Chandrasekhar told us.


CHANDRASEKHAR


FOWLER

While the citation for the Nobel award appears to single out Chandrasekhar's very early work and two pieces of later work done during the 1960s, his main scientific output has been in other areas. As he has written in his biographical note for the Nobel Foundation,

> After the early preparatory years, my scientific work has followed a certain pattern motivated, principally, by a quest after perspectives. In practice, this quest has consisted in my choosing (after some trials and tribulations) a certain area which appears amenable to cultivation and compatible with my taste, abilities, and temperament. And when after some years of study, I feel that I have accumulated a sufficient body of knowledge and achieved a view of my own, I have the urge to present my point of view, *ab initio*, in a coherent account with order, form, and structure.
>
> There have been seven such periods in my life: stellar structure, including the theory of white dwarfs (1929–39); stellar dynamics, including the theory of Brownian motion (1938–43); the theory of radiative transfer, including the theory of stellar atmospheres and the quantum theory of the negative ion of hydrogen and the theory of planetary atmospheres, including the theory of the illumination and the polarization of the sunlit sky (1943–50); hydrodynamic and hydromagnetic stability, including the theory of the Rayleigh–Bénard convection (1952–61); the equilibrium and the stability of ellipsoidal figures of equilibrium, partly in collaboration with Norman R. Lebovitz (1961–68); the general theory of relativity and relativistic astrophysics (1962–71); and the mathematical theory of black holes (1974–83). The monographs which resulted from these several periods are:

▶ *An Introduction to the Study of Stellar Structure* (1939, University of Chicago Press; reprinted by Dover, 1967).

▶ *Principles of Stellar Dynamics* (1943, University of Chicago Press; reprinted by Dover, 1960). "Stochastic Problems in Physics and Astronomy," *Reviews of Modern Physics* **15**, 1 (1943); reprinted in *Selected Papers on Noise and Stochastic Processes* by Nelson Wax, Dover, 1954.

▶ *Radiative Transfer* (1950, Clarendon Press, Oxford; reprinted by Dover, 1960).

▶ *Hydrodynamic and Hydromagnetic Stability* (1961, Clarendon Press, Oxford; reprinted by Dover, 1981).

▶ *Ellipsoidal Figures of Equilibrium* (1968; Yale University Press).

▶ *The Mathematical Theory of Black Holes* (1983, Clarendon Press, Oxford).

Fowler, after receiving his bachelor's from Ohio State in 1933, did his graduate work in nuclear physics in the Kellogg Radiation Lab at Caltech under Charles C. Lauritsen, whom Fowler describes as "the greatest influence in my life." After receiving his PhD in 1936, Fowler stayed on at Caltech, continuing his nuclear-physics experiments.

After World War II, Charles Lauritsen, his son, Thomas, and Fowler decided that the Kellogg Lab would continue to work in low-energy "classical" nuclear physics. The lab would have a unique emphasis on what they called "nuclear astrophysics"—those nuclear reactions that occur in stars. Fowler recently told us, "I've made it my life's work to take experimental data produced in Kellogg or other nuclear laboratories and turn it into thermonuclear reaction rates in stars. It's kind of a service to the astrophysics community, to make sure the nuclear physics part is right, to at least remove one uncertainty."

In 1939 Hans Bethe at Cornell and Carl Friedrich von Weizsäcker in Berlin independently suggested that hydrogen could be converted into helium in stars by a catalytic process involving the isotopes of carbon and nitrogen, which they called the CN cycle. Starting with radiative capture of protons by C^{12}, the net result is the conversion of four protons into an alpha particle, two positrons and two neutrinos, plus another C^{12} nucleus to start the process over. Much later two more cyclic reactions involving oxygen isotopes were found, so that the cycle is now called the CNO tri-cycle. Bethe and Charles Critchfield suggested another process, the proton–proton chain, to convert hydrogen directly into helium. This pp chain is now known to dominate in the Sun, and the CNO tri-cycle is the dominant process in stars somewhat hotter than the Sun. In any case, Fowler recalls, it was quite clear in 1939 that to apply nuclear physics to astronomy, detailed and accurate measurements of nuclear reaction rates were needed. At the time the CN cycle was proposed, Fowler and the Lauritsens were bombarding the new isotopes of carbon and nitrogen with protons in the lab. In the late 1940s and early 1950s, Fowler and his collaborators were measuring cross sections and reaction rates for the light elements.

Hydrogen burning in stars produces helium. Once hydrogen is exhausted, what happens to the helium? Even though energy generation stops at the center of a star, gravitational forces cause contraction and compression, thus raising the temperature. Fowler recalls that in the early 1950s the big question was: How does helium burn?

Before World War II Hans Staub and William Stephens had confirmed in Kellogg that there was no stable nucleus at mass 5. At Kellogg, after the war, Alvin Tollestrup, Charles Lauritsen and Fowler confirmed that there was no stable nucleus at mass 8, that Be^8 broke up as fast as they could make it. Recalling that period to us, Fowler said that these mass gaps spelled the doom of George Gamow's idea that all nuclei heavier than helium could be built by adding one neutron at a time in the Big Bang.

While at the Kellogg Lab in the summer of 1951, Edwin Salpeter of Cornell found a way that helium might burn even though Be^8 is unstable. He showed that a small equilibrium concentration of unstable Be^8 will radiatively capture a third alpha particle to form C^{12} and release a substantial amount of energy. He proposed that $3\,He^4 \rightarrow C^{12}$ is the nuclear source of energy in red-giant stars.

Fowler told us that Fred Hoyle (then at Cambridge) came to Caltech for the first time in 1953 and announced there had to be a resonance in the reaction $Be^8 + He^4 \rightarrow C^{12} + \gamma$ at an interaction energy near 0.3 MeV, corresponding to an excited state in C^{12} at 7.68 MeV excitation. He had obtained this result from his idea that elements beyond hydrogen are produced in stars and in particular that He^4, C^{12} and O^{16} are produced in red giants. His predicted resonance was needed (among other reasons) to make the production ratios agree with the abundance ratios of helium, carbon and oxygen in the solar system and other stars. Succumbing to Hoyle's insistence, Ward Whaling, some of his grad students and postdocs looked for the state in the reaction $N^{14} + d \rightarrow C^{12} + He^4$ and found it at almost exactly the excitation energy predicted by Hoyle.

Although the state was then established, could it in fact be formed from three alpha particles? The two Lauritsens, Charles Cook and Fowler produced the excited state in the radioactive decay of B^{12} and showed it broke up into three alpha particles as well as decaying into the ground state of C^{12}. Thus, Fowler recalls, "on very general physical grounds we knew C^{12} could be formed from three alpha particles and take part in the nuclear transformation of helium into stable C^{12}. Helium burning did indeed occur and was sufficient to warm the hearts of red-giant stars."

In 1956 Hans Suess and Harold Urey published a paper on element abundances based on data from the Earth, meteorites, the Sun and other stars [in *Reviews of Modern Physics* **28**, 53 (1956)]. They adjusted element abundances to make isotopic abundances from one element to the next vary smoothly because neutron capture reactions were known to vary in a regular way. That table was a powerful tool for isolating the types of nuclear reactions that could occur in various stellar environments. Suess and Urey showed that at three places in a plot of abundance of heavy elements versus atomic mass there were double peaks, relative to the nearby region—at mass 90, 140 and 196.

Meanwhile Fowler had spent a Fulbright in Cambridge 1954–55 and had begun a collaboration with Hoyle and with Margaret and Geoffrey Burbidge. By the time the Suess–Urey paper appeared, all three were in residence in Pasadena with Fowler. Eventually the Burbidges, Hoyle and Fowler together developed a comprehensive theory of nucleosynthesis in stars of all of the elements and their isotopes. One key step, Fowler recalls, was the recognition that the abundance of the nuclear species beyond iron showed that the major synthesis in this region involved the successive capture of neutrons. "This was quite natural since charged-particle reactions with the heavier nuclei became very infrequent because of the relatively high Coulomb repulsions involved. In addition, Jesse Greenstein and A. G. W. Cameron independently pointed out that neutrons became available in helium burning through the $C^{13} + He^4 \rightarrow O^{16} + n$ reaction, the C^{13} having been produced previously in the CN cycle." Cameron recalls that he had taken his cue from the discovery of technetium (by P. W. Merrill in 1952) in evolving red giants. Finding observable quantities of this unstable element in stars suggested that element synthesis by neutron capture was occurring.

Fowler recalls, "The neutron capture story took some unraveling since two processes are involved—one in which the neutrons are captured slowly compared to the intervening beta decays, called the s (for slow) process; and one in which the neutrons are captured rapidly, called the r (for rapid) process. The s process could account for the abundance peaks described by Suess and Urey at $A = 90$, 138 and 208 and the *r* process for those at 80, 130 and 190.

In 1956 the Caltech collaboration produced a short paper in *Science* followed by a *Rev. Mod. Phys.* paper (in 1957), now known as B^2FH for Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle.[5] This classic paper describes the synthesis of all naturally occurring nuclear species, by a series of processes taking place in successive generations of stars; with this approach they could account for the observed abundances of elements and nuclides. The pp chain converts hydrogen into helium, then He^4 is converted to C^{12}; successive charged-particle processes continue the synthesis up to the group of nuclei around Fe^{56}. The iron group nuclei served as seeds for the *s* and *r* processes. The paper also described a *p* process to account for the proton-rich side (or neutron-deficient elements) of the valley of stability. As stars evolve, they return some of the matter to interstellar space, either gradually the way the Sun does, or suddenly the way a nova or supernova does; eventually the matter is incorporated into other stars, which then convert hydrogen to helium through catalytic processes such as the CN cycle, producing other isotopes of elements from carbon through sodium.

Meanwhile, Cameron, working independently at Chalk River, also analyzed the Suess–Urey abundances to find a similar set of nuclear processes and associated astrophysical environments. [Cameron published his results as a Chalk River report in 1957 and then in the *Proceedings of the Astronomical Society of the Pacific* **69**, 201 (1957)].

The Swedish Academy announcement says that this complete theory of the formation of the chemical elements in the Universe "is still the basis of our knowledge in this field, and the most recent progress in nuclear physics and space research has further confirmed its correctness." The announcement cites Fowler's extensive work on the experimental study of nuclear reactions of astrophysical interest as well as his theoretical calculations.

Fowler told us, "I'm very fortunate the Nobel prize can be given for team work. I consider it to be an award to the Kellogg Radiation Lab." He cited his collaborators—Charles A. Barnes and Ralph Kavanagh, and earlier, Ward Whaling and Thomas Tombrello. Still enthusiastic about nuclear astrophysics, Fowler feels this is one of the most exciting times. "The whole bugaboo is that we have to measure nanobarn cross sections and then extrapolate by many orders of magnitude" to the much lower energies in stars. For example the effective energy at which the reaction $C^{12}(\alpha,\gamma)O^{16}$ takes place in a red giant is about 0.3 MeV. But lab measurements have only gone down to 1.4 MeV, where the cross section is one nanobarn. Extrapolating to 0.3 MeV, however, the cross section drops to about 10^{-8} nanobarn.

After the B^2FH paper, Fowler continued measuring nuclear reactions with the Kellogg electrostatic accelerators and encouraged other experimenters elsewhere. Fowler and his collaborators in the last two decades have written a series of papers fitting experimental data and developing analytical expressions for reaction rates that can be used by theoretical astrophysicists.

Around 1964 Fowler started emphasizing theoretical astrophysics, working on gravitational collapse, quasars and supernovas. His most recent work has been on electron and neutrino capture during the collapse of supernova cores. Fowler told us he intends to remain active until they carry him out. He complained about preparing a Nobel lecture because it prevented him from completing two papers he is working on currently. "I want to see as many problems solved in my lifetime as possible because I prefer not to go into the afterworld and learn the answers by private communication." —GBL

References

1. S. Chandrasekhar, Phil. Mag. 11, 592 (1931).
2. S. Chandrasekhar, Astrophys. J. **74**, 81 (1931).
3. S. Chandrasekhar, Phys. Rev. Lett. **12**, 114 (1964); **12**, 437 (1964).
4. S. Chandrasekhar, Phys. Rev. Lett. **24**, 611 (1970); **24**, 762 (1970).
5. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957).