Chapter 11. **The Astronomy of Radioactivity**

Important family decisions pressed when my family and I returned from London to Houston in September 1967, just prior to the beginning of classes. To allow search time for a residence we stayed in a long term residential hotel near Texas Medical Center. For the first time we felt justified in looking at homes for sale rather than for rent. I had just been promoted to Associate Professor and my nine-month salary was increased to $15,000. Donald and Devon were both of required school age by this time, and from conversations we had come to favor Poe Elementary School in the Southampton neighborhood just north of Rice University. Our great luck was that an elderly couple at 2346 Tangley Street, rather central in that block between Greenbriar and Morningside, had decided to sell and move. It was perfect! After our summer in Great Wilbraham we were relieved to find another home that all four of us could love. At $23,500 it was easily within reach by mortgage. It was ours. Within a month we took possession and the boys were in nearby Poe Elementary. The school and district reminded me so much of University Park Elementary that I was extremely comfortable with this. I purchased bicycles for the boys and coaxed them toward that decisive moment of bravery when I would lift my hand from the bicycle while running alongside on Tangley Street. There is no substitute for the experimental physics of learning that the bicycle is much more stable while rolling than at rest. I would learn some things relevant to myself during the decades to follow from the sentimental lifelong attachment to this house made by Donald, who was seven years old when we moved into the Tangley house. Repeated evidences of that attachment during the next four decades of Donald's life stimulated me somewhat to revisit my own sense of loss of my childhood homes. A curious cultural coincidence was to be the featuring of Tangley Street as the set in the movie *The Evening Star* which was the sequel to *Terms of Endearment*, the final part of Larry McMurtry's Texas trilogy, coming after *Moving On* and *All My Friends Are Going to Be Strangers*. Larry McMurtry and I had become friends in 1965 when both of us were faculty associates of Brown College of Rice University and he was teaching creative writing. His easy going speech was just perfect for his appearance and writing style. Several Rice faculty members provided character models for characters in Larry's trilogy.

Looking for Radioactivity

Bob Haymes was taking graduate students into his research program in gamma ray astronomy at Rice University. Bob's design of a shielded sodium-iodide crystal as detector[4], pointed by an active collimation shield that defined its angular aperture, was very successful and was copied by many subsequent instrument makers. Because the scientific objectives for detecting radioactivity in the galaxy relied on nuclear astrophysics and nucleosynthesis, Bob naturally asked his research students to enroll in my course, *Stellar Evolution and Nucleosynthesis.* Now returning from my year away at Caltech and Cambridge I found a robust enrollment awaiting me. Two of these students were to become among the most significant colleagues of my career. Several were students in Bob Haymes's program. One of these, Jerry Fishman, was destined for great success in this field. His attendance in my class led to one of the important serendipitous stimulants to my research career. And Stan Woosley, who became my own research student, taught me more than any other student of my career. Both later earned fame as scientists.

Several issues about gamma-ray astronomy need to be understood. Firstly, it means different things to different people. Gamma rays arise from many different physical mechanisms giving them differing ranges of energies. The gamma ray is akin to light and X rays in that all are fundamental quanta, particles with no rest mass, each being an excitation of the electromagnetic fields. Each is a bundle of electricity and magnetism tied into a knot by the laws of physics. Those natural processes that create the most energetic quanta differ from those that create less energetic ones. Gamma rays are the most energetic of these quanta, those that are broadly speaking too energetic to be useable in an optical system. Optical systems rely on the wave properties of the quanta. They focus quanta, or diffract them into members having differing wavelengths. Gamma rays are too energetic for that.

Secondly, the flavor that my research was to give to gamma-ray astronomy at Rice University was a focus on radioactivity. A radioactive nucleus has too much internal energy, with the result that it is excited by extra motions that are not required. It may shed this extra energy by creating a quantum of electromagnetic energy, a gamma ray. The gamma rays created in this way possess energies in the range 0.1 million eV to about 10 million eV. The eV is the energy range of ordinary light, so a million eV, written MeV for short, is a million times more energy than a light quantum.

Thirdly, if Haymes' gamma-ray astronomy detector was to detect such gamma rays from the galaxy, it is necessary that the galaxy contain radioactive nuclei. My own scientific thrust focused on the processes that maintained radioactive nuclei in the galaxy. Because each radioactive nucleus is characterized by a halflife, that time during which half of a collection of them will decay, simple reasoning shows that they should all be gone today. Consider that the main radioactive nucleus that our work would expose was ^{56}Ni, having halflife of 6 days, and that the average age of a stable nucleus is about 10 billion years. Clearly, no ^{56}Ni nuclei remain unless some were very recently created, within the past few weeks. My work focused on the creation of that "new ^{56}Ni". Finally, the radioactive nucleus must emit a gamma ray if it is to be detected from afar.

On the heels of publication with Bodansky and Fowler of our quasiequilibrium description of silicon burning, the nucleosynthesis process that creates the ^{56}Ni, I naturally gave that process a lot of emphasis in the nucleosynthesis portion of my course during spring semester of 1968. I created several problems to assign to the students and explanations that made their way into my textbook. One day I was describing the nuclear reasons for a most fascinating transition on which much was to depend; namely, at atomic weight 40 and below, the most abundant A=4n isotopes are all stable against radioactive decay and are found on earth. These include ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca, which are respectively the most abundant isotopes of silicon, sulfur, argon and calcium; but at atomic weight 44 and above, the most abundant A=4n isotopes are all radioactive so that they are not found on earth. These include ^{44}Ti, ^{48}Cr, ^{52}Fe and ^{56}Ni, which are respectively the most abundant species at those atomic weights, but which subsequently decay by positron emission (positive beta decay) to stable atoms ^{44}Ca, ^{48}Ti, ^{52}Cr and ^{56}Fe. Those decays have become today the celebrated sources of the most abundant isotopes of titanium, chromium and iron. The reason for this transition between stable nuclei and radioactive nuclei is a subtle nuclear conspiracy involving the law of nuclear masses, which are determined by details of nuclear structure and which also are influenced increasingly by the Coulomb repulsion within the larger nuclei. The mutual electrical repulsion of the positively charged protons renders their binding energy less than that of the neutrons, which experience no electric force. Consequently the most stable nuclear structures are those having more neutrons than protons. For example ^{56}Fe is more stable than ^{56}Ni, which has equal numbers of protons and neutrons, so that ^{56}Ni must decay to ^{56}Fe. But the silicon burning quasiequilibrium does not have enough excess neutrons to create ^{56}Fe, so it must create radioactive ^{56}Ni instead. I became fond of saying in class, in colloquia and in writings, "Iron is a radiogenic element." And for analogous reasons the abundances established by the silicon-burning quasiequilibrium are of stable nuclei in the lower half of atomic weights and of radioactive nuclei in the upper half.

I had been explaining all of this in Space Physics 551. After this class one of Haymes' graduate students, Jerry Fishman, approached me to ask,

"Do those radioactive nuclei emit gamma-ray lines?"

"Probably, but I never looked" I replied. "Let's go check it out."

My mind raced as Fishman and I walked back toward my office in our newly constructed building, Rice University's *Space Sciences Laboratory*. Because these nuclei were explosively ejected by the thermonuclear explosion, the radioactivity within the rapidly thinning ejected mass would rather quickly be able to be seen from the outside. This might be the idea that I had long awaited, the idea better than the *Californium hypothesis*.[2] Jerry Fishman, on the other hand, was very aware of my paper with Wade Craddock because that paper was serving as a motivating target for the attempt to detect gamma-ray lines from radioactive nuclei, even though I had made known my skepticism about the Californium hypothesis upon which it was based. Haymes's detector was mounted on a gondola[4] that dangled from the high-altitude balloons that were Bob's space vehicles in the 1960s. One must get above the atmosphere to detect gamma rays from astronomical objects, because the gamma-ray photons, gamma rays being simply photons but photons of very high energy, interact so strongly by colliding with the atoms of the earth's atmosphere that they can not reach the ground. The gamma rays collide both with the atomic electrons of the air atoms and also with the concentrated charge of the atomic nuclei, in the presence of which they transform into a electron-positron pair, a particle and its antiparticle. The experimental situation is very rich, and Jerry Fishman was busy learning all that Bob Haymes had to teach him on that subject.

In my office I took Viola's compendium of nuclear energy levels and decays from my shelf and turned impatiently to ^{56}Ni. There it was, loud and clear. Almost every decay of ^{56}Ni was accompanied by gamma rays having special energies that identify the ^{56}Ni decay. At the blackboard I calculated that if a supernova ejects a mass of ^{56}Ni that I estimated to be equal to $1/10^{th}$ of the mass of the sun[1], that object would be detectable by Haymes' gamma-ray telescope as gamma-ray lines of energies 0.847 MeV and 1.24 MeV. My feet practically left the floor! Jerry was also excited by our discovery.

"Would you like to work on this with me?" I asked him. "It will definitely make a publishable paper."

"I sure would", Jerry replied.

So it was agreed. I loaned him Viola's book and asked him to check for detectable gamma rays from all of those nuclei between atomic masses A=44 and A=62 that were prominent in the quasiequilibrium. And I gave him a copy of my paper with Bodansky and Fowler so that he could read more of its details. In those pre-internet days that now seem as if from the dark ages, the only way to share a paper not yet out in the journal was to give one a copy of it. Fortunately I had several copies from Fowler's mass-reproduction system that mailed out preprints bound in orange covers, preprints that he, in a typical Fowlerism, named *Orange-Aid Preprints*. So Willy had given me five copies, and Jerry got one of those.

As it always was with me, my mind could not quit thinking about this discovery during that evening. At dinner I shared it with Mary Lou and the boys. Later I focused on a special peculiarity of great discovery as it occurred several times during my life. Why had it taken me so long to think of this, needing Jerry's question after class to prod me? Why did it take me so long despite the fact that I had been seeking this moment since my paper with Craddock in 1965 that first brought the idea of testing nucleosynthesis by detecting gamma-ray lines into print? I had begun work on the quasiequilibrium in winter 1966 at Caltech, and I had continued it through the Cambridge spring and summer of 1967. I had convinced not only Willy but also Fred Hoyle that their *e* process was wrong, that iron and chromium and nickel were synthesized as radioactive progenitors during silicon burning without the large number of excess neutrons that their *e* process required. Why had I not taken one more step to this new and beautiful opportunity? At the time I felt somewhat inadequate for having taken so long. Later I realized that new scientific ideas happen like that. The discoverers who always seem so brilliant to the world at large have in fact pounded their heads against a puzzle for a long time before finally discovering the intensely satisfying resolution. The human brain, at least my own, focuses on the ideas that motivate daily activities. My science life experienced so much excitement in the 1966-68 time span that my brain was always focused on the next task of its flow. My attention had been diluted by so many issues that were not science but rather my scientific life. I had not been sitting around for two years asking repeatedly where I would find the new and better hope for testing nucleosynthesis with gamma-ray lines. There are always so many new questions. It is only in retrospect that I, and I suspect almost all discoverers, can say, "I should have seen it sooner." Inventors may make a new invention in a flash, but scientists conceive a new idea only slowly, burdened by the weight of skepticism that is the scientific method, burdened by having to understand all that has gone before in order to understand what is truly new.

Jerry Fishman and I worked fast. We had all of the decay schemes mapped out within two weeks, and I had turned my attention to the question of whether the gamma rays can get out of the supernova so that they might be detected from outside. While the quasiequilibrium is being established after the heating of the supernova event, the matter lies deep within the structure of the expanding postsupernova star. The overlying layers of supernovae are completely opaque to gamma rays, vastly thicker than the earth's atmosphere which is itself sufficient to prevent gamma rays from reaching ground. The ^{56}Ni halflife is only 6 days, but it first decays to ^{56}Co, which is the nucleus whose decay to stable ^{56}Fe is the one accompanied by the 0.847 MeV gamma ray. The ^{56}Co halflife is 77 days, so even 77days after the explosion half of the initial ^{56}Ni still remains alive in the form of ^{56}Co. After 154 days, one quarter of the initial supply would remain. These exciting ideas and numbers encouraged my optimism. The surface layers of the supernova expand into the near vacuum at speed near 10,000 kilometers per second, so the amount of mass along a line of sight might decline sufficiently rapidly to allow escape of gamma rays. Each interior layer expands more slowly than the surface in proportion to their distances from the center, so the quasiequilibrium radioactivity might, I reasoned, expand at 2000 km/sec. This is still very fast. But supernova models were primitive in 1968, so that I felt that this Type II supernova was too much in doubt. Fortunately, most of the ^{56}Ni might be formed instead in an exploding white dwarf star, the structure Fowler and Hoyle had suggested for the Type I supernova. So we decided to focus on that small Type I object for our paper. Type Ia supernovae remain today the brightest prospect.