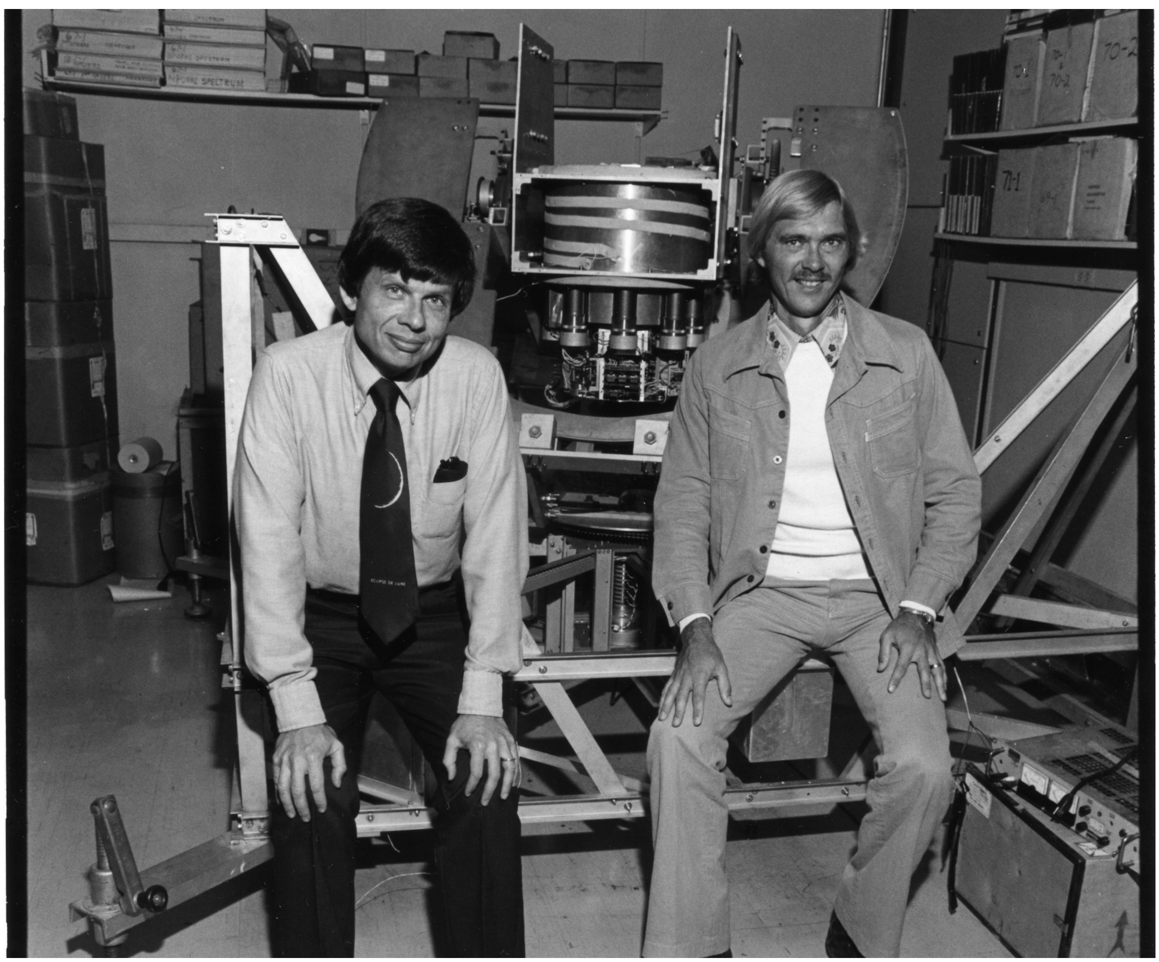
Astronomy with Radioactivity: Gamma Rays

During my first academic year at Rice we recruited another new faculty member, Robert C. Haymes. This portended very good luck for me. For his thesis from NYU Bob had been detecting neutrons in the earth's atmosphere, and he arrived with the idea that he might detect gamma rays arriving from outer space. This change of thrust was supported by the faculty, although some favored instead continuing work on atmospheric neutrons. One fateful day Bob approached me with a stimulating question:

"Does stellar nucleosynthesis produce sources of gamma rays by ejecting radioactivity?"

This was a pregnant question. I described a theoretical idea of supernova explosions that produced transuranic elements via the *r* process, which by its very nature must be explosively ejected from the sources in order that the *r* process work properly. Radioactivity from the main line of nuclear fusion reactions, on the other hand, was thought at that time to decay within the star's deep interior, rendering it unobservable. I happened to be preparing a paper defining the dynamics of the *r* process for publication at that very moment, continuing the project started with Fowler and my Caltech classmate, Phil Seeger, at Caltech; so I gave Bob a rundown on its ideas. I described how Burbidge, Fowler and Hoyle had even speculated that the transuranic radioactivity produced by the *r* process might be the cause the slow, roughly 60-day, decline of the optical light after supernova events, as first recorded by Chinese astronomers in the year 1054. Burbidge, Fowler and Hoyle suggested that a newly created isotope of the element californium was responsible. The transuranic elements Neptunium, Plutonium, Americium and Curium, elements not found on earth but that are known from nuclear properties to be created by the intense neutron burst that is the *r* process, subsequently decay to isotopes of the elements Uranium and Thorium, which are found in terrestrial rocks and which also decay but over much longer geologic times to the heavy metal lead. Among my notes at Caltech I had gone so far as to calculate the energy input today to the *Crab Nebula*, the remnant of that 1054 explosion, owing to the energetic alpha particles that are emitted into the nebula by such radioactivity. I had hoped to explain the hints of apparent acceleration of the speed of expansion of that remnant, as suggested by time-lapse photography by astronomers; but I gave it up as probably too small. What had not yet occurred to me was to calculate the gamma rays given off. Gamma rays pass easily through dilute matter, so they could not heat the remnant, but by the same token those gamma rays travel at the speed of light through the interstellar matter of our galaxy to us. That very evening I did a hand calculation at home to show that if the amount of radioactivity was as great as would be required in order to qualify as a sufficient energy source for the 60-day decline of the optical light it would also be capable of producing observable gamma rays at earth. This excited me, perhaps providing the new direction that I felt I should seek. .

I gave this news to Bob Haymes and asked him if he could detect a rate of arrival as small as one gamma ray arriving per square meter each second. That rate of arrival per fixed area is called *the flux of gamma rays*. That was the expectation that I had calculated the night before. I was astonished that Bob thought that his detector could do that, so I asked for a description of his detector system. When he did so it seemed that it might just work! But my calculation needed more careful bookkeeping of its details. In particular, these gamma rays would arrive having very specific energies determined by each isotopic nuclear decay scheme. Each radioactive isotope produced gamma rays having their own characteristic energy. So from my class I enlisted my first graduate student, a young man named Wade Craddock. I taught him how to read from reference books the detailed gamma-ray-line decay schemes emitted following each decay, how to read the halflife of each decay, for they differed from isotope to isotope, and how to use the laws of radioactive decay to then determine the numbers of each gamma ray emitted per second, and to do this calculation for various ages of the remnant. Wade worked zealously in response to the chance he had been given. Within a month the calculation was done, then checked by repeat calculations until I was satisfied. The largest flux from the *Crab Nebula* came from a mass-249 isotope of Californium, ^{249}Cf, having halflife 351 years, just less than half the age of the supernova remnant that is the *Crab Nebula*. We submitted our paper[3] to *The Astrophysical Journal* on January 18, 1965. It opened a new area of astronomical spectroscopy at just the time that Bob's balloon-borne detector would soon stimulate the field of gamma ray astronomy. I would pursue the hope for gamma-ray-line astronomy for four decades. Clearly in this work I could not have conceived it with being technically aware of Bob Haymes' expectation for his gamma-ray telescope.



Robert C. Haymes and his gamma-ray telescope with the author

There was a fly in this ointment. From my work on this at Caltech I had already come to the conclusion that the so-called *californium hypothesis* that had inspired it was a false hope. Burbidge, Fowler and Hoyle must be wrong. The californium hypothesis was the proposition that ^{254}Cf was synthesized abundantly by the *r* process intense neutron flux and would, with its 60-day halflife, generate the light from the young but aging remnant so that that light might also decline with a 60-day halflife. All of this was a lot to suppose, but this idea by celebrated pioneers of nucleosynthesis was regarded by many contemporary writers as a foundation stone for the reality of nucleosynthesis, whereas it was in fact only an interesting phenomenological suggestion. Before my paper with Craddock was submitted I went through those old numbers again and was again discouraged. If all supernovae ejected that much *r*-process matter there would exist in nature one-hundred-times too much uranium as well as other *r*-process nuclei. To make this idea work restricted the *r* process to occur only in some rare type of supernova rather than in all, one so rare that it might occur only once in 10,000 years. But the number of observed supernovae revealing that two-month decline in the emitted light was observed to be more common that that. So I wrote up my reservations and included it in our paper[3] on page 193. This is what scientists do, to express our reservations about our own work as we display our results. This tacit agreement is an essential part of the scientific process. A scientific paper should not be a sales pitch. Furthermore, I saw no easy way within a supernova remnant following a month of its rapid expansion for the kinetic energy input from the spontaneous fission of ^{254}Cf to be converted into light. Despite praise given to me for the stunning idea of this paper, I privately thought, *No. This is not the explanation for the light curves, and we will not find these gamma ray lines from the Crab Nebula*."

On a more positive note a powerful new idea was set loose. If the correct ideas and the correct telescopes for gamma-ray lines could be designed, detecting radioactivity could test or confirm the theory of nucleosynthesis. That theory was, although already believed to be true by most astronomers, woefully short of experimental confirmations. For that reason alone the halflife coincidence between many supernova light curves and that of ^{254}Cf had elicited much overly enthusiastic admiration. But I now realized that positive detection of radioactivity shortly after a stellar explosion could confirm unequivocally that the event had synthesized new nuclei. Radioactive nuclei are the only demonstrably *new nuclei*. Any stable nucleus could be either new or thirteen billion years old or any age in between. But a radioactive nucleus can not be much older than a few times its halflife. Detecting radioactivity in interstellar matter would prove that nucleosynthesis was happening today, not in some distant unknowable past. This simple new idea had beauty and power. Having myself now given birth to this idea I was determined to pursue it for better hopes than those that had been offered by the flawed californium hypothesis.