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MY LIFE IN ASTROPHYSICS*

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■ **Abstract** Astrophysics has been an important part of my personal and scientific life three times. The first was in 1938 when I did work on stellar energy production. The second was a joyful period nearly 30 years later when that work was rewarded with the Nobel Prize in physics. And the third has lasted over the time since my retirement in 1975 during which Gerry Brown and I have had a very satisfactory collaboration exploring various aspects of supernovae and, more recently, binary pairs.

1. INTRODUCTION TO ASTROPHYSICS

My first involvement with astrophysics came as a result of Carl Friedrich von Weizsäcker's suggestion to investigate the fusion of two protons to form a deuteron, namely

$$\mathrm{H} + \mathrm{H} \quad \Rightarrow \quad \mathrm{D} + \mathrm{e}^+ + \nu. \tag{1.1}$$

This is obviously a beta interaction. George Gamow and Edward Teller had previously shown that beta interactions do not need to be scalar, as Fermi had originally proposed, but can also be (given) by any of four other covariant expressions. We now know that the correct expression is $\nu - \alpha$, vector minus axial vector.

Gamov suggested to one of his graduate students, Charles Critchfield, that he actually calculate the proton-proton reaction. When Critchfield had finished his calculations, in early 1938, Gamow suggested that he submit his paper to me because I had worked in detail on nuclei consisting of two nucleons. I found the calculations to be correct, and we wrote a joint paper.

In stars, the proton-proton reaction is usually followed by a chain of reactions with the end result of producing ^{4}He. The most common chain is

$$\mathrm{D} + \mathrm{H} \Rightarrow {}^3\mathrm{He} + \gamma \tag{1.2}$$

$${}^3\mathrm{He} + {}^4\mathrm{He} \Rightarrow {}^7\mathrm{Be} + \gamma \tag{1.3}$$

$${}^7\mathrm{Be} \Rightarrow {}^7\mathrm{Li} + \mathrm{e}^+ + \nu \tag{1.4}$$

$${}^7\mathrm{Li} + \mathrm{H} \Rightarrow 2\,{}^4\mathrm{He}. \tag{1.5}$$

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Several other chains are possible. Reactions 1.1 and 1.4 are important for observation of solar neutrinos. Reaction 1.4 is a necessary consequence of the formation of ^{7}Be. However, Reaction 1.4 starts from a preformed nucleus, ^{7}Be, whereas in Reaction 1.1 the protons have to find each other and overcome the potential barrier.

As observed above, the end result of these chains is the combination of four protons into one α-particle. This reaction releases a large amount of energy, which can be calculated from the exact atomic weights of hydrogen and ^{4}He. The rate of the reaction is determined by the first element of the chain; the following reactions are very fast.

We had a problem, however. At the time, Arthur Eddington's estimate of the central solar temperature was 40 million degrees. At that temperature, the rate of the reaction was much too high compared to the observed radiation of the sun.

2. THE WASHINGTON CONFERENCE

Every spring, a small conference was held in Washington, sponsored jointly by the Carnegie Institution and George Washington University. Gamow and Teller usually suggested the subject of the conference. In 1938, they suggested energy production in stars. They invited about five astrophysicists and ten physicists, including me. I did not really want to go because at the time my main interest was quantum electrodynamics. That subject had to wait another decade to be solved.

Teller urged me to come, and I finally gave in. The conference turned out to have one really important piece of information: Strömgren, a well-known Scandinavian astrophysicist, reported that the central temperature of the sun was now estimated as 15 million degrees, not Eddington's 40. This is still the estimate. This change came as a result of assuming that the sun was predominantly hydrogen with approximately 25% helium, rather than assuming it had about the same chemical composition as the earth. The lower atomic weight of the revised mix lowered the temperature.

The lower temperature meant that the reactions calculated in the paper by Critchfield and me correctly predicted the luminosity of the sun, that is, the amount of observed radiation. So we had a theory of energy production by the sun that was immediately accepted by the conference.

This left unsolved the question of energy production in larger stars. From observations, one could show that core temperatures increase slowly with increasing mass, but luminosity increases very rapidly. The proton-proton reaction could not predict this, as the rate of the reaction increases fairly slowly as the core temperature rises.

The other key question explored at the conference was how to build elements heavier than helium. The major problem was that no nucleus of atomic weight 5 exists, nor does any of weight 8. Both immediately disintegrate, which had been shown by laboratory experiments. Elements of weight 6 or 7 in a proton sea will quickly decay into two helium atoms in reactions similar to Reaction 1.5.

Ed Salpeter, a Cornell colleague, eventually solved this problem. The principal reaction that enables crossing the atomic-weight-8 barrier is for three alpha particles to combine to form carbon. This only happens at very high temperature and density. This, in turn, occurs when the core protons are used up, and the core contracts because of gravity. The contraction is adiabatic: Both temperature and density increase until they are sufficient to start "burning" helium. The problem of how to create heavier elements is one that I have returned to in recent years.

3. THE CARBON CYCLE

I did not, contrary to legend, figure out the carbon cycle on the train home from Washington. I did, however, start thinking about energy production in massive stars upon my return to Ithaca. Because the observed energy production increased faster than the proton-proton reaction could explain, there had to be another reaction, and it had to involve heavier nuclei. Lithium, beryllium, and boron are the lightest elements heavier than helium. They could all be ruled out because of comparative scarcity. The next element is carbon.

Repeated reaction of carbon with protons yielded a favorable result:

$$^{12}\mathrm{C} + \mathrm{H} \Rightarrow {}^{13}\mathrm{N} + \gamma \qquad (3.1)$$
$$^{13}\mathrm{N} \Rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu \qquad (3.2)$$
$$^{13}\mathrm{C} + \mathrm{H} \Rightarrow {}^{14}\mathrm{N} + \gamma \qquad (3.3)$$
$$^{14}\mathrm{N} + \mathrm{H} \Rightarrow {}^{15}\mathrm{O} + \gamma \qquad (3.4)$$
$$^{15}\mathrm{O} \Rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu \qquad (3.5)$$
$$^{15}\mathrm{N} + \mathrm{H} \Rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}. \qquad (3.6)$$

All these nuclei are well known in the laboratory. ^{13}N and ^{15}O are positron radioactive with half-lives of approximately 10 min.

There are two basic forms of nuclear reactions in stellar energy production. One involves penetration of the potential energy barrier. The other involves a weak interaction, namely beta decay. Both of these are unlikely events, so reactions that require both, such as the basic proton-proton combination of Reaction 1.1, are significantly less likely than those that require one or the other only, which is the case in all the reactions of the CN cycle. The reactions requiring potential barrier penetration become significantly more likely as temperature and density increase; the weak interactions are essentially unaffected. The heavy nuclei involved in Reactions 3.1, 3.3, 3.4, and 3.6 have much stronger potential barriers than the protons in Reaction 1.1. The lower probability of the penetration of these barriers is compensated by the accompanying need for a weak interaction in Reaction 1.1, making the combination of all four occur with approximately the same probability as the one.

Perhaps the major surprise of the CN cycle is that Reaction 3.6 does not lead to the formation of ^{16}O in the same type of reaction as Reaction 3.1, 3.3, and 3.4.

This indeed does happen, but only in about one event in 1000. The conversion to ^{16}O requires an interaction with the electromagnetic field in addition to the rearrangement of nucleons needed for either reaction. This further requirement reduces the probability by a factor of at least e^2/hc. On the other hand, Reaction 3.1, 3.3, and 3.4 do not lead to formation of an α-particle and a lighter nucleus because the binding energy of the boron and ^{11}C nuclei are low and there is not sufficient energy to permit those reactions. ^{12}C is exceptional in having a very high binding energy because it is a multiple of α-particles.

The result of the CN chain is remarkable. At the end, the starting ^{12}C nucleus is recovered, and four protons have been combined into an α-particle, just as in the chain starting with the proton-proton reaction, but through a totally different mechanism. The ^{12}C nucleus serves essentially as a nuclear catalyst, so that relatively few carbon nuclei are needed to allow frequent occurrence of the reaction.

4. SUBSEQUENT DEVELOPMENTS

The discovery of the CN cycle took me about two weeks. I first wrote of the result to my close friend, Rudolph Peierls, who wrote back that it was a very nice result. I also told Edward Teller, who was equally pleased and congratulatory. Soon after I had finished, I gave a physics colloquium at Cornell. This excited R.C. Gibbs, the chairman of the department. He suggested to the Cornell public relations officer that I had done something noteworthy. I explained the theory to the publicity officer, and he managed to get the *New York Times* to print an article about it. Other interviews followed, and several friends asked when I was going to Hollywood to help make the movie!

More important was an invitation from John Van Vleck to speak at the Harvard physics colloquium, which I accepted happily. In the front row at the colloquium sat Henry Norris Russell of Princeton, the acknowledged leader of American astrophysics. When I had finished my presentation he asked a few searching questions. He was convinced and became my most effective propagandist.

Of course, not everyone was convinced. Some wanted experimental proof. Stanley Livingstone, who was then at Cornell, had built a small cyclotron. He ran an experiment bombarding carbon with protons. He quickly saw evidence of the formation of ^{13}N from the resulting radioactivity. Later, Willy Fowler and Charles Lauritsen of Caltech ran a more complete experiment and produced helium from continued bombardment of carbon with protons. Because of this experiment, I went down to Pasadena after teaching summer school at Berkeley. This led to a long friendship with Fowler and an association with Caltech that only ended recently when I could no longer travel.

Of course, I wrote up my discovery and submitted it to the *Physical Review*. Before it appeared, however, a very advanced graduate student Robert Marshak came to me. Marshak already had an M.A. from Columbia and now wanted a Ph.D. He already knew quite a lot of physics but, more importantly for me, knew a lot about money available from prizes. For example, he knew that the New York

Academy of Sciences was offering a prize for the best original paper on energy production in stars. Because the paper could not have been previously published, I withdrew my write-up of the CN cycle from an understanding *Physical Review* and submitted it to the Academy for consideration. Once the prize, $500, was safely in hand, I resubmitted the article, but this delayed publication until 1939.

The prize was very convenient. I gave $50 to Marshak as a “finder’s fee.” The reason he had known about all these sources of money was his own poverty at the time, and he found this fee very welcome. Another $250 was used as a “donation” to the German government to secure the release of my mother’s goods because she had finally decided to emigrate.

As an aside, Marshak was interested in astrophysics. I suggested he look into white dwarfs, the final phase of the life of fairly small stars, from about one to about eight solar masses. His thesis was excellent. Years later, the Caltech white dwarf specialist told me that it still (then) served as the basis of all understanding of this type of star.

But the trip to Pasadena in 1940 was the end of my involvement in astrophysics for a long time. First, World War II intervened, and after the war, for many years I concentrated on nuclear physics.

5. THE NOBEL PRIZE

5.1. The News and Preparations

On Tuesday, October 11, 1967, the phone rang at about six in the morning. This was about an hour and a half before my normal time to get up. It was a phone call from a Swedish journalist who told me that I had been awarded the Nobel Prize in Physics that year. The stated work for which I was being awarded the prize was the discovery of stellar energy production mechanisms. This, of course, made me very happy.

The phone never stopped ringing that morning. If it wasn’t friends or family calling with congratulations, it was journalists wanting to know how I felt. My brother-in-law, who was visiting from England, was afraid that World War III had started and that it was the government calling so often. My wife was sleeping blissfully in another room. She finally woke up around 7:30 A.M. I had just enough time to tell her what had happened before the Swedish reporter Mr. Feldkirch arrived to film my day. At about the same time, a call came, which Rose answered. It was from the University wanting to know whether they could schedule interviews and a reception. Knowing my dislike of disruptions of my normal schedule and still half asleep, she responded, “Okay. The day is shot anyway.” This answer made the local news, and she had to live with it for a long time.

The next two months were among the happiest of my life. It was a perpetual fair of congratulatory letters and telegrams from a great many people, including a number of Bethes who wanted to claim a relationship. Some also had plans for spending the prize money! Among the preparations for the trip to Sweden, I did something for the first—and only—time in my life: I accompanied my wife clothes shopping. She needed formal dresses for several occasions including the Prize ceremony and a dinner at the palace, and warm clothing for daytime wear while we were there: unexpected complications of winning the Prize.

The other complication was that I felt a need to catch up on the developments in astrophysics. I had not looked at the subject for nearly 30 years, and among other duties, the prizewinner is expected to talk about the prizewinning topic. Most of the time not spent in various aspects of setting up the trip was spent boning up on stellar energy. I felt like a student cramming for an exam.

5.2. The Trip

On December 6, 1967, Rose and I were joined by our son, Henry, for the flight to Stockholm. Our daughter, Monica, who lives in Japan, would join us from there, and my stepmother, Vera, would come up by train from Germany. The Nobel experience is amazing and unforgettable. The SAS crew on the flight cosseted us. Despite a very full schedule, and attention to minute details of protocol, I never felt hurried but felt continually wrapped in comfort and a sense of my own importance. From the moment of departure to the moment of return to native soil, initiative was taken out of my hands in such a kindly way that I could just relax and enjoy.

Upon arrival in Stockholm, we were met by Mr. Rydberg of the Nobel Foundation. A very nice young man and an equally nice young lady who were assigned to make our time in Stockholm as easy as possible accompanied him. A batch of reporters also greeted us. After a fairly brief press conference—the first of many—we were whisked to the Grand Hotel in downtown Stockholm. We were given a portfolio of instructions and schedules. Both Rose and Henry were asked whether they had any special desires. Henry's request to play some bridge was arranged through the good offices of the columnist for one of Stockholm's newspapers. Rose's interest in sex education in Swedish schools was also satisfied.

The first three days were occupied with acclimating ourselves to Stockholm, renting necessary formal clothes for both Henry and me and attending various luncheons, receptions, and news conferences. Some of these conferences were fairly impromptu. We had rooms on the third floor of the hotel. My wife and I shared a suite, and the others had single rooms elsewhere on the floor. Between our rooms and Henry's was another suite. One morning Henry was awakened by a clamor on the staircase, which was directly outside our room and his. He peeked out of his room and saw about half a dozen reporters camped on the landing. Out of the middle room, a well-known actor appeared looking annoyed at the noise. He, it turned out, was in Stockholm for the local opening of his latest movie. "Oh no, sir," said one of the reporters, "we don't want you. We were hoping to see Dr. Bethe." Stockholm during Nobel week must be the only place in the world where this could happen.

The nicest of the various affairs during the run-up to the ceremony was lunch at the Nobel Foundation. Among other topics of conversation, Mr. Rydberg told me something of the selection process. Perhaps the most interesting to me was the reason that I was the first to be honored for work in astrophysics. Nobel's wife, he told me, had run off with one of the leading mathematicians and astronomers of the time. So the Prize bequest had specified that the work honored had to have practical application and that neither pure mathematics nor astronomy could be considered. Otherwise, Nobel feared, this man would have been one of the first winners. In addition, Nobel had specified that the work must not have weapons as the primary application. Until peaceful fusion power was at least a glimmering hope, stellar energy production could not be honored. Unfortunately, peaceful fusion power is still at best a very distant glimmering hope.

Another unexpected but charming event came one morning when we were awakened by three very pretty young girls clad all in white except for a crown of lit candles. They were singing a song, the only words of which that I can remember were "Santa Lucia" and offered us a choice of glögg, a warm spiced wine, or hot spiced cider. If I had had three young blonde daughters, I surely would have taught them this particular custom.

There were other planned events during the three days leading up to the ceremony. There was a luncheon at the American embassy for the three American prizewinners of the year, and a cocktail reception at the German embassy for the two Germans. The "other" German, Manfred Eigen, was an extremely nice young chemist who later became a Distinguished Visitor at Cornell. The Germans were now proud to claim me, as they had not been in 1933.

I also visited the Swedish Atomic Energy Commission. They were very proud of their plans for nuclear power plants to supply Sweden's energy needs. They stopped building them a few years later, and I wonder now how they hope to replace the power as those plants reach the end of their useful lives.

5.3. The Prize Ceremony

The prize is always given on the evening of December 10. Of course, evening in December in Stockholm is a misnomer. The sun never really gets very far up, and by 2:30 or 3 in the afternoon the sun has set, the lights are on, and it is cold and dark. So, in the early evening, perhaps around 4 P.M. or so, we were taken to the State Theater for the ceremony. This is a huge room with 1000 or more seats on the main floor and three balconies besides. The laureates and their introducers sit on the stage under the watchful eye of all the spectators and Swedish television. The families of the Nobelists and royal sit in the front rows.

Everyone is seated, then they rise as the blare of trumpets announces the King's arrival. Each winner is then announced by a short speech given in Swedish. The winner then walks down off the stage, is met by the King who hands over the medal, and then must back away to return to his seat on the stage. I found this last action by far the hardest part of the trip.

When the last of the prizes, literature, has been given, the entire crowd takes a short walk from the theater to the town hall. There, dinner is served in a gilded ballroom. The royal entourage, the prizewinners, and spouses are seated on a raised platform. Protocol puts the physicist's wife on the King's right and the writer's wife on his left. Because that year the literature laureate's wife spoke only languages in which the King was not fluent, Rose had a pleasant conversation throughout dinner. They talked mostly about Etruscan graves: Rose and I had visited some of the archeological sites, and the King had done some of the archeology. Hers was certainly the most interesting of the dinner conversations that any of us had. My own companion was an elderly princess. I hope I entertained her adequately.

After the dinner, each of the laureates had to "sing" for their supper with a short speech. I remember little about any of them except that George Wald, an American biologist, gave the funniest. He said the life of the biochemist was getting to know molecules, first small molecules, eventually bigger and more complicated ones. The most important thing is to remain friendly with the molecules.

When dinner was over, the party moved to the room next door where there was dancing until the wee hours. I even had a dance with Rose and another with my daughter.

5.3.1. OTHER EVENTS We stayed for two more days. On Friday morning there was a television show arranged by Mr. Feldkirch with the three Americans, one of the English winners, and the Swedish winner. It was surprisingly enjoyable. In the afternoon, I gave my Nobel lecture at the Swedish Academy. In the evening, Rose and I went to a quiet dinner at the Royal Palace with the other laureates, their wives, and a few members of the royal family.

On Saturday, Rose and I went to Uppsala, home of the oldest university in Sweden. I would have liked to see Uppsala in June. In December, the trip gave us a real taste of Sweden in winter: damp, dank, and dark. Stockholm, however, had not really made us feel this way because the snow and bright street and building lights made the whole city look like a Christmas decoration. I gave my Nobel lecture again.

In the evening, the physics students at the University of Stockholm hosted us for dinner. This was a joyful affair. I was initiated into a number of Swedish customs. One that I remember is that a person must not drink wine alone. First, a man must find a woman and invite her to share the drink by looking deep into her eyes. At the time, this had to be initiated by the man. I wonder whether gender equality has extended to this custom as well. I was also initiated into the Order of the Frog. I have no idea why the frog, but I still have the ceramic frog among my Nobel souvenirs.

On Sunday, we sadly boarded SAS for the trip back to the United States.

5.4. Speeches

Nobel Laureates are expected to give a speech about the work that led to the Prize, first to the Royal Swedish Academy, then repeated at one or more universities. I found this a fairly forbidding prospect because I had not looked at astrophysics for almost 30 years. As I studied, I decided that my lecture would only be interesting if it covered the developments in the field that resulted from understanding stellar energy production. The CN cycle is by now high-school physics!

5.4.1. PREPARATIONS Fortunately, Ed Salpeter had kept up and was able to direct my reading during the available two months. The first thing I reviewed was nuclear reaction rates. The proton-proton reaction that is dominant in the sun increases in proportion to approximately the fifteenth power of core temperature. The CN cycle, however, increases much more rapidly in rate, in proportion to approximately the twentieth power of core temperature. The core temperature is essentially dependent on the mass of the star, so for most stars significantly larger than the sun, the CN cycle becomes the dominant method of energy production. The exception is very, very old stars that started life with no carbon and thus could only utilize the proton-proton reaction.

As long as there is a significant amount of hydrogen in the core, conversion of protons to α-particles will be essentially the only source of the star's energy. The length of time it takes to consume the hydrogen depends on the size of the star and the core temperature. The sun will last ~10 billion years altogether. It is ~5 billion years old now and has converted approximately one half its original core hydrogen to helium. Larger, hotter stars use up the hydrogen much more quickly.

When the supply of hydrogen is exhausted, there is no longer radiation pressure to maintain the size of the core, and the core begins to fall in on itself. It becomes denser and more compact. The density will increase from ~100 g/cc to ~10^5 g/cc. The in-fall of the core releases gravitational energy; this was proposed in the mid-nineteenth century by Helmholtz and Kelvin as the source of stellar energy. The energy flows to the surface of the core. At the surface, there is still hydrogen, which is heated to a temperature sufficient for the proton-proton reaction to occur. The energy produced at the surface needs an escape route. To accommodate this, the outer portions of the star expand and dilute; the star becomes a giant with a radius many times that of the original star. The surface temperature declines substantially because it is so much further from the energy source, and the star becomes red in the visible spectrum, a red giant.

The giant star gradually loses mass from its surface where the gravitational attraction is small. Paczynski studied this. He concluded that the giant stage continues for a long time, with the primary energy source, the CN cycle, in the shell around the core. Some of this shell is carried outward by convection and eventually escapes, thus forming clouds outside the star. Clouds have been observed near red giants that contain an excess of nitrogen relative to carbon and oxygen, a useful confirmation of the CN cycle.

In these giants, the core at the time of collapse consists primarily of α-particles, carbon, nitrogen, and oxygen. There is an abnormally high amount of nitrogen involved in the CN cycle. The collapse of the core increases the temperature. At about 100 million degrees the nitrogen begins to react with α-particles and much is converted to carbon or oxygen restoring the normal relative abundance.

The core continues to contract and increase in temperature, and at about 130 million degrees three α-particles will start to combine to form carbon nuclei, thus bridging the atomic-weight-8 gap.

All stars undergo a transition to a red giant when the core hydrogen is used up. In this transition, the core contracts and the outer part of the star expands enormously. The core contraction heats the core. If the core is large enough, the temperature will get high enough for helium to combine to form carbon. The star uses up its helium also, leaving a core remnant that is almost completely carbon and oxygen. For most stars, a helium or carbon-oxygen core is the end of the road. The hydrogen surrounding these stars drifts away, leaving a "white dwarf," which is luminous because of the residual heat of the core. In larger stars, the heat generated by the contraction of the carbon-oxygen core reaches temperatures sufficient for the carbon and oxygen to combine and eventually form iron. (Interestingly, even now, with much better observation facilities, very few iron white dwarfs have been seen.)

Hertzsprung plotted the relationship between the size of stars and their absolute luminosity (Figure 1). The long line sloping down and to the right is the so-called main sequence. The fairly flat line that breaks off about half way down is the stars burning helium. So, I learned that understanding the way in which stars produce energy had indeed allowed astrophysicists to understand the life cycle of stars and to explain many observed phenomena.

6. RETURNING TO ASTROPHYSICS

After winning the Nobel Prize, I again abandoned astrophysics for a number of years. There was a brief excursion in the spring of 1970 when I collaborated with Baym and Pethick, both thermodynamics specialists, on a paper discussing the structure of neutron stars. But after it was done, I returned to nuclear physics.

In 1975, I retired from Cornell. At the retirement party, Gerry Brown came to me and suggested that we collaborate. Unfortunately, this had to wait a few more years, as I was deeply involved in the energy crisis at the time. Finally, in April 1978, both Gerry and I were in Copenhagen. "This year we will do supernovas," he said, starting an effort that would last two decades.

6.1. Phenomena

From time to time, bright objects suddenly appear in the sky, remain bright for a few months, then gradually fade away. These are called supernovae. Close supernovae are fairly rare events. Tycho Brahe and Johannes Kepler observed two around 1600 and kept careful records. The Chinese observed about ten previous supernovae, including one around A.D. 1000, another in 4 B.C. Baade and Zwicky rediscovered supernovae in the twentieth century. There is now a systematic search for supernovae, organized by the University of California at Berkeley. Approximately 50 are seen annually. It is estimated that a large galaxy like the Milky Way has about two each century.

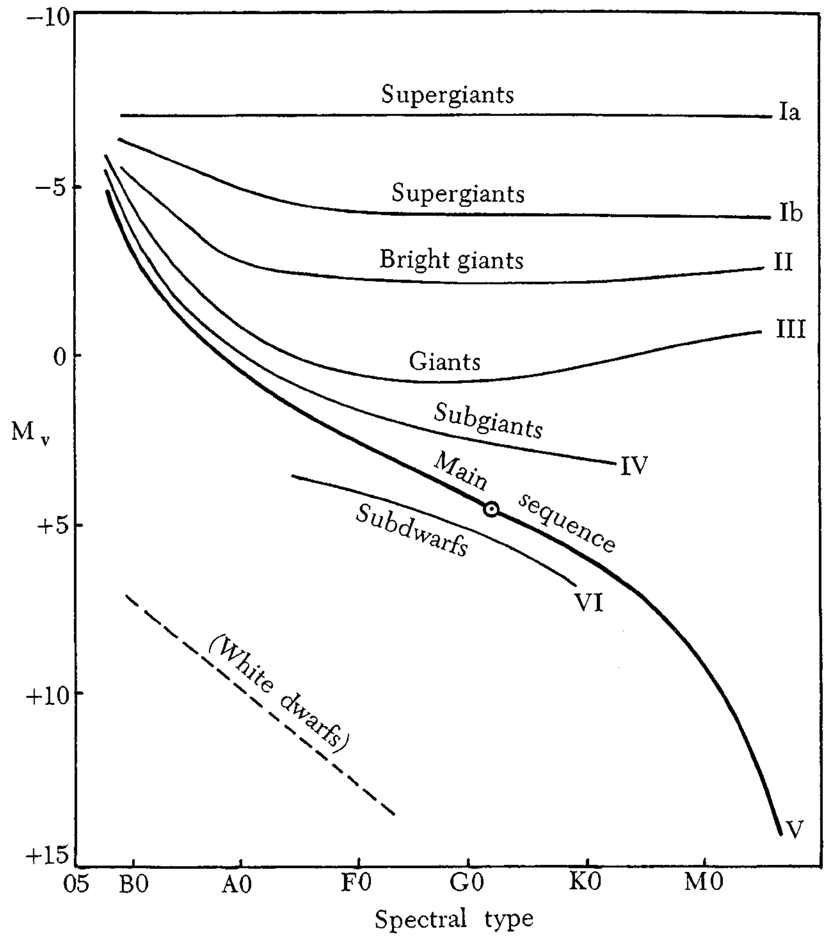

Figure 1 Spectral classification and the Hertzsprung-Russell diagram. M_V: visible magnitudes (by astronomical definition).

There are two types of supernova: Type I does not show spectral lines of hydrogen; Type II does. Type II is much more common. It is the type that Gerry proposed we "do."

Type II supernovae are the funeral pyre of massive stars. In a final conflagration, the supernova radiates approximately 10^{51} erg, about equal to the lifetime output of the sun over 10 billion years. This energy release is called a foe, which stands for (10 to the) 51 ergs.

The basic phenomena of the supernova were already known. When most of the helium has been consumed to make carbon and oxygen, there is no longer any source of energy in the core. The core collapses (again). This time, heavy nucleus formation continues until the core consists almost entirely of iron. Interestingly, probably almost all matter in the universe has gone through at least one supernova. We know this because iron is the most abundant element after hydrogen and helium.

The collapse and the formation of iron produce a great deal of energy, a small amount of which escapes to produce the visible supernova.

6.2. First Efforts

On April 1, 1978, I arrived in Copenhagen from a trip to Turkey. I had been working with increasing frustration on pions at the time. During our visit to Turkey, Rose and I had walked up Mount Pion, and I had sprained my ankle. Gerry Brown met us at the Copenhagen airport, heard this, and suggested that it was a message from the gods that it was time to change subjects. I left Rose to unpack and went to the Bohr Institute. On my desk, Gerry had put the existing literature on the core collapse of massive stars. I quickly found what I thought was an error. At the time, the consensus was that the core collapse ended when the core density reached about 10% of nuclear density. I did some calculations that convinced the two of us that the collapse continues to densities well in excess of nuclear density. Only then is the pressure repulsive and sufficient to stop the continued collapse.

We quickly wrote a paper showing the calculations and convened a hasty mini-conference in Copenhagen to discuss the result. The paper (and the conference) was a success, and Gerry and I were launched on our astrophysical career.

What we were really interested in, however, was the mechanism of the spectacular stellar explosion. Gerry and I went every year to Caltech (or some other sunny spot in California) for the month of January, and every year we would slightly revise our analysis of this bang. Every year, Gerry would return to Stony Brook and involve an associate in improving the computer model to see whether it would "explode," and every year it failed. There were several other groups working on the problem, notably Jim Wilson and associates at Lawrence Livermore and Stan Woosley at the University of California at Santa Cruz. None of them could get their models to explode either. By 1985, we thought we knew enough to write a "popular science" version of our results. It appeared in *Scientific American* in May that year.

We knew a number of things. The initial mass of stars, known as **z**ero-**a**ge **m**ain **s**equence (ZAMS), that become supernovae is at least eight times the mass of the sun ($M_\odot$). We knew that smaller stars that become supernovae, up to about ZAMS $= 15\ M_\odot$, leave a neutron star as a sort of tombstone. We knew that the maximum mass of a neutron star is $\sim$1.5 $M_\odot$.

It is possible to calculate the amount of gravitational energy released in the collapse to a neutron star. It is $\sim$400 foe, $\sim 10^{54}$ ergs, a prodigious amount of energy. The nuclear binding energy is $\sim$20 foe. The visible released energy is $\sim$1 foe. The balance of the energy is stored as thermal energy of electrons and neutrinos trapped in the neutron star. Approximately 300 foe escape in the form of neutrinos during the next minute.

6.3. 1987A

In January of 1987, Gerry and I decided to abandon the supernova explosion. We felt that there was no more to do without some observations. The last observable supernova explosion had been almost 400 years earlier. He and I began some other, nonastrophysical work. As we parted, Gerry said it was time for an observable, nearby supernova. As if responding to our request, on February 23, 1987, one appeared in the Southern Hemisphere sky a mere 150,000 light years away. This supernova became known as 1987A. One of my great regrets is that I could no longer go in person to look at it.

In any case, it came at just the right time. Like us, almost all the groups looking into supernovae had reached a dead end. However, the tools for good observation were only recently in place. Two neutrino observatories, one in the Pittsburgh Plate and Glass Mine in Ohio and Kamio-kande in Japan, both reported seeing extra neutrinos at just the right time. All sorts of telescopes, any that could be, were immediately trained on the supernova. Reports of the observations came quickly. The observations both confirmed much of what we had surmised and contained surprises.

The greatest difficulty for theorists has been to convert the rapid collapse of the core of the original star into the rapid expansion of the outer material in a supernova. By 1990, many of us who were working on the problem had concluded that convection plays a major role in the process. The observations of 1987A seem to support this idea. The best formulation of this, in my opinion, was by a young physicist, Herant. With Benz and Colgate, he showed that convection could actually transport energy from the surface of the core outward in approximately the necessary amount. He did not, as far as I know, tackle the problem of getting the energy from the core to its surface. Supernova theorists produced many papers to explain what had been seen. Jim Wilson and I proposed that neutrinos and radiation carry energy from the core to the surface.

Notwithstanding the further insights into the mechanisms of the supernova gained after 1987, as far as I know no one has built a model that "explodes." So there is still work to be done.

Another aspect of the supernova that still needs to be explained is the so-called rapid (r)-process. Supernovae are the only possible source of elements heavier than lead. We find them in nature, so we know they must be made. The slow (s)-process explained by Margaret Burbidge, Geoffrey Burbidge, Willy Fowler, and Fred Hoyle explains most of the creation of the majority of the elements between iron and lead. Some of the known isotopes of these elements could not have been produced by the s-process and must come from the r-process. I have explored this from time to time, occasionally with great hope that I have had an insight, but each time I have proved myself wrong.

In any case, Gerry and I worked for about nine more years on supernova theory, producing various interesting results, but never a model that exploded.

6.4. Gravity Waves and Binary Pairs

By 1995, after 17 years, we had again exhausted our capacity for new insights into the supernova. During our annual visit to Caltech in 1996, Kip Thorne asked us for help. He was, and is, working on LIGO (Laser Interferometer Gravitational-wave Observatory), an apparatus designed to detect the gravity waves predicted by relativity theory. He wanted to know how often he might get a detectable event. The most promising source is the merger of similar-size massive objects. Several people had developed estimates for the frequency of the merger of two neutron stars. Kip asked us to look at mergers of small black holes with neutron stars.

"You guys," he said, " are very good at calculations of things that nobody has ever seen." This was a nice problem. Within a fairly short time, we were able to show that such pairs are much more common than neutron star pairs. By the time Gerry and I were finished with the paper, we were able to promise Kip that, instead of a couple of waves a year, he would be able to detect a few per month.

This work led to a more general interest in binary stars. Over the next few years, Gerry, with some assist from me, looked at various types of pairs. We looked at large black hole–neutron star pairs. We looked at white dwarf pairings with neutron stars. We looked at X-ray and γ-ray burst black hole systems. Most recently, we have been exploring the effects in binary systems of a small companion within the envelope of a massive giant star, i.e., common envelope evolution.

7. CONCLUSION

I have now spent over a third of my working life, the past 24 years plus brief periods before that, working in astrophysics. It has been a true joy trying to understand and explain the rarely or never-seen phenomena of the universe. I thank friends and colleagues who shared insights, results, inspiration, and mental perspiration. I especially thank Gerry Brown for his unwavering support. Without him, I would never have begun, or continued, the scientific journeys I have taken in this quarter century.

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