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Summary of a Life in Observational Ultraviolet/Optical Astronomy Postprint

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Abstract

I reminisce on my early life in Section 1; on my education in Sections 2 and 3; on the years at Princeton as a research astronomer in Section 4; on the years on the faculty at Chicago in Section 5; on research on Diffuse Interstellar Bands (DIBs) in Section 6; on construction of the 3.5 m telescope at Apache Point Observatory (APO) in Section 7; on work on the Sloan Digital Sky Survey (SDSS) in Section 8; on work in public education in Chicago in Section 9; and on my travels in Section 10. My main science research is of an observational nature, concerning Galactic and intergalactic interstellar gas. Highlights for me included my work on the orbiting telescope Copernicus, including the discovery of interstellar deuterium; early observations of absorption associated with five-times ionized oxygen; and discoveries concerning the phases of gas in the local interstellar medium, based on previously unobservable interstellar UV spectral lines. With other instruments and collaborations, I extended interstellar UV studies to the intergalactic cool gas using quasi-stellar object QSO absorption lines redshifted to the optical part of the spectrum; provided a better definition of the emission and morphological character of the source of absorption lines in QSO spectra; and pursued the identification of the unidentified DIBs. For several of these topics, extensive collaborations with many scientists were essential over many years. The conclusions developed slowly, as I moved from being a graduate student at Chicago, to a research scientist position at Princeton and then to a faculty position at Chicago. At each stage of life, I was exposed to new technologies adaptable to my science and to subsequent projects. From high school days, I encountered several management opportunities which were formative. I have been extremely fortunate both in scientific mentors I had and in experimental opportunities I encountered.

Full Text

Preamble

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Summary of a Life in Observational Ultraviolet/Optical Astronomy

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Abstract

I reminisce on my early life in Section 1; on my education in Sections 2 and 3; on the years at Princeton as a research astronomer in Section 4; on the years on the faculty at Chicago in Section 5; on research on Diffuse Interstellar Bands (DIBs) in Section 6; on construction of the 3.5 m telescope at Apache Point Observatory (APO) in Section 7; on work on the Sloan Digital Sky Survey (SDSS) in Section 8; on work in public education in Chicago in Section 9; and on my travels in Section 10. My main science research is of an observational nature, concerning Galactic and intergalactic interstellar gas. Highlights for me included my work on the orbiting telescope Copernicus, including the discovery of interstellar deuterium; early observations of absorption associated with five-times ionized oxygen; and discoveries concerning the phases of gas in the local interstellar medium, based on previously unobservable interstellar UV spectral lines. With other instruments and collaborations, I extended interstellar UV studies to the intergalactic cool gas using quasi-stellar object QSO absorption lines redshifted to the optical part of the spectrum; provided a better definition of the emission and morphological character of the source of absorption lines in QSO spectra; and pursued the identification of the unidentified DIBs. For several of these topics, extensive collaborations with many scientists were essential over many years. The conclusions developed slowly, as I moved from being a graduate student at Chicago, to a research scientist position at Princeton and then to a faculty position at Chicago. At each stage of life, I was exposed to new technologies adaptable to my science and to subsequent projects. From high school days, I encountered several management opportunities which were formative. I have been extremely fortunate both in scientific mentors I had and in experimental opportunities I encountered.

Key words: Interstellar Medium (ISM) – Nebulae – (galaxies:) quasars: absorption lines – ultraviolet: stars

1. Early Life

I was born in 1944 to Virginia Maxine (Huntwork) York (b.1921–d.2011) and Maurice Alfred York (b.1917–d.1953) and had two sisters, Carolyn (b.1946–d.2019) and Diana (b.1951). I grew up in Shelbyville, Illinois, almost exactly at the center of the state. It is a small farming town with little industry. When I visited at age seventy for my mother's burial, the main changes that I noticed had occurred in the intervening 60 yr were a few small restaurants and shops, a Dixie cup factory and a flood control dam that made a new recreational lake, Lake Shelbyville.

My mother was a housewife and my father was an accountant. They jointly ran a floral shop. I lived within walking distance of the Kaskaskia River and sometimes walked there to pick up arrowheads and fossils on the riverbank. Those items were my first knowledge of an earlier indigenous civilization on Earth, and I was fascinated.

My father died when I was eight years old and my family moved to Terre Haute, Indiana, where my mother's parents lived. We lived with my grandparents for a year, then moved to a home a few blocks away. For the rest of her life, my mother was a secretary.

My life during grades 5–9 was moderately uneventful. My male role-model was an uncle who provided me early access to a wood shop and a dark room. He and his wife provided us with music lessons. I owe Uncle Russell McCoy (b.1917–d.1991) a deep debt of gratitude for taking over as a surrogate father. I did well in school and had no doubt I would go to college, but I do not recall a particular interest in science in grades 1-9.

Wiley High School (grades 10–12, Class of 1962, 235 students) was more interesting. I continued to do well in school and became interested in physics, chemistry and economics, largely because of three outstanding teachers. I was one of five valedictorians. I played football for three years. But the access to advanced math courses at Wiley was limited and my preparation for college was not exceptional. I applied for admission to undergraduate school to Wabash College, a few miles away from Terre Haute, and to the Massachusetts Institute of Technology (MIT), in Cambridge, Massachusetts. I was admitted to both. I matriculated to MIT in 1962, majoring in physics.

Throughout my life, I was afforded many opportunities to manage non-academic organizations in which I was involved, a theme that will occur throughout this article, each of which involved more and more responsibility and contributed to skills I needed later in life. The first of these was management of a boy scout camp, Camp Krietenstein, near Poland, Indiana, where I worked for seven years, in the summers, during high school and college.

A major consequence of the Krietenstein experience was meeting my wife, Anna. I managed the camp at the end of a few summers for a church organization that rented the camp, that she attended. At the end of my experience there, we

realized we were interested in each other. We each went our separate ways to college and were married after I graduated from MIT (1966 June).

2. Massachusetts Institute of Technology (MIT) (1962–1966)

MIT proved to be a very challenging educational experience, given my lack of preparation and the very high level of competition from students from among the best secondary schools in the world. I was in my junior year before I started to be able to compete. I selected a physics major from the many choices available at MIT but did not focus on any particular area of physics. For a senior thesis, I worked with Prof. James Overbeck on a balloon payload to detect cosmic radiation with a very large sodium crystal.

Other interests that caught my attention at MIT included concentrated humanities activities, including taking three years of humanities in French, learning Italian, reading Dante in the original and studying the works of James Joyce. I also played rugby for four years and in that activity met David Schramm (b.1945–d.1997), who was one year behind me in college, and was a national champion wrestler for MIT, well-built to be my scrum partner. We both ended up as astronomers and were on the University of Chicago (UC) faculty together for fifteen years (1982–1997). We had overlapping science interests that frequently brought us together, as will be noted later. He was the department chair when I was hired in 1982.

The management activity in which I was involved at MIT was working to make extra money in the Ashdown Graduate House Dining Hall for four years. I managed student staff activities, serving banquets and dining hall meals, and ran a snack bar.

3. University of Chicago Department of Astronomy and Astrophysics (1966–1970)

In the rest of this reminiscence, I will have occasion to use common acronyms, astronomical terminology, dates and names of individuals. For names of instruments, astronomical objects and institutions, I explain the acronyms on first use. Here, I list acronyms used repeatedly. ISM: interstellar medium; LISM: local interstellar medium (material within a few hundred parsecs of the Sun); LSR: local standard of rest; MW: the Milky Way galaxy; spectral regions: XR: X-ray; UV: ultraviolet; IR: infrared. QGPs: quasi-stellar object (QSO)/galaxy pairs. When multiple wavelengths are quoted together, the string of wavelengths is preceded by “ $\lambda\lambda$.” Wavelengths of light are given in Angstrom units ($1 \text{ \AA} = 10^{-8} \text{ cm}$). Wavenumbers are used to express the number of waves per centimeter (cm^{-1}) in light radiated between closely spaced energy levels in molecules (equivalent to expressing the energy difference between the identified levels.) Various uses of astronomical terminology and definitions that will be useful to the reader are detailed here. Bright stars are referred to by their Bayer names (Greek or

Roman letters preceding three letter constellation abbreviations) or Flamsteed names (numbers, preceding constellation abbreviations) and fainter stars are referred to mainly by their number from the Henry Draper (HD) Catalogue (Cannon & Pickering 1924). A few stars are referred to by their notation in the Bonner Durchmusterung (BD) Catalog (Argelander 1863).

The notation $N(X)/N(Y)$ refers to the ratio of column densities of elements X and Y , for instance, $N(D)/N(H)$. The notation $[X/H]$ refers to the abundance of element X with respect to total hydrogen (log scale, $H = 12$). The fraction of total hydrogen that is molecular (H_2) is denoted as $f(H_2)$, where $f(H_2) = 2N(H_2)/[N(H\text{ I}) + 2N(H_2)]$. Different ions of single elements are denoted by element symbols followed by the ionization stage (e.g., N I, N II, N III). Emission lines are denoted by brackets around the element symbol (e.g., [N I], [N II], [N III]). The phases of the Sloan Digital Sky Survey (SDSS) are referred to as SDSS I, II, III, IV and V (through 2025). Individual data releases are referred to as DR1, 2, 3, etc.

Several types of light filters are noted in the text. The special glass filters in the SDSS camera are denoted by u' , g' , r' , i' , and z' . The range of light passed by each is often denoted by u -band, g -band, r -band, i -band or z -band. It took several years to establish the calibration of the natural system for the 2.5 m SDSS telescope. Once that was done, as described in Section 8.9, the magnitudes of objects were denoted by u, g, r, i, z . In the earliest SDSS papers (before publication of DR1 in 2003 October) the filter destinations sometimes had primes and sometimes asterisks, for various reasons. Other filters used in other projects are denoted B, V . The central wavelengths and FWHM of the filters are described in the text on first use and by Fukugita et al. 1996.

Dates in parentheses after names of individuals are birth and death dates, which I insert for individuals with whom I worked closely. Dates in parentheses after events or institutions refer to the period I was employed there. I refer to a number of individuals with whom I collaborated. I include titles or positions, depending on context. In some cases, I include first and last names, at least on first use. When referring to the same individuals later, I refer to them by last name or first name only, depending on how well I knew them. I include references to other work to frame the context of my contributions.

3.1. Graduate School at the University of Chicago

I was admitted to the UC graduate school in astronomy, where, at the time (1966), students were taught in bucolic Williams Bay, Wisconsin at Yerkes Observatory on Geneva Lake. My wife and I spent three and a half years there. I commuted to the main campus in Chicago for selected courses during my second year of classes. I count my captivation with astronomy, most of my later opportunities in astronomy and my lifelong career in astronomy as stemming from the years at Yerkes. After I joined the Chicago faculty in 1982, Anna and I made frequent, relaxing weekend trips to Williams Bay from Chicago, which sadly

ended when the Observatory ownership was transferred to a private foundation.

Most of the courses at Yerkes were taught by full professors who lived in Williams Bay. There was great ambiance between the faculty, students and staff, who were happily in the situation of being in a small community, sharing in sailing outings, field games, Friday night fish-fries and holiday events. I knew all the faculty well and collaborated with several of them after I returned as a faculty member. Those student days were wonderful.

At various times in the last 60 yr, my fellow researchers have talked about “the current golden age of astronomy.” During the 1960s, and into the 1970’s, several unanticipated astronomical discoveries would certainly have merited that description. Examples that most impressed me at the time: quasars, pulsars and the numerous new ISM molecules, made up of more and more atoms, that were continuously being discovered. Unidentified IR emission bands (UIBs), between 3 and 11 μm were found in the late 1960s. Persuasive evidence for the existence of dark matter as a major constituent of galaxies was presented. Binary XR sources were found by satellites in space and some were eventually interpreted as containing likely black holes. New Earth satellites continued to open windows on previously unknown aspects of space astronomy. Gamma-ray bursts (GRBs) were discovered in 1967 (but confusion over their solar system or extra-solar system nature prevented their general astrophysical nature from being revealed until 1973). The advent of fast computers led to the emergence of an overall stellar evolution sequence (thanks in large part to Professor Martin Schwarzschild (b.1912–d.1997), complete with stellar ages, which, of course, were to be refined over the next 50 yr. These are just a few examples that created opportunities for astronomy graduates in the 1960s and enabled us to enter exciting new fields. Of the listed new fields, space astronomy, dark matter and quasars most affected my later life.

Professor C. Robert Odell was the Department Chairman when I was at Yerkes. I worked with him as a summer observer of emission line nebulae before I started classes in 1966. I worked with him on a National Science Foundation (NSF) Traineeship and some National Aeronautics and Space Administration (NASA) grants and he was my advisor. O’Dell was chosen as the first Project Scientist for the Space Telescope, launched by NASA, later named the Hubble Space Telescope (HST). He left Yerkes soon after I did. My other research experience (pre-thesis) at Yerkes was taking astrometric plates using the 40 inch refractor, for Professor William Van Altena.

Other major influences from Yerkes in the late 1960s included Professors William Morgan (b.1906–d.1994), Lewis Hobbs, Nelson Limber (b.1928–d.1976), Peter O. Vandervoort (b.1935–d.2020) and Richard Miller (b.1926–d.2020). Nelson Limber was uniquely helpful to me through a period of low confidence during which I was not sure I was cut out for a career in astronomy. He convinced me to keep on an astronomical career path.

3.2. Thesis

For my thesis, O'Dell and I settled on the topic of “Structure in the Interstellar Extinction Curve.” Reddened stars display what is known as an extinction curve, generally showing the increasing attenuation of light at shorter and shorter wavelengths by “interstellar dust.” It was thought by most astronomers (but not all) to be caused by scattering and absorption arising from dust grains in the ISM lying between the Earth and the targeted star. The optical extinction curve (decreasing extinction versus increasing wavelength, 3500 to ~ 10000 Å) had been known for years (Greenstein 1938) to have a predominantly $1/\lambda$ shape. This shape could be revealed by dividing spectra of reddened stars by spectra of unreddened stars of matching spectral type. There were indications in the literature of weak, poorly delineated features (structure in emission and absorption) that might provide clues to the nature of the attenuating material. I wanted to document subtle structures in that curve, in hopes of identifying the nature of the material. As will be clear by the end of the article, this issue was not settled by 2023. The IS extinction curve provided me with an introduction to the long-standing mystery of the Diffuse Interstellar Bands (DIBs), discussed more thoroughly in Section 6 of this Reminiscence, to which I devoted extensive effort later in my life. The DIBs are a set of hundreds of unidentified IS absorption lines which may be related to the IS extinction curve.

The nature of that “dust” (variously called grains or “soot”) might in fact have been a mix of solid, 1000 Å particles; smaller grains; small molecules; or large molecules. Estimates of the mass of the attenuating material were uncertain, as the nature of the material was not known. The color excess, $E(B - V)$, had to serve as a surrogate. The color excess of a stellar object indicates the amount of extinction in space between an astronomical object and Earth. It is based on measurements of the apparent magnitudes in two broad band filters, denoted B and V . B has an effective wavelength of 4384 Å and effective FWHM of 1008 Å. V has an effective wavelength of 5437 Å and an effective FWHM of 826 Å. Indicating the magnitudes B_r and V_r of a reddened object and similarly B_u and V_u of an intrinsically identical unreddened object as $E(B - V) = (B_r - V_r) - (B_u - V_u)$ yields an indication of how much interstellar extinction exists between the Earth and the object.

By the time I finished my first year of courses, a new 41 inch reflecting telescope had been installed at Yerkes, with a new spectrograph, meant to accommodate the electronic image tubes that were destined to replace photographic plates. O'Dell obtained a new Carnegie image tube, but the expected speed gain over bare photographic plates did not materialize for this device. I took advantage of the large amount of telescope time available to me and some excellent weather by using the time to take multiple exposures of my target stars, to increase the signal-to-noise ratio (S/N) of my spectra. I took an average of five spectra for each star. I modified a Gaertner microdensitometer to produce output of the photographic plate scans on paper tape, stacked the set of exposures for each star and analyzed the resulting data on an IBM 1130 computer, at Yerkes.

The total visual extinction, $A_V \sim 3 \times (E(B - V))$, ranged from 0.87 to 4.08 for the reddened stars and from 0.00 to 0.30 for the unreddened comparison stars. Three pairs of unreddened stars were included as a check on the basic methodology.

The digitized multiple spectra of each of the twelve reddened stars were added point by point. The unreddened stars were likewise added together and divided into the spectra of the appropriate reddened star for which we wanted the extinction curve (each pair had to be aligned in wavelength so the nearly identical spectra lines in each pair canceled in the division). This resulted in multiple extinction curves for each pair. These were averaged to produce twelve high S/N extinction curves, nearly free of the effects of the thermal continuum and the stellar lines of the stars themselves. The extinction curves could then be compared for similar features. Producing the extinction curves was my first experience with any type of electronic computing. The IS extinction curve was known to extend throughout the visible spectrum. The photographic plates I had (Kodak emulsion types 103aF and 103aO) gave adequate spectral coverage for the project but were notoriously non-linear in sensitivity. The spectral sensitivity varied somewhat with the chemicals used for developing the plates and the particular bath of chemicals in which each plate was developed. Calibration of the sensitivity of each exposed and developed plate was thus critical to the derived shape of the extinction curve. Lacking the precise calibration techniques that became available later with fully electronic detectors, the best that could be done with the equipment and materials at hand was to expose a pattern of light spots of known relative intensities onto a plate with the same type of emulsion used for the stellar spectra of interest for that night. This spot exposure was made over the same length of time as the spectra and developed in the same bath of chemicals as the spectral plates taken on that night. Similar techniques had been used for about a hundred years and, while not precise, were the best I could do.

Anna and I left Yerkes on 1970 April 1, three and a half years after entering graduate school, to take a job with Professor Lyman Spitzer on the “soon” to be launched NASA satellite Copernicus. The thesis was published after I left Yerkes (York 1971).

4. The Princeton Years (1970–1982: Copernicus, Local Interstellar Matter, Quasar Galaxy Pairs and DIBs)

4.1. Background of my work with the Copernicus Satellite

My main position, post-doctoral, was being part of the small Princeton University (PU) team of astronomers headed by Professor Lyman Spitzer, to assist in testing, operating and using the Copernicus satellite for science. Anna and I lived near Goddard Space Flight Center (GSFC), in Greenbelt, Maryland, for the testing of both the prototype (for about a year) and the flight model. Dr. Jerry Drake was hired at the same time I was, to share the heavy testing

burden. After the successful launch, I remained at GSFC for a few years, sharing shifts with others, operating the orbiting Princeton telescope, then started commuting to Princeton four days a week to focus on science. Anna and I finally moved to Princeton in 1976. Drake remained at GSFC full time.

The instrument testing process had been delayed for various reasons. Since I left Chicago before submitting my thesis, I used my evenings, up until launch, finishing my thesis. During this period, I also worked with Don Morton and Ed Jenkins on two papers on rocket spectra of hot stars (Morton et al. 1972; Jenkins et al. 1974). The delay in the testing period proved, in completely unanticipated ways, to be excellent preparation for my later leadership of the SDSS project (spanning the years 1988–1997).

Copernicus, an 80 cm diameter telescope, carried a high-resolution spectrometer between 912 and 3000 Å (Rogerson et al. 1973a). For various reasons, the equipment had to be highly specialized for this task. The brief account that follows on the genesis of the project, under Lyman Spitzer, is necessary to make clear the revolutionary technology developments that preceded my involvement.

4.2. Brief History of Copernicus

The birth of telescope satellite science as I knew it has a history going back to the end of World War II (WWII). Lyman Spitzer (b.1914–d.1997) is known as the father of the HST. Estimating the properties of the IS gas was a major interest of his, after graduating from Princeton as a graduate student of Henry Norris Russell in 1935 (Spitzer 1947, 1948). He realized that the technology (post-war) existed to place a telescope in orbit above the atmosphere. The UV spectral region that contained most of the main IS resonance lines of the elements in the periodic table, blocked to ground-based observation by the atmosphere of Earth, could be observed with telescopes orbiting above the atmosphere (Spitzer 1946, cited as a reprint from 1990). He later detailed the spectroscopic science he envisioned (Spitzer & Zabriskie 1959). Furthermore, images of astronomical objects ten times sharper than yet existed from Earth could be obtained with a telescope of modest size equipped for imaging in orbit because of the absence of the blurring of stellar images by the atmosphere of Earth. Of course, even though rockets existed by then, cameras and spectrographs required new digital detectors so that data from space could be transmitted to the surface of Earth. A multi-year lifetime presence of the UV equipment in space was also necessary to obtain the data (~ 10 yr). Steering the instrument from star to star, for several stars per day over that many years required a system to unload the momentum of the envisioned wheels used to steer instrument. Spitzer analyzed the main considerations for the design of an optimum solution to this slewing issue. It was a system for dumping the momentum built up in the wheels into the magnetic field of the Earth (a “magnetic unloading system,” an alternative, for instance, to de-spinning the wheels with gas jets (Spitzer 1960). The realization of all the necessary developments did not finally occur until the late 1960s with the construction of the series of the three Orbiting Astronomical Observa-

tories (OAOs), of which Copernicus (OAO-3) was the last. The other successful OAO was managed by the University of Wisconsin (OAO-2), which preceded the launch of Copernicus by about 3.5 yr and provided the first high quality stellar data in the UV. A fourth version in the series suffered equipment failure soon after launch and the third version failed to reach orbit. The eventual implementation of these developments enabled what is now modern space astronomy. Lyman became the leading astronomical advocate of launching a UV telescope into space. Inspired by the progress in rocket technology after WWII, his vision was to eventually see the launch of a telescope with a 200 inch diameter (as large as the largest optical telescope on Earth at that time). He and Professor John Bahcall, of the Institute for Advanced Study (IAS) in Princeton, became the chief sales team to Congress for the Large Space Telescope (fondly called, informally, the Lyman Spitzer Telescope). What became the HST was funded by Congress in 1976. It was launched in 1990. It has operated from 1991 to the present time and is one of the most successful astronomical projects of all time (Williams 2020).

4.3. Early Work on Copernicus at Princeton

Preparing the tools of space astronomy occupied Lyman (along with plasma physics) for a number of years. After NASA was founded in 1958, Lyman proposed a satellite to carry the Princeton Telescope-Spectrometer (Rogerson et al. 1973a). (The satellite, upon successful achievement of orbit, was named Copernicus.) The specific UV science program he envisioned for IS matter research with the satellite was laid out by Spitzer & Zabriskie (1959). Lyman and his good friend, fellow Princeton Professor Martin Schwarzschild, undertook several programs to further develop the scientific case for UV sensitive, orbiting telescopes and to solve key technical issues.

The programs included eight flights of balloon-borne telescopes (two with a 12 inch diameter mirror and six with a 36 inch mirror, called Stratoscope I and II, respectively) flown between 1957 and 1971 (Light et al. 1974) and a rocket program, (implemented by Drs. Don Morton and Ed Jenkins between 1960 and the early 1970s). The long-term goal of these programs included development of electronic detectors for use in space, of UV sensitive coatings for space optics, of star acquisition and tracking systems for balloon-borne and orbiting telescopes and other prerequisites for the envisioned imaging space program of UV sensitive, high-resolution, telescopes that Spitzer and Schwarzschild had in mind.

The ~ 20 yr Stratoscope program and the rocket program cost about one-sixth of funds awarded to Princeton for Copernicus construction, testing and science, over 40 yr. The various delays for coping with problems in development and testing cost Drs. Don Morton and Ed Jenkins a significant part of their lives, but it all paid off with the success of Copernicus. This realization was very important to me for the two later projects I led: construction of a 3.5 m telescope at Apache Point Observatory (APO) near Sunspot, New Mexico, and

SDSS, also at APO, spanning the time between 1982 and 1997). Both projects at APO also required much patience, though from many more people than the six related to space astronomy at Princeton: Schwarzschild, Professor Robert Danielson, Morton and Professor Jack Rogerson, the principals on Stratoscope, and Spitzer, Schwarzschild, Danielson, Rogerson, Morton and Jenkins, the principals on Copernicus, all of whom were heavily invested for many years.

4.4. Launch of Copernicus

The satellite was finally launched in August 1972. It was preceded by launches of several astronomical satellites of similar mass that were part of the legacy of the Copernicus developments noted earlier. Copernicus operated almost flawlessly for nearly ten years, from launch to termination of operations, except for a correctable stray light problem in the far ultraviolet (FUV) spectrograph; gradual (expected) diminution in sensitivity of the FUV detectors (the main detectors, used for $\lambda < 1450 \text{ \AA}$); and a serious particle background issue in the near-ultraviolet (near-UV) detectors planned for use at $\lambda > 1650 \text{ \AA}$. This latter issue was partially correctable (Snow et al. 1979).

That is not to say that there were not some tense moments before the satellite reached orbit. After four days to allow the instrument to fully reach the vacuum of space, we settled on our first star ($\lambda \text{ Sco}$) and saw, via telemetry, the UV spectrum at 1000 \AA , confirmation that the special UV mirror coatings had survived ground-based testing and launch, and that the telescope was in focus. There were some concerns in changing the focus from the value used for ground-based testing to the value needed in the vacuum of space, but this was resolved by Spitzer's last-minute calculations just before launch. We knew we had many years of science ahead of us. I was at the satellite controls for that event, certainly the high point of my young scientific life. Spitzer had arranged with NASA to have the data sent routinely by a computer link to the Princeton astronomy building (Peyton Hall) and the data were plotted daily there for the full team to see and use. The various delays in testing put the launch off by over two years from when I arrived at GSFC. I had a beard at that time, and I asked Lyman to cut it off after the successful launch, so all would know that the long wait was over (see Figure 1).

4.5. Spectroscopy with Copernicus

The Copernicus spectroscopic equipment was based on five photocells. There were two UV, FUV windowless detector systems called U1 and U2, both of which produced scans of the target star spectrum in the second order of the grating, U1 from 710 to 1500 \AA at 0.05 \AA , two-pixel resolution, and U2 that produced a scan of 0.2 \AA , two-pixel resolution from 750 to 1645 \AA . There were two windowed detectors, the near-UV tubes, V1 and V2, for use in first order at about half the spectral resolving power of U1 and U2 (0.1 and 0.4 \AA , respectively) at twice the wavelengths of the U1 and U2 tubes. Little use was initially made of the long wavelength detectors because of high, radiation-induced phosphorescence

from the windows of the V1 and V2 tubes. There was also a monitor tube at 3430 Å to allow corrections for star motion on the slit.

The main, high-resolution mode (based on the data tube known as U1) was used initially for short scans around each spectral line, one at a time, and was programmed for the lines of interest for each star (usually at a rate of eight minutes per line). It required about a day to complete single scans of 70–100 spectral lines, targeting a single star, including various overheads. A complete scan of the continuous spectrum at high-resolution required about 20–24 days. Only 10 or so stars were observed in this mode over the 10 yr life of the mission.

4.6. Science Mission of Copernicus

The science mission of Copernicus can be summarized as follows. The priorities assigned to our early observations were to: (1) determine the fraction of hydrogen in molecular form and the temperature of H₂ in IS clouds (Spitzer et al. 1973); (2) obtain abundances (with respect to solar abundances) in IS clouds (Morton et al. 1973); (3) determine the nature of the intercloud medium (Rogerson et al. 1973b); (4) search for new molecules in the UV for stars of intermediate extinction (Jenkins et al. 1973); and (5) explore the properties of the UV extinction curve (York et al. 1973). The five papers cited were based on observations of a few UV bright stars, so preliminary results would be available in the event of an early satellite/telescope failure. An instrument paper was included with this set of papers in the 1973 May edition of the *Astrophysical Journal Letters* (Rogerson et al. 1973a). Jack Rogerson (b.1922–d.2021) was the Program Manager for the NASA-Princeton contract, awarded in 1962, for the duration of the mission. The cited papers were co-authored by the six of us.

A seventh paper, published that same year, on the detection of IS deuterium, is not mentioned as part of the mission goals, because it was a serendipitous discovery (Rogerson & York 1973). Essential to most of the conclusions that came from the early revelations were the Copernicus surveys of the column densities of molecular and atomic hydrogen for ~ 100 stars (respectively, Savage et al. 1977; Bohlin et al. 1978), and oscillator strength compilations by Morton & Smith (1973). Over the years, the team members diversified their science interests somewhat. Astonishingly to me, Lyman never added his name to the papers in which he was not intimately involved, beyond the first six, even those he was the Principal Investigator of the Copernicus program.

Lyman continued to focus on the properties of H₂ in space (Spitzer & Cochran 1973; Spitzer & Morton 1976). Jack Rogerson later focused on acquiring complete UV spectra of B stars, of types B0 V, B2 IV, B3 IV and B8 Ia, respectively, for the stars τ Sco (Rogerson & Upson 1977); γ Peg (Rogerson 1985); ι Her (Upson & Rogerson 1980); and β Ori (Rogerson & Upson 1982). Don Morton focused on the complete FUV spectrum of the O9 V star ζ Oph (Morton 1975) and the O6 star ζ Pup (Morton & Dinerstein 1976) and especially on the rich spectra of the H₂ lines in both stars. (Together with the B stars studied by Jack

Rogerson, these two O stars meant that Copernicus left a legacy of a select set of the six FUV hot, bright stars with complete Copernicus spectra.) Ed Jenkins later focused on IS O VI (Jenkins 1978a, 1978b), on various stars with special ISM properties (Jenkins 1976) and improved IS gas abundances (Jenkins 1986, 2009). Jerry Drake worked on surveys of H I and H₂ column densities. My main Copernicus work after 1973 was on the brightest unreddened stars and the LISM (see below).

Five individuals joined the science team later: Drs. Ted Snow, Walter Upson, Ed Weiler, Ed Barker and William Oegerle. Snow worked on ISM properties and various lines of sight to individual stars (Snow & York 1975). Upson worked with Jack Rogerson on stellar spectra of hot stars. Ed Weiler worked on RS CVn stars and emission in late type stars, and Ed Barker worked on several comets. Bill Oegerle worked on IS lines in the little-used near-UV spectral region. Of course, the noted programs do not constitute a complete list.

4.7. My Focus on the Intercloud Medium

A major part of my time in the next few years involved a more detailed look at the intercloud medium. Following the first results concerning unreddened stars (Rogerson et al. 1973b), I scanned several additional bright, unreddened stars to survey more completely what was in the little known, unreddened sightlines in the LISM. I scanned stars for which few IS spectral lines had been detected with the express purpose of finding what phases of gas existed in lines of sight to stars with the least reddening. These were early type O and B stars. Copernicus found dozens of UV IS lines (strong and weak) in those stars. They included γ^2 Vel and α Cru AB, and HD 28497, μ Col, α Vir, β Cen and λ Sco, lines of sight with $E(B - V)$ less than or equal to 0.04 (also used for extended studies of O VI and deuterium).

Following are six key results from this work on the physical nature of the general space between the IS clouds, in which only modest values of $N(\text{H}_2)$ and reddening are found: (1) The ratio $N(\text{D})/N(\text{H})$ in the LISM today is much lower than previously indicated by less direct determinations (discussed further below); (2) While C II, N I, O I, N II, Si II and Si III are strongly detected, the strengths of second ions, requiring higher energy photons for their creation, C III (C^{+2}), N III (N^{+2}) and S III (S^{+2}), make up $< 1\%$ of the amount of C, N and S, allowing the ruling out of models of pervasively high levels of XRs, cosmic rays or gamma rays predicted by some models published before the launch of Copernicus. (3) C IV, N V, Si IV and S IV are mostly absent in the LISM near the Sun, whereas O VI is strongly detected (as discussed below). (4) Multiple velocity components of (N I, C II, N II and others) were detected in these dust-free sightlines, as in reddened stars. (5) The average density of neutral hydrogen in ten unreddened stars, all with $E(B - V) < 0.04$, was 0.01–0.1 cm^{-3} (York 1976), somewhat lower than earlier inferred from 21 cm observations. (6) All but three of the stars with $E(B - V) < 0.04$ had molecular hydrogen at $N(\text{H}_2)/N(\text{H I}) < 10^{-6}$, mostly in the first rotationally excited level of the ground state (as expected if

any traces of H_2 are present, given the statistical weights of the levels).

4.8. The Difficult Task of Discovering Exactly what causes the Interstellar Extinction

One of the major questions that it was hoped that Copernicus could reveal was the makeup of IS dust which required extensive study of IS gas and molecule abundances. The discovery of the continued rise of the UV part of the extinction curve (York et al. 1973) raised the possibility that there was a wider range of dust particle sizes than previously considered (in the sense of more numerous smaller grains). The details of abundances of more elements missing from the IS gas might have shed light on the nature of the grains. Limitations on studying IS gas abundances in both unreddened stars (little H_2) and reddened stars (abundant H_2) were similar. The multiple narrow velocity components lines-of-sight precluded precise derivation of abundances if component separations were not more than 10 km s^{-1} , a very rare situation. If the spacings of components were smaller, we could only derive estimates for the sum of column densities of the most abundant heavy elements, because of overlapping, individual, saturated components. Doing precision work on abundances involved finding stars with special component configurations or using profile fitting which is not generally amenable to error estimation. In the initial observations, precise abundance determinations were possible only in special situations (Nachman & Hobbs 1973).

Reasonably accurate IS cloud abundances could be inferred in a few cases with Copernicus. For example, the problem of the deuterium to hydrogen ratio in unreddened stars was a special case, because it was possible to derive the gas temperatures from the line widths of deuterium, which were high enough that the saturation problem was not severe for the light nuclei D I, and H I often had damping wings (which produced strong, broad lines with Lorentzian profiles, that were easy to fit). For zeta Oph, the component velocity structure made it possible to derive reasonable components for some elements, and hence, to obtain abundances for multiple components. The ratio of abundances for iron to sulfur $[N(\text{Fe})/N(\text{S})]$ in the gas toward ζ Oph (Morton 1974) was found to be lower than in the line of sight to α Vir (York & Kinahan 1979), even in the early days. ζ Oph is 10 times more reddened than α Vir, hence it has more dust, higher extinction, higher $E(B-V)$ and shows higher depletion of iron from the gas phase, presumably into solid particles that cause the extinction curve. It was inferred that the ratio of Fe/S in the integrated line of sight was higher in the dust toward zeta Oph than toward α Vir. Even though the uncertainties for several other cases were somewhat larger, other star pairs showed similar trends.

Field (1974) concluded from early Copernicus results that the trends for the depletion pattern of 11 elements were consistent with theoretical computations of condensation temperatures in stellar atmospheres or nebulae, implying that a portion of dust grains in space could be made in those locations. For the rest of the estimated mass of dust, elements might be accreted by grains “after their

arrival in space.” He speculated the grains might be composed of “silicates, graphite, silicon carbide and iron, with mantles composed of complex molecules of H, C, N and O.”

The earliest Copernicus observations focused on intrinsically strong transitions of heavy elements, so that many lines were saturated. It took some years for laboratory scientists, theoreticians and observational spectroscopists to determine the intrinsic strengths (oscillator strengths, or f -values) for the intrinsically weakest lines of more elements, needed to minimize saturation effects. Theoretical oscillator strengths for very weak, spin-forbidden lines of species with very strong resonance lines that were often saturated (C III, N I, N II, N III, O I, O III, Al II and Si III) were calculated (Cowan et al. 1982). It also took some time to get the observations necessary once the needed intrinsic line strength information was available.

Component blending remained a severe issue in many stars. There was thus renewed interest in determining oscillator strengths for weak IS lines that could yield accurate abundances based on new Copernicus scans. While such lines were sometimes free of the problem of saturation, they could nevertheless not always be used to compute column densities, for lack of known f -values (oscillator strengths). Based on techniques pioneered by de Boer & Morton (1974) for neutral carbon (C^0), improved f -values appeared in the literature for O^0 , N^0 , Fe^+ , Mg^+ , Mn^+ , Si^+ , Ar^0 and dominant ionization stages of other species. Repeated observations, improved data reduction techniques and new f -values led to new IS abundances for 88 stars (Bohlin et al. 1983). An expanded set of elements with varying degrees of depletion was generated from the new results, showing lower Fe/S ratios in reddened stars compared to unreddened stars. Reliable depletions were confirmed for Fe/H, Mg/H, Mn/H, Cu/H, Ni/H and others, yielding improved observational hints of what heavy elements might account for the extinction in IS space.

With additional abundances measured with the much larger HST (Hobbs et al. 1993), a distinctive pattern of depletions was confirmed. This and subsequent studies from space confirmed and amplified the general impression derived from previous observations of ground-based spectra of IS Na I, Ca II, K I and Ti II, that the pattern of the element abundances in IS clouds was similar to that inferred from spectroscopy of stellar spectra, except for the apparent depletion of elements such as iron, but with three or four significant pattern differences related to the average gas densities of the lines of sight in which the IS line blends are encountered. Results for denser regions of space consistently showed much lower ratios of [Fe/H], [Si/H] and several other elements (Jenkins et al. 1986), compared to the ratio [S/H], relative to solar abundances, than in lower density regions seen in unreddened stars. Jenkins (2009) combined depletion studies of 243 sightlines from HST and Copernicus of 17 elements to analyze differences in depletions of elements in different regions of the Galaxy and the Universe (QSO absorption line system, QSOALS).

Conclusions as to how the depletions came to exist over time varied. Snow (1975) pointed out a possible correlation between the first ionization potential of an element and IS depletions from Copernicus observations. The question of the origin of the differing abundance ratios has not been resolved, to my knowledge. Nonetheless, the patterns of abundances with mean line of sight density, though not understood, are generally attributed to atom-gas-grain interactions within the IS clouds. Later analysis combining 26 elements for six reddened stars from observations (Hobbs et al. 1993) favored the similarity of depletions to the condensation hypothesis over Snow's hypothesis, but without a physical explanation.

4.9. Deuterium in Space

The detection of deuterium in space occurred after the initial results of the Copernicus team were prepared for publication. I commenced the extensive program of study of the lowest density, intercloud regions near the Sun, noted above. Early in 1973, I made a 20 day scan of the spectrum of the B1 III star β Centauri A. The reasons to pick the star were that it was one of the brightest on my list of early type stars, was only about 80 pc away, had high stellar rotational velocity (to avoid confusion of the narrow IS lines with stellar lines) and had minimal reddening. To my knowledge, no optical IS lines had ever been detected in the star and I wanted to see what might show up in the diffuse, unreddened parts of space previously unobserved with UV spectrographs.

The Copernicus data were routinely sent to Princeton from GSFC by a remote link and regularly plotted the next day on a cal-comp plotter. Each day, most of us examined the new data, looking for surprises. The day after the data from the 20 day scan of β Centauri came in, Jack Rogerson was looking at the data and saw dozens of strong IS lines, including the resonance lines of atomic hydrogen ($Ly\alpha$, $Ly\beta$, $Ly\gamma$, $Ly\delta$, $Ly\epsilon$, etc.) and of the isotope deuterium (shifted by 80 km s^{-1} shortward with respect to the hydrogen lines). He showed the deuterium features to each of the team and Lyman commented, "Hmmm, I think that is important." This first measurement of the ratio D/H in IS space was $1.4 \pm 0.2(\text{m.e.}) \times 10^{-5}$ (Rogerson & York 1973). The value was much lower than expected. The ratio D/H (by number) had recently been estimated by new measurements of deuterated molecules in IS clouds and by a measurement of the 21 cm analog of D I at a wavelength 91.6 cm. The range of values of these measurements was large. The estimates of the ratio $N(\text{D})/N(\text{H})$ ranged from 10^{-7} to 2×10^{-4} . A direct measurement of the ratio of D/H, if confirmed elsewhere in space, and corrected to the primordial value, might confirm the big bang origins of the Universe.

Using the new ratio of primordial [D/H], the hot phase of nucleosynthesis calculations of the big bang (Wagoner 1973), the facts that (1) no source of deuterium other than nucleosynthesis in the big bang was known or expected and (2) that the astration correction from the model of Truran & Cameron (1971) (primordial deuterium would be destroyed as stars evolved, leading to successively lower

and lower IS values of $[D/H]$ as stellar evolution moved forward) yielded a value for the mean density of baryons in the Universe today. That value was found to be $1.5 \times 10^{-31} \text{ g cm}^{-3}$. This density was over 20 times lower than the formal closure density of the Universe and implied the Universe would evidently expand forever. More recently, the net result of the astration (negative) correction and a new infall correction (positive) (Dvorkin et al. 2016) has been decreased so the local (measured) value is probably closer to the primordial $[D/H]$ value than was realized initially.

To check that the value we had derived and that implications inferred could be widespread in the MW galaxy, Jack Rogerson and I observed four additional hot, bright Copernicus stars (to see if the ratio $[D/H]$ was the same throughout the LISM, as would be expected on the hypothesis that all deuterium came from the big bang). Two of the stars were at the same distance as β Cen A (α Cru A and α Vir) and two were 4–10 times further away but still unreddened (μ Col and γ Vel). The average measured value of $[D/H]$ we found was $[D/H] = 1.8(\pm 0.4 \text{ m.e.}) \times 10^{-5}$ (York & Rogerson 1976). The low value of $[D/H]$ implied that the density of the gas today yields a total mass of baryons in the Universe that is far below the value needed to close the Universe, and that, according to the calculations then being made, the Universe would expand forever (Gott et al. 1974).

An further extended Copernicus observing program of unreddened stars confirmed the low value of IS $[D/H]$ (Laurent et al. 1979), but as more distant stars with more complex IS velocity component structure were observed with Copernicus, the individual $[D/H]$ values, while consistent with the values quoted above, began to reveal apparent scatter in the star to star ratios of IS $[D/H]$, with larger error bars because of analysis complications (saturation, velocity component overlap and other issues). Using more powerful UV instruments to observe fainter objects that were safely within 100 pc of the Sun, i.e., chromospheres of cool stars in Ly α with HST (Linsky 1998) and 12 faint white dwarfs using the Far Ultraviolet Spectroscopic Explorer (FUSE) (Moos et al. 2002), the average value of $[D/H]$ was found to be $1.52 \times 10^{-5} \pm 0.08$, confirming the first Copernicus results for $[D/H]$ (Rogerson & York 1973), for stars in the same ~ 100 pc volume of space around the Sun. A recent paper (Friedman et al. 2023) has shown that variations remain, star to star, despite attempts to remove all sources of measuring errors and the source of the variations is unknown. Possibly they relate to slight depletion of deuterium onto grains, or to variable infall of primordial deuterium onto the Galaxy.

Interestingly, two contemporaneous discoveries affected the interpretations of the day. First, Penzias & Wilson (1965), discovered the cosmic microwave background radiation (CMBR), explained as the remnant radiation of the hot big bang (Dicke et al. 1965), so detailed models allowing predictions of primordial element abundances could be calculated (Wagoner 1973). Second, Ostriker & Peebles (1973) showed that the apparent stability of spiral galaxies implied that they generally must have large amounts of very faint stars (Vandervoort 1970)

or dark matter (Zwicky 1937) in their halos. This would imply that galaxies had much higher amounts of unseen mass than visible mass, be it in the form of low mass, low

Note: Figure translations are in progress. See original paper for figures.

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