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Louis G. Henyey

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LOUIS HENYEY, ONE OF the eminent members of the faculty of the Department of Astronomy at the University of California, Berkeley, during the period 1947-70, is best known for his pioneering research in the field of stellar structure and evolution. The numerical technique he developed for the solution of the equations of stellar structure, known worldwide as the Henyey method, resulted in breakthroughs in research and has since become the standard tool in the field.

His interests included a variety of other problems in theoretical astrophysics and ranged from diffuse interstellar matter to radiative transfer to nuclear physics to cosmological models. He had practical interests in astronomical spectroscopy, optical design, and electronic computing. He played an important part in the education of graduate students and, as a teacher, he was characterized by exacting standards as well as warm relationships with his students. Major administrative posts included service as chairman of the Berkeley Astronomy Department, director of the Leuschner Observatory, director of the Berkeley computer center, and president of the Astronomical Society of the Pacific. He was elected to the National Academy of Sciences in 1968.

Louis Henyey was born in McKees Rocks, Pennsylvania, on February 3, 1910. His parents, Albert and Mary Henyey, were immigrants from Hungary. He attended West High School in Cleveland, Ohio, where he received his diploma in June 1927. He then studied at the Case School of Applied Science in Cleveland, where he obtained his B.S. degree in 1932 and his M.S. degree in 1933. During his Case years he collaborated in research projects with his mentor J. J. Nassau. Henyey married Elizabeth Rose Belak, born in Budapest, on April 28, 1934; they had three children: Thomas Louis, Francis Stephen, and Elizabeth Maryrose.

He spent the years 1934-37 as a graduate student at Yerkes Observatory of the University of Chicago, where he served as an assistant astrophysicist and earned his doctorate in 1937, with a mathematical thesis on the topic of reflection nebulae. In 1937 he was appointed instructor at Yerkes. During the year 1940-41 he took a leave of absence as a Guggenheim fellow to study under Hans Bethe at Columbia University. There he concentrated on the application of quantum mechanics to astrophysical problems. In 1942 he was appointed assistant professor at Yerkes, a position he held until 1947.

During much of this time at Yerkes Observatory he collaborated in astronomical research with Jesse Greenstein. From 1943 to 1945 he also worked under a contract to the Office of Scientific Research and Development under the supervision of the National Defense Research Council. As technical representative he was in charge of the work at Yerkes under this contract, which involved the design and construction of optical instruments of military value.

In 1947 he accepted a position as assistant professor in the Department of Astronomy at the University of California, Berkeley. He was promoted to associate professor the following year and to professor in 1954. At Berkeley he became head of his own research group in the field of stellar evolution and he supervised and collaborated with numerous graduate students, postdoctoral fellows, and scientific visitors. He died unexpectedly of a cerebral hemorrhage on February 18, 1970.

During his years at Yerkes Henyey worked primarily in the area of the physics of the diffuse gas in interstellar space, considering problems, for example, of the reflection of starlight from clouds of gas in space, the absorption and reddening effects of such clouds on the light from background stars, and the theory of spectral line formation in gaseous nebulae. He developed considerable expertise in the field of optics. He and J. L. Greenstein, in collaboration with director Otto Struve, invented a wide-field camera suitable for studying the diffuse gas in space, which they used as a basis for several papers in a collaboration that was to last several years. As Greenstein[1] remarks, "His perfectionism blended with my somewhat coarser energy into confidence that we could finish everything we tried." The combination of observational and theoretical work involved both elaborate analytic radiative transfer calculations as well as observations of the spectra of emission and reflection nebulae, for example, those of the North America nebula and the γ Cygni nebula.

During the war years, however, most of the effort of those staff members who remained at Yerkes (including Henyey and Greenstein) went into design of lenses and optical systems for military application under the Office of Scientific Research and Development. An optical shop was established there so that the optical devices designed by the group could be tested. The designs involved viewing and fire control optics and fast wide-angle cameras. Henyey developed original designs and became an expert in complicated lens and mirror systems and their aberrations. As Greenstein describes,[1] much laborious numerical calculation with the mechanical calculators of the time was required. The optical group at Yerkes was regarded as one of the most skillful and ingenious in the United States at the time. After the war Henyey remained in charge of the optical shop at Yerkes.

Sturla Einarsson, chair of the Berkeley Astronomy Department in 1947, considered it necessary to rebuild the department and to develop expertise in modern astrophysics.[2],[3] Henyey was the first in a series of new appointments, taking the position left open by the resignation of C. D. Shane, who became director of Lick Observatory. He joined faculty members Cunningham, Einarsson, Meyer, and Trumpler in that department. He was followed in the next few years by Otto Struve, John G. Phillips, and Harold F. Weaver.

After arrival at Berkeley, Henyey became interested in the area of stellar structure and evolution. This field, one of the cornerstones of modern astrophysics, was restricted at the time by the lack of adequate computational facilities. The calculation of the evolution of a star, including all the physical effects required for meaningful comparison with observation, is simply not possible to do by analytical methods. Henyey spent the year 1951-52 on leave of absence at Princeton University, where he was involved in classified defense work. There he had contacts with J. von Neumann and learned about general numerical methods for solving nonlinear problems. He also developed links with the Livermore Radiation Laboratory, which had probably the world's most powerful computational facility during the 1950s. There, in collaboration with scientists at the laboratory, he was able to develop specific numerical methods for stellar evolution and to publish several papers on the subject.

He was active in the effort to provide the Berkeley campus with a powerful computational facility, spending a considerable amount of time as chair of the operations subcommittee of the computer center. In 1958 he became the first director of the Berkeley computer center, and although he resigned that post in the following year to become chair of the Berkeley Astronomy Department, he continued to serve on the center's advisory committee. During the next several years when development of larger and faster computers was very rapid the center was able to upgrade its equipment to keep abreast of the best university centers in the country.

Louis Henyey is most remembered for two major scientific contributions. First, he developed a method for automatic solution of the equations of stellar evolution, suitable for electronic computers and applicable to a wide range of physical conditions and phases in the lifetime of a star. Second, he made a significant new calculation of the evolution of stars during their early history when gravitational contraction provides the main energy source, and during the transition phase when nuclear energy takes over from the gravitational source. The method, described succinctly in one line by Henyey,[4] is "an iterative procedure which is essentially a multidimensional generalization of Newton's method for finding the root of a function." For the calculation of the structure of a star at a given point in time, four differential equations are generally solved for four unknown functions, for which two boundary conditions are specified at the center and two at the surface.

Until about 1960 most investigators in the field used the "fitting" method to solve the equations. This procedure involves repeated inward and outward trial integrations starting from both boundaries and adjustment of the boundary parameters until the solutions match at some interior fitting point. The Henyey method involves dividing the (spherical) star into a set of Lagrangian zones, expressing the differential equations as difference equations on the finite grid, setting up an initial guess for all values of the unknown variables at all of the zones, expanding the difference equations in terms of first-order corrections to all the variables, and solving, by matrix inversion, for all the corrections simultaneously. The result is a second approximation to the actual solution. The process is repeated until it converges. If there are N zones in the star, and 4 dependent variables whose variations through the star are to be solved for, the method essentially involves solving 4N linear equations for the 4N unknown corrections to the basic variables. Once the model has converged, the time is advanced and the next model in the evolutionary sequence is computed using the previous model as first guess. The advantage of the method is that it is more efficient and has better convergence properties than the earlier methods. It provides solutions, for example, during advanced phases of stellar evolution where the earlier methods fail. It is flexible in the sense that the choice of physical approximations can be as simple or as complex as the investigator desires.

The basic principle of the method was published in *The Astrophysical Journal* in 1959, but the terse style of that paper made it difficult to understand. Apparently the power of the method was not appreciated by the international community of researchers in the field until Henyey, at the request of Professor Schwarzschild, then president of Commission 35 (stellar constitution) of the International Astronomical Union, gave a lucid presentation of it before a meeting of the commission during the general assembly of the IAU held in Berkeley in the summer of 1961.[5] Several groups around the world then began to develop their own versions of the method. The result was an outpouring of new results during the decade of the 1960s, a significant amount of progress in finding agreement between theoretical calculations and observational phenomena, extensions of the theory into problems that had not even been considered before, and, in general, a substantial advancement of the field of stellar evolution.

The major paper on calculation of stellar evolution during the gravitational contraction phase[4] appeared in *Publications of the Astronomical Society of the Pacific* in 1955. It established Henyey as a leader in the area of numerical solutions of systems of nonlinear differential equations. It was significant not only because it was the first application of the new method but because it was able to go beyond earlier restrictive assumptions and produce more accurate solutions during this phase than had been possible previously. This paper recently has been recognized as a significant contribution. As part of the centennial volume of the *Publications of the Astronomical Society of the Pacific* it was reprinted[6] and accompanied by a review article[7] on the subject of the evolution of young stars by Steven Stahler of the Massachusetts Institute of Technology.

By 1955 it had been well established that the principal energy source of the stars during most of their lifetime was the nuclear fusion of hydrogen into helium. The evolutionary phase during which a major portion of this conversion takes place is known as the main-sequence phase. At the time, observational evidence was beginning to become available regarding the earlier pre-main-sequence phase, during which the stars are not hot enough in their interiors to allow nuclear reactions to generate significant energy. Today it is recognized that stars form in the cores of clouds in interstellar space, where the typical density of matter is twenty orders of magnitude lower than that in stars. Once gravitational instability sets in, the protostar collapses in near free-fall until internal temperatures and pressures become high enough so that the collapse is stopped and the star approaches hydrostatic equilibrium. At this point maximum temperatures fall around 1-2 million K, far too low to result in nuclear reactions. Therefore, the star contracts slowly, radiating and heating at the expense of its gravitational energy, until the central temperature reaches about 10 million degrees, at which point the onset of nuclear burning occurs. The calculation of Henyey, LeLevier, and Levée (1955) addresses the latter part of this phase of gravitational contraction in quasi-hydrostatic equilibrium, and, in particular, the transition to the main sequence, during which nuclear burning gradually replaces the gravitational energy source. Their calculation was the first to treat this transition properly.

The calculations were performed on the UNIVAC computer at the Livermore Radiation Laboratory. The full time-dependent equations of stellar structure were solved, including hydrogen-burning nuclear reactions, approximate radiative opacities, and provision for a central convection zone that would be induced by highly temperature-sensitive nuclear reactions. However, a possible surface convection zone was not allowed for, and the models remained almost completely radiative. The results showed that as a star contracts and heats in the interior, the luminosity gradually increases and the surface temperature increases until nuclear reactions become important. As the nuclear energy source gradually replaces the gravitational energy source the track changes direction and the star gradually declines in luminosity and decreases slightly in surface temperature before settling onto the main sequence. Henyey's calculations included several different masses ranging from 0.65 to 2.3 times the mass of the Sun. The calculation indicated that the lifetime of a star of a solar mass in the contraction phase was about 3 x 10^7 years.

The surface temperatures of the model stars at the beginning of the calculation fell in the range 2000-4000 K. Henyey was aware that in the atmospheres of stars cooler than about 6000 K the ionization of hydrogen generates a surface convection zone. In the same year that Henyey's paper was published F. Hoyle and M. Schwarzschild[8] published an important paper, which traced the evolution of a star beyond the main-sequence phase to the red giant phase and showed that provision for a surface convective layer was crucial. With it the models made a transition from evolution at almost constant luminosity on the way over to the giant branch to rapidly increasing luminosity and slowly varying surface temperature in the giant branch itself; these theoretical models agreed with observations. It was demonstrated in 1961 by Professor Hayashi of Kyoto University[9] that stars, in their evolution prior to the main sequence, exhibit roughly the inverse behavior. When contraction starts at a radius several times the main-sequence value, convection dominates the structure so that the evolution proceeds at nearly constant effective temperature and decreasing luminosity. As the star contracts and heats, a radiative zone develops near the center and gradually includes more and more mass. The star then makes a transition to an evolutionary path of gradually increasing luminosity and increasing temperature, which is what Henyey calculated. However, he missed the earlier convective portion of the tracks because of the surface boundary condition he used. He has often been criticized for this omission. In fact, his tracks are valid for the final approach to the main sequence as long as the mass is greater than about 0.6 solar masses, but not for the earlier phase of the evolution when the surface temperature is less than about 4000 K. The convective boundary condition was not included in the 1955 version of the code, first, because there were numerical problems at the surface, and second, because he was not satisfied with the very approximate nature of the theory of convection in stellar surface layers.

For several years Henyey distrusted Hayashi's result, which was originally based on a number of approximations and, for example, did not include possible superadiabatic effects in surface convection zones. He wished to see a confirmation based on a full numerical solution. Before Hayashi made his discovery of the nature of pre-main-sequence evolution, Henyey had been in the process of developing an advanced stellar evolution computer code that took into account a wide variety of physical processes, including a detailed "mixing length" theory of the surface convection zones on cool stars. He invited Karl-Heinz Böhm, an expert on astrophysical hydrodynamics, and his wife Erika Böhm-Vitense, an expert on the theory of convection in stellar atmospheres, to spend some time at Berkeley to work out the atmosphere problem. Mahendra Vardya, who spent several years at Berkeley, developed a detailed atmosphere computer code to join with the Henyey stellar evolution program. However, it turned out to be quite difficult to get the combined code into full operation, because of its great complexity, the use of assembly language, and the limited power and storage of computers at the time. Other investigators were already beginning to learn about the Henyey method and, using somewhat simpler versions than Henyey's own, were getting results. Some of them were able to prove that Hayashi was right. The superadiabatic effects, while present, were not sufficiently important to vitiate the result.

My role as a graduate student in Henyey's research group was to investigate the Hayashi problem and to determine whether the result was sensitive to initial conditions. For example, if the assumed initial model was largely radiative rather than convective, would Hayashi's tracks still result? Of course, the actual initial condition is determined by events during the preceding protostar collapse phase, which at that time (1964) was just beginning to be studied.

My calculations started with an artificially chosen entropy distribution that produced a radiative region in most of the model. Nevertheless, on a very short time scale the surface regions of the model relaxed to conditions very close to those predicted by Hayashi. Although the interior radiative zone persisted for some time, its presence did not appreciably affect the evolution of the surface temperature and luminosity, which proceeded according to Hayashi's theory. By this time there was also convincing observational evidence supporting Hayashi's evolutionary tracks. For example, essentially no stars have surface temperatures below 2500 K, in agreement with the theory. Also, the agreement between observed main-sequence lithium abundances as a function of surface temperature and my calculation of lithium depletion during the pre-main-sequence contraction was a strong point in favor of the existence of deep convection zones in the early phases.

Henyey insisted on as much accuracy as possible in describing the physical processes in the stellar interior, and he was always pushing the available computing power to the limit. In the early 1960s his computer program, nicknamed STEVE by his research group, had a degree of sophistication well beyond that of most codes at the time. Approximations were, of course, necessary, but the code followed, nevertheless, with non-equilibrium reaction rates, the time dependence of several nuclear species involved in hydrogen and helium burning. It also had a separate model atmosphere calculation that was fitted to the interior solution, and it had a detailed equation of state that was correct over a wide range of physical conditions. Some of the refinements were probably unnecessary in view of the inherent uncertainties in both theory and observations, and the various complications resulted in some delays in progress.

Although he was recognized as a world leader in the field of stellar evolution, he was at times criticized for failing to publish voluminously. In part, this reticence followed out of his high standards and self-critical attitude. Nevertheless, the fundamental importance of his work was internationally recognized.

He did publish three papers in collaboration with members of his research group in 1964-65. The first of these described the new version of the mathematical method, discussed the physics that went into the calculations and presented a flow chart of the overall computer program. The second paper presented several calculations of the late pre-main-sequence and main-sequence evolution of a star of 2.3 solar masses, with different assumed initial abundances of the elements carbon, nitrogen, and oxygen and a comparison of the results with the present observed properties of the star Sirius. The third paper considered the physical and mathematical approach to the calculation of the model atmosphere boundary condition that was combined with the stellar evolution program, identified several uncertain parameters in convection theory, and tested the influence of those parameters in the pre-main-sequence and post-main-sequence evolutionary phases of a star of five solar masses. These results helped to establish that the Hayashi phenomenon was insensitive to uncertainties in the treatment of stellar surface layers.

The stellar evolution project produced a number of further research papers during the late 1960s, but he did not include his name as co-author on many of them. During that time he concentrated on studies in the rigorous theory of radiative transfer in stellar atmospheres and on the diffusion of energy in the stellar interior and its relation to the larger question of why stars develop a red-giant structure.

Henyey was very generous with the time, assistance, and recognition he gave to his graduate students. During the mid-to-late 1960s he had more students than any other faculty member in the department, and his relations with them were unusually good. He treated them with respect and as intellectual colleagues and encouraged them (also with financial support) to attend scientific meetings to present their results. On several occasions he invited groups of them to his home, which was beautifully located in the hills overlooking San Francisco Bay and was surrounded by a very fine garden to which he devoted much attention. The meetings were sometimes social affairs, but at other times they involved discussions of particularly difficult problems with the stellar evolution code.

Several papers were published during this period by his students under their own names even though he himself played a major role in the development and testing of the numerical techniques and physical input that led to those results. For example, I published three papers[10] ,[11] ,[12] under my own name in 1965 and 1966. The results were based on a version of the Henyey code and they concerned the depletion of lithium, deuterium, and beryllium during pre-main-sequence evolution, as well as the effect of initial conditions on the theoretical tracks during the early pre-main-sequence phase. In 1968 Jack Forbes, who worked long and hard on the development of the Henyey code, published his thesis results[13] on the effect of mass loss during post-main-sequence stellar evolution.

Robert Benson[14] used the code to study the evolution of close binary star systems in which mass is transferred from one component to the other. He was the first to show that the star that accepts mass evolves out of thermal equilibrium, expands rapidly, and soon comes into contact with its companion, a crucial realization in the theory of close binary evolution.

Silvia Torres-Peimbert[15] ,[16] studied the effects of enhanced (above solar) metal abundance on the evolution of stars and discussed the effects of metal abundance on cluster ages, which are found by fitting observed Hertzsprung-Russell diagrams to the results of stellar evolution calculations.

Erik Simpson[17] completed his thesis on the effects of semiconvection on the evolution of massive stars. He discussed which version of the theory was most likely to be correct through a comparison with observed cluster stars.

Three students jointly published a paper[18] in which they used the Berkeley stellar evolution program to produce solar models and to compare the theoretical neutrino fluxes observable at the Earth to the early experimental results. Another student project involved a comparison of Berkeley stellar evolution isochrones with the Hertzsprung-Russell diagrams of several galactic clusters to determine their ages.[19] The age of the Pleiades found in this investigation was generally accepted by observers and it has not been substantially modified in more recent determinations.

Other students of Henyey performed thesis research on projects that were closely related to stellar evolution but did not involve direct use of the computer program. Roger Ulrich[20] developed a theory of convection that was an alternative to the mixing-length approach. It examined the coupling, through mass motions, between adjacent layers with different properties in the superadiabatic region of an atmosphere.

Richard Hillendahl[21] developed his own hydrodynamic code with radiation transport to describe the oscillations of Cepheid variables and the generation of extended envelopes and mass loss in luminous stars. William G. Mathews[22] did a pioneering study on the numerical treatment of expanding regions of ionized hydrogen associated with hot, young, and massive stars. William B. Hubbard[23] solved difficult problems in transport theory in dense plasmas; this work later became of fundamental importance in the development of detailed tables of thermal conductivity for stellar matter under electron-degenerate conditions.[24] These tables are still the standard source for electron-conduction opacities in stellar evolution calculations. All in all, the Henyey research group produced very respectable scientific results during the period 1965-70.

Those Berkeley graduate students who did not choose to do research in areas related to stellar evolution also benefitted from Henyey's expertise and high standards. For over twenty years he was the mainstay in the graduate teaching program in theoretical astrophysics, giving the basic courses in stellar structure and evolution, fundamental principles of physics, and occasionally stellar atmospheres. He earned his unofficial title of "the tiger" with his generally rigorous standards of instruction and by being "fierce" on, for example, qualifying exams. Nevertheless, he was often regarded by the students as their best friend on the faculty. His lecture courses were very well organized. He was extremely clear and at times brilliant. He provided an excellent set of lecture notes for his students. And he covered both the fundamental physical principles of a subject as well as the latest results at the frontiers of research. The courses were generally aimed at the level of the best students.

Henyey also devoted considerable energy to departmental and university affairs. When Otto Struve took a leave of absence in 1959 to become director of the National Radio Astronomy Observatory, Henyey took over his position as chair of the Astronomy Department and director of the Leuschner Observatory for the next five years. He took on the chairmanship during a time of rapid, nationwide expansion of the field of astronomy. Several new faculty members and research associates joined the department during this time, and the number of graduate students also increased substantially.

One particular area of research that Henyey strongly supported was radio astronomy. A radio astronomy laboratory had been established on the Berkeley campus during the late 1950s and an observing site had been set up at Hat Creek in northern California. He served on the advisory committee of the laboratory from 1961 to 1965. About the time he took on the chairmanship, the department moved from the old Leuschner Observatory buildings near the north gate of the campus to new, modern quarters on the top floor of Campbell Hall. Henyey was the departmental representative on the Campbell Hall subcommittee, which had an important role in planning and designing the new building. He was also heavily involved in moving the Leuschner Observatory itself to a new, more suitable, but still close-by site in the Berkeley hills. He was instrumental in locating the new site, obtaining funding from the National Science Foundation, and in designing the new 30-inch reflecting telescope that was put into operation there. He generally took on more than his share of the local administrative responsibilities, and he discharged his duties thoroughly, carefully, and with meticulous attention to detail. His judgment and opinions were highly valued among his colleagues.

In summary, Professor Louis Henyey was an excellent scientist who was interested less in building his personal scientific reputation than in service to others, and more interested in scientific rigor than rapid, superficial publication. He had a wide range of interests in astrophysical subjects ranging from highly theoretical to very practical; in particular, he played a key early role in the development of electronic computing as a technical aid in astronomy. His major accomplishment was the development of an automatic computational method for the calculation of stellar evolution. As a result, there was rapid progress in this field, which brought it onto a quantitative level and into a state where useful comparisons with many different types of observations could be made.

I THANK THE BERKELEY Astronomy Department and, in particular, Ms. Mary Brunn, for providing the photograph and other historical information from the faculty files. Although this article is based primarily on my personal experience as a graduate student in the Berkeley department from 1960 to 1965, I have also benefitted from Professor Greenstein's vivid review,[1] from comments by Professor Martin Schwarzschild and from an article by Berkeley professors John G. Phillips, Ivan R. King, and L. V. Kuhi that appeared in the University of California volume *In Memoriam* in May 1977.

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