Hans Bethe and Astrophysical Theory

A scientific colleague and friend reminisces about a nearly 30-year collaboration working on supernovae, collapsing binaries, and California condominiums with nice bathtubs.

Gerald E. Brown

I got to know Hans Bethe in the 1950s, when I was a lodger at the home of Rudolf and Eugenia Peierls in Birmingham, England. Bethe and Peierls had been close friends ever since they were graduate students together under Arnold Sommerfeld; the two went on to devise a comprehensive theory of the deuteron. Their comradeship affected many people, including some of the authors in this special issue of PHYSICS TODAY. My room still had University of Canberra stationery from when Edwin Salpeter lived with the Peierlses, and I bought the bicycle Freeman Dyson had left.

During his 1955 sabbatical at the University of Cambridge, Hans worked on the nuclear many-body problem and, in particular, on difficulties associated with Brueckner theory. (See the article by John Negele on page 58.) Shortly after that, I began work on applying to finite nuclei the effective interactions he had obtained for infinite nuclear matter, and visited him often at Cornell University. After he retired from Cornell in 1976, he and I worked together on astrophysics problems; Hans also continued to work on neutrino physics, arms control, and energy issues.

I soon learned why Hans had no long-term collaborators earlier in his life, aside from Peierls. (The two are shown together in figure 1.) Even after he retired, it was nearly impossible to keep up with him. Not that he worked rapidly, but right away he could identify the essential physics and see the light at the end of the tunnel. Then, like a bulldozer, he moved toward that light, undeterred by temporary obstacles. The scope of problems he could solve pretty much had no limit: In that sense, I think he was the most powerful scientist of the 20th century.

He was famous for his statement "I can do that!" A couple of years after his retirement, I unleashed Hans's arsenal of physics knowledge and experience on a problem worthy of his abilities.

Not enough entropy

On the morning of 1 April 1978, my wife Betty and I picked up the Bethes from the airport in Copenhagen, then proceeded to take them to the house where they were renting some rooms. Hans had sprained his ankle on Mount Pion in Turkey, and on the way I said that the accident was a bad omen for his work on the pion–nucleon many-body problem, in which each new higher-order term was about as large as all the previous lower-order terms put together. Hans asked, "What should we work on?" I replied, "Let's work out the theory of supernovae." Hans countered that he didn't know anything about them.

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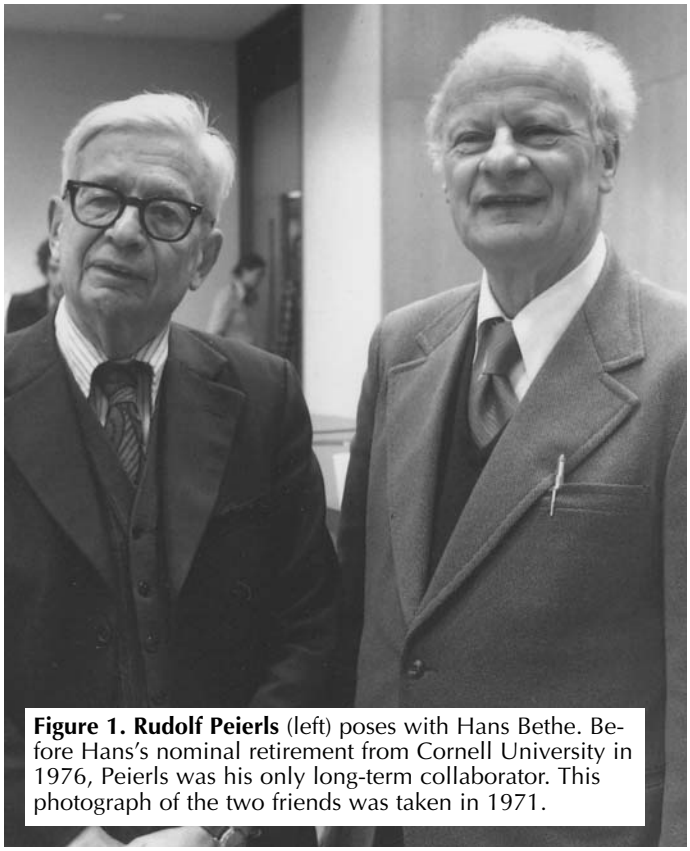

Figure 1. Rudolf Peierls (left) poses with Hans Bethe. Before Hans's nominal retirement from Cornell University in 1976, Peierls was his only long-term collaborator. This photograph of the two friends was taken in 1971.

I told him that workers in the field had the nuclear physics all wrong and that I knew how to correct it. I'd written a research paper with James Lattimer and Ted Mazurek showing that the many excited states of nuclei had essentially been left out in works to date.[1] But, I told Hans, in order to work out the theory, I needed an expert on explosions. Hans, who had worked at the Los Alamos Laboratory as head of the theory group for the Manhattan Project, admitted that he knew something about them. We delivered Hans and his wife Rose to their apartment, and then I went to work at the Niels Bohr Institute. Before going home that afternoon, I left on Hans's desk a computer printout of a large star that Stan Woosley had evolved up to the point of collapse. At that point, stellar fusion has converted all the core material into iron, the nucleus with the greatest binding energy per nucleon, and no additional energy can be produced via stellar burning.

I came in the next morning and went to see Hans. He said, "The entropy in the iron core is very low, less than

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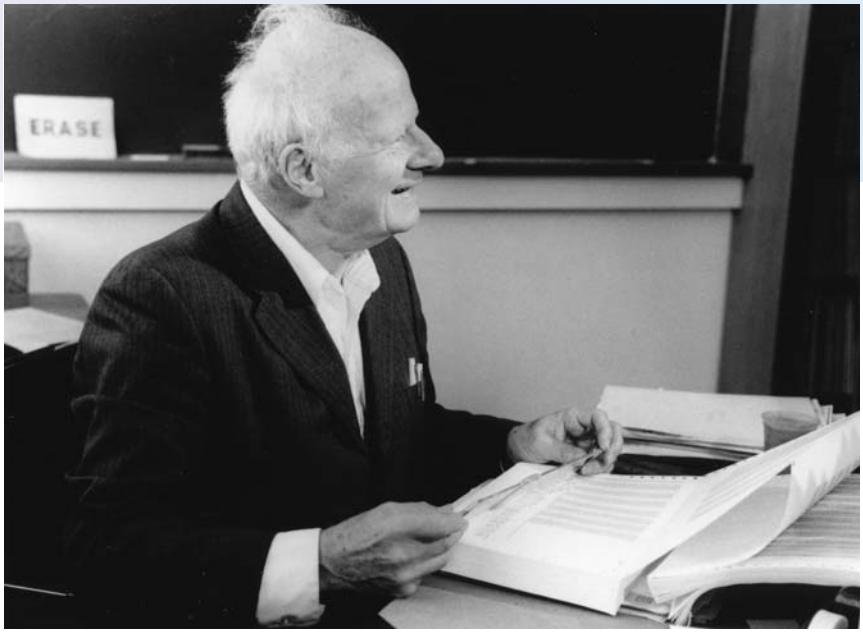


Figure 2. The slide rule was Bethe's calculational tool of choice. In this photo, taken at Cornell University around 1986, Bethe analyzes computer output. (Photograph by Kurt Gottfried, courtesy of AIP Emilio Segrè Visual Archives.)

unity [in units of Boltzmann's constant k_B] per nucleon."

"So what?" I asked.

He said, "That means that the iron core will collapse, without being held up, until the iron nuclei merge into nuclear matter at nuclear-matter density. There isn't enough entropy for them to break up." I said that since World War II, all supernova calculations had shown that the collapse is held up at about 1/1000 of nuclear-matter density.

"They're wrong!" he replied.

Hans was right. Stellar collapse is slow when considered on the time scale of the strong interaction, so, setting the weak interactions aside for the moment, entropy is conserved. And there simply isn't enough entropy for iron to break up. The weak interactions actually decrease the entropy in the core via neutrinos that carry energy and entropy out of the star. To stop the infall of matter, a strong repulsive force is necessary, and such a force is available only if the density is well above nuclear-matter density. In that regime, the high compression modulus of nuclear matter can stop the collapse.

Stellar explosions

Because each iron nucleus in the core contributes about $1/27$ as much to a star's pressure as do the relativistic, highly degenerate electrons of the atom, the collapse of the core is comparable to the collapse of a white dwarf. And as discovered by Subrahmanyan Chandrasekhar, the maximum dwarf mass M that can be supported by relativistic degenerate electron pressure is given by $M = 5.76 M_\odot Y^2$, where $M_\odot$ is the mass of the Sun and Y is the ratio of the number of electrons to the number of nucleons (protons and neutrons). In relativistic white dwarfs, $Y = 1/2$, but in large stars some electrons are captured by protons before collapse, so that Y is typically about 0.43 in the crucial stage of the collapse. Thus the mass of the so-called homologous core of a collapsed large star is about 1 solar mass, or perhaps a little greater. The result of the collapse, astrophysicists believe, is a neutron star, typically with a mass of $1.4 M_\odot$.

By 1978 the basics of the collapse were understood. The homologous core collapses subsonically, but the matter beyond the core's outer edge is supersonic. When the density at the center of the star exceeds the density of nuclear matter, pressure waves that travel at the speed of sound are formed. Those waves, which tend to bring infalling matter to rest, can only get as far as the edge of the homologous core: Were they to go beyond, they would be swept back in by the supersonic flow outside. Pressure and density discontinuities build up at the edge of the homologous core. Eventually they lead to a shock wave that blows off the part of the star well outside the homologous core. Explosions of stars that had previously converted all their core material into iron are called type II supernovae. They provide the universe with the heavy elements such as carbon and oxygen that make up human bodies.

The devil, of course, is in the details. Hans could solve almost any problem, but in attempting to understand the explosion, he probably had not encountered one more suited to his abilities and experience—especially in light of what he learned at Los Alamos. Alas, when the details were worked out, the better the calculation, the less well the explosion succeeded at blowing off the outer part of the star. The shock wave spent so much energy in dissociating the iron outside of the homologous core—about 10^{51} ergs (10^{44} joules) for each $0.1 M_\odot$ of iron dissociated—that it didn't have enough remaining energy to blow off the outer region; instead it just traveled some few hundred kilometers and stalled, until the investigator ran out of computer time.

The energy scale of 10^{51} ergs came up often enough in our work that I gave it a special name: the foe (short for 51 ergs). In 1990 Hans and Pierre Pizzochero[2] analyzed the speed of the hydrogen recombination wave in the supernova SN1987a and showed that the total mechanical energy in the explosion was 1–1.4 foe. Thus, dissociation of $0.1 M_\odot$ of iron would remove from the shock wave about as much energy as was contained in the mechanical part of the explosion.

But the explosion has another source of energy: gravitational binding. As the core of the large star settles into the tightly bound neutron star, neutrinos carry off about 300 foe of gravitational binding energy. So Hans tried to see if some of that energy could be deposited into the matter outside the homologous core but inside the shock. Then, through convection, the hot matter could move up behind the shock and repower it.

In late 1987 Hans discussed his convection ideas at the Nuclear Theory Institute in Seattle. When he came to the calculation, he said he had two coupled differential equations that he had to solve numerically. For Hans, "numerically" meant with his slide rule. Throughout our entire supernova work, he would take out sections of computer output, check different quantities against each other, and then pose questions to whoever had made the computation (see figure 2).

To this day, calculated explosions have yet to achieve success. Investigators are refining ideas about convection and relaxing assumptions about sphericity to get the explosions to work.

About the future

For nearly 25 years, Hans and I spent every January together in California. We'd share a condominium in Santa Cruz or Santa Barbara, or, most often, in Caltech housing.

Figure 3. In our final years in California, Hans and I were joined by our wives. Shown here, from left to right are Hans, Rose Bethe, Betty Brown, and me. The photo was taken in 1999, at the 60th birthday celebration of nuclear theorist and colleague Chun Wa Wong.

I did the cooking since Rose was looking after her parents and my wife Betty was caring for our children. But in the last years, the four of us were all joyfully together (see figure 3). After supper Hans and I would discuss history, politics, and so forth, always in a structured way. At times, he would lapse into German and reminisce about his childhood and youth. He greatly appreciated my ability in German and gave me Johann Wolfgang von Goethe's book of poems *Das Leben, es ist gut* for a birthday present. Before we went to bed, I'd outline for him the problems we had still to solve, and he'd promise to think about them in his half-hour bath in the morning—we always required a bathtub for him in whatever condominium was furnished for us. So it was when we were together.

During a massive, hour-and-a-half breakfast of various sliced leftover meats, red currant jam, numerous hot rolls, and lots of tea, we would discuss how to attack the day's problems. Then Hans would estimate how far we could get, and we would go to our office. He usually identified a piece of the problem that he could do before lunch, then filled the pages of blank paper on the top left-hand part of his desk at a steady pace. He was really cross if he needed to work until 10 minutes past noon to finish his preassigned part of the problem, since he clearly desired lunch. But I cannot remember that we ever got severely stuck for long. In the evening we compared solutions; his had been calculated with his slide rule and mine with my $12 calculator. Since I was 20 years and 20 days younger than Hans, I could just about keep up with him!

At the end of January 1996, the day before I was to return to Stony Brook, Kip Thorne came to the office Hans and I shared at Caltech. He said the production of gravitational waves that LIGO (the Laser Interferometer Gravitational-Wave Observatory) should measure from coalescing neutron stars had been estimated by several research workers theoretically, but mergers of neutron stars and black holes had not received as much attention. Hans and I, he continued, were good at calculating things that had not been seen. Could we calculate the contribution of those less-studied mergers?

The previous year I had found that the accepted scenario for evolving a neutron-star binary resulted in a binary comprising a neutron star and a low-mass black hole.[3] So I knew that binaries with a neutron star and a black hole would give at least an order of magnitude more mergers than neutron-star binaries. I said to Hans, "You've now calculated Roman numeral VI of your theory of supernovae. It's time to change." After all, he was only 90. I went on to say that we now had a topic to work on next year at Caltech. He replied, "Oh, no! I want to begin now." So after I got back to Stony Brook, I sent him a 20-page paper by Evert Meurs and Edward van den Heuvel.[4] A few days later, I received from him a page-and-a-half fax, in which he'd derived their main conclusions. "I don't seem to have done it as accurately as they did, but I got the same results," he noted.

We wrote a paper, "Evolution of Binary Compact Objects that Merge," that I think is the best thing Hans and I did.[5] The paper appears in about the middle of the collected works[6] that I edited along with Hans and Chang-Hwan Lee. It and the papers that followed are mostly "about the future," like Ejlert Lövborg's manuscript in Henrik Ibsen's great play *Hedda Gabler*. But since Lee coauthored several of those papers, they cannot be thrown into the fire and burned; in any case, he has computer backups of them.

Hans and I made lots of predictions that only the future will test. The chief among those will not be checked for at least a decade, when LIGO II is completed: We predict that LIGO II will find 20 times more mergers of low-mass black-hole, neutron-star binaries than of neutron-star binaries.

A large piece of life

I hope to see our predictions come true. I am on a low-fat, chiefly fish diet in order to live until LIGO II can test our prediction about mergers of neutron stars and black holes. One of the key ingredients that went into the merger prediction was a result we had obtained for the maximum mass of a neutron star. I must admit I had to do a bit of selling to

convince Hans of a strangeness-condensation calculation[7] that we worked out in 1994. Based on that calculation, we concluded that the maximum neutron star mass was about $1.5M_\odot$. But Hans believed the result, and the next year we calculated a comparable maximum mass starting from the approximately $0.75M_\odot$ of nickel production in SN1987a that we were certain went into a black hole.[8]

My close friend Marten van Kerkwijk, who is an excellent observational astronomer, keeps asking me if I still believe the neutron-star mass limit. When I firmly say, "Yes," he responds, "Good," because he thinks it's lovely for observers to be able to refute theoretical predictions. Marten's measured mass of $1.86M_\odot$ for the neutron star Vela X-1 exceeds our limit even when statistical errors are accounted for,[9] but he would be the first to admit that the binary is messy, and notes that "no firm constraints on the equation of state are possible, since systematic deviations in the radial velocity curve do not allow us to exclude a mass around $1.4M_\odot$ as found for other neutron stars." In any case, Marten has been absolutely crucial to the whole program that Hans, Chang-Hwan, and I had been working on. He has checked most of our papers and helped us to avoid published errors. To have our work critiqued by such a skeptical expert as Marten can only be stimulating.

Hans had a particular warm side that he exhibited to his family and to friends such as Rudi Peierls and Viki Weisskopf, as well as to graduate students and colleagues. I was the young interloper who crassly broke into this honored circle—and he loved it. Following my talk at the 1993 symposium "Celebrating 60 Years at Cornell with Hans Bethe," Hans said, "I knew we had a lot of fun working on the supernova problem, but I didn't know that we had that much fun!" But revealing the warmer part of his character must be assigned to the angels because he would hate me becoming maudlin. As evidence, I note that after I had written a several-page dedication to his wife for the collected works I mentioned earlier, Hans shortened it to "We dedicate this collection of papers to Rose Bethe, who throughout their long evolution fed us, walked us, consoled us and cheered us on."

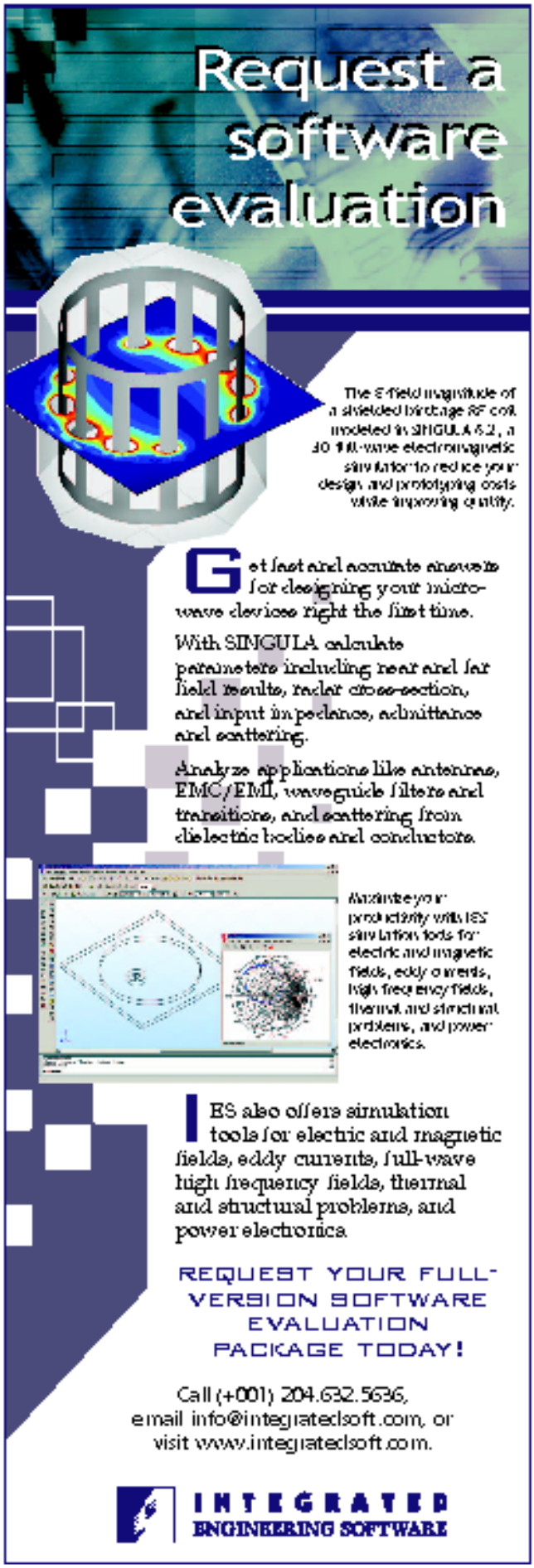
The two of us worked together right up to his death. In fact, on the phone the morning of the day he died, I told him that C. N. Yang would prepare an article for the centennial volume of *Physics Reports* that I was putting together for Hans's 100th birthday, 2 July 2006.

On the night in 1995 when Rudi Peierls died, Hans had phoned me and said, "A large piece of my life—and yours—has gone." The night that Hans died another large part—father figure, collaborator, and friend—was taken from my life, which is greatly diminished without him.

This article is based in part on my commentaries to chapters 1 and 12 of reference 6. I thank World Scientific for permission to use them.

References

1. T. J. Mazurek, J. M. Lattimer, G. E. Brown, *Astrophys. J.* **229**, 713 (1978).
2. H. A. Bethe, P. Pizzochero, *Astrophys. J.* **350**, L33 (1990).
3. G. E. Brown, *Astrophys. J.* **440**, 270 (1995).
4. E. Meurs, E. P. J. van den Heuvel, *Astron. Astrophys.* **226**, 88 (1989).
5. H. A. Bethe, G. E. Brown, *Astrophys. J.* **506**, 780 (1998).
6. H. A. Bethe, G. E. Brown, C.-H. Lee, eds., *Formation and Evolution of Black Holes in the Galaxy: Selected Papers with Commentary*, World Scientific, River Edge, NJ (2003).
7. G. E. Brown, H. A. Bethe, *Astrophys. J.* **423**, 659 (1994).
8. H. A. Bethe, G. E. Brown, *Astrophys. J.* **445**, L129 (1995).
9. O. Barziv, L. Kaper, M. H. van Kerkwijk, J. H. Telting, J. van Paradijs, *Astron. Astrophys.* **377**, 925 (2001). ■



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