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FAST FORWARD FIFTY YEARS

Dr. Robert L. Forward

A fifty year journey through the multifaceted professional career of Dr. Robert L. Forward from 1952 to 2002.

Acknowledgment: To Martha... I could never have done it without her.

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INTRODUCTION

I will never finish this autobiography. I will keep adding to it until I can no longer do so. It will then be up to someone else to close out the chapters, add the final dates to the obituaries, and send it on its way.

I have decided not to make this a straight chronological record of my personal history. Because I have worked in parallel on many different scientific fronts at the same time, I will segment this story into separate topical chapters. Most of this book will be history, but toward the end I will have two chapters: one, Future Tasks, will outline what I intend to do, and how I am planning on doing it. This chapter will be constantly changing as I accomplish some of the tasks, while new tasks will continually crop up. The other chapter will be Exercises for the Reader, containing a listing of problems and mysteries that I have found over the years and which I believe need further work and study.

THE Fun FIFTY YEARS

I am an aerospace engineer, with 134 publications to date.
I am a physicist, with 35 publications to date.
I am an inventor, with 28 patents to date.
I am a popular science writer, with 61 articles to date.
I am a science fiction writer, with 11 novels and 21 short stories published to date.
I have been a research department manager directing more than 50 scientists and engineers at one time.

I pioneered the field of gravitational engineering, and invented the gravitational mass detector.
I pioneered the fields of smart structures, of ultra-cold neutrons, of antimatter propulsion, of space tethers, of rocketless propulsion.
I was the first to figure out a way to go to the stars using laser-pushed light sails.
I was the first to invent a method for levitating spacecraft without its being in orbit.
The space tethers, which I invented and pioneered, will revolutionize space travel within the solar system.

Many of the fields in which I have done pioneering work are now being advanced by other people and other technologies. My philosophy as a scientist has been to work on problems that other people consider impossible. I chose that philosophy as a very young man, because if you make any progress at all on that problem, it is still an advance. When I felt I had launched a new technology, I wanted to move on to something new, different, and more difficult.

Interwoven through the technology aspect of my career is my separate and distinct occupation as a writer. The reason I write is to teach. Every time I found a facet of science that I thought was interesting, I would try to find a way to pass on that information to the public. I was very fortunate to be able to generate words that people would publish, and read.

FAMILY

I am my mother's son. I have her language-skill genes, her musical and artistic genes, her leadership and intelligence genes, and, fortunately, her hair genes. From my father I also got a good dose of intelligence and leadership genes, plus the desire to "be your own boss".

I was born on 15 August 1932 to Robert Torrey Forward, 32, and Mildred Lull Forward, 29, in what was then the small town of Geneva, NY. When my parents met, he had been a paid employee of the Boy Scouts, in charge of a Camp on Lake Seneca, and she had been a paid employee of the Girl Scouts running a similar camp on the opposite shore. They were generally a happily married couple. There were very few babies born that year, as we were in the depths of the Great Depression. (This fact made it a lot easier for me to find jobs when I grew older.) My mother, of course, was not employable any longer since she had children to care for. I don't know what my father was doing for a living, but I don't think he was employed by the Boy Scouts, as we were desperately poor. The situation was made even more difficult by the birth of my brother, David Ross Forward, two years later. But the family managed to get by, and my brother and I had a happy home life except when we were squabbling with each other. David was born with a feisty personality, and resented being "bossed around" by his older brother. It would probably have been better for both of us if he had been born first.

Then came Pearl harbor, on Dec. 7, 1941. Things changed for the world and for the Forward family. My father got a full-time job with the Red Cross, organizing and running the overseas Red Cross Canteens for the troops. After a stint managing the one at the Navy's Submarine Base in New London, CN, he was sent overseas after the successful Allied invasion of North Africa in 1942. As the troops advanced across the Sahara Desert, across to the Island of Sardinia, and up the Italian Peninsula, he would follow along behind, setting up Red Cross canteens for the troops returning from the front lines for R&R. He stayed there until the German surrender in 1945. He was thus gone for three years during some of my most impressionable years. After the war, my father was given a desk job at the Red Cross Headquarters in Washington, DC. The family finally settled down in Silver Spring, MD, where we were to stay until I started life out on my own.

There was one major thing that my father did for me which changed my whole life. He sent me away to Boy Scout Camp for the summer...but this "camp" was in France. Using his contacts within the Boy Scouts, he arranged to have his 14-year old son selected as one of the 20-30 Maryland delegates to the Sixth World Boy Scout Jamboree, which was to be held outside Paris, France. I came back at the end of the summer a mature grown-up 15-year old. Little did I know what was in store for me. The phone calls and letters started coming in from Rotary Clubs, Boy Scout troops, Ladies Coffee Klatches, and others, wanting me to come and lecture to them about: "What is Europe Now Like?" So, thanks to my father, I, previously a solitude-loving bookworm and science nerd, was winkled out of my shell at age 15 and forced to become a public speaker.

I became good enough at public speaking that I probably could have gone into politics, but I can't remember names. I also probably could have become an actor, but I can't follow scripts (the writer in me keeps improvising on my lines, which louses up the cues for the other actors). Instead I have become a popular-science lecturer. I go into a lecture bringing a bunch of pretty color slides about some scientific topic, such as "Interstellar Flight", and, using no notes, improvise my speech as I go along - based on what shows up on the screen.

There was also a major thing that my mother did for me and my brother besides dedicating her life to bringing us up right. She paid our way through college. She did it through her writing. She entered a contest run by a manufacturer of boys' shirts, where you had to write the last line of a jingle that ended: "It has more value in it..." and she added "than first meets the eye." Five words... five thousand dollars! In those days, $5,000 would pay for tuition and books at the University of Maryland for two boys for four years, provided they lived at home. So we did, and we didn't have to work at part-time jobs to pay our way through college. We could concentrate on our studies. As a writer I have yet to match that payment of a thousand dollars a word, and I don't think even Hemingway ever got close to that figure.

I attended Montgomery Blair High School in Silver Spring, MD, and went to Christ Congregational Church in town. It was through the Youth Fellowship group at church that I met my future wife, Martha Neil Dodson . She was my first date, and except for some "friends of Martha" dates that she arranged for some of her friends whom she felt sorry for, my only date.

Martha and I were married on 29 August, 1954. I was 22 and she was 20. I had just graduated with a BS degree in Physics and a Second Lieutenant Reserve Officer Commission in the US Air Force. The Korean War was still on and we were stuck with the "infringe benefits" of service life for two years. When I finished my tour of duty in September 1956, I joined the Hughes Aircraft Company Fellowship Program. We moved to California where I would attend UCLA full time on the Fellowship and work part-time at Hughes when I wasn't going to school. Martha was now pregnant with twins. Unfortunately, there was a miscarriage and both babies were lost.

A year later a new baby was on the way. All the grandparents were pleased to hear the good news, especially my father, who was sick in the hospital with internal bleeding inside the esophagus. It was a serious condition caused by liver failure, which in turn had been brought on by a combination of yellow jaundice that he had picked up in North Africa and excessive drinking. He had left his secure desk job at the Red Cross Headquarters a number of years previously, and decided to "be his own boss". He set up a series of small businesses, each of which failed, and this led him to drink. Fortunately for the family finances, my mother was a well-respected, well-paid teacher in the Montgomery county Public School system, one of the best in the country, so the two of them managed on her salary.

Robert Torrey Forward died in November 1957, and his grandson, Robert Dodson Forward, was born on 5 March 1958. He was followed two years later by Mary Lois Forward on Leap Year Day - 29 February 1960, and by Julie Elizabeth Forward on 12 October 1961. Martha and I had talked about having four children, but there didn't seem to be any more coming, so we enjoyed the three children we had.

The children were a lot of work for Martha, especially since I was working on my Ph.D. in Physics at the University of Maryland during the school year, and working at the Hughes Research Laboratories in Malibu, CA, during the summers, which meant moving back and forth between rented apartments twice a year. Rob was born in Santa Monica, CA, and Mary Lois and Julie were born in Takoma Park, MD. There was one final year of extreme stress, where Martha was pregnant with Julie, and we were living with Martha's parents, Edwin Neil Dodson and Lois Young Dodson. My thesis adviser kept dragging the thesis work out, and finally Martha informed me, after the birth of Julie, that it was time to go. We left while we were still friends with Martha's parents, although my thesis was not finished yet, and I started working full time at the Hughes Research Labs.

After looking around in the Malibu area and surrounding areas, in early 1962 we bought a new four-bedroom house in the town of Oxnard, CA, a 45-minute drive up the coast from Malibu. We stayed put for over 20 years, giving stability to the whole family. We finally had our fourth child, Eve Laurel Forward, on 17 January 1972. As of 2002, all the children are married and doing well.

Writing fiction is now a Forward Family tradition. Three of the children are authors. As "Bob Forward", my son makes a good living writing scripts for movie pilots and writing, editing, directing, and producing shows for animation television series. He and I have jointly outlined a book, "Heaven Must Fall", but we haven't been able to sell it yet. Julie has co-authored two books with me, "Return to Rocheworld" and "Rescued From Paradise". Eve has had two books published in hard-cover and paperback by a major publisher, Tor books, and has contributed many scripts to a number of the animation series that Bob was Senior Editor for. Martha has also co-authored two with me, "Ocean Under the Ice" and "Marooned On Eden".

After taking early retirement from Hughes in 1987, when I had reached 55 years of age and had 31 years of employment, Martha and I sold the Oxnard house as the older kids had gone. We joined Eve in Idyllwild, CA, where she was going to the Elliot-Pope Preparatory School. At the same time, we bought a house in Scotland.

Back in the summer of 1985, Martha had taken Mary Lois on an educational trip to Scotland, while I stayed home with the others. They traveled as far north as Wick, in Caithness, and Martha enjoyed Scotland so much she dragged me back there the following year. I too liked it very much, especially the friendliness of the Scots (after all, we were Americans, not English, and we came from the magical Disney-like world of California.) That year, and the year after that, we, sometimes with Eve, stayed in a Guest House in Nairn, near Inverness, at the entrance to Loch Ness. We drove north from there and the further north we went, the better we liked the scenery and the people. We drove along the top of Scotland through Caithness and Sutherland. The population is so low in Sutherland, the main road along the coast is single track - one lane for both directions, with "passing places" every few hundred yards, where the road is wide enough for two cars to pass. We stopped to look at the real estate ads in the shop-windows of the solicitors - the legal profession handles real estate sales in Scotland - and realized that we could buy a large mansion for what we expected to sell our house for in California. We eventually settled on a small three-bedroom place that used to be the "field-servants-cottages" on Sandside Estate, in the village of Reay, Caithness. We bought the property in 1987 and stayed almost a full year the first time, bringing Eve over to live with us while she did her school-work through correspondence. Martha and I go back as often and as long as we can. We have more friends and social life there than we do in our present rented house on Whidbey Island in Washington state.

Living in northern Scotland is not all fun. In 1995 I had my first heart attack just before we were to return to the US. It was a 45-minute ambulance ride from the town of Thurso to the Caithness Hospital in Wick. Although the UK Health Service is good, it doesn't have the depth of the USA Health System. Fortunately, I only had a minor blockage episode. Eve came over to help Martha nurse me back to health enough that I could take a transcontinental flight, so for a while the three of us were back together again, but it was not as much fun as the times before.

The Scotland venture will be closing down in 2002. We have found a Dutch attorney who wants to buy the house to use while he goes deer-hunting in the surrounding hills. He is willing to let us come use the house when he is not there. We may do that for a few years, but it won't be the same.

EARLY LEARNING

I enjoyed math classes. The pure logic of mathematics and the certainty of it was a pleasure. (It was only much later that the "certainty of it" was knocked into a handbasket when I learned about Godel's Theorem.) I had a good mathematics teacher in High School, Mr. Hitchcock, a burly man who made learning mathematics fun. When I was taking Algebra from him, I worked ahead in the class and independently invented a method for calculating the coefficient in front of each term when you expanded an equation. Mr. Hitchcock appreciated my "discovery" and then gently led me to the back of the books, where he showed me the tables for Pascal's Binomial Theorem, first published in 1665 - almost 300 years earlier than my discovery. I wasn't disappointed, or even surprised, for I knew that algebra had been around for a very long time. Instead, I felt a little proud that I had done it on my own.

I experienced the thrill of "discovery" again the following year, when I was taking Analytic Geometry. I discovered a formula for calculating the area of a complex polygon of irregular shape by just knowing the coordinates of each of the vertices in the polygon. When I brought this little gem to Mr. Hitchcock, he again expressed appreciation for my ingenuity in mathematics, and then showed me a reference book describing Simpson's Area Rule, which could handle the area of any planar shape, even one with curved lines, and which worked especially well for polygons with straight sides. Simpson had published in the 1750s. I actually felt quite good at learning that. In one year of study, I had gained 100 years on the old masters of mathematics. In a few more years of math, I figured I would be up to speed and beginning to invent new mathematical theorems before other people did.

That never came true, because although I liked math and did well in math, I was really not a mathematician. I was a physicist. A physicist works with mathematical logic tempered with reality. A mathematician does not allow his logic to be "contaminated" by reality. This was forcibly brought to my attention in college. After taking progressively more difficult mathematics courses through college and getting almost straight A's, I had completed every math course that a physicist needed, including Differential Calculus and Quantum Mechanics. Then I decided to take Advanced Calculus. The problem was that, unlike the Differential and Integral Calculus courses which had been taught by physicists in the Physics Department, the Advanced Calculus course was taught by mathematicians in the Math Department. I whizzed through the course, thinking I was doing well, although puzzled a little with the "epsilons" and "deltas" which seemed to have to be "bounded" around the point of integration. After the first semester test was over I was called into the Professor's office.

"Mr. Forward,", he said, looking up at me with a sorry shake of his head, "If you promise not to take the second half of my course, I will give you a C."

I still don't fully understand what I was not understanding. The basic problem I was having was that in physics there is no such thing as a "discontinuity" in a physical quantity that you are describing with a mathematical function, whereas in mathematics the discontinuities are not only allowed, but "expected", since it is the discontinuities in a mathematical function that make the mathematics fun. For example, if you take an equilateral triangle, divide each side in thirds and take the middle third and turn it into an equal-sided "point" pointing outward, you end up with a six-pointed star. If you then divide those sides into thirds and turn the middle third into points, you end up with a spiky star. If you keep that up forever (and mathematicians are good at that) you end up defining a spiky planar polygon that contains a finite area but has an infinitely long perimeter. In addition, that perimeter contains an infinite number of discontinuities which plays havoc with the integral calculus which you need to calculate the area. The mathematicians, by carefully bounding the discontinuities with epsilons and deltas can somehow get a finite area by integrating an infinite perimeter. Physicists can get as close as they want to the same answer for the area by successive approximations. My teacher was trying to teach me how to do it properly, the mathematical way, the *exact* way, but I was unable to do so. I not only didn't know how to do it, I didn't even understand *why* I didn't know how to do it. It was then I was glad that I had long ago decided to major in physics rather than mathematics.

IN THE MILITARY

The Korean War was going on when I completed high school I was deferred from the draft to go to college and join the Air Force Reserve Officer's Training Corps at the University of Maryland. Outside of ROTC classes and parade formations once a week, my military career was a minor influence on my life, for I still lived at home. I graduated in June, 1954, and in short order had a Bachelor of Science Degree in Physics, a Commission as Second Lieutenant in the United States Air Force, a wife, and apartment in Bethesda, MD, and orders to report to the 727th Tactical Control Group at Shaw Air Force Base in Myrtle Beach, SC, on 29 September 1954. Martha stayed at the apartment and attended American University, while I went to South Carolina to live in the Bachelor Officers' Quarters until she finished the semester and I found us an apartment.

The task of the 727th was to supply radar coverage and direction for the Air Force planes that would be supplying air cover to the Army troops on the ground. I was in a small forward Mobile unit. We had a range-azimuth radar that would scan in a circle out to about 100 miles, and a height-finding radar that could be directed at a suspicious track on the range-azimuth radar and determine the height of the track. This information would be used by our controllers to guide our aircraft to a given target, and to warn our aircraft about the approach of enemy aircraft. We thus had two large radars, a command and control center, and all the radio equipment needed to communicate with the Air Force base at the rear, the Army troops all around us and just ahead of us, and the Air Force pilots up above. My primary job was to be the Radar Maintenance Officer, keeping the radars running. Thus, right out of college, I was given a leadership job over a fairly large crew of Technical Sergeants and radar maintenance technicians. In the wisdom of the Air Force, since I had a degree in Physics and was a ham-radio Operator to boot, I should be telling well-trained radar technicians what to do. I knew enough, however, to ask the Master Sergeant what we should do, and then recommended that we do it his way.

Very fortunately, shortly after taking command of my small group, we ran into a technical problem with one of the power systems for the radar. The crew was baffled, for all the tubes in the unit were glowing properly, but the power wasn't coming out. I walked into the tent and smelled something. Something very familiar from my early ham radio days, when I had fried many a power supply. It was the smell of burnt cabbage.

"A selenium rectifier," said my nose. I opened up the cabinet and the smell was even stronger. I looked down at the bottom of the cabinet and there was a bank of selenium rectifiers that are often used instead of tubes to turn ac voltage into dc voltage. A burnt-through selenium rectifier looks just like a working one, so you have to take measurements on it, not just look at it. I suggested they check, and my nose turned out to be right. My relationships with the men improved remarkably after that bit of nasal detective work.

My other job was Mobility Officer. Since the 727th had to be near the front lines, not way back like most Air Force facilities, we had to be as mobile as the Army around us. All of our heavy equipment was built permanently on trucks and trailers, and everything that wasn't on a truck, had to be built so that it could be dismantled and put into a truck - fast. My job involved planning where every piece of equipment and cable and consumable item would go on which truck. This wasn't a paper exercise, for we then proceeded to go on maneuvers with the Army through the scrub forests and swamps of South Carolina and

Alabama. We loaded everything and drove south. (I got very good at driving a Jeep ahead of the convoy, then stopping to hold up traffic while the convoy thundered past. We did it again and again over the next few months as the mock battle moved back and forth over the southern states. (Even today, I can look at a bunch of wrapped Christmas presents, go into the garage where we keep empty boxes, and pick the perfect box to hold all the presents with only the smallest amount of space left over.)

The major things I got out of my two years of service life were an excellent knowledge of the inner workings of real-life radar systems, and two years of experience as a leader, both of which came in very handy in my next (and final) job at the Hughes Aircraft Company. When I finished my tour of duty in September 1956, we moved to California, where I began to attend UCLA full-time on the Hughes Fellowship Program, and to work part-time at Hughes.

INTERSTELLAR FLIGHT

I have been interested in interstellar flight my entire life. Even in my early career I was enamored with the concept.

The Hughes Fellowship program was designed to be a work-study program. I wasn't allowed to work 40 hours a week. I would go to UCLA and arrange my class schedule first, typically about 25 hours a week. I would then go to my Hughes boss and arrange my work schedule around the class schedule. My bosses didn't mind - since I came "free - the fellowship program paid my salary. This gave me plenty of free time, which I spent in the UCLA Library looking up new papers on interstellar flight, adding to the Interstellar Travel and Communication bibliography I had started. I tried to collect and read everything. I would correspond with the authors, sometimes giving them useful tips to improve their papers, sometimes telling them about another similar paper that they may not have been aware of. In the process I became known as a person with a broad and unbiased knowledge in the field of Interstellar Travel. I kept dreaming, however I would find a better way to travel to the stars than those I had read about in all the hundreds of papers in the bibliography.

The Hughes Program was designed to end in three years with the award of a Master's Degree in Engineering, and with the employee switching to full-time work. I knew, however, that as a physics major, I needed to continue my Graduate studies until I obtained my Ph.D. So, although I liked Hughes, I had the G. I. Bill to help support the family, and the University of Maryland was able to supply additional funds. When the Hughes Research Lab Directors heard that I had been accepted, they understood immediately. They knew how important the Ph.D. degree was to the career of a physicist. They arranged one of the first Hughes work-study Ph.D. Graduate Fellowships for me, and both I and the University of Maryland were pleased to accept.

When I arrived in Maryland in 1961, one of the first things I did, indicating my strong interest in the field, was to try to set up an "Interstellar Research Foundation", along the lines of the fairly successful Gravity Research foundation. It was not to be source of funds but a repository of knowledge. I was planning on holding an annual essay contest and maintaining a circulating library. I had already had many brain-storming sessions with Mr. Marty Willinski, when he and I were fellow worker-students at Hughes, and together we had come up with about 50 people who might be interested in sharing information.

I got a Post Office Box and a mailer program, and in April mailed out 50 Announcements, calling for efficient methods for interstellar travel which did not use rockets, and for efficient methods of interstellar communication. I didn't get many responses, so after a while I dropped that idea; the mailer is in my book of Bound Papers 1961-1962.

Things suddenly changed dramatically in my own personal thought. I invented my own way to go to the stars! In early 1961, Ted Maiman at the Hughes Labs and shown that he could make a visible laser. I had been working with Ted, earlier, to develop a microwave maser for use in radar, and had published a paper in 1959 on that. When I read in the newspaper, in Maryland, of the laser, I was interested to learn that the laser color was brighter than the sun. On earth, it is the only color that is. The other thing, that really struck me, was that the laser light does not spread.

And I knew right then that I had an idea for sending human beings to the stars.

I knew a lot about solar sails, and how, if you shine sunlight on them, the sunlight will push on the sail and make it go faster. Normal sunlight spreads out with distance, so after the solar sail has reached Jupiter, the sunlight is too weak to push well anymore. But if you can turn the sunlight into laser light, the laser beam will not spread. You can send on the laser light, and ride the laser beam all the way to the stars!

I wrote the idea up in an internal memo to the Lab Director in May 1961 - Ground-based Lasers for Propulsion in Space. I liked the idea so well that I spent the time to work out the numbers. I found that if you think big, the whole concept becomes more and more feasible. The larger the laser sail, the lower the laser light flux on the sail material - until it is only three to six times brighter than sunlight - and the sail can be made out of aluminum.

The laser sail in the Beamed Laser Propulsion system is the same as a solar sail, so no new engineering is involved in that part of the system. The laser part of the system should not be designed as a "cannon". Instead, it should be imbedded at the image point in a telescope-like structure that is designed to spread out the straight beam from the laser so that it always fills the full sail diameter.

If you send the laser light backward through this big telescope, and adjust the amount of beam spread with time, the beam will stay in a straight line for many lightyears without stopping. The real trick to making this work is to think big. Fortunately, because my basic structure was a solar sail designed to reflect sunlight, I was already used to sails more than a kilometer on a side. Since this was a tough interstellar mission that had to beam a long distance, I was not afraid to consider laser beam spreaders 10's of kilometers in diameter and laser sail collectors 100's of kilometers in diameter. I was able to find lots of combinations that would work, and choose those combinations with higher speed, less laser sail mass, less laser power, etc. Once I calculated those solid engineering numbers I knew I had invented something really significant.

The first publication I did of the idea was in a popular magazine - "Missiles and Rockets"-April 1962. The article, "Pluto - the Gateway to the Stars", was reprinted in "Science Digest" in 1962, and that established my claim to having invented the first interstellar vehicle that used known technology.

I still didn't have a good way to stop.

I continued on with my Ph.D., while still collecting new ideas on interstellar travel. In late 1964 I finished my thesis work and returned to Hughes. I invented the Rotating Gravity Gradiometer Mass Detector in 1964, and the ramifications of that dominated my time until 1975. The first time most aerospace engineers knew that I was active in interstellar travel thought was in 1967, when Eugene Mallove and I published the first Interstellar Bibliography; it was already 18 pages long.

In 1973 I had a visit from science fiction authors Larry Niven and Jerry Pournelle. I gave them a lengthy briefing on a lot of far-out physics. They took away a lot of ideas on miniature black holes, which they immediately turned into award-winning short stories. They also took away my idea of a laser-pushed lightsail. I had warned them that the light from the Sun was not strong enough to stop the sail, but, being science fiction writers, when they wrote Mote in God's Eye, they ignored my advice and pretended it would work.

In 1975 I was approached by a group of people who knew that I was interested in interstellar flight. They were staffers to the House Committee on Science and Technology of the US House of Representatives 19th congress. What the Committee was aiming for was a plan for a Future Space Program 1975. They asked me to contribute, along with many other people working on Earth-to-Orbit launch, Orbit-to-Orbit launch, mars Transit, and similar near-term topics. They wanted someone to look further out than that, so they asked me to come up with a National Space Program for Interstellar Exploration.

I did.

It is a lengthy document, published in its entirety in the Congressional Proceedings, and contains a large number of ideas for deep-space exploration and interstellar exploration. There are a number of ideas in there that were not in my original ideas, including ideas by other people on how to go about stopping; nobody at that time had any good idea how to go about stopping a laser-pushed lightsail.

That document, in 1975, seven years after the first publication of the "Bibliography of Interstellar Travel and communication" was a tour de force which summarized all the ideas that I had which I had not had a chance to publish nor a chance to work on to the point where they could be published. I spent a lot of time on that Report, and I think it was very valuable at the time. There were a number of ideas, including fusion. Still, the only way which could take a probe and send it to the nearest stars and do it with known and tested technology was laser-pushed lightsails; it was still the best idea.

Once I had published the idea of laser-pushed lightsails, I then proceeded to publish a number of popular articles on the concept. At the same time, I published the "Bibliography" in a number of different places, most importantly in the "Journal" of the British Interplanetary Society.

I also condensed the House Committee paper into a single article, called "Program for Interstellar Exploration" for the "Journal" of the BIS, which appeared in 1976.

In 1976, there were only five good ideas for interstellar propulsion: Atom bombs, Ram Jets, Fusion, Anti-Matter, and Laser Beams.

The Atom Bomb propulsion concept was a vehicle designed in 1960 by Freeman Dyson and Stanislaw Ulam; it was based on classified data that Dyson and others had been able to generate, and may in fact have been tested under atomic bomb conditions but we don't know that. The design consisted of a vehicle pushed to close the speed of light by atom bombs. This may sound ridiculous, but if you make the vehicle very large and very tough and the bombs very small, and explode the bombs not too far away, say 100 feet, the bombs will heat up the big vehicle pusher plate but will not melt or damage it, so the pusher plate can be used hundreds of thousands of times. The final vehicle design carried 45 tons of passengers and supplies, which is enough for a small city of 2 or 3 hundred people, and was comparably large. The total vehicle weight was 400 tons. It consisted of two-thirds tons of bombs or 300 tons of bombs, each bomb weighing about one ton. That was the world's supply of atom bombs and I can't think of a better way to get rid of them. It was designed to accelerate over one g for 10 days, by using up the bombs once every three seconds. It could reach 1/30 of the speed of light. At that speed it would take 130 years to get to Alpha Centauri, but the system would work; it could have been built back in the 1960's and fired off in the 1960's. It was designed to get there in a hurry, and it didn't have a way to stop. (The way to stop would be to divide the bombs in half, use half of them to get up to speed and the other half to slow down, making the total trip time 260 years.) I would call that a World Ship, but a workable World Ship. It was the best we had, and was good enough. However, we would like to get there faster.

Another idea that was in the article was called the Bussard Interstellar Ram Jet. It was designed as a very large fusion-powered vehicle which wouldn't carry its own fuel. Instead, it carried a scoop, which would somehow scoop hydrogen out of space, over an area of thousands of miles, pulling the hydrogen atoms into a central core and feeding them into a fusion engine of unknown design. The engine would convert the hydrogen into hot helium, and expel it out the rear. The beauty about the Ram Jet Concept is, that since it collects the fuel from space it never runs out of fuel. It can go through the entire galaxy, it can go through the entire universe, provided the scoop works. The faster it goes, the faster it collects fuel, and the faster it can go. It's a wonderful concept, except nobody knows how to build the fusion engine and nobody knows how to build the scoop. In fact, analysis of the scoop shows that it will not work. If it was made of magnetic fields, it would simply send the hydrogen atoms back rather than collecting them, so it doesn't do any collection at all. It's still a wonderful idea, but it's more of a dream than anything else.

The other propulsion technique which has had a lot of work put into it was a fusion rocket. Fusion reaction is much more energetic than atom bombs, and so it would be nice to have. But nobody has come up with controlled fusion even on the ground, so until we do that, fusion propulsion has no future, because we can't make it. It also would be a rocket, and so would have to carry its own fuel; therefore it is limited to the total amount of thrust it can obtain.

Also in that 1976 paper is the first mention of using anti-matter as a fuel. As rockets, they would require fuel, but anti-matter is so powerful that we find on analysis that you don't need much of it. For every ton of vehicle you would need about 4 tons of some kind of reaction mass for the anti-matter to heat. The total amount of anti-matter we will be talking about will be in kilograms, so its weight is nothing. If you want to do an easy job with an anti-matter rocket, you just use a small amount of anti-matter to heat up 4 tons of fuel. If you want to do a tough job, then you use more anti-matter to heat the fuel even hotter to get more thrust out of it. At the time of the 1976 paper, people were just beginning to be aware that you don't want to use half and half of anti-matter and matter.

The last concept, Laser Beam propulsion, I invented. The only thing that has happened since my first paper in 1961 is that, although I originally didn't think of a way to stop, a gentleman named Noram realized that once I had gotten that interstellar probe up to speed, and visited briefly the target star, I could stretch out long wires and charge them up, and then use the magnetic field out in space to turn the interstellar probe around and send it back to Earth. It was a great idea, and I had published it myself, however I had never connected it to possible use with the probe. So that was the state of the field in 1976.

In 1981, I finally invented an improvement to my one-way beamed power sail - a way to stop at the target star. I was starting work on my novel, Rocheworld. The basic theme of the book was to teach the reader that the world is not always round - and what it would be like to live on that world. I didn't care what propulsion system I would use to get to this strange new world. Fusion would have been OK. I would have liked to use my new laser-pushed lightsail concept, but I didn't have a way to stop. Then suddenly I thought of a way it could be done.

The idea was to divide the sail into two pieces. As the crew approached Rocheworld, a large ring-shaped portion of the sail would be cut loose, leaving the central portion carrying all the mass of the cargo and crew. The much larger ring sail would be designed to curve a little bit so that the laser light from Earth would bounce off the retro-ring and onto the backside of the crew sail. The strong laser beam from the large retrosail would counter the weak laser beam from Earth, and after a year or so, bring the crew sail to a stop at Rocheworld. That idea was published in the "Journal" of the British Interplanetary Society in 1984, as "Round Trip Interstellar Travel using Laser Pushed Light Sails", where you will find credit given to my novel for its technical contribution to the retrosail method of stopping.

It was a year later that I developed a microwave version of the beamed power sail.

((FAST FORWARD FIFTY YEARS CONTINUATION))
(It was a year later that I developed a microwave version of the beamed power sail.)

That idea was based on a visit with Freeman Dyson. We were discussing the pros and cons of poking very small holes into lightsails, to lower their mass. If the holes were smaller than a wavelength of light, the reflectivity of the sail should not be drastically affected. He said he had a sail design that was really perforated. He went to his file cabinet, and brought out three sheets describing the idea for a microwave sail that had very large holes. His analysis had found that the larger the holes, the faster the mesh sail traveled. But he didn't know what to do with this idea. He could send a large sheet of chicken wire to the stars, but what could he do with it when it got there?

Fortunately, I was trained in microwave transmitters and receivers, retrodirective arrays, neural nets, image processing, etc., and was able to combine all of those ideas to give the microwave sail an intelligent capability to collect microwave power from Earth, then to process television images during the fly-through and send them back to the Earth. That was the start of the Ultra-light Interstellar Probe. I published that idea in 1985 as "Starwisp".

It is difficult in this field to come up with new ideas, so I made it my job to collect all the new ideas and once every 5 or 10 years to present a review of the status of interstellar travel. I did this in 1986, 1991, and again in 1996.

In the years since 1976, the Atomic Bomb-propelled rocket had developed no changes. The Fusion rocket had no changes. The Ram-Jet idea, remarkably, did have a change. Jackson suggested that instead of the ram-jet scooping up its fuel, which we were having difficulty doing, we drop the fusion system from the entire ram-jet concept, and just use the ram-jet collector. We could then beam power to the collector to heat up the scooped-up hydrogen, and that power could be lasers, anti-matter, or any technique for supplying power at a distance. The problem was, we still didn't know how to build the scoop. Maybe that idea will inspire someone else.

In the Anti-Matter division, increased knowledge and technical work revealed that the idea looked better and better. First of all, we had learned we should concentrate on the anti-protons, because once they annihilate, they produce particles that last a short time but travel a long distance. Most of the particles generated will travel 21 meters, or 60 feet. And if you wind up that distance, using a moderate magnetic field, you can build a big tank which will control and contain most of the particles. If you add hydrogen or water particles, they will interact with the fuel particles and heat up, converting something like 30% of the annihilation energy into workable thrust. Two other advances had been made in the last 10 years: both the USA and the USSR had spent a lot of time and money developing proton-beam factories, which produced anti-protons to be used in scientific experiments; at the same time, many atomic-physicists were working on dozens of ways to catch, contain, and trap hydrogen and other particles, which meant that they could do the same with anti-particles. Thus it was possible to show that making anti-protons is feasible;

collecting them is difficult, but once collected and slowed down, they can be contained and used.

In the area of beamed power, a new concept came up called Pellet-pushed Propulsion. Instead of using atoms, it used physical pellets, sometimes even little tiny directed devices. That idea has had a lot of thought and calculation, but no one has taken it much farther.

In my 1996 review, I found that other people had also come up with new ideas for stopping a beamed-laser lightsail. One of them involved a magnetic sail.. After using the laser to get the sail up to speed, you dropped the sail and spread out a big loop of current-carrying super-conducting wire. The magnetic field from the current will push against the atmosphere of the star, and bring the probe to a halt. There is yet another way to do this, using a plasma wave.

Now that other people were solving the problem of stopping, more people were working on finding alternate ways to get to the stars. The Jet Propulsion Lab facility can now push a small interstellar probe partway to the stars, using a solar sail.

I finally realized I wouldn't see any progress on a true interstellar vehicle before my career was over, so I decided to switch to work on space tethers. So at age 70, I have turned over the field of interstellar travel to Geoffrey A. Landis.

I still maintain contact with everybody in the field; from 1961 to 1991, I was one of the pioneers and inventors in interstellar flight, and I am proud of the contributions I was able to make.

SMART STRUCTURES

I was active in the aerospace field of smart structures from 1979 to 1985.

A "smart structure" is defined as an engineered mechanical structure built of integrated materials which can sense thermal, mechanical, elastic, and inertial loads; and which can apply forces and moments, when powered by control electronics, in such a manner as to adapt the geometric shape and dynamic response of the structure, based on a set of rules.

These complex mechanical structures usually start with composite-material -laminated bases, like carbon-carbon fiber. By inserting between the laminates things such as piezoelectric ceramic transducers, shape memory alloy wire actuators, passive viscoelastic dampers, temperature sensors, power control electronics, etc., the structure can be converted from merely a "stiff stick" into a flexible, adaptable, component part of a complex structure, such as a very lightweight telescope that is many times lighter than a standard space telescope, but with much better performance.

By proper design and operation you can obtain different elctromechanical properties out of the same "smart structure". The new piezoelectric ceramics along with new high-strength materials became a very powerful means for controlling the properties of a very large and massive structure.

The big change about during the Cold War. It started with the navy. They had a desire to make sonar more and more efficient, in terms of the coupling of electrical power in the piezoelectric ceramic transducer with the sound put into the water.

Tests on these transducers revealed that you could put a great deal of energy into the structure through them, and get a lot of the energy back out again, with almost no loss.

The Navy was able to get a high coupling of electrical power into sonar power. Now I had found that if a structure had any vibrations in it, small transducers could not only sense the vibrations, but "suck" the energy out of them. I became aware of this capability during my work on gravitational radiation detectors.

My Thesis/Dissertation Abstract in 1986 was: Vibration control of flexible structures using piezoelectric devices as sensors and actuators was analytically predicted and experimentally demonstrated.

For my thesis, I had used piezoelectric transducers to extract vibrational energy from a one-ton bar of aluminum. I should be able to apply the same techniques to the kilogram-sized mechanical struts in typical aerospace structures. I realized it was important for the war effort and for the control of aerospace designs that we start looking at the ultimate capabilities of these transducers. I had had a great deal of experience with them as stress elements, so my major contribution in this field was to write papers showing how powerful they could be in terms of putting energy into a structure and getting it out again.

I concentrated primarily on structures which had unwanted vibrations in them If you are trying to build a lightweight aerospace structure which will be out in space and subjected to noise, you want to arrange it so that you can get that energy out and stop the structure from vibrating. I immediately began demonstrating to people at the Hughes Labs that it was possible to stop very heavy objects from vibrating, with a little slab of piezoelectric material.

Further, as I was extracting energy from a structure with these transducers, I learned that not only could they damp vibrations, they could cool it electronically. Essentially redoing my thesis, I demonstrated to the engineers that not only can you detect vibrations smaller than an atom, you can extract energy from them, and furthermore, you can measure them exactly. It was as I worked with the equipment for my thesis that I really got to know the potential of working with the single modes in the bar.

To show the seriousness of the work of these piezoelectric transducers, I spent some months on an effort which resulted in two papers, one on theory, the other on experiment. I had a theorist work with me, and he did such a beautiful job of analyzing what was going on that we decided he should be the primary author of the theory paper, and I was the primary author of the one on experimental results. The titles were "Electronic Damping of Orthogonal Bending Modes in a Cylindrical Mass", and C. J. Swigert was my associate. Both were published in 1981, in the "Journal of Spacecraft and Rockets". In this pair of papers, especially the experimental one, we show that we can take an antenna mast, designed to be used on the Pioneer Venus spacecraft, which had vibration problems, and stop it from vibrating.

The mast was about 2 feet long and made of fiberglass as stiff as they could make it. The mast strut weighed about 337 grams, which is about a pound, and it was loaded with a fake weight that massed 1.5 kg so the total was almost four pounds. We glued eight of our tiny piezoelectric ceramic transducers to the base of the mast. The transducers were 1 inch long by 0.25 inch wide, and massed only 1.6 grams. We found that we could stop that mast from vibrating with those tiny little transducers, even with that heavy weight attached to it.

That convinced a lot of people that this was really a powerful technique. We also answered some other important questions, in that people had wondered if we had the electronics actually working, and was the vibrational mode really being stopped, or was the vibration just sneaking around to some other part of the mast and hiding from us.

It was this tour de force of both experimental and theoretical demonstration that got people to really believe that electronic damping of structures can work. It all came to a head, very interestingly, in my visit to the Airborne Laser Lab airplane.

This is where the Smart Structures field really took off. Since I had demonstrated that I could damp structures with piezoelectric transducers in the lab, I was given the challenge of trying to do the same in an airplane. I took my equipment and my technician, and joined the Airborne Laser Lab group at Kirkland Air Force Base, in New Mexico. There, I was joined by Captain Michael Obal, who worked then at the Air Force Weapons Laboratory.

The Airborne Laser Lab was a converted 707 jet. The Air Force had taken one of the older models, and ripped out everything inside. Right in back of the pilots they put in a blast barrier, to protect them from the rocket-fueled laser. In back of that were tanks of carbon monoxide and oxygen, which were to burn to create a laser flame.

The way the laser was made, is that two small rocket engines were placed through the middle of the plane, so that their flames would shoot down it's length. The light from the flames would be captured by mirrors at the end of the plane, by what is called an optical bench. An optical bench is a region where the light gets bounced back, and is brought back up through the second rocket flame. The optical bench was seven feet long and four feet wide, built of composite and honeycombed materials, and weighed one and a half tons. When the rockets were running, the flames would be pushed down by deflectors situated on the belly of the plane. The optics on the bench were supposed to avoid the rockets' motors and the flames' exhaust, while they collected the light from two beams, combined them into a single laser, and sent the laser beam out the top of the plane.

The optical bench was vibrating a lot, to an unacceptable degree. This was a tough problem, so I had brought along some piezoelectric transducers about the size of a dinner knife - four and half inches by a half-inch by a quarter of an inch thick. It took us a little while to develop the exact combination of electronics that we needed to handle the noise and vibration, but we succeeded. We were able to do a good job of damping the vibrations in a one and a half ton bench for a total quantity of less than a third of a pound of transducers.

When we showed that it would work, during a live firing, Captain Obal was very pleased with the results. Originally, he had been a skeptic, along with everyone else. He had difficulty believing that these tiny transducers could handle a ton and a half of material, but he came away convinced. So much so that he went on to get his Ph.D. in "Optimal Vibration Control by the use of Piezoelectric Ceramic Sensors and Drives". I consider him to be, now, one of the leaders in this field. And with this particular effort, I felt I had done my job as a research scientist.

I went on to spread this new idea within Hughes, to a number of different applications, and published with different co-authors, to enable new work to be done.

ANTIMATTER: How I took on the world-wide established particle-physics community.

By using non-confrontational techniques, I convinced the international particle-physics community that they could turn their existing machines into antimatter factories.

The field of particle physics is a prime source of the coveted Nobel Prize, and the US, Europe, and Russia have long competed to build bigger and faster machines, pouring magnetic strength and energy into them to smash atoms, thereby, hopefully, creating new particles. These particles were captured and stored within a huge hollow ring. They were counted and analyzed. Then the machines were turned on again, smashing the particles against each other, until the result was protons, and, interestingly, about 5% anti-protons.

As the anti-protons accumulated, they provided targets for the proton beam, to create smaller and smaller particles.

As I read the results of the three big national facilities, I could see that, while they were very good at capturing, controlling, and directing antimatter, they were limited by budgets from much expansion, and they were also not doing much research using antimatter for medicine or other fields. With their primary interest being particles, they were only collecting about 5% of the energy spread. I wanted to build an antimatter factory, and I could see, step by step, how it should be done. I thought that antimatter could be turned into anti-ice and kept cold enough to store, while experiments to use it were planned. Frank Mead, at the Air Force Rocket Propulsion Laboratory, allowed me to use my contract money to study this, and I concluded there were no barriers to this idea, so I obtained a 300K, 3-year contract to further it.

I developed many unofficial contacts at the three major labs by writing to the engineers involved, praising their work, and suggesting that they could get better results with some of the newer equipment. They agreed that they could, but they were hampered by costs. As the contacts grew, I began to write the "Mirror Matter Newsletter". I visited several of the smaller and more friendly labs, and we talked about all of the problems, while I brought in my interest in antimatter as a result of their work.

After visiting most of the labs in the US, I was able to arrange a visit to CERN, where I learned a great deal and met more people. A few months later, I was allowed to visit a formal particle-physics meeting, purely as a spectator. At the end of the meeting, to my surprise, Carl Robea stood and began to sneer at the idea of making antimatter, mentioning the difficulties and stating that improvements with his system were impossible. But I replied that he was right, as long as he was using his system. Then I explained that other systems, which I outlined, could improve the angles, and other magnets, which I also outlined, could improve the results. For everything that he had said, I mentioned a technique which he and the others knew about, but which they could not use within the system they were currently limited to. With this non-confrontational technique I was able to get attention directed to the possibility of antimatter collection, rather than its difficulty.

There were lots of people who could really use some antimatter. The best example is in medicine; one way to kill a brain tumor, which is full of hydrogen is to shoot a particle beam at it. At Loma Linda Cancer Research Center, they shoot protons at the tumors.

Typical x-ray treatment of tumors results in damage to everything within the path of the x-ray, including healthy tissue. You send the beam vertically through the tumor and you get 90% of its energy destroying the brain, while 10% destroys the tumor. You send the beam horizontally through the brain, and a different 90% of brain tissue is destroyed, along with an additional 10% of the tumor. There is a gain to this method, but it is far less than if protons were used. Protons are moving at such high speeds that they do not do much damage until they slow down, in the tumor, where they stay. Nothing comes out the other side. It is almost like a magic bullet. That is a very powerful technique.

If I only had one brain tumor or two, I would be at Loma Linda Cancer Center. But I have at least six tumors, and it doesn't work too well.

If we had antimatter in a bottle, and could feed it into the Loma Linda proton beam therapy machine, we could be shooting antiprotons into the tumor. Theoretically, antiprotons could be used to scan the body for tumors and then destroy them. By calculation only a million antiprotons could successfully scan and kill tumors. Fermi Lab at that time had already made trillions, but they were not in a bottle at Loma Linda, where they could be tried.

In all, I wrote 18 issues of the "Mirror Matter Newsletter" and had a subscription list of 300 people.

I took my results back to Frank Mead, believing I had answers to all the questions regarding building an antimatter factory, but not wanting to run such a large program myself. The Air Force decided to spend quite a lot of money, principally on two workshops for engineers who could reasonably be expected to do the job.....

UNFINISHED

A WALK THROUGH MY NOVELS

From 1981 to 1995, I wrote eleven science fiction novels. I stopped writing science fiction in 1995. What I would like to do in this section is to take you through each novel quickly and point out the important things I think those novels teach.

The first novel, Dragon's Egg, published in 1981, came about very differently from the way most novels do. Most novelists start out wanting to write a specific story, and proceed to do so. Frank Drake and Larry Niven instigated this novel. It all started with an interview - article by Frank Drake, the astronomer. He also was a popularizer of science. In the interview, he pointed out that he liked to think of the idea of life on a neutron star as a way of teaching physics. The basic premise he was working on, was, "supposing there was life on a neutron star, what would it be like?"

If the star was made of neutrons, tiny creatures could live on it and have human qualities, if they were constructed of the same number of neurons as we have atoms. They would be visible to humans only through a microscope. That was the good basic idea, and it was a lot of fun. Larry Niven knew about that idea and was intrigued by it, especially about the idea of communication between humans and alien beings who live millions of times faster.

Back in 1972, I met Larry Niven and Jerry Pournelle. Jerry had written an article on black holes, in which he hypothesized that black holes, formed in a supernova explosion, would generate gravity waves so powerful they could kill people thousands of kilometers away. I had been just in the middle of the preparation of a scientific article which said the same thing. I was impressed with the scope of this science fiction writing. I called Ben Bova, who put us in touch, and they came out to visit me in 1973.

I had been collecting a lot of strange data about black holes, including Hawking's black holes, so I fed them all the information I had, hoping they could get a story out of it. In the process, I also fed them the idea of a laser-pushed lightsail to go to the stars. I admitted I had no way to stop the lightsail, but that did not bother them; they just pretended that there was such a way, and they used the idea in God's Eye.

Later, they were asked to prepare a summer course on "Science Fiction Meets Science". They did, and they put together a pretty good program of speakers including Poul Anderson and many others, and me. My top subject was the same old gravity stuff I had fed them already, but it added to the mixture and we had a nice time. At the party afterwards, Larry Niven said, "You know, I am intrigued with this idea of trying to write a story on this time difference, in these creatures' lives and ours." I pointed out that what Frank Drake probably had forgotten or was not aware of is, you cannot have an abrupt transition between a neutron star and vacuum, there must be some kind of atmosphere in between. When you go through the analysis, you find that there is a stable form of star formation, and the surface of a neutron star would be less dense than the interior, and more dense than the vacuum. It would be of white dwarf star material. Creatures made of it would be visible to the human eye, and about the size of a sesame seed.

I told him that I had learned a great deal about neutron star and white dwarf star physics, and that I could fix up a bible for him, which would describe what the creatures can and cannot do. It would describe what might be plants and what might be varmints, and then he could decide whether he could write a novel with it, or not. He said that was fine, and I wrote, quite quickly, some pages about that and brought them back to him.

Then Larry said, "I am right in the middle of writing Lucifer's Hammer with Jerry Pournelle, so why don't you write the first draft of a novel yourself?" I said "Great! I'll be a co-author with Larry Niven!"

I went off to write my first draft and brought it back. Larry said he was still too busy, and suggested I finish it myself. I did! I took it to Del Rey Publishing, in New York. Lester read it, and said it was good, but that it needed rewriting by someone like Larry Niven or Jerry Pournelle. But then he took pity on me, and wrote a fourteen-page, single-spaced critique of the whole novel. He told me that if I made those corrections to his satisfaction, he would buy the book. So I finished the manuscript and it finally got published.

An interesting side note to this, is that back in the 1960's, I wrote a letter to hal Clement suggesting a novel written about tiny little creatures living on the surface of the sun. He sent me a very polite "No."

The story of Dragon's Egg is straightforward. It is the description of life on a neutron star and the living creatures' interaction with a human crew in orbit around them. Wanting to be thorough, I first found a likely neutron star, which was easy enough. A neutron star always has a 10-kilometer diameter: any bigger and it would be a white dwarf; any smaller and it would be a black hole. It makes it easier when you know that the size of its mass is always one-and-a-half times the mass of the earth. I had very little leeway in terms of its construction. The problem from the point of view of plot, is, how do we get a neutron star to a place where humans can interact with it?

Well, it turns out that when a neutron star is made, it is made from a rapidly spinning star which is about to turn into a black hole. It has very strong magnetic fields in it. As it rolls around in space on its axis, the magnetic fields act like a fan, pushing on the plasma that exists around the star. So, normally, it is moving quite rapidly, because it has a propeller and also something to push against. After the star goes supernova, that energy is still in the star, and it still has magnetic fields which continue to accelerate the star in space. Some of the fastest objects in space are black holes and neutron stars which have been pushed up to 100 kilometers a second. This gave me the way to get the message to humans, and it also fixed the elements of the story.

For plot reasons, I wanted to have the neutron star coming straight at the earth or very close to it from the North Pole region. My first job was to find a place to hide the white neutron star all during history, and then reveal it in the story. I was able to find the spot in the constellation Pluto; that is the dragon constellation. So I titled the book Dragon's Egg because the neutron star had been laid by the constellation.

I next had to invent the biology of the creatures on the neutron star. I wanted them to be as smart as humans, but not super-smart, so I assumed that their total number of atoms equaled the total number of atoms in our bodies, which would make them about the same intelligence. This, combined with their density, gave them the size of a sesame seed.

Star Quake is the sequel to Dragon's Egg. The human crew, orbiting above the neutron star, succeed in communicating with the Cheela who live on the star's surface. Despite the fact that their lives are so short in human terms, the Cheela learn a great deal from the humans and rapidly out-develop them in technology, inventing wonderful things such as gravity catapults, most of which I invented. Then the star quake hits, and it is quite easy to recognize that this would be a tremendous energy explosion. My task was to find a way to save a few Cheela from the quake, which I did in three different ways. They were able to begin rebuilding a civilization, with the helpful advice of their human watchers.

My next novel was Rocheworld. It is quite long, and I built into the story several other planets, thinking that I might write some sequels.

The idea I was trying to present to the public, in Rocheworld, is that a world is not always round. You can have a stable world that lasts for eons, consisting of two spheres so close together that they resemble a dumb-bell. The two I invented share a common atmosphere, and the waters of one periodically flow to the other. I arranged this world-system configuration so that this double planet and another, larger one named Garganutua rotated around each other, and interacted geologically with each other, as they also rotated around the sun, Barnard's Star. I also invented a few other planets for the system, each with their own interesting problems of geology and biology. And I invented the flouwen, alien creatures who also participated in several of the sequels.

In Return to Rocheworld, I continued to explore the new discoveries of the humans among the islands and other features of the original planet, and also developed the idea that there would be more sequels. The crew was ready and able to explore some of those other planets. I planned to enlist some co-authors in these further adventures, particularly for describing the humans, and I persuades my wife, Martha, and one of our daughters, Julie Fuller, to take this on. I enjoyed the characters they created, but my editor, Jim Baen, was not pleased.

Ocean Under The Ice is the first new adventure, and I invented a watery world, to explain and examine the ramifications of life under water. I included under-water volcanoes, room-temperature oceans, and some very strange life-forms. The inter-connection between some of these life-forms meant inventing some new and interesting biology.

The next story takes some of the human crew and crash-lands them, permanently, upon another planet. This is Marooned On Eden. I wanted to do a sort of Swiss Family Robinson adventure, with the humans adapting and surviving. I also invented yet more interesting alien inhabitants on this world. This story grew quite large, and needed its own sequel, so that the characters could be allowed to develop and the story come to an end. The sequel was Rescued From Paradise, and my daughter Julie and I had some fun, and quite a few arguments, as we settled the fates of the characters.

My next novel was completely independent of the rest of them. It was Martian Rainbow. At that time, many people were spending a lot of time, money, and thought about trying to land on Mars. They were not realistic. I decided to begin with the premise that Russia had succeeded in landing on Mars before the US, and had colonized it. Then, in my story, as it developed around twin brothers who were both world-leaders, I could teach in an interesting way all the differences between the worlds, and how civilizations can grow with entirely different rules.

The next story, which is also independent of the others, is Timemaster. The objective I had in that story was to teach the reader about time machines. For the story, I invented a creature made of negative matter. Negative matter can also be used to make black holes, and the creatures were able to do that, and then go through them at unbelievable speeds, coming out into the future. They then made bridges of these time-warps, and traveled from future to past and back. At one point, I was able to arrange for one person to be in three different times of his life in the same place.

In my next novel, Camelot 30K, I gave myself the challenge of creating life-forms which could exist on distant worlds with a chlorine-based chemistry and no source of warmth. I used the crawfish as the model for my creature, and invented fungus and spores that could interact with it and build up a biology that produced energy through radiation.

They finally developed a civilization, and communicated by electronic magnetic vibration of their antennae. Their interaction with humans is illuminating for both species.

Saturn Rukh is the name of my last novel. It is primarily an exercise in the possiblity of life on Saturn. Back in 1961, I wrote my very first story on the planets in their order. I was intrigued, even then, by Saturn, which is two-and-a-half times the size of earth, but is mostly gaseous. I learned that something the size of humans could float comfortably in balloons in the upper atmosphere of the planet. Further, if clad in a wet suit and with an adequate supply of oxygen, a human could dive into the interior of the planet and eventually reach a stage of equilibrium in which the gravity would be just like earth's, and so would the temperature. The atmosphere, of course, would be mostly ammonia and other harsh substances, so the explorer would need full space-suit equipment.

So I had my human explorers do just that, and sent them descending into the unknown, searching for helium as a mission, and not expecting to find any form of life. to their surprise, they find many, mostly variations on the idea of balloons and jellyfish, which I invented and which the crew can establish communication with. Once again, cooperation leads to mutual benefit.