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Excerpt
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Introduction

1 Preface

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The past few decades have been characterized by the rapid development of astronomical polarimetry that has resulted from the following developments, often originating through the joint efforts of international teams:

(1) new polarimetric instrumentation and techniques, including imaging and long-slit spectro-polarimeters of high accuracy and sensitivity;
(2) new theories allowing sophisticated modeling of the polarimetric characteristics of a variety of astronomical objects;
(3) theoretical simulations that have been complemented by laboratory studies of polarization from simulated cosmic materials and particles, including experiments in microgravity conditions to provide a realistic cosmic environment;
(4) unique results produced by polarimeters on board spacecraft and space telescopes, used to explore our solar system.

Such advances have aided the exploitation of polarimetry in areas ranging from solar system bodies to exoplanets and allowed the development of completely new fields of polarimetric exploration such as cometary nuclei, icy satellites, transneptunian objects, protoplanetary and debris disks, and applications in astrobiology.

The year 1974 was a special year in the history of astronomical polarimetry. It was the year the book *Planets, Stars, and Nebulae Studied with Photopolarimetry* was published by the University of Arizona Press, and became the main reference book for several generations of scientists; and it can still be found on the desks of those who use polarimetry in their work, in particular astronomers. This book helped to support the rapid increase in the use of polarimetry over the last several decades and has become an invaluable tool in many areas of remote sensing. The editor of this outstanding book was Tom Gehrels, who made many important contributions to the field of polarimetry, both instrumental and observational. Tom was a very active and productive scientist to the very last day of his life that unexpectedly ended on July 11, 2011. At Tom's memorial service, his contribution to astronomy and the lasting impact of his book were discussed by many of those present. It was recognized that the progress in astronomical polarimetry since 1974, was so large that it was timely to publish a new book that would cover achievements in the field since that time. The book that you are reading now is an attempt at a modern "reincarnation" of the book *Planets, Stars, and Nebulae Studied with Photopolarimetry* and is dedicated to the memory of its editor, Tom Gehrels.

After this Preface, the book starts with a biographical essay that describes the life and achievements of Tom Gehrels. It was written by Tom's sons, daughter, and widow, whose contribution to and support of this book we highly appreciate.

Although such decisions are difficult, it was decided that the book would concentrate on our galaxy, including the solar system, and would largely be limited to optical and IR astronomy, although some results of submillimeter polarimetry are also covered. This is not to argue that polarimetry has not played a major role in extragalactic astronomy and at all wavelengths, but rather that it was necessary to keep the book within manageable proportions. The twenty-four following chapters were written

Polarimetry of Stars and Planetary Systems, ed. Ludmilla Kolokolova, James Hough and Anny-Chantal Levasseur-Regourd. Published by Cambridge University Press.

by fifty-five different experts in the field, from at least twelve countries in the world. Each chapter was carefully reviewed by at least two experts in the field.

The first section of the book is dedicated to the fundamentals of modern polarimetry, the developments in theory, instrumentation, and laboratory simulations.

The second section covers polarimetric studies of stars at different stages of their evolution, including star-forming regions, and objects that are associated with stars, for example circumstellar disks and interstellar dust, and a chapter on stellar magnetic fields.

The next section of the book focuses on our solar system and includes chapters on the Sun, planets, small bodies (planetary satellites, asteroids, comets, transneptunian objects), and interplanetary dust.

The last section introduces the new fields of exoplanets and astrobiology.

Finally, we present some definitions that are particularly relevant to a number of the chapters, with references to other texts where the reader can find more lengthy treatments of the basic principles of polarimetry.

We hope that the book will be of interest to all astronomers who work in the field of astronomical polarimetry and, for those that don't, they will see, after reading the book, how their astronomical observations would greatly benefit from including polarimetry. We believe that the book will be especially valuable to graduate students, postdocs, and young scientists, as it presents both a broad review of instrumentation, theory, computer and laboratory modeling, and detailed results for a number of astronomical objects. We also hope that the book is a valuable source of information beyond its astronomical applications, especially in geophysics, atmospheric science, optics, and even biomedical research and wherever polarimetry is used for remote sensing.

We would like to thank the many authors for their contributions to this book and to the external reviewers of each of the chapters. We have been very impressed by the consensus reached by co-authors working from different institutes and often different countries. We were extremely happy to work with them, and thank them for their dedication and patience.

2 The life of Tom Gehrels

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George E. Gehrels, *Geology Department, University of Arizona, Tucson, AZ, USA*
Jo-Ann Gehrels, *Phoenix, Arizona*
Aleida J. Gehrels, *Tucson, Arizona*

Page, Arizona, is not known as a launch site for high-altitude research balloons, but that is where Tom Gehrels was with his polariscope balloon payload in 1968. The National Scientific Balloon Facilities (NSBF) team was testing balloon launches in Page, trying a new technique of inflating the balloons in the wind-quiet spot in Glenn Canyon just below the new Glenn Canyon dam. The bubble is released and carries the payload straight up until it rises out of the canyon where it catches the wind above … hopefully not blowing hard enough to slam the payload into the side wall on exit!

Polariscope was an instrument to measure the polarization of solar system bodies and interstellar dust grains. It was a prototype for an instrument on the Pioneer spacecraft to fly-by the major planets in the 1970s. It was an innovative instrument that detected weak polarization with a rotating polarimeter that scanned repeatedly across the object of interest.

It flew four times successfully, providing solid engineering proof of concept. Still, the Pioneer proposal was a long shot since Gehrels and his team did not have previous spaceflight experience. In the end, it was successful based on the ingenuity of the design and balloon test. Interestingly, this polarimeter turned out to be the only imaging instrument on Pioneers 10 and 11 and so made popular headlines for producing the first in situ pictures of Jupiter and Saturn.

The Gehrels story leading to Tucson and polarimetry is a fascinating one, known to many through his autobiography *On the Glassy Sea* (Gehrels 1988). Tom (Anton M. J.) was born in 1925, as the youngest of five children, on a large wheat and potato farm in the Haarlemmermeer polder, not far from Amsterdam. When he was a teenager, one of his older brothers inherited the farm and his family moved away from the polder, settling in the city of Baarn, a suburb of Amsterdam. His father became a well-to-do banker and businessman as well as an important leader of the Dutch Reformed Church.

Gehrels was fifteen when World War II broke out, undoubtedly the most dramatic event that changed his outlook on life for good. From the moment the Germans occupied the Netherlands, young as he was, he joined the Resistance and participated in spying on German military maneuvers. What helped him was that he looked like a kid, younger than his age, so that he could ride his bike everywhere without being picked up by German soldiers. However, things became much more serious a few years into the occupation, in 1943, when his oldest brother, Cornelis, an engineer at the electronic firm Philips in Eindhoven, was picked up by the Germans. Cor also belonged to the Resistance and his job was to illegally distribute food coupons to families who hid Jews in their homes. He was betrayed and immediately taken to a Dutch prison from where he was transported to the infamous German concentration camp of Dora Nordhausen where the prisoners were forced into working on von Braun's V-2 rockets. He died in the camp on April 1945, a few weeks before the end of the war. He left Grietje, his wife, and eight children behind. Gehrels named his oldest son

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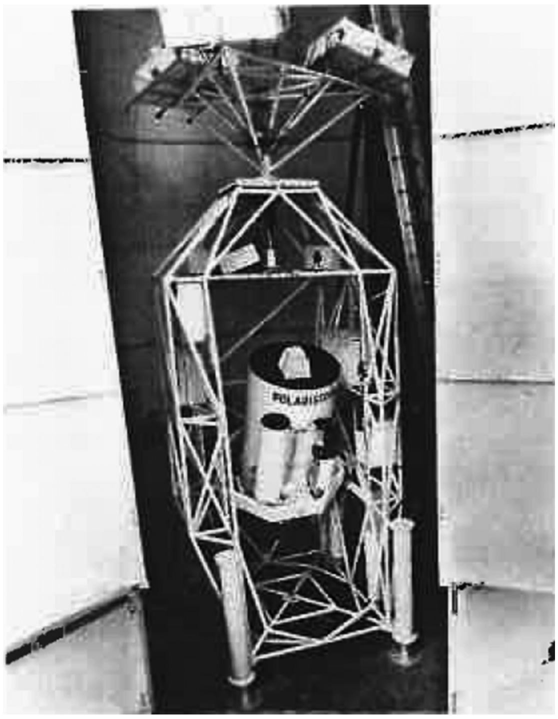

FIGURE 2.1 Polariscope balloon payload, 1965.

Cornelis in honor of his brother (author NG, now going by the name Neil).

From the moment Tom found out about his brother's capture, he decided to escape from Holland and cross over to England. His idea was to train as a paratrooper and jump into Germany to reach Cor's concentration camp. He prepared his escape by taking private lessons in English, French, and Spanish because he planned to ride his bike through Belgium, France, and Spain. At this time, the allies had reached Brussels and Antwerp but the Germans were still holding the bridges over the rivers Rhine and Maas near the Belgian border. Gehrels waited until dark and walked his bike across the front line avoiding being stopped by the enemy.

He kept going southwest, in the direction of France, meeting British troops who were too busy to pay attention to a Dutch kid on a bike. He reached Cherbourg on the French coast where he met a Dutch captain who allowed him to sail across on his ferry. It turned out that the more difficult part came when Gehrels arrived in England. Without proper identification and not knowing anyone in England, how would the British military know that he was reliable and not a Nazi spy? After weeks of stern interrogations, he was finally allowed to join British Special Operations, as part of British Intelligence, where he was trained to parachute back into Holland and make contact with the Dutch Underground. By means of radio, he would be able to transmit information from the Dutch Underground that had been actively spying on German military advances. After several jumps into different parts of the Netherlands, but never into Germany, the war came to an end and the Germans marched out of Holland exactly five years after they had marched in.

Gehrels flew back to London, but the war was not yet over for him. He and another twenty Dutch volunteers signed up to do the same type of intelligence in the Far East against the Japanese. The troops ended up in Indonesia, in the city of Hollandia on the island of New Guinea. Unfortunately, this military effort coincided with the Dutch Government's decision to resist a movement in Indonesia to fight for independence. The paratroopers in New Guinea (all Dutchmen) were recruited but, since they had just been part of the liberation of their own country, some of them requested permission to leave New Guinea and be excused from fighting against the Indonesians. Permission was granted and Gehrels returned home.

It took almost a year to get back into normal life. Gehrels struggled with loneliness, uncertainty about his religious beliefs (he had earlier left the Calvinistic church), and his future. He eventually decided to pursue his passionate interest in astronomy and entered the University of Leiden as an undergraduate, studying under the well-known professor, Jan Oort. A new world opened for Gehrels; he considered the staff and students as his new family, loved the difficult tasks and tests, and became fascinated with the structure of the Milky Way (many family camping trips were spent watching our galaxy under brilliantly clear Arizona skies), and of the motions of planets and stars.

While studying in Leiden, the largest telescope in the world, the 200-inch reflector at Palomar Mountain in California, was put into operation and it became Gehrels's dream to visit it. In 1950, a year before finishing his undergraduate classes, he took a month-long trip to the US to explore possibilities and visit Palomar Mountain. It was a hitchhiking trip following his "rules of the road" that included a clean appearance and a large sign giving his destination. The sign read "Holland To California," and he had no trouble getting rides.

He was dropped off at the bottom of Palomar Mountain one clear evening and started walking up the long road. Late at night, a single car came by and gave him a ride. It was Hap Mendenhall, one of the ranchers on the top of the mountain and a great supporter of the observatory. Gehrels was driven straight up through the back gate and to the house of the sleeping observatory superintendent,

FIGURE 2.2 Tom Gehrels hitchhiking, 1950.

Byron Hill. In spite of the late hour, he was welcomed and stayed for several days becoming good friends with Hill. The 200-inch is called the "Hale telescope" after the founder George Ellery Hale. When Gehrels's second son was born in 1956, he was named George Ellery Gehrels (author GEG).

After such a fine introduction to American astronomy, Gehrels was hooked on returning to the US for future studies. He managed to finish his undergraduate degree a year early, married in 1951 to Aleida Joanna Gehrels (author AJG), and arranged immigration papers for the US. His graduate work was done at Yerkes Observatory of the University of Chicago. Gehrels was soon the graduate student of Gerard Kuiper making brightness measurements of asteroids. The light curves were puzzling, showing non-linearity of the brightness with phase angle. He took detailed observations with a newly available photometer through the entire rotation of a bright asteroid to find the solution. He discovered that the brightness had a sharp peak near full phase when the asteroid surface is viewed straight on, the so-called "opposition effect" or opposition surge (Gehrels 1956). It is still not well understood and several mechanisms, among them the absence of shadows at full phase (shadow-hiding effect) and interference at multiple scattering (coherent-backscattering effect), are discussed in this book (Chapters 7 and 18).

Gehrels's postdoc was at the University of Indiana in Bloomington working with Frank Edmondson and Dee Owings on minor planets. He developed an interest in dust grains, both in the solar system and interstellar space, and came up with the idea that polarization measurements could be a sensitive new probe of dust. Since dust grains would absorb and scatter light, any resulting polarization could give information on their shape, size, and composition.

A photometer was obtained from Yerkes and converted to the "Minipol photopolarimeter." With the help of Tom Teska and electronics engineer Bob Weitbrecht, its capabilities were expanded to perform the polarimetry measurement in various filters to give wavelength dependence. The first night of operation in 1959 on the 82-inch at McDonald Observatory gave tremendous results with polarization observed from many objects including interstellar grains, the Moon, and Venus. The next years were filled with great excitement as many new polarimetric observations were made, papers written, and talks presented.

In 1960, Kuiper moved to the University of Arizona and founded the Lunar and Planetary Laboratory. Gehrels soon joined him there as an associate professor, straight away with tenure. He continued observations of polarization culminating in a series of papers in the *Astronomical Journal* on the wavelength dependence of polarization of various objects (e.g. Gehrels *et al*. 1964). These were the early days of space research and he became fascinated with the idea of flying a polarimeter on a spacecraft. After consulting with Roger Moore at NASA, he decided that a sub-orbital balloon test flight would be crucial for eventually winning a space flight instrument.

These were early days of scientific ballooning in the US and the first idea Gehrels had was to fly himself in the gondola operating the telescope and polarimeter. Real science could be done flying above most of the atmosphere and observing in the UV band that is blocked by the air. He did an actual test flight at 7000 ft in an open gondola under a helium balloon from Minneapolis to Oshkosh accompanied by a Navy pilot and doctor. It was indeed possible to point the telescope and make observations. The next step was to be a flight in pressurized suits at 100 000 ft. After a meeting with the Navy in Washington, it was decided that Gehrels could not go on the first high-altitude flight, but the Navy personnel would operate the telescope. A test flight occurred, launched off an aircraft carrier, and achieved an altitude record of 103 500 ft for manned ballooning. But then disaster struck when, on recovery, the Navy doctor, Victor Prather, fell from a hoisting sling into the ocean and drowned.

Gehrels decided to go the route of building a fully autonomous balloon payload with gondola, telemetry, telescope, and instrument. It was a large engineering project at the University of Arizona to build the new polariscope. It was a 28-inch telescope, making polarization measurements at 225 and 275 nm in the UV band. The system was completed by 1964 and then flown successfully four times from Page, Arizona, and Palestine, Texas. It was real adventure science with tricky balloon flights and operations. In one famous episode, the balloon was launched from Page and then drifted in the dangerous direction toward the Grand Canyon. When the preset timer cut the payload loose from the balloon, the gondola came down on its parachute directly over the canyon. At the last minute, a low-attitude wind caught the parachute and pushed it away from the canyon to land in the desert on the South Rim.

Scientifically, the polariscope provided the first UV polarization measurements of Venus and dust grains. From a technical standpoint, the project was a flight proof of the instrument and established Gehrels and the University of Arizona as a capable team for building flight instruments.

The proposal for an instrument on Pioneers 10 and 11 was submitted to NASA in 1968. Gehrels was the principal investigator for the imaging photopolarimeter (IPP). A partnership was formed between the University of Arizona and the Santa Barbara Research Center in California, an affiliate of the Hughes Aircraft Companies, to produce the instruments. The Pioneers were designed to be pathfinders for the later Voyager spacecraft. They were simple and low weight and were planned without imaging cameras, which were to follow on Voyager. The beauty of the IPP is that it could produce images through a scanning technique with an instrument that weighed only 4.2 kg. The instrument had a 2.5 cm telescope and performed polarization measurements in the blue and red spectral bands. It imaged the sky using a novel spin-scan technique that took advantage of the spinning Pioneer spacecraft. The Pioneer instrument performed photopolarimetry of the atmospheres of Jupiter and Saturn and gave unique information on the aerosols and molecules. It is best known for providing the first in situ pictures of the giant planets. It was a remarkable success.

Gehrels had a keen interest in asteroids going back to his graduate days with Kuiper and the discovery of the opposition effect. His interest continued throughout his career and he spent many nights on telescopes in Texas, California, and Arizona making asteroid observations

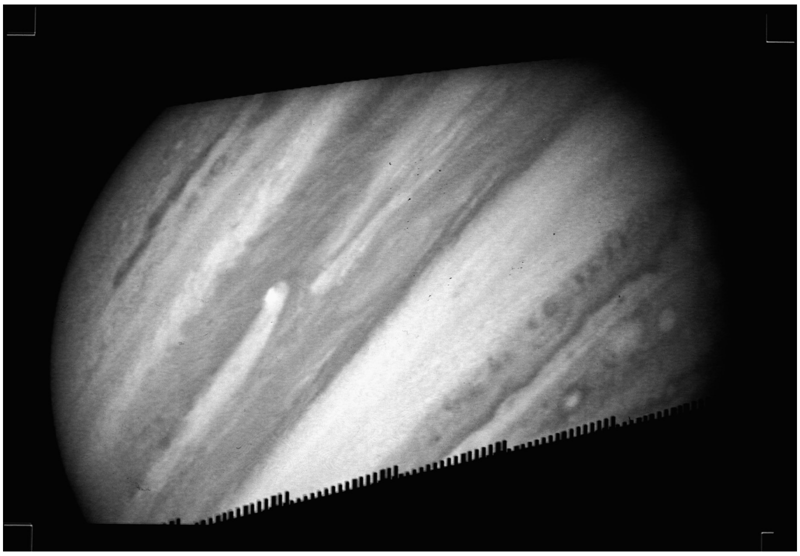

FIGURE 2.3 Image of Jupiter from IPP.

(e.g. Gehrels 1957; Gehrels and Tedesco 1979). Using the Palomar 48-inch Schmidt telescope he and Ingrid and Cornelis van Houtens performed a sky survey for moving objects and discovered over 4000 asteroids. He was one of the early scientists to recognize the dangers of near-Earth asteroids to our planet and to propose that surveys be performed to find objects with threatening orbits.

In 1981, Gehrels and Robert McMillan proposed to NASA building a dedicated Spacewatch Telescope for such survey work. It would have a wide field of view and use charge coupled device (CCD) detectors instead of photographic plates. A novel idea was proposed to scan the sky at exactly the rate of frame transfer on the CCDs and continuously read them out to avoid the loss of observing time to the read-out. The technique was called "scannerscopy" (Gehrels 1991). The eventual goal was to build a 72-inch telescope, but the proposal was first funded to test the scan technique on the 36-inch Steward telescope built in 1919. The original telescope had been planned by Andrew Douglass at the University of Arizona and was funded by Lavinia Steward, so the observatory on campus became the Steward Observatory. The telescope was sited on campus for many decades and then moved to the new Kitt Peak National Observatory in 1962. Through a large fund-raising effort and further proposal, the 72-inch version of Spacewatch was eventually built and saw first light in 2001. It is a beautiful dome and telescope on Kitt Peak and continues its discovery work to this day.

Gehrels also founded and was the first editor of the well-known Space Science Series of books, which is still published by the University of Arizona Press. Large reference books were written on different planets and objects in the solar system, with authors working together on chapters in their area of expertise. The books can be found on the bookshelves of planetary astronomers throughout the world.

Travel, lectures, and teaching were areas of great interest to Gehrels. He traveled to universities around the world, on many occasions with daughter Jo-Ann (author JG). Each fall, he taught an undergraduate course for non-science majors at the University of Arizona and, each spring, he gave that course at the Physical Research Laboratory in Ahmedabad, India, where he was a Sarabhai Professor. His recent research interests were in universal evolution and that was a key subject of his classes and lectures between 2000 and 2011. He was winner of the 2007 Harold Masursky Award for his outstanding service to planetary science. Gehrels passed away on July 11, 2011, at the age of 87, while still working full time as a professor in the Lunar and Planetary Laboratory.

FIGURE 2.4 Gehrels at the Spacewatch telescope, ca. 2002.

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