Research in Astronomy and Astrophysics, 24:016001 (43pp), 2024 January https://doi.org/10.1088/1674-4527/acf35d

Summary of a Life in Observational Ultraviolet/Optical Astronomy

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Received 2023 June 29; accepted 2023 July 5; published 2023 December 29

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. IS: interstellar; 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 are 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 $\mathrm{\AA} = 10^{-8}$ 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 $N(\mathrm{X})/N(\mathrm{Y})$ refers to the ratio of column densities of elements X and Y, for instance, $N(\mathrm{D})/N(\mathrm{H})$. The notation [X/H] refers to the abundance of element X with respect to total hydrogen (log scale, $\mathrm{H} = 12$). The fraction of total hydrogen that is molecular (H_2) is denoted as $f(\mathrm{H}_2)$, where $f(\mathrm{H}_2) = 2N(\mathrm{H}_2)/[N(\mathrm{H\ I}) + 2N(\mathrm{H}_2)]$. 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 IS 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).[1] 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, that 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")[2] 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

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[1] Long GRBs were later confirmed to be core-collapse SNe and short GRBs were later confirmed to be merging neutron stars and sources of gravitational waves.

[2] The small particles of dust considered for many years to give rise to the extinction curve (a hypothesis developed in the early part of the 20th century based on the well delineated dark nebulae or nearly opaque clouds seen in the ISM such as Barnard (1927) imaged using the same 40 inch refractor, and the same photographic techniques I used for the work I did for William Van Alena and that William Morgan used in developing the O-B star Morgan-Keenan spectral classification system at Yerkes (Morgan et al. 1943).

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 unreddended stars were likewise added together and divided into the spectra of the appropriate reddended 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.[3]

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 for studies of IS absorption lines between 912 and 3000 Å (Rogerson et al. 1973a). For various reasons, the equipment had to be highly specialized for this

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[3] The results involved thousands of spectral measurements, which I recall preparing for publication by transferring black paste-on dots to paper for photographic presentation, an arduous, time-consuming job. (Anna helped with this because Joe Tapscott, the Yerkes graphic artist, would not do it for students.)

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 for these telescopes 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 wheels used to steer the envisioned 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 Observatories (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).[4] 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[5] (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 program of UV sensitive, high-resolution, imaging space 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

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[4] Lyman realized he was not an eloquent speaker and often joked that if he had simply set up a cardboard cut-out of himself on what became weekly visits to Congress in the 1970s, it would have had the same impact as his presentations, given his eminent standing as a famous physicist.

[5] O'Dell was awarded GI time for research for his years of service to HST. Lyman Spitzer was not. In a remarkable show of gratitude to Spitzer, O'Dell gave Spitzer enough observing time to publish papers in the late 1990s based on HST, to see what his 40+ yr of effort to get HST into orbit had brought forth (Spitzer & Fitzpatrick 1992, 1993).

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 $\lambda < 1450$ Å); and a serious particle background issue in the near-ultraviolet (near-UV) detectors planned for use at $\lambda > 1650$ Å. 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.[6]

After four days to allow the instrument to fully reach the vacuum of space, we settled on our first star (λ Sco) and saw, via telemetry, the UV spectrum at 1000 Å, 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).

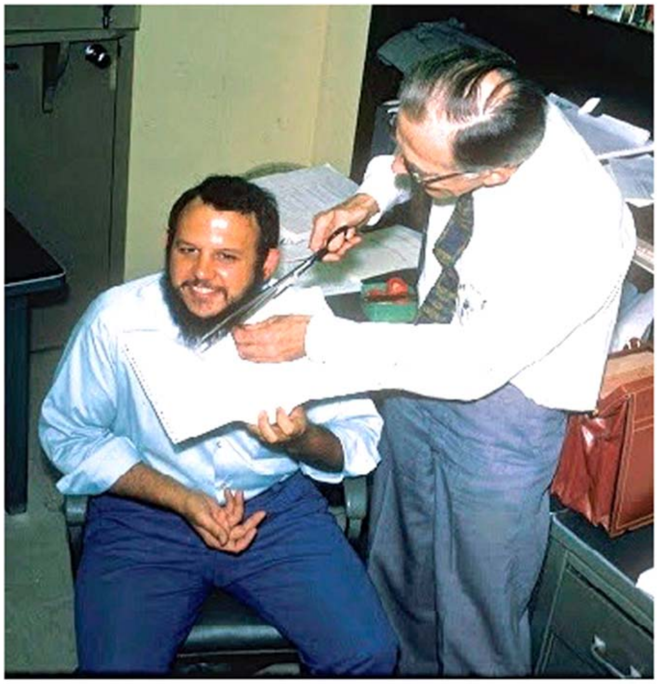

Figure 1. Lyman Spitzer removing my beard after first light was achieved with the Copernicus UV telescope/spectrometer in 1972 August. Photo credit: Ed Jenkins.

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 Å at 0.05 Å, two-pixel resolution, and U2 that produced a scan of 0.2 Å, two-pixel resolution from 750 to 1645 Å. 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 Å, 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

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[6] Failures of hardware were not unexpected at the time of the launch of these early space science satellites. It was rumored that there were at least 1000 single point failures associated with our launch, enough to make Lyman's 25 yr wait for the moment of launch a little nerve racking. I recall particularly one example. The stability of the focus of the main mirrors required that they be held in suspension, isolated from the vibrations that occurred at launch. The system was spring-loaded: explosive bolts had to be fired after launch to put the mirrors into position. The explosive bolts were an example of one of the single point failures. If one failed, the optical system would be hopelessly out of alignment and the launch would have been a failure. Once the bolts were fired, the mirror position was telemetered to the control system near the launch site at Cape Kennedy, Florida. Just after launch, the system indicated that the secondary mirror was out of position. We had to wait four days to turn on power to confirm the success of the explosive bolts (to see if the first star, λ Sco, was in fact, in focus). As recounted in the text, the telescope was in focus, after all. The telemetry signal was an error. We had four days of nervousness to contemplate a feasible use of a very expensive, out-of-focus telescope, fortunately, in vain.

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 H_2 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).[7]

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 though he was the Principal Investigator of the Copernicus program.

Lyman continued to focus on the properties of H_2 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 H_2 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 H_2 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 $N(H_2)$ and reddening are found: (1) The ratio $N(D)/N(H)$ 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)

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[7] For use in the earliest Copernicus papers, tabulations of wavelengths and oscillator strengths in the space UV had to be made from scratch, which Charlotte Moore assisted in, at the National Bureau of Standards in Washington, D.C. She had worked for Princeton Physics Professor Henry Norris Russell, Lyman's thesis advisor, from 1897 until the 1940s.

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 $N(\mathrm{H}_2)/N(\mathrm{H\ I}) \sim 10^{-6}$, 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 in Copernicus lines-of-sight precluded precise derivation of abundances if component separations were not more than 10 $\mathrm{km\,s}^{-1}$, 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 $[N(\mathrm{Fe})/N(\mathrm{S})]$ 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, it appeared, 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^o, N^o, Fe^+, Mg^+, Mn^+, Si^+, Ar^o 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 (Lyα, Lyβ, Lyγ, Lyδ, Lyε, etc.) and of the isotope deuterium (shifted by 80 km s^{-1} shortward with respect to each of the hydrogen lines). He showed the deuterium features to the Copernicus 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(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(D)/N(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 nucleosynthesis calculations for the hot phase 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 1.5×10^{-31} 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 the 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 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).

A 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., 13 chromospheres of cool stars in Lyα 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 luminosity stars or some other form of matter, which came to be called "dark matter." The subsequent discovery that many radio rotation curves of normal spiral galaxies are flat beyond where the optical luminosity drops off [there were only three known cases at the time (Roberts & Rots 1973)] led to the conclusion that there was more dark matter than baryonic matter in the Universe. While there was little evidence of such behavior in 1973, subsequent observations revealed that extended rotation curves were the rule, not the exception. The result was later interpreted as evidence for a large abundance of "dark matter," possibly primordial, of uncertain origin, in the Universe. Modeling then showed that the Universe is likely closed (with the amount of dark matter exceeding the amount of baryonic matter by more than a factor of ∼10) and would eventually collapse on itself (Gott et al. 1974). The nature of the dark matter and its distribution in the Universe create intense discussion to this day.

Observations of foreground intergalactic absorbers at high redshift ($2.5 < z < 3.5$) QSOs, in which [D/H] averaged 3.0×10^{-5} over six systems, confirmed that the low value of D/H extended throughout the Universe (Dvorkin et al. 2016). York (2002) discussed the lower level of accuracy of the intergalactic values, but the generally low value became a cornerstone of "precision cosmology."

4.10. Detection of Interstellar O VI (O^{+5})

A major success of the earliest Copernicus observations was the discovery of IS five-times ionized oxygen (O VI, O^{+5}). The first Copernicus publication of unreddened stars revealed the presence of IS O VI absorption (Rogerson et al. 1973b). Spitzer had famously predicted that O VI, C IV and N V might be detected in the ISM. He postulated this as being necessary to explain the apparent pressure confinement of IS clouds seen in optical spectra of MW halo stars (Spitzer 1956). The O VI features were broad and shallow, thus requiring very high S/N spectra for detection, because of blending with stellar lines in many cases: thus, further observations of selected stars were necessary to get reasonably clean detections.

I pursued a follow-up program on a few hot stars which had very few stellar lines to confuse with the O VI IS lines (rest frame $\lambda\lambda$1031, 1037) and in which the component structure of the lines from cool IS gas was moderately simple (York 1974). The new line profiles for O VI were consistent with temperatures of 2×10^5 K (York 1977), later taken as an upper limit, whereas previous indications were that the temperature of a hot halo might be consistent with $>10^6$ K for an intercloud medium if one existed. Ed Jenkins pursued a somewhat larger sample and focused on confirming the IS nature of the O VI (Jenkins & Meloy 1974).

A second study by Ed Jenkins (Jenkins 1978a, 1978b) using an unculled sample of hot stars indicated that the phenomenon of O VI absorption was widespread in the one kpc region around the Sun. Further, Cowie et al. (1979) suggested there was a correlation between the median O VI velocity and the mean velocity of the blends of the cooler cloud components on the same sightlines, as if the hot gas was associated with the cold gas in some way. Subsequent discussion led to a concluding paper interpreting the O VI as being in relatively low column density evaporative zones into a hot intercloud medium around the cooler <10,000 K clouds. This configuration explained the Jenkins results of the extent of the volume of space that included O VI (the hot intercloud gas envelops all the cool clouds), the velocity effect noted above and the weakness of the C IV and N V lines, relative to O VI lines, in Copernicus spectra. Evaporative layers create a temperature structure in the warm outer shell of IS clouds in which the column densities of O VI, N V and C IV are, respectively, decreasing from the outer edge of the shell toward the cool inner portion, explaining the dominance of O VI in the Copernicus spectra among these three high ions.

Extended surveys of larger volumes of space with the FUSE confirmed these results and showed that the scale height of the O VI is consistent with the reach of the cool clouds (Sembach et al. 2003).

Concerning the dearth of C IV and Si IV in Copernicus stars, studies with International Ultraviolet Explorer (IUE) showed extensive regions in distant Galactic O-star associations, not observable by Copernicus, with abundant C IV and Si IV near the hottest stars, presumably created by the stellar photons from those stars and high velocity shock waves created by supernovae (SNe) in the same regions (Cowie et al. 1981).

4.11. Detection of Wide-spread, Intermediate Velocity, Intermediate Ionization Gas

Examination of profiles of blends of IS lines, centered on H II regions of stars, revealed that there was ubiquitous intermediate velocity material (IVM) associated with IS gas in the general ISM. While still at Princeton, I somewhat inadvertently became interested in the systematics of the IVM through interactions with undergraduate Halden Cohn, thesis students Michael Shull and Antoinette Cowie, and Post-doc Lennox Cowie. My interest related to studies of gas in the halo of our Galaxy, which led to my later research at Chicago on QSOs. The first step in studying this IVM came from working with Princeton student Halden Cohn on the modest but most extreme velocities at the edges of line profiles in a sample of 30 initial Copernicus survey stars (Cohn & York 1977). We noted that there was IVM detected in the strongest UV transitions in our early Copernicus spectral surveys of stars, apparently blended with the stronger, low velocity C II, C II* (collisionally excited C II), Si III, N I, N II and N III. The latter were interpreted as being associated with the emitting gas in the vicinity of the stars being observed, ionized by the radiation of the stars themselves, at the velocity of the stars and within a few parsecs of the stars. These were called H II regions and were well known from years of observation of the Balmer α emission line from the regions from the ground. The IVM spanned from 20 km s^{-1} $< |v| <$ 60 km s^{-1} compared to the velocity of the individual stars themselves. The gas was not evident in C IV, N V or O VI. Len Cowie and I pursued these observations in additional stars (Cowie & York 1978a, 1978b) and speculated on the origin of this material, in particular the extreme wings of the features of N I, N II and Si III. The velocity profiles indicate that the gas is not associated with the stars, contains both H I and H II gas on the lines of sight and is due to a system of small clouds in the disk of the Galaxy, possibly related to long-known clouds containing intermediate velocity Na I and Ca II from optical observations. The phenomenon is possibly due to shocks from various sources traveling through the ISM. There is no evidence of highly ionizing radiation generally affecting these regions of IVM. Gas at $|v| >$60 km s^{-1} is very rare, except in unique regions clearly associated with O associations.

The widespread nature of the IVM is important because it points to the existence of a low-density phase of the ISM, at a temperature above 10^6 K with densities of less than 0.02 cm^{-3} consistent with the existence of the evaporative interfaces of the cooler IS clouds that create the wide-spread existence of IS O VI discussed above (Cowie & York 1978b)

4.12. Searches for Additional Intermediate to High Velocity Gas in the Wider Milky Way Halo

Follow up of the absorption lines of IVM blended with H II regions around low velocity, nearby stars in Copernicus surveys raised the question of whether longer sightlines extending into the outer regions of the MW might reveal IVM not confused by stellar H II regions. Answering this question required using distant background sources that were not stellar in nature, such as diffuse clumps of stars in the MW called globular clusters, or luminous distant cores of galaxies or stars in nearby galaxies which allowed H II regions around those objects to be distinguished from MW IS IVM because of the relative motions of the Galactic globular clusters or of the nearby galaxies, compared to motions of galactic IVM on the long sightlines.

Antoinette Songaila, a graduate student at Boston University did a thesis I supervised, making a series of observations of distant objects probing the MW halo, including distant Seyfert galaxies, using observations of IS Na I and Ca II lines. The main goal was to see if additional intermediate or high velocity material might be present in more distant parts of the MW, possibly associated with the set of high velocity 21 cm clouds (HVCs) of neutral hydrogen detected with radio telescopes within the MW (York et al. 1986a).[8]

She concluded that the number of absorption line detections was comparable to what was expected from the areal coverage of the 21 cm gas seen in the high latitude sky and not inconsistent with the suggestion that clouds in the halos of galaxies foreground to distant QSOs might create absorption lines in the spectra of the background QSOs, as suggested soon after such lines were detected (Bahcall & Spitzer 1969). This idea became known as the intervening hypothesis. There was little sign, however, of the most complex of the profiles found in the absorption lines observed in spectra of QSOs. She used echelle observations from Cerro Tololo Interamerican Observatory (CTIO): observations of five distant Galactic globular clusters that had very concentrated central cores (M15, NGC 362, NGC 1851, NGC 2808 and 47 Tuc); three bright Seyfert galaxies (Mrk 509, Fairall 9 and NGC 106) the QSO 3C273; and twelve hot stars from the literature, that reside in the dwarf galaxies called the Large and Small Magellanic Clouds (LMC and SMC respectively). The first set of objects are at distances from Earth of 4 to 10 kpc, the Seyferts and QSO are many Mpc from Earth, and LMC and SMC stars are 50-60 kpc from Earth. Those objects illuminate a portion of the halo of the MW, and might have shown the suspected QSOALS clouds if they existed. All these objects probe the halo of the MW and any associated halo MW H II gas would be recognizable by its velocity separation from IS gas in the spectra of the background objects chosen.

I wrote an invited review on IS gas in the halo of the MW (York 1982) which included the results of the CTIO observations that led to a clear conclusion: there was no evidence in the admittedly small sample (Songaila & York 1980,

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[8] One of the efforts along this line which I most regret not completing is the study of the high velocity 21 cm clouds, especially studies of their distances, abundances and stellar content. Completion of such studies in our Galaxy would add, I thought, new insights to our understanding of several topics mentioned in this article. (Wakker et al. 2007).

Songaila et al. 1981) of halo sightlines, for gas more than 50 km s^{-1} from the rotation curve of our Galaxy (Gunn et al. 1979). There was also little evidence for material more than 10 kpc above the disk. The observations thus offered no clear analogy to the production of QSO absorption lines in distant QSOs. Absorption lines were detected, but the extent of the halo of the MW could not be asserted. Very broad blends of QSOALSs as found in QSOs could not be verified along MW halo sightlines. Better S/N observations were needed or intrinsically stronger lines in the UV spectral region, such as Mg II, Fe II, Si II or C IV, needed to be observed. These observations are discussed below. The targeted objects used by Songaila were too faint for Copernicus. They had to be observed with the IUE, as described below.

4.13. UV Extinction, DIBs, and the Ultraviolet Spectral Region

With several colleagues involved with UV satellite instrumentation, I pursued several possible relationships between DIBs and UV data on stars that were newly available starting in the 1960s. For example, Copernicus was used to search for the mysterious DIBs, mentioned earlier in Section 3.2. It was hoped that the availability of a new window of observation below 3000 Å might supply new DIBs that could provide new insights into the mystery of the unexplained phenomenon of DIBs (Snow et al. 1977a), but only one possible DIB, at 1416 Å, was found. Seab & Snow (1985) did an unsuccessful search of comparable sensitivity with the IUE. A number of apparently new, unidentified narrow IS lines appeared in Copernicus spectra, but were eventually confirmed as atomic lines, not DIBs.

Wu et al. (1981) did a literature search to look for correlations of DIB strengths with UV extinction, which might have indicated some relationship of optical DIBs with the smallest solid grains thought to cause the extinction curve in the UV. For that study, we made a catalog of DIB strengths in common across several optical catalogs from the literature (Snow et al. 1977b) and derived strength relationships between measurements made with different instruments for three strong and well observed DIBs ($\lambda\lambda$4430, 5780 and 6284). However, all the broad band UV, optical and IR measures of extinction were better correlated with the [1800-V] color excess than with any of those three DIBs, based on the best data available at that time. We wrote a paper while at Princeton commenting on the puzzle of the DIBs (Smith et al. 1977), laying out a wide-ranging program to pursue the DIB problem in the future, highlighting the issue that molecules should continue to be considered as likely as grains, of any size, to be the source of the DIBs.

4.14. Other Activities at Princeton: The Copernicus Guest Investigator Program and Preparations for HST

While at Princeton, I engaged in several management and instrumental activities not directly related to IS or intergalactic matter. These included (1) establishing a Guest Investigator (GI) program to allow non-Princeton astronomers to take and publish Copernicus data (Snow 1975); (2) the testing of SEC Vidicon detectors and charged coupled device (CCD) detectors for possible use on NASA's upcoming space telescope; and (3) work on proposals for the space telescope camera and for management of the science operation center for the space telescope.

After two years of Copernicus operation, Lyman and Dr. Nancy Roman (NASA) agreed to dedicate up to 50% of the observing time to GIs. It was thought that this would be a good chance to test some ideas that would be useful for later astronomy satellites. Lyman asked me to manage that program. I hired Dr. Ted Snow to assist me. Ted wrote the documentation needed for visitors to use time awarded to them. Ted joined the research team and worked on reddened stars and dust.

Potential GIs wrote a formal proposal. The initial requests were limited to 24 hr of observing time, and programs were renewable. Ted and I reviewed the proposals and selected the ones for observation, after scientific and technical review following any needed discussions with the other Princeton team members and, as necessary, after needed review by external referees. There were no restrictions on the topics that were acceptable, except that they had to be technically feasible and of high scientific quality. The Princeton team members could collaborate on the science and be co-authors on any results, in areas of their interest. Otherwise, the publications did not require collaboration with Princeton team members.

GIs had to come to Princeton to learn how to program their own observations, and to write the programs themselves, to be uploaded to the Copernicus on-board computer. They also had access to sample data so they could learn how to reduce the data. They could come back to Princeton to pick up the data set and work with it, or we could send it to them. Travel was covered for accepted investigators.

An incomplete list of the diverse programs of the GIs included systematic studies of abundances in different stellar types; mass loss in bright supergiants (e.g., γ^2 Vel, ζ Pup); characteristics of various stellar categories (i.e., WR, Be, Oe, Ap and Bp stars); XR binaries; close binaries; searches for coronal emission in A, G and K stars; IS lines (H I, D I, H_2, HD, B II, C I, F I and Fe II); high velocity IS gas (Vela and other nebulae); Lyα emission in the solar system (geocorona, planets and comets); search for extraterrestrial intelligence (SETI, Ar laser emission from other civilizations); and calibration programs for other UV satellites (OAO-A2 and TD1). Some Copernicus team members became involved as collaborators in programs of interest to them. In the first 2.5 yr of the GI program, 75 GI proposals were accepted. In the first 2.7 yr, 200 stars were observed for Princeton and Guests. For comparison, over the 10 yr mission, about 600 stellar targets were observed, in addition to several solar system targets (day glow of Earth, geocoronal Lyα, Mars, Jupiter, Saturn, Titan and comets.)

I received a NASA Public Service Award (1976) for setting up the program. The success of that program led to NASA policy guidelines for later major missions beyond those dedicated to UV spectroscopy.

A second activity I was involved with at Princeton was a program to test SEC Vidicon detectors. As noted in the earlier section on the precursor preparations for space astronomy before 1970, there was a need to develop electronic detectors for future space telescopes, notably for HST. Spitzer and Schwarzschild obtained NASA contracts to procure, from Westinghouse, large Vidicon detectors and to test them in the lab, in preparation for making a proposal to build the imaging camera for the Space Telescope. I tested dozens of these tubes to characterize their linearity, microphonics, point-spread functions (PSFs), spectral sensitivity, flat field properties, etc. Eventually, I joined Spitzer and a few others for monthly trips to Westinghouse to be involved in discussions and to provide feedback on the tube properties. This test program and other non-Copernicus projects turned out to be bridges to the future for me.

Implementation in actual observing programs with ground-based telescopes with Vidicons was also essential for use in future proposals. The team of engineers at Princeton, led by John Lowrance (b.1932–d.2011), packaged the best of the Vidicon tubes for testing on the Princeton 36 inch Boller and Chivens telescope (previously used for tests for the Stratoscope) and a 60 inch telescope on Mt. Lemmon. Martin Schwarzschild, Ted Williams, Ed Jenkins and I used narrow band images for the study of image rotation effects in nuclei of elliptical galaxies (Williams & Schwarzschild 1979). Earlier, Don Morton had used a Westinghouse Vidicon on the 200 inch telescope at Mt. Palomar to observe QSO absorption lines in the QSO PHL 957 (Lowrance et al. 1972).

The engineering group mentioned above was starting to purchase CCDs for testing and for observing. It was thought that an auxiliary CCD detector in the Space Telescope Camera would eventually contain small CCDs as well as one of the large Vidicon detectors as the principal detector and would strengthen the upcoming Princeton proposal. Working with Professor Fred Roesler of the University of Wisconsin, a Princeton Vidicon camera was adopted as the sensor on one of his Fabry–Perot (F-P) imagers. The imager could be used for narrow band imaging of emission lines (with the F-P etalons); for broad band, wide-field imaging (with the Vidicon tubes and no etalons); or with pressure scanning of the etalons (with a photocell) as a spectral scanner. However, when a computer accident occurred in operating the SEC Vidicons for ground-based testing, a small CCD was the most readily available replacement detector. A Kitt Peak National Observatory (KPNO) observing run was coming up in a few months. Fortunately, Paul Zucchino (b.1939–d.2013), who worked in John Lowrance's engineering group, was a model railroader, who used TRS 80 laptop computers to control his model railroad trains. In a very short time, he had the new computer system working with the new CCD.

The original F-P project was to image the forbidden [S II] and [S III] emission lines in narrow bands associated with the plasma torus of the Jupiter moon, Io, using a KPNO 36 inch reflector. While there were several mishaps on the run (March 1980), it was a success (Roesler et al. 1982), although the CCD failed to function after two nights of use. The F-P system was then used as a scanning spectrometer, with a photocell as the detector, for two nights.

Eighteen months later, Len Cowie led another group with the same instrument and broad band filters (no etalons) to study 11 rich clusters of galaxies (including Abell 426). They used the 84 inch reflector at KPNO. In November 1981, the system was equipped with a new, larger CCD, without the F-P installed, but with 20 Å or 70 Å filters at Hα 6563 Å, [N II]6583 Å, [S II] 6716 Å, 6731 Å, [Fe X] 6374 Å and associated continuum filters (Cowie et al. 1983). They were studying gas accreting from the outer parts of the clusters onto the central galaxies to examine the cooling flows created and forming filaments. Then in April 1982, Cowie and Esther Hu put the FP etalons into the instrument to observe the morphology of Hα emission from the core of the anomalous emitter NGC 1275 (in the Perseus cluster, Abell 426), confirming that another galaxy was colliding with the cooling flow of that cluster's central galaxy, explaining the extra energy source from this luminous central galaxy of a cluster (Hu et al. 1983).

The Io program and the cluster cooling flow programs were successful from the point of view of testing new detectors and from the point of view of new science. Both projects led to the idea and data reduction techniques used to search for emission lines in candidate galaxies producing absorption lines in QSOs, discussed later.

In 1978, NASA issued a call for instruments for the recently funded Space Telescope. Lyman proposed a camera for high angular resolution imaging in the UV, optical and IR parts of the spectrum, backed by our test results and observing experiences with Vidicons and CCDs, on which I was a co-investigator. That instrument was in direct competition with another camera proposed by JPL/Cal Tech (Jim Westphal and Jim Gunn) which relied on CCDs as detectors. That team had a similar characterization program using Texas Instruments (TI) CCD's. The TI CCDs proved superior in resolution, linearity and noise properties so the Wide Field and Planetary Camera (WFPC) was chosen for HST. The small area of the CCDs (less than 15 mm compared to 50 mm for the Princeton Vidicon detectors) was partially compensated for by using multiple CCDs in the camera. While the Vidicon devices did not win the competition, the well-known existence of at least one candidate viable electronic detector to take images to use for the future HST (namely the SEC Vidicon) was critical to congressional funding of the entire HST project in 1976.

I also participated in a second major proposal related to the Space Telescope with Lyman as the Principal Investigator, to operate the science operations center for the telescope, at Princeton [which was won by The Association of Universities for Research in Astronomy (AURA) and located at Johns Hopkins University (JHU), located in Baltimore, Maryland].

I later applied for and won an NSF grant to manage a science program to distribute and evaluate the use of the TI CCDs that were to be utilized for the imaging camera on the Space Telescope that was actually accepted by NASA. Experience in the science use of the new devices for a wider range of science programs than had already been attempted was necessary, a task which NSF funded. Later, after moving to Chicago, I procured seven TI CCDs to be developed for use in instruments at several ground-based observatories to "commission" the device for application to the new horizon that stood before HST with the use of these virtually new devices for astronomy.

5. The Early Chicago Years (1982–1991)

By 1980, NASA had announced their intentions to cease operations of Copernicus. I started applying for jobs elsewhere. In the winter of 1981, David Schramm, Chair at Chicago, called to ask if I would accept a tenured position at Chicago. I was pleased that my professors from the Yerkes student days, many of whom were still active, and most of whom knew me well, would authorize such an offer. I accepted immediately. Anna and I made a home-hunting trip to Chicago/Yerkes in the early summer of 1982 and relocated to Chicago in August 1982.

5.1. Searching for Quasar Absorption Lines with the International Ultraviolet Explorer (IUE) Satellite

From 1982 to 1991 after our move to Chicago, I led a small team using IUE to obtain UV spectra of the objects noted above (A. Songaila's thesis), in addition to the Seyfert galaxy Akn 120 and the gas rich dwarf NGC 1705. This program involved obtaining many long exposures to search for the UV absorption lines (generally stronger than Na I and Ca II that made up the CTIO program). This program led to numerous data reduction problems because the targets were at the limits of the capabilities of IUE.[9] All the publications from this work came after I moved to Chicago. The team contributing to the large set of multi-hour exposures with IUE included J. C. Blades, R. C. Bohlin, A. Caulet, L. L, Cowie, J. Gallagher, D. C. Morton, S. Ratcliffe, P. Rybski, A. Songaila, W. Wamsteker, C. C. Wu and D. G. York.

A main purpose of the UV program with IUE was to see if C IV and Si IV doublets, two prominent absorption line pairs in the QSOALSs, but not then known to be prevalent in the halo of our Galaxy, could be prominently seen in the halo of the MW, the halo we could best study at that time. This work led to detections of ions for S II, Si II, Fe II, C IV and Si IV in the MW halo directions probed, but neither the velocity profiles nor the frequency of detection revealed any need to change the conclusions of York (1982) regarding the extent of the gaseous halo of the MW (Burks, et al. 1991). The broad Lyα emission line of 3C273 is redshifted to the position of the Galactic IS Si IV absorption doublet (rest wavelength 1393, 1402 Å) of the Galaxy in that direction, possibly associated with Radio Loop I of the MW. The main result of stacking ten high-resolution IUE exposures totaling 600,000 s of exposure time showed clearly that the velocities of both members of the Si IV doublet were directly centered at 0 $\mathrm{km\,s^{-1}}$ LSR, indicating that no high velocity material from the MW halo was detected.

5.2. The Nature of QSOALSs

Once I was at Chicago, I became engaged more deeply in the study of intergalactic IS lines, more specifically the absorption lines in the spectra of QSOs. The gas in QSOALSs was at high redshift, so the same UV lines studied in Copernicus IS spectra of Galactic O and B stars ($z \sim 0$) could be observed from Earth in redshifted QSOs. It was a natural switch of emphasis to concentrate on intergalactic absorbers. I continued working on data taken by Copernicus, for the unreddened star program described above. I was heavily influenced in this pursuit by Dr. Priscilla Frisch, a research associate at Chicago with similar interests to mine, particularly on the LISM (Frisch & York 1983; York & Frisch 1984).

QSOALSs were first noticed in QSO spectra in the late 1960s, when I was in graduate school at Yerkes, and were interpreted as spectral lines in otherwise unseen extended gaseous halos of normal galaxies that lay either at lower redshifts than the QSOs themselves or in hot gas regions associated with the QSOs with $z_{\mathrm{gas}} \sim z_{\mathrm{QSO}}$ (known as Broad Absorption Line [BAL] systems [or associated systems]). The most common absorption lines detected were C IV and Si IV and it was not clear that normal galaxies were the source of the absorption lines. The notion that "normal galaxies" might have extended halos (50–200 kpc) (Bahcall & Spitzer 1969) was considered. Since few galaxies of such size were known at that time, it had to be postulated that extended regions of gas surrounding the luminous parts of normal galaxies could produce absorption lines that would show up in the spectra of QSOs behind the extended halos of those galaxies. The morphology of such "halos" could not be directly discerned because they could not be visibly detected at that time and the QSO beam intercepted only a tiny portion of the postulated halos. A particular halo could not be mapped in multiple absorption sightlines. (There were few if any places where there were enough QSOs bright enough to be observed that lay

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[9] Thanks to the cooperation of IUE Project Scientist, Yoji Kondo (1933-2017), and IUE Resident Astronomer, Dr. George Sonneborne, it proved relatively easy to observe remotely for the multi-shift exposures necessary to build up this long, total integration time. This included observing through shifts normally controlled from the IUE ground station in Vilspa, Spain. The longest total exposure time obtained was 600,000 s for the QSO 3C273.

within 200 kpc of a given QSO to map the lateral extent of the postulated halos.)

Later, in the 1960s, Mg II and Fe II appeared in absorption lines in QSO spectra. The first QSO found to have Mg II absorption lines from an evidently overlapping (intervening) galaxy was PHL 1226 ($z_{\rm QSO} = 0.404$) (Bergeron et al. 1988). Ironically, the galaxy was in a foreground cluster and either one of two galaxies, or both, could have been the origin of the Mg II line that appeared in the spectrum of PHL 1226. The QSO showed a Mg II doublet with $z_{\rm gal} = 0.1602$ and the two galaxies in the cluster had known redshifts of 0.1592 and 0.1597.

Several other examples of galaxies in front of QSOs with redshifts matching those of the QSOALS quickly followed (Bergeron & Boissé 1991) and the "intervening hypothesis" was taken as confirmed. Pairs of this type were referred to as QSO/galaxy pairs or QGPs. Since an intervening galaxy was not confirmed for some 20 yr after the discovery of absorption lines in QSO spectra, the name "QSO absorption line systems," or QSOALSs, continued to be used.

The conclusions from the intensive observing program done by Songaila while I was at Princeton and the related IUE observations (started from Princeton and finished while I was at Chicago) left me with three general feelings about QSOALSs. First, that these obvious checks on the general picture of intervening galaxies in front of QSOs did not seem, empirically, encouraging. The long sightlines observed through the MW halo without C IV ions neither provided encouragement nor did the lack of extended gas in a halo of O VI as found by Jenkins (1978a, 1978b). Furthermore, many of the absorbing systems in QSO spectra were hundreds of km s^{-1} wide. Even with the extended, flat rotation curves of massive halos, single lines of sight through such a halo could not produce such broad spreads from a single foreground intervening galaxy (Weisheit & Collins 1976).

Additionally, it seemed to me that low excitation H II regions, in terms of their spectra, made a good description of the halo "clouds" that astronomers were looking for, a thought I pursued after moving to Chicago.

5.3. Detection of Emission Lines from H II Regions in Intervening Galaxies

My personal pursuit of detections of QGPs and their nature stretched over 41 yr (1980–2021). The intervening hypothesis was by no means confirmed while I was working in Princeton and I had my doubts. These doubts led to a paper on the possibility that the foreground "galaxies" were H II regions (York et al. 1986b), either free standing H II regions with physical characteristics such as seen in the LMC H II region 30 Doradus, or possibly multiple dwarf galaxies clustered in halos of galaxies. This suggestion was based on several persistent analogies between QSOALS and spectra of H II regions. In that 1986 paper, the authors suggested that searches in QSO fields be made for emission line objects, using narrow band filters.

An early apparent confirmation of this hypothesis occurred in 1986 (Yanny et al. 1987). Referencing an early version of a list of high-quality candidates of QSOALS to use in searching for emission lines matching the redshifts of QSOALSs (York et al. 1991, discussed later) in the near-fields of the QSOs, we mounted a Rutgers F–P system on the CTIO 4.0 m telescope for a search. One object was found to have an object in emission. The QSO was QSO 0453-423, with redshift 2.66 (Sargent et al. 1979); the QSOALS had absorption lines of Mg II, Mg I and Fe II; the redshift of the QSOALS was 0.7256; the emission line searched for was [O II] 3727 Å rest frame; the filter used was 6432 Å (3727 Å at $z = 0.7256$) with a full width at half maximum (FWHM) of 6.9 Å. We borrowed the critical filter for this observation from Dr. Bruce Woodgate (GSFC). A strong signal of what turned out to be, in fact, the [O II] emission line we sought was detected from a small, resolved ($1\rlap{.}''8$ FWHM) object 29″ (140 kpc) from the QSO 0453-423. Confirmation of the detection was obtained with a detection of both [O II] and [O III] (5007 Å, rest frame) emission lines, common in star-forming galaxies, using the long slit spectrograph on the 4 m telescope, near Tucson, Arizona (Yanny et al. 1987).

I bought some narrow band filters for direct use with focal plane CCDs to pursue other cases of probable QGPs, analogous to the case just discussed. Another field on our list was the complicated case of the variable BL Lac AO0235+167, which showed a QSOALS at $z = 0.525$ with Mg II, Fe II and other absorption lines. The emission line redshift of the BL Lac was $z = 0.94$ (Cohen et al. 1987). In spectroscopic studies of the complicated spectrum, Cohen et al. (1987) found narrow emission lines of [O II] and [O III], at the same redshift as the QSOALS. My student Brian Yanny pursued narrow band imaging at the KPNO 4 m telescope with a CCD, using a 5684 Å filter with width 15.6 Å to search for [O II] emission at $z = 0.525$ possibly associated with the QSOALS. Several emission regions were detected near the BL Lac image, together with an [O II] emitter 26″ (100 kpc) from the BL Lac (Yanny et al. 1989). This appeared to be a case of foreground emission from star formation very far from the QSOALS in a background active galactic nucleus (AGN). (BL Lac objects and QSOs are notable as galaxies with bright nuclei, seen at different orientations, at cosmological distances).

Using our search list of candidate QGPs (York et al. 1991), we pursued narrow band searches in six additional QSOALSs for [O II] or [O III] emitters. The QSOs selected had z between 1 and 2 and the QSOALSs in those objects ranged from $z = 0.4$ to 1. Four to five hours of exposure time plus overhead and allowance for cloudy weather were necessary for each candidate QGP and we could only get two or three nights on 4 m telescopes at a time. We pursued this total of eight candidate QGPs for two and a half years (Yanny et al. 1990b).

The results were encouraging. However, indications were that the distances of the foreground galaxies in projection from the QSOALS objects were up to one arcmin and filters with the necessary size were expensive, for either a direct imaging approach or the F–P approach. But, while the redshifts of many QSOALSs were known to us in selecting narrow band filters to search for candidate galaxies with [O II] emission, there was evidence that there were several galaxies in a number of cases that needed to be checked for emission to be complete, but more efficient instrumentation was necessary, which came along with the launch of HST, the use of the Very Large Telescope (VLT)/Multi Unit Spectroscopic Explorer (MUSE) integral field unit (IFU) instrument and the development of the SDSS survey, as discussed later. For some of the 40 candidate [O II] objects found to match the QSOALS redshifts in the search for the eight fields, the aperture of 4 m class telescopes was not adequate. The [OII] technique was clearly interesting, but mainly as an indicator of the morphology of star formation associated with some of the intervening galaxies.

Searching for extended foreground objects overlapping QSOs containing QSOALSs at a corresponding redshift made any galaxies within 10–200 kpc in projection a candidate QGP. But assuming the closest such object to the QSO was the suspected object, as was often done, using galaxy colors or morphology, and in the absence of an emission line clue, was unreliable and not unique. I worked for several years trying to detect emission in ionized oxygen, as found for the two cases above (luminous star-forming regions in the candidate QGPs), including the use of nested fiber optic bundles at Kitt Peak called dense-packs (Yanny et al. 1990a) and of an F–P optical system owned and maintained by Dr. Bruce Woodgate (GSFC), assisted by Carol Grady (GSFC), mounted on the 3.5 m telescope at APO (Straka et al. 2010). Yanny et al. (1990b) utilized both narrow band filters and the Rutgers F–P to confirm four additional emission line objects that helped identify probable sources of the QSOALS that appeared in background QSOs, in addition to 33 candidate objects.

5.4. A Literature Catalog of QSOALS and Early Spectroscopic Observations of QSOs

I made my first high-resolution spectroscopic observations of QSOALS on the Multiple Mirror Telescope (MMT) (York et al. 1984) and the 4 m telescopes at KPNO and CTIO (Meyer & York 1987; Khare et al. 1989), in my first decade at Chicago.

Meanwhile, with students, I started to catalog, from the literature, as many high quality QSOALSs as possible, to answer such basic questions as whether the range of elements encountered in high z galaxies was similar to that in Galactic ISM clouds (systems with heavy elements) (York et al. 1991). This reliable data set was assembled for the purpose of selecting samples of QSOALS suitable for defining classes of systems by elements detected, abundance, saturation, or as QGPs, for instance. After searching the literature stretching from 1965 to 1989 for absorption lines in 280 QSOs, we cataloged a total of 282 C IV systems (absorption doublets, near rest frame 1549 Å) and 131 Mg II systems (also, absorption doublets, near rest frame 2800 Å). The selection of objects was restricted to systems most likely to be relevant to the intervening hypothesis (as discussed in Section 5.3, above). Thus, broad associated systems (previously mentioned BALs) and systems with only Lyman series lines of hydrogen or Lyman limits were not analyzed.

A few QSOs had only one absorption line system listed in the catalog, while three had over 12 systems (unrelated to each other), out of 269 QSOs with redshifts from 0 to 4. A more typical number was six QSOALSs per QSO. Systems with resonance absorption lines of a C IV or Mg II doublet and additional species found at the same redshift as a C IV or Mg II doublet were graded A. Systems with only a doublet of C IV or Mg II having the appropriate strength ratio of the two lines of the doublet (between 1 and 2) were graded B. Data that appeared to yield unreliable measurements were graded C and were included but not used for analysis. Of 186 QSOALSs found in 48 QSOs with $z > 3$, 13% were grade A, 67% were grade B and 20% were grade C. We tabulated 11 other heavy element transitions of seven additional species (C II, Mg I, Al II, Si II, Si IV, Al II and Fe II) after rejecting low quality measurements. We also assigned upper limits for most of the measurements.

The relative equivalent widths of the lines of the elements noted above showed large differences between systems. A survey of doublet ratios, saturation levels and spatial correlation functions of the various absorption systems with each other was made. (This survey served as a prototype of the much larger SDSS QSOALS catalog to follow, discussed below in Section 5.5.)

The conclusion we reached was that, while interesting trends in relationships between different ions appear with redshift for sample sizes of ∼250, much larger samples were needed to verify that they were significant. Ratios of column densities of different ionization stages seemed to have large variations from one QSOALS to another over the relatively small sample. The number of Mg II absorbers per unit z averaged one and was roughly flat from $z = 0$ to $z = 1.5$. The number of C IV absorbers per unit z was not well observed below $z = 1.5$, but was near 2 at $z = 1.5$ (where data were available in the sample) and dropped to near zero by $z = 4$. There was an indication that the doublet ratios indicated the C IV lines were less saturated as the redshift increased. The strongest Mg II 2796 lines were generally ∼1 Å but could be as large as 4 Å when the QSOALS was a blend of components. The strongest C IV 1548 Å lines were generally ∼0.5 Å but could be as large as 1.5 Å (blends).

The sample sizes needed to be much larger (thousands) to detect clustering amplitudes over angles 20° in size on the sky. As discussed later, samples exceeding tens of thousands eventually became available (>200,000) from SDSS, with more detected species. However, the data have yet to be analyzed to check the realities of the trends found in the York et al. (1991) paper.

During the period from 1988 to 2019, I supervised eleven Chicago Ph.D. thesis students.[10] Six of them continued the work on observations of QSOs (A. Caulet, B. Yanny, J. Lauroesch, V. Kulkarni, D. Vanden Berk and G. Richards). The thesis papers related to QSOALS between 1991 and 2002 constituted much of what I learned about QSOALS in that period.

A comparison of high-resolution observations of the ISM in the MW and nearby galaxies (the Local Group) over a wide range of redshifts (1982–2020) was an attempt to understand the gas in QGPs. The first observing experiences with QSOALS and the supervision of the student thesis topics set the stage for extensive work with several collaborators[11] between 1992 and 2020, on Galactic stars (disk and halo, reddened and unreddened), SMC/LMC stars, and QSOALS, while I was devoting virtually all my personal observing to a major survey of DIBs in the MW (discussed later). To limit the length of this article, I do not detail that work on QSO high-resolution spectra here, but I list in a footnote the collaborators and projects done over that period, involving the nature of QSOs and QSOALSs and related ISM studies, in which I participated or which I followed closely.

During this period, the archival Copernicus and IUE measurements for the ISM were available and new instruments added significant new capabilities (HST, FUSE, the ESO VLT). Higher resolution UV observations (resolution $\sim$3 km s^{-1}) of fainter objects could be made. An increased number of elements in the ISM could be studied using unsaturated or weakly saturated lines. Foreseeable, significant improvements in the quality of information available on IS lines, and hence on the physics of cool and warm ($T < 1000$ K) IS clouds, will probably come from higher resolution, orbiting or possibly rocket-launched UV spectrographs with spectral resolution of 0.5 km s^{-1} for resolving narrow, blended IS components, especially of the rotationally excited levels of molecular hydrogen and unsaturated lines of IS elements and molecules between 912 and 1150 Å (rest frame). Of course, additional observations with the existing instruments will increase the statistical significance of our knowledge of the numerous unsolved mysteries of the ISM in our own Galaxy and the many galaxies that we can apparently study through QSOALSs.

5.5. A New SDSS Catalog of QGPs

We used the SDSS databases to increase the number of known QGPs from several hundred (York et al. 1991) to tens of thousands. Once the SDSS QSO pipelines were ready and released, I set out with students and SDSS collaborators to make a new catalog of QSOALS spectra based on the high quality but modest resolution SDSS spectra of both intervening systems (foreground to the QSO, $z_{\rm abs} < 0.02 \times z_{\rm QSO}$ and systems likely associated with the immediate environment of the QSO $z_{\rm abs} \sim z_{\rm QSO}$ (most likely not associated with QSOALS) for a massive and quantitative (photoelectric) study of the QSOALS phenomenon (York et al. 2005). As of SDSS DR7 (Abazajian et al. 2009) the assembled QSOALSs in Mg II and C IV totaled over 39,000 each. All the other species of absorption lines detected by our automatic software that were stronger than $\sim$0.1 Å were measured in redshift, system velocity width, equivalent width and other key measurables (York, D, G., Lundgren, B., Alsayyad, Y., et al. 2023, to be submitted).

This catalog contains the results of a search of 107,000 QSOs, resulting in 75,866 high confidence QSOALSs, based on 243,698 absorption lines. System grades were assigned: A and B for the highest quality; grades C to E for systems that needed confirmation. Equivalent widths were automatically determined prior to assigning line identifications and continua were automatically determined in the software to avoid issues with narrow emission lines arising in foreground galaxies, QSOs or the night sky. Thirty-two transitions of 19 species of 13 elements made up the line IDs. Extensive efforts were made to avoid basing line IDs on blends, artifacts or any assumptions about abundances. A website (unpublished) documents all the reliable spectra and system properties and displays the results of the likelihood of the reliability of each system based on a machine learning algorithm. While the resolving power of the SDSS spectrographs ($\sim$1800) is inadequate for precise abundance determination for the most abundant elements because of component blending, stacking of spectra of weak transitions over multiple systems should yield abundance information for a number of elements.

The catalog has been used in numerous publications by several authors. Three examples in which I was involved follow.

An early example of such a project was to select and co-add, in the rest frame, spectra of some 800 QSOs containing intervening systems with Mg II absorption, for the purpose of determining the abundances for the lines most likely to be on

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[10] For all of the Chicago thesis students I supervised, the dates of their theses and some indication of the topics of their theses are as follows: Adeline Caulet 1988, evolution of QSOALS with redshift; B. Yanny et al. 1989, QGPs; G. Burks et al. 1991, halo of the MW; T. Rodriguez-Bell, 1992, mass loss in A stars; J. Fowler, 1995, LISM; Lauroesch, 1995, abundances in QSOALS at $z = 2$; V. Kulkarni, 1996, physical properties of damped Lyα systems (DLAs) and sub-DLAs in QSOALS systems; D. Vanden Berk, 1998, clustering of QSOALS; G. Richards 2000, QSOALS with $z_{\rm intervening} \sim z_{\rm QSO}$; C. Rockosi, 2001, MW halo stars and streams; C. Mallouris, the IS spectrum of Sk 108 in the SMC with FUSE, 2002. I also supervised the thesis of H. Fan et al. (2017) at NAOC, Beijing, DIB Behaviors; 2019, A catalog of $\sim$559 DIBs.

[11] Contributors on high-resolution ISM MW reddened stars (seven stars): D. Welty, T. Snow, P. Sonnentrucker, B. Rachford, S. Friedman, L. Hobbs, L. Spitzer, D. Morton, J. Fowler and D. York. Contributors on high-resolution ISM MW unreddened stars (six stars): D. Welty, L. Hobbs, J. Lauroesch, E. Jenkins, J. Raymond, C. Mallouris, D. York, L. Spitzer and E. Fitzpatrick [sole author papers]. Contributors on LMC/SMC stars: D. Welty, J. Lauroesch, C. Blades, L. Hobbs, P. Frisch, G. Sonneborne and D. York. Contributors on QSOALS's: J. Meiring, D. Meyer, V. Kulkarni, C. Peroux, P. Khare, J. Lauroesch, G. Vladilio, A. Crotts and D. York.

the linear portion of the curve of growth (York et al. 2006). The main direct results were that the abundance [Zn/H] was nearly solar in QSOALS at a wide range of redshifts between one and two and that the extinction curves of the intervening galaxies did not have detectable 2175 Å bumps.

A second example of such a project began when it was found that SDSS spectra of QSOs, with QSOALSs at $z_{\rm abs} < 0.8$, so identified on the intervening hypothesis as arising from a foreground galaxy, sometimes contained emission lines from H II regions (especially Hα [6563 Å] and [O III] [5007 Å]) that could be detected directly in the SDSS spectra. The ten key emission lines are Hα; Hβ; [O II] λλ3727, 3729; [O III] λλ4960, 5008; [N II] λλ6550, 6585; [S II] λλ6718, 6733 (York et al. 2012; Noterdaeme et al. 2010; Straka et al. 2013).

At low redshifts, light from galaxies, offset by only a few arcsec from a background QSO (i.e., < 10–12 kpc), might illuminate all or part of the three arcsec fiber aperture, on which the 1″ diameter targeted QSO was centered. If the galaxy has emission lines, they appear superimposed on the SDSS spectrum extracted from the fiber. The emission lines give the redshift of the galaxy. That redshift should match that of the absorption lines (the QSOALS) created by the gas in the foreground galaxy and seen in the background QSO.

The accurate spectrophotometry of SDSS allows the galaxy and QSO spectra to be separated and the emission and absorption redshifts compared. For galaxies that match, one can estimate the luminosity of the galaxy (by subtracting the QSO flux), the star formation rate (SFR, from emission line strengths), the size and morphology of the galaxy (as seen in SDSS images), and the amount of extinction (from photometry of the galaxy after correcting for the QSO colors as determined from the spectrum). Thus, the galaxy type can be determined.

Three samples of QSOs containing QSOALS in two redshift zones, $0 < z_{\rm abs} < 0.4$ (Straka et al. 2013) and $0.4 < z_{\rm abs} < 0.8$ (Noterdaeme et al. 2010), (each zone found to have ∼50 objects) were assembled. For the combined sample, 90% of the galaxies were blue, late type, star-forming dwarf galaxies, confirming suggestions of York et al. (1986a, 1986b).

Dwarf galaxies exist at all redshifts. It was thus plausible that some dwarf galaxies foreground to some QSOs at any redshift could be responsible for QSOALSs and that searching for emission lines in spectra of those QSOs would be an efficient way to identify galaxy types of the foreground galaxy in the QGPs. But for QSOs at $z > 0.8$, the main optical H II region spectral lines would be redshifted out of the range of the SDSS spectrographs, so this way of identifying QGP types would not work. As more and more SDSS spectra are obtained, the number of QGPs that can be typed in this way will continue to grow, but only slowly because the foreground intervening galaxy must lie so close to the three arcsec diameter SDSS fiber for the emission lines to show up in the SDSS spectrum. The properties of the galaxies were similar among the three samples noted above and a final set of 103 was published by Straka et al. (2015). This special set of objects was identified by automated searches for emission lines of some 105,000 QSOs from SDSS DR7 (2009). For the total sample, the galaxy-QSO offsets (impact parameter [b]) ranged from <1″–12″ (0.37–12 kpc), the SFR ranged from 0.01 to 12 solar masses per year and the masses were in the range of dwarf galaxies.

A third project based on the SDSS catalog of QSOALS relates to finding large numbers of QGPs at higher redshifts. For some 20 yr after the confirmation of the intervening hypothesis in the early 1990s, finding galaxies within ∼200 kpc of a QSO that contained QSOALSs was time consuming in terms of telescope time, in cases when confirming emission lines did not show up (as discussed above). One had to obtain images of the field of a QSO with a QSOALS, identify possible host galaxies, then obtain spectra of each candidate to see if the galaxy redshift matched that of the QSOALS. But around 2012, there began to be signs that redshifts of multiple galaxies might match a single QSOALS. Complete searches of redshifts of all galaxies in a 200 kpc region around a QSO with multiple QSOALSs became desirable, to find all the (supposed) galaxies to explain all these unrelated QSOALSs in a given QSO. This required wide field spectroscopic search instruments with wide redshift coverage. One could not just pick from images of a single candidate foreground object in the field that was brightest or closest to the QSO on which to focus an efficient spectroscopic confirmation effort that a QGP had been found.

Two such instruments became available in the first part of the 21st century: an IR grism on HST that could be used to search for a selection of nine key H II region lines from multiple emission line galaxies, simultaneously, over a field of <200 kpc, and an integral field spectrograph, the MUSE on the VLT. These instruments would expand the redshift range of the most efficient searches for QGPs.

The very large number of QSOs in DR7 had varying numbers of QSOALSs in each QSO. From a list of DR7 QSOs created by York and students and a list of QSOs from the Baryon Oscillation Spectroscopic Survey (BOSS) spectrograph (Pâris et al. 2012), Lundgren et al. (2021) selected nine QSOs with over five QSOALS each and used the HST/Wide Field Camera 3 (WFC3), with grism G141 installed, to image the nine fields. (WFC3 was a fourth generation instrument, a new imaging imaging camera mounted on HST in May 2009 May by astronauts working on a Space Shutttle visit to HST.) In the redshift range $0.64 < z < 1.6$, the nine QSOs yielded a total of 34 QGPs for 38 QSOALS (an 89% confirmation rate of QGPs using only 18 orbits of HST observing time). The 38 independent QSOALS all had doublets with Mg II absorption lines that matched in redshift to 34 galaxies with Hα emission within a ∼200 kpc search region. Nearly half of the QSOALSs matched the redshifts of two or more galaxies. Four QSOALS matched three galaxies. Thus, the number of intervening galaxies that could be typed and studied multiplied considerably using the HST/WFC3 grism spectra. The clustering and masses of these galaxies will be of interest.

Hamanowicz et al. (2020), published a few months before Lundgren et al. (2021) (on both of which I was a co-author) examined five previously published fields of QSOs that had one known QGP by looking for emission lines in spectra of the ESO VLT/MUSE IFU spectra. For the total of five QSOs, they found 14 QSOALS and 42 foreground emission line galaxies with $z_{\rm gal} < 1.4$. The impact parameters were < 250 kpc, and the SFR limits reached were 0.01 to 0.1 solar masses per year. Excluding the previously found galaxies that matched the redshift of one QSOALS, the success rate of matching the remaining QSOALS was 89%. One QSOALS had no galaxy match, five QSOALSs had one galaxy match, two QSOALSs had two galaxies match, one QSOALS had three galaxies match, two QSOALSs had four galaxies match, one QSOALS had five galaxies match, one QSOALS had six galaxies match and one QSOALS had eleven galaxies match. Thus, an additional 42 QGPs could be typed using MUSE archival spectra from the original search material.

Evidently, over a few years, a sizable number of QGPs can be fully characterized and the nature of a large number of the QGPs at a wide range of redshifts can be determined, greatly augmenting the data on galaxy evolution at modest redshift.

The cited HST and MUSE discoveries showed that a key assumption previously used in identifying QGPs was incorrect: the brightest and closest galaxy that matches the redshift of a QSOALS cannot be declared the only QGP associated with a given QSOALS.

QSOALSs with a foreground galaxy with no emission lines could neither be found this way (early type galaxies) nor could "dark galaxies" with very low luminosity at the redshift of the QSOALS in the QSO field being searched.

5.6. The Revelation of the Complexity of Apparently Single QSOALSs

The conclusion of both these particular studies shows that the simplifying assumption originally used to find QGPs, namely that a given QSOALS can be attributed to a single foreground galaxy, is not true in all cases. Both research groups discussed above used QSOs with multiple component Mg II absorption lines in wide field searches for emission lines in all galaxies in the field of each QSO to seek redshift matches with each Mg IIs absorber pair with emission lines in any galaxies within some ∼200 kpc of the QSO. The samples each involved multiple, independent Mg II absorbers in 5–9 QSOs with $z \sim 2$ and each yielded ~37 foreground intervening emission line objects with $z \sim 1$.

Groups of emission line objects (in the two cases cited, dwarf galaxies) can evidently produce multiple absorber systems in a particular QSOALS spectrum, which are blended together, forming an apparently single foreground object because they all arise at the same redshift, plus or minus the group velocity dispersion. Each of the detected emission line galaxies lie within 10–200 kpc of the QSO in which the absorption appears, so are, of necessity, extended.

Both research groups were able to reach to galaxies with R band magnitudes of about 24th magnitude and galaxies with SFRs below 1.3 solar masses per year. The independent studies found that over 40% of QSOALs had more than one matching foreground galaxy per Mg II doublet, with an average of 3 ± 1 galaxies per Mg II doublet matching to better than $\Delta z/(1+z) = 0.007$.

In both cases, a new instrument enabled the searches for intervening QGPs that allowed the low ionization absorption lines in QSO spectra to be freed of the previous constraints of inadequate photometric sensitivity, inadequate field of view and inadequate spectral sensitivity.

An important aspect of multiple galaxies at very similar redshifts contributing to a single QSOALS is that the ability to assign narrow components to a particular one of the galaxies is essentially lost. Apparent velocity structure in an apparent single absorption line system, possibly with multiple system velocity components, could be a blending of such structures from the multiple foreground galaxies. In that case, abundances are difficult to derive for any of the well separated single galaxies in the foreground. It is not clear how to know when multiple foreground galaxies are present in a single case, even by replicating the types of observations noted above, because very faint foreground emission entities, with redshifts matching a given QSOALS, that are not detectable in reasonable exposure times, may impose detectable absorption features on the background QSO, but the corresponding emission may not show up in the foreground galaxy.

The techniques used above serve to show that QGPs can be readily identified using wide-field, multi-object imaging and spectroscopy; that groups of extended dwarf galaxies may be common even at $z \sim 1$; and that apparent velocity structures in QSO absorption lines can arise from multiple groups of galaxies producing Mg II lines that are not just velocity components within single star-forming objects or multiple gas clouds filling dark matter halos, but may also arise from the velocity dispersion of galaxies in the foreground group of objects. The contributions to the often wide-spread of components of a QSOALS now include random motions of gas clouds within each involved intervening galaxy; systematic outflows or inflows of gas in each intervening galaxy that is contributing to the spectrum of a QSOALS; projected rotational motions of the galaxies contributing to the different intervening galaxies contributing to the QSOALS; and the dispersion of velocities within groups of galaxies just discussed. Separating these poses a non-trivial problem for the future.

The search for QGPs using emission lines went so slowly (1989–2020) because we could not reach, with the earliest mentioned emission line search techniques, an adequate continuum S/N level to detect the emission line flux levels to match the galaxy requirements in the vicinity of $z \sim 1$. New telescopes (VLT and HST) and new instruments (MUSE and the HST near-infrared (near-IR) grism) were required. The morphology of each of the multiple foreground objects (averaging, in the case of the MUSE sample noted above, three per QSOALS, but rising to as many as 11 in one case) or appearing, in the case of the HST sample, in groups of two-four, is not clear.

It is extremely rewarding to see these conclusions come from a field I pursued for 41 yr, starting with studies of the gas halo of the MW with several colleagues. The work was intermittent, as allowed by new technology. This work lays the groundwork for new studies of the evolution of abundances in galaxies and of galaxy formation over a very wide range in redshift, the reason that many of us have worked so long in the field.

6. Diffuse Interstellar Bands

6.1. Summary of Properties of DIBs

My other major research at Chicago involved the DIBs. My work on these unidentified IS features extended over the years 1968 to the present time. Part of this work goes back to my Chicago Ph.D. thesis. Part of it was done at Princeton, with Ted Snow, Dan Welty and others, but the largest part of my work was done with the research group I formed and worked with for 20 yr of remote observing on the echelle spectrograph at APO. A summary of DIB properties as they are known today follows.

Based on observations of hundreds of stars, DIBs are IS absorption lines because they occur at repeatable wavelengths (to within tenths of Angstroms) in stars of a wide range of spectral types and are "stationary" when observed in spectra of binary stars. A few may be blends. Over 550 DIBs are known in the region 4000 to 8000 Å (Hobbs et al. 2008, 2009; Fan et al. 2019); possibly five are known near 9500 Å; and some 40 are confirmed in the near-IR between 9600 and 24500 Å (Ebenbichler et al. 2022). Virtually none are known in the UV to the limits searched for.

The exact number of DIBs is uncertain. DIBs wider than 6 Å exist. As many as 11 of 22 possible cases could not be confirmed in a special search by Sonnentrucker et al. (2018). Problems of drawing the continuum over such broad features mean that some such DIBs may have been missed in high-resolution echelle spectrographs (Hobbs et al. 2008). Blends with telluric lines are difficult to correct for in parts of the visible and IR spectral regions, which may cause weak DIBs to be missed in some searches. Blends with stellar lines in the stellar spectrum may mask DIBs if the target star has a low $v \sin i$. Blends of two or three DIBs may be resolved with higher resolution. A number of researchers suspect that more DIBs remain to be detected, particularly as larger and larger molecules are considered as candidates. Higher S/N and higher resolution may eventually be necessary to remove these impediments. As the number of known DIBs has grown by a factor of over twenty over the last six decades, several researchers have suggested that there must be many types of molecules or grains that produce DIBs.

Structure appears in some DIB profiles, which may be a consequence of molecular structure of the DIB carrier, of impurities in solids, of blends of DIBs with other DIBs, or of blends with unrecognized stellar lines or telluric lines. Thus, central wavelengths of features containing DIBs may differ from star to star. Modeling of profiles suggests some of the DIB carriers may be as small as 5–6 atoms, and some as large as 150 atoms or larger.

The FWHMs of the DIBs in the optical region range from a minimum of ∼20 km s^{-1} (0.4 Å at 6000 Å) to a maximum of 1700 km s^{-1} (34 Å at 6000 Å) (Sonnentrucker et al. 2018). In contrast, single components of IS atomic lines are usually $<$ 1 km s^{-1} in thermal width ($T <$ 10,000 K), often found in blended groups less than 10 km s^{-1} in width, but usually distinguishable from DIBs by wavelength and profile. There are two very broad absorption features in the IS extinction curve, one at ∼2175 Å, discovered in by Stecher (1969) (typically ∼250 Å wide) and a broad feature at 7700 Å discovered by Maíz Apellániz et al. (2021) of width ∼175 Å. Both may be related to DIBs but may have a different origin. Few if any of the DIBs appear to be saturated. (That is, the equivalent widths of even the strongest DIBs are possibly directly related to the column density of the carrier.) The equivalent widths range from milli-angstroms (mÅ) to tens of Angstroms to a maximum of thousands of Angstroms.

Historically, there is little conclusive evidence of multiple DIBs that arise from a specific carrier. Ironically, the one molecule that has been possibly confirmed as the carrier of any DIB, C_{60}^{+}, has five lines attributed to it. Short sequences of weak, harmonically spaced, unidentified lines have been reported (Herbig 1988), (energy separation of 35 cm^{-1}). Duley & Kuzmin (2010) identified DIB-like features with energy separations ∼5, 21, 32 and 34 cm^{-1} arising from bending and stretching or torsional modes of large molecules in the excitation energy range 300–3300 cm^{-1}. However, it is unclear where the excitation of such high levels could come from in the ISM. The latter paper, based on data from the Apache Point DIB surveys cited above (Hobbs et al. 2008, 2009), suggests that future observations may reveal many carbon chain (aliphatic) or carbon ring (aromatic) molecules that produce low lying harmonic progressions from bending and stretching modes that yield many weak "DIBs" from single molecules.

Generally speaking, the origin of the many unidentified, demonstrably IS, DIBs is unknown. It is considered likely that any DIB molecules contain mostly carbon, with some N, O, P, S, Si and Fe. If porphyrins are considered, Mg should be added to the list (Johnson 2006).

At the time of my thesis, the origin of the DIBs was thought to be tied to IS dust particles, but discussion today includes more consideration of aromatic or aliphatic molecules or molecules that are a combination of both: mixed aliphatic/aromatic organic nanoparticles (MAONs, Kwok & Zhang 2013). Only one molecule (C_{60}^{+}) has been possibly successfully confirmed by wavelength (Cordiner et al. 2019) to produce DIBs (at least four of them, $\lambda\lambda$9348.4, 9365.2, 9427.8 and 9577.0.), but doubts remain (Galazutdinov et al. 2017).

To seek an understanding of the very large number of unidentified absorption lines observed, various attempts to classify the DIBs have been made using line strength correlations (or anti-correlations) or data science techniques to find families of DIBs, clusters of DIBs with similar behaviors, or types of molecules by chemical structures. It was hoped in this way to find guidance in the search for specific DIB carrier molecules. One family, the C_2 DIBs, is discussed later, but it contains only 3% of cataloged DIBs. Suggestions of other groupings have been made, but no further specific molecular suggestions for DIB carriers have resulted from this approach.

6.2. Historical Considerations of the Identity of the DIBs

There was much discussion of 1000 Å solid particles to explain the extinction curve, at the time of my thesis, with lattice defects to account for reported emission wings on DIBs, with various layered structures (such as cores with ice mantles), and with internal conversion in molecules to explain the width of some of the DIBs. Earlier, Platt (1956) had pointed out that small molecules (10 Å) with unfilled energy levels could produce attenuation that could possibly explain the optical extinction curve. Donn (1968) pointed out that large, ∼100 Å carbon ring molecules, such as polycyclic aromatic hydrocarbons (PAHs), might explain the curve, if there were a way to make them in space, and even suggested that structure associated with the 10–100 Å grains might be responsible for DIBs in the optical. Detailed discussions of a variety of suggestions of mechanisms by which the optical DIBs might be produced, current up to the publication of my thesis, were published by Wu et al. (1981) and Smith et al. (1977), and specific molecules that have been proposed and, if rejected, for what reasons, were commented on by Snow (2014). A thorough historical review was published by Herbig (1995).

Further developments occurred between 1960 and 2010, which I summarize here, to show the changed context in which we undertook the new work on DIBs in 1998. Around the time of the Donn (1968) paper on small grains of polycyclic carbon layers, and around the time of the launch of Copernicus, UIBs were being discovered with new IR spectrometers on ground-based telescopes, airplanes, rockets and, eventually, satellites. They were technically unidentified but were generally suggested to be PAHs (Leger & Puget 1984; Sellgren et al. 1985). Eventually, the UIBs (i.e., 3.3, 3.4, 6, 7.7. 8.6 and 11.3 μm) were found to exist in numerous astronomical sources where UV sources of radiation were available to excite emission: bright H II regions, planetary nebulae, reflection nebulae, Young Stellar Objects, post-asymptotic giant branch (AGB) objects, and many star-forming galaxies (Leger & d'Hendecourt (1985). See the extensive review by Tielens (2008).

There were several suggestions that ionized Buckeyballs (C_{60}^{+}) were a possible explanation for five DIBs near 9500 Å ($\lambda\lambda$ 9348, 9365, 9428, 9577 and 9632), the first three contaminated by telluric lines in Earth-based spectra (Leger & d'Hendecourt 1985).[12] After C_{60} was found in reflection nebulae (Sellgren et al. 2010) and planetary nebulae (Cami et al. 2010) (the first confirmed IS detections of a PAH-related molecule in space), Cordiner et al. (2019) claimed robust detection of four lines of C_{60}^{+} in several stars using spectra from HST, free of telluric lines. The lab line at 9632, blended with a stellar Mg I line in a number of cooler stars, was not scanned in the HST program.

Recently, McGuire et al. (2021) discovered two naphthalene (double ring PAH) variants in a dense molecular cloud, Taurus Molecular Cloud-1 (TMC-1), with enough resolution of rotational structure to confirm the spectroscopic identification with a ground-based radio telescope. Detection of additional PAH molecules with radio techniques has revealed a rich aromatic chemistry in dense IS clouds.

PAHs and other large molecules[13] are now considered to exist in planetary nebulae, in reflection nebulae, in extremely dense IS clouds and possibly throughout the diffuse ISM. Spectroscopic assignment of the cataloged DIBs to specific molecular carriers has yet to follow, except possibly for four or five DIBs assigned to C_{60}^{+} mentioned earlier. The theoretical and laboratory challenges in pursuing the many carbon cluster molecules such as C_6+-C_9+ and the larger C_{60}+ and C_{70}+ fullerenes that might exist naturally in space are discussed by Buntine et al. (2021). The goal would be to find absorption transitions that might be produced under laboratory conditions to match with lines seen in the many IS absorption lines known in the many DIB studies now extant or being created. However, computation of the energy levels expected in the lab is difficult for possible carrier molecules (Lyhkin et al. 2019).

6.3. A New Program for Observing Diffuse Interstellar Bands

Once the 3.5 m telescope was commissioned at APO (described below), with its new echelle spectrograph in 1998, I

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[12] The 1996 Nobel Prize in Chemistry was awarded for the discovery of fullerenes in the laboratory, to Harold Kroto, Robert Curl and Richard Smalley. Fullerenes are pure carbon molecules with single and double carbon bonds that are three-dimensional and cage shaped. PAH molecules have both H and C molecules that can be transformed into very stable fullerenes (Kroto et al. 1985).

[13] Kroto et al. (1980), seeking to set boundaries on the existence of large molecules in IS clouds, detected linear chain molecules up to molecular weight 99 (HC_7N).

formed a research team,[14] to observe DIBs in a large number of stars, using S/N of at least 1000 per pixel, or greater where possible, at a resolving power of $\lambda/\Delta\lambda \sim 38{,}000$, to attack anew the long-standing problem of the origin of the DIBS and their distribution in space.

Our main, very ambitious goal for the new program, of course, was to seek a solution to the 100 yr old mystery, the origin of the DIBs, the two best observed of which, $\lambda\lambda$5780 and 5797, were announced by Heger (1922). In the century since, 559 optical DIBs have been found (Hobbs et al. 2008, 2009; Fan et al. 2019). The first two papers were based on two stars (the first one HD 204827, a binary, the second HD 183143). The third paper, "The APO Catalog of DIBs," was based on DIBs that showed up in five or more of 25 stars representing a wide range of IS conditions, each exhibiting a rough correlation with $E(B-V)$. Only 22 new DIBs showed up as meeting these two criteria that did not show up in at least one of the two Hobbs papers. The suggestion that some of the DIBs might be caused by the molecule C_{60}^{+} (Foing & Ehrenfreud 1994; Foing & Ehrenfreund 1997), which now has been possibly confirmed, led to what looked like a surprising but good lead. Evidently, extensive laboratory observations are necessary for a large number of molecules to see if molecules with confirming DIB wavelengths can be found. Surprises seem to be in store.

A secondary goal of our program was to empirically relate the behavior of DIBs in IS lines-of-sight to the physics of normal aspects of IS clouds (densities, radiation fields, etc.). In this secondary goal, we have obtained some new information on how DIBs interact with atoms and molecules in IS space.

Our insistence on very high S/N paid off in several ways and the higher resolution DIB spectra allowed the rejection of some candidates based on improved wavelengths: C_7^- (McCall et al. 2001) and l-$C_3H_2{}^-$ (McCall et al. 2002). Furthermore, a claim of an optical detection of an 11 Å wide line of naphthalene ($C_{10}H_8^+$, a double ring PAH ion) in the spectrum of star Cernis 52 (BD+31 640) (near the dark cloud TMC-1) was made by Iglesias-Groth et al. (2008) but could not be confirmed by stacking high S/N spectra of 15 highly reddened stars from the 3.5 m telescope (Searles et al. 2011). Note that the case of TMC-1, where naphthalene has been detected using radio techniques (McGuire et al. 2021), and the detections of harmonic progressions noted by Duley & Kuzmin (2010) suggest that more sensitive searches for optical DIBs with appropriate spectrographs may prove fruitful.

Several influences of the properties of diffuse clouds on the properties of DIBs were noted in the course of our work. First, Julie Thorburn recognized a weak set of DIBs, mostly below 6000 Å, that are most prominent when lines of diatomic carbon (C_2) are noticed to be present (Thorburn et al. 2003). This represented a new type of DIB family (with at least 18 DIBs) with a connection to an easily detected molecule which exists in common IS clouds and indicated a possible connection of some DIBs with an easily identifiable property of normal gas clouds in space. This small set of weak C_2 DIBs was confirmed by Elyajouri et al. (2018).

A second clear relationship of molecules with DIBs is the "lambda effect." In a study of 186 stars from the APO Catalog of DIBs (Fan et al. 2017), five of the strongest and best studied DIBs ($\lambda\lambda$5780.5, 5797.1, 6196.0, 6283.8 and 6613.6), three of the strongest C_2 DIBs ($\lambda\lambda$4726.3, 4963.7 and 4984.8), and four common IS diatomic molecules (CO, CN, CH and C_2) were compared with the ratio of molecular hydrogen to total hydrogen, by mass. Using $E(B-V)$ to normalize the equivalent widths of the four diatomic molecules and eight DIBs, this work showed diminishing normalized strengths of the five strong DIBs with increasing fractional values of molecular hydrogen $\{f(H_2) = 2N(H_2)/[N(\text{H I}) + 2\,N(H_2)]\}$, while the normalized strengths of the four diatomic molecules listed above increase dramatically with $f(H_2)$ and the strengths of the C_2 DIBs are random with $f(H_2)$. A pattern was found (with scatter) that this parameter rises quickly from $f(H_2)$ of 0 to 0.2, then slowly decreases to very low DIB parameter strengths at high $f(H_2)$. Interestingly, using similar normalization of the diatomic molecules CO, CN, CH and C_2, those molecules tend to strengthen when the five strong DIBs weaken. The normalized strengths of three of the strongest C_2 DIBs are notably flat from $f(H_2) \sim 0.2$ to $f(H_2)$ of 0.8. These relationships are, as noted, necessarily based on integrated line-of-sight equivalent widths, not individual equivalent widths for single clouds.

In general, high densities and sizes of dust grains tend to correspond to the centers of IS clouds and to high densities of neutral diatomic molecules, including H_2. So, the above results imply that the formation (and / or destruction) processes for DIBs differ for different parts of clouds, further implying different interactions of DIB molecules from the edges of clouds to the centers. Both the noted differences between DIBs and diatomic molecules and the existence of the C_2 DIBs indicate that, by studying DIBs, we may eventually understand much more about IS chemistry and cloud structure than we do at the present time. For now, the noted trends cannot be confirmed as due to effects noted because the co-location of DIBs with unresolved atomic and molecular component lines cannot be verified to the required precision. Previous work on

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[14] The diverse group included: Dr. Scott Friedman (STScI); Professor Lew Hobbs (UC); Mr. Ben McCall (a grad student in chemistry at UC); Professor Takeshi Oka (UC), Professor Brian Rachford (Embry-Riddle Aeronautical University); Professor Ted Snow (University of Colorado), Dr. Paule Sonnentrucker (Space Telescope Science Institute, STScI), Professor Julie Thorburn (now Dahlstrom), (Carthage College); Dr. Daniel Welty (initially a researcher at UC, now at STScI); and myself. Later, we were joined by Dr. Haoyu Fan (NAOC, originally a thesis student in Beijing, working with me in Chicago). Eventually, Professor Adolf Witt (University of Toledo) became an active member of this group. Our program utilized echelle spectra from the APO 3.5 meter, as well as low resolution spectra, more suited for studying DIBs wider than 6 Å.

DIB 4430 (Wampler 1966) and DIBs 5780, 5797, 6196, 6284 and 6614 (among the strongest DIBs) (Snow & Cohen 1974) also showed systematic weakening of those DIB strengths in certain types of IS clouds, related to reddening and location on the sky.

A third effect of this nature is that correlations among the very strong DIBs are stronger with H I and with each other than with dust (as determined by $E(B-V)$) and/or H_2 (Friedman et al. 2011). The five strong DIBs noted above (DIBs 5780, 5797, 6196, 6284 and 6614) are closely related to each other no matter the environment in which they are formed (or destroyed). Correlations of eight strong DIBs were tested against other DIBs and against other measures of quantities of IS materials ($E(B-V)$, etc.). Fan et al. (2017) showed the better correlation of DIB 5780 with N(H I) (correlation coefficient, $r = 0.96$), than with $E(B-V)$ ($r = 0.82$) and $N(H_2)$ ($r = 0.62$), a surprising result to me, noted by Herbig (1993), for a smaller sample of stars. DIB 5780 is a good surrogate for N(H I) in 98% of the 74 stars with both measurements available at the time of publication. But not knowing all the contributors to the actual physical source of the extinction, one cannot say the same for the relation of extinction and DIBs. The fact that the eight DIBs studied by Friedman et al. (2011) have correlations (r) of 0.97–0.93 with 5780, 0.84–0.80 with $E(B-V)$ and 0.78–0.94 with N(H2) was also surprising to me because the seven best mutually correlated DIBs in the group were not as closely related to $E(B-V)$ or molecular hydrogen as to other DIBs. Those DIBs, in order of decreasing Pearson's correlation coefficient with DIB 5780.6, are $\lambda\lambda$6204.5, 6283.8, 6196.0, 6613.6, 5705.1, 5797.1 and 5487.7. McCall et al. (2010) showed previously that DIBs 6196.0 and 6613.6 had a correlation coefficient of 0.97 with each other, but they do not have obvious profile relationships that would confirm a common (molecular) origin. Such comparisons remain to be done (Smith et al. 2021; Fan et al. 2022). Fan et al. (2017) found that the strongest of the (generally weak) family of C_2 DIBs was also better correlated with each other than with color excess or H_2.

A fourth piece of evidence for influence of conditions in the IS clouds on the DIBs in the clouds was found by Dahlstrom et al. (2013). They reported detection of absorption lines of CH and CH^+ not seen in other IS clouds, arising from higher energy levels of those molecules than are normally populated. This is seen in the spectrum of the O-star Herschel 36 in conjunction with several anomalous DIB profiles (including DIBs 5780.5, 5797.1, 6196.0 and 6613.6), located in the cluster NGC 5620 and the H II region Messier 8, and the Hourglass Nebula. The energy levels of those four DIBs are possibly pumped by a very nearby IR star (Her 36 SE) (<1 pc in projection from the apparent source of the DIB absorption). The noted DIBs in the spectrum of Herschel 36 show an "extended (wing) to the red" (ETR), as an example, compared to their normal wavelengths and profile widths. The unique asymmetry of the four DIBs could be due to excitation of rotational levels in their carrier molecules that are not excited in normal regions of IS space. The special circumstance in this location was postulated to be the same IR radiation that apparently excites the upper levels of CH and CH+, which is, so far, also a unique feature of star Herschel 36 among IS sightlines. Oka et al. (2013) built a general molecular energy level diagram for a linear, polar molecule that could explain the ETR, but no specific molecule was suggested. However, since virtually all DIBs are wider than atomic IS lines in single components ($\sim$20 km s^{-1} as opposed to <1 km s^{-1} for atomic IS lines) and some could have widths explained completely by radiation pumping by the CMBR, radiation pumping of energy levels above the ground state of some DIB carriers may provide a mechanism to explain the asymmetric width of some DIBs near bright IR stars in star-forming regions, as suggested in the case of the evident pumping of the upper levels of CH and CH^+ in the vicinity of the IR star Her 36 SE. This unique location is most likely another example of the conditions in or near the cloud with excited CH and CH^+ affecting the profiles of the four DIBs with anomalous, asymmetric profiles toward Herschel 36.

6.4. *Fragments of Large Molecules Producing DIB Carriers throughout the ISM*

The struggle to find identifications for the hundreds of known DIBs (it took almost 100 yr to apparently confirm even one carrier for a few DIBs, C_{60}^+) and the surprising discovery that PAHs provide reasonable fits to various blends of vibrational bands (the UIBs found in the 1960s) have led to a different line of thinking on DIBs. Rather than looking for possible molecules known to exist in normal diffuse IS clouds as sources of known DIBs, larger molecules are now considered as likely carriers of DIBs. Such large molecules might be formed in atmospheres of dying stars (a very old idea) or, as found recently (McGuire et al. 2021), in very dense IS, star-forming clouds. The latter possibility arises because of the discovery of numerous PAHs, by means of radio techniques, in clouds where the stars or protostars in or behind the clouds are too reddened to permit optical absorption spectra to be used. Over timescales of millions of years, such molecules may be dispersed into the diffuse regions of IS space where the optical spectra can be observed in stars with little IS reddening and the multitude of known DIBs are seen. Such molecules may also fragment into smaller sections (for instance, aromatic or aliphatic pieces of MAONS, Kwok & Zhang 2013). Grains or large molecules formed in dense, expanding regions of AGB stars or that grow in dense clouds but subsequently fragment under various IS processes as they evolve, are examples (Duley 2006; Ziurys 2006; Zhen et al. 2014; Campbell et al. 2016). Such evolution from complicated materials made naturally under the noted conditions might provide abundant variants of molecules to produce the numerous DIBs of which we are now aware. C_{60}^{+} may be just such an example, fragmented from a large PAH and evolved into a very stable dehydrogenated, molecule (Berné et al. 2015). Both research on grains and DIBs is now very active in defining specific pathways to production sites and fragmentation sites that might be feasible (Jones et al. 2017; Hensley & Draine 2023).

7. The Origin and Construction of the Apache Point Observatory (APO) 3.5-Meter Telescope

7.1. Formation of the Astrophysical Research Consortium

The first steps toward constructing the 3.5 m telescope were taken as soon as I arrived in Chicago. Almost immediately on arrival at Chicago, I took the traditional first meeting with the Dean of the Physical Sciences Division (PSD). I began discussions with several faculty members about future observing projects: Lew Hobbs, whom I knew from graduate school, and newer faculty members, Al Harper, an IR astronomer, and Rich Kron, an optical observer. We had some very preliminary discussions about future observing projects. Within a few months, the Dean of the PSD, Professor Stuart Rice, made an infrequent visit to the monthly departmental faculty meeting. A discussion ensued about the fact that Chicago/Yerkes astronomers had had access to the McDonald Observatory 82 inch telescope since the 1930s, and later to the 107 inch telescope, but the 35 yr arrangement was coming to an end. The observing astronomers thought we had two options: use the highly competitive time on public telescopes, such as KPNO (to which a single person might gain 4-7 nights per year by application) or build instruments at Chicago and arrange with private observatories to share the instruments with them, in return for observing time. Dean Rice wondered aloud if we should not consider building our own telescope.

During my final few years at Princeton, Professor George Wallerstein from the University of Washington (UW) visited Princeton to work with Ed Jenkins on Copernicus data. He informed Jenkins of an initiative at the UW to find partners in building a ~2.5 m telescope for ground-based observing. Jenkins mentioned the project to the Princeton chairperson, Professor Jeremiah Ostriker. Ostriker thought Princeton might be interested, but that a larger instrument would be more attractive. He appointed me to be liaison for further discussions while I was still at Princeton.

Following the faculty discussion with Dean Rice, I was immediately in touch with Ostriker, thinking we might be positioned to join the Washington-Princeton discussions, and add enough resources to make the telescope larger than previously envisioned. With the possibility of Chicago joining in the Washington project, and of Princeton joining as well, discussions went forward with UW, New Mexico State University (NMSU), PU, UC and Washington State University (WSU) to build our own telescope. The desiderata for the facility were to have a 3.5 m diameter light-weight mirror; to locate the telescope at the best site we could afford; to have several observatory instruments mounted with detectors cooled, continuously, to take advantage of targets of opportunity (TOOs) in a timely fashion; to allow members to provide their own instruments for mounting to the telescope; to be able to change instruments quickly; to allow fully remote observing from all member institutions and any non-Astrophysical Research Consortium (ARC) astronomer's institutions a member institution might choose to grant time to; and for each member institution to allocate its share of time in any way they wished. (Figure 2 shows the layout of the site; the caption identifies the main structures.)

Figure 2. View of the APO site from the meteorological tower at the site (not visible). The largest telescope enclosure (center top) holds the 3.5 m telescope, to the north in the photo. In the valley to the far left is White Sands, New Mexico (near Alamagordo, New Mexico). To the far right is the conical Solar Tower of the Solar Observatory. The operations building (now the Baldwin Operations Building) is the large building connected by the tunnel to the large enclosure. The first dorm built is to the right of the operations building, mostly hidden by trees. The smaller dome near the base of the big telescope is a 36 inch telescope owned and operated by NMSU. In front of the NMSU telescope is the 20 inch PT relocated from JHU (now owned by ARC) used for calibrating the Sloan photometry. The buildings added later for SDSS include the 2.5 m telescope (now the Sloan Foundation Telescope, southwest of the 3.5 m) with its roll-off enclosure. To the east and south of the 2.5 m is a building where the plug-plates for the 640-optical fibers for Sloan spectroscopy are populated. Further to the east is a small storage building for the plates and yet further to the east is a vehicle garage (not shown). The parking area for staff and visitors, and two future telescope sites, are out of view, to the south. (Photo Credit: APO staff member Dan Long. 2001 May 1).

The choice of telescope aperture was mainly a cost-related decision: the 3.5 m mirror was to come at no cost (thanks to Roger Angel and the U.S. NSF). The new-technology honeycomb structure of the mirror would reduce the cost of other aspects of the telescope compared to telescopes using more traditional thick mirrors. The mirror was light weight (for its collecting area), as compared to solid mirrors of contemporary telescopes, owing to the one inch-thick mirror

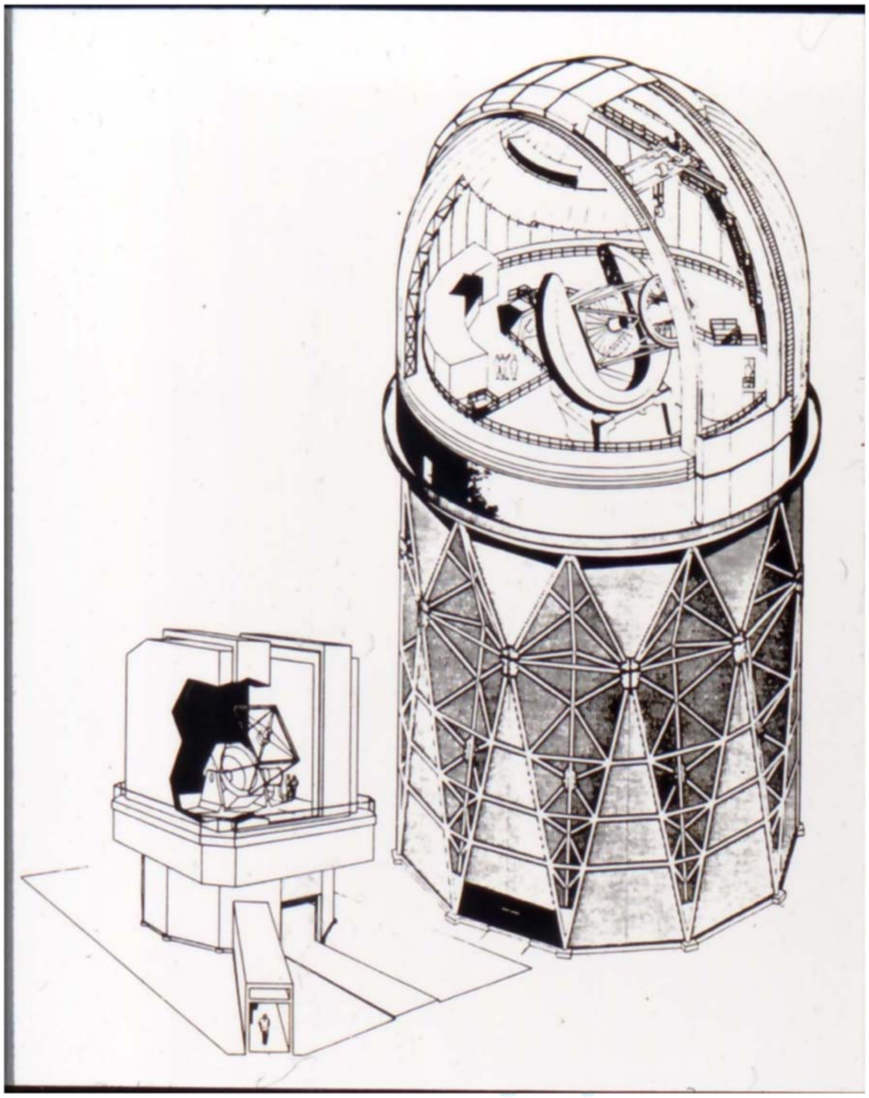

Figure 3. A cutaway of the KPNO 4 m telescope enclosure (on the right) with the APO 3.5 m telescope enclosure beside it, showing the relative size of the two structures. The choice of a fast primary mirror and the altitude-over-azimuth telescope structural design accounts for the smaller dome volume of the 3.5 m enclosure, together with the choice to keep major heat-generating equipment out of the main building. The volume of the entire enclosure of a particular telescope is a significant factor in the project cost. (Image credit, for the image in the lower left: Asa Bullock, L&F, 1986).

faceplate, one inch-thick back plate and one-half inch thick honeycomb cell wall thicknesses, all of which led to a reduced mass of the mirror support structure. These properties also made it easier to control the mirror temperature through the night. The major cost of the telescope enclosure was to be reduced substantially by the use of a fast primary (see Figure 3). The cost reductions would help NSF in the ongoing debate about what technology to apply to future 8 m telescopes (or larger), by adopting the newly spun cast mirrors being developed by Roger Angel of the University of Arizona (UA).

UW had arranged to use the first of three 3.5 m honeycomb mirrors to be spun-cast by Roger Angel and his team to test new techniques for making very large, light-weight mirrors. NMSU arranged to use the site that became known as Apache Point (9200-foot altitude), one mile from Sacramento Peak Solar Observatory (SAC Peak), for which Dr. Jacques Beckers, the Director, had done site testing (Beckers et al. 1979; Schneeberger et al. 1979). Chicago and Princeton would build instruments. We estimated the project could be done for $10 million dollars, if the Angel mirror development moved apace, a very significant cost reduction from the costs of contemporary telescopes of similar aperture, partly because of the use of new mirror technology and the significantly reduced telescope enclosure volume. The group of universities noted above formed the ARC. The five university presidents appointed two board members each, one with a science background and one with an administrative background. The ARC Board of Governors (BOG), meeting in early 1983, arranged for a funding plan and for delegation of observing time shares among the partners. I was appointed to be the Director. Professor Bruce Margon of UW was elected Chairperson of the BOG. Don Baldwin of UW was elected Treasurer.

The consortium grew with the joining of the Princeton IAS in 1990 and JHU in 1992. Both events were precipitated by separate discussions to build and carry out what became known as the SDSS. The enlarged BOG of ARC later took on financial oversight of the SDSS project (1989) and formed an oversight committee for that project. Over the subsequent years, the members of the Consortium changed, with some members dropping out as institutional interests changed, and new members joining. The current (2023) BOG consists of 18 members, appointed by the university presidents as described above. The ARC BOG continues its financial management role of SDSS. The current member institutions use pre-agreed time percentages of the telescope based on capital invested in the project. There are also rental agreements with of order six institutions that change from year to year. The four Directors to date and their tenures were Donald York, UC, 1984-1998; Ed Turner, PU, 1998-2005; Suzanne Hawley, UW, 2005-2016; and Nancy Chanover, NMSU (2018-present).

7.2. Construction of the Telescope at Apache Point Observatory (APO)

The Washington group had worked for some years on site selection. Professor Nick Woolf (UA) consulted on the site qualities, based on the site survey done by Dr. Jacques Beckers. Space was available on Forest Service land near SAC peak with water and fire protection. NMSU undertook to manage construction of a road connecting the observatory to the Sunspot Highway, in 1985–1986, as well as the clearing of the site chosen on which to place the 3.5 m telescope and the construction of an operations building, one dorm and a garage. Additional structures were built after 1989 (paid for by SDSS). Three other sites were cleared for possible placement of future telescopes, one of which became the site for the SDSS 2.5 m telescope. The enclosure for the 3.5 m was contracted for under the supervision of the engineers at UW (Siegmund & Comfort 1986).

The small engineering staff at UW had been slowly added to, as the UW faculty raised funds and searched for partners. These staff included Ed Mannery, Walter Siegmund, Charles Hull, and later Russell Owen, Siri Limmonkol and, eventually, Patrick Waddell. The UW engineering staff took over the main design aspects (Balick et al. 1983) and contracted procurement of the 3.5 m telescope to L&F Industries, Los Angeles, CA. The telescope was to be driven by friction drives, with all the weight on a single small bearing at the base of the cone on which the telescope sat.

7.3. Telescope Optics

The technology for producing the honeycomb casting of a mirror as large as 3.5 m in diameter was still being developed when ARC started the project and there were significant delays in developing the techniques at Steward Observatory Mirror Laboratory (SOML), renamed the Richard F. Caris Mirror Lab (RFCML) in the 1990s. The rotating oven for the 3.5 m mirror blanks was completed in 1988. UW engineer Ed Mannery assisted SOML in this process. A ceremony with Angel shaving my beard (grown for the purpose, see Figures 4 and 5) using the completed cast mirror blank as the shaving mirror, was held. Figuring and polishing of the mirror were contracted for in 1989 and finished in 1991, after final polishing at SOML.

The final polishing was accomplished with a novel stressed-lap polishing tool developed for the purpose as part of the NSF-funded development of the production of large cast honeycomb mirrors. UW Engineer Walter Siegmund participated in the analysis of the stressed-lap polishing facility. The latter facility (partially funded by the STARFIRE project) was also used for polishing the 1.8 m Vatican Telescope mirror; the Wisconsin-Indiana-Yale-NOAO (WIYN) telescope at KPNO and the STARFIRE USAF telescope; the two 8.4 m mirrors for the Binocular Telescope; the 8.4 m mirror for the Large-Aperture Synoptic Survey Telescope (Legacy Survey of Space and Time, LSST) of the Vera C. Rubin Observatory; and, eventually, the seven 6.5 m mirrors for the Giant Magellan Telescope (GMT: three are completed, and four are in process currently). ARC is very grateful to Roger Angel, John Hill and Buddy Martin for their work on the 3.5 m mirror.

The development work associated with the casting oven, the mold assembly and the stressed-lap polishing involved a significant delay in the final delivery of the 3.5 m mirror to ARC, but the final product represented a significant advance in

Figure 4. Roger Angel removing Don York's beard with the surface of the as-cast 3.5 m honeycomb mirror in the background. Photo credit: Ed Mannery.

Figure 5. Don, finishing the job using the mirror surface as a shaving mirror. 1988 August. Photo credit: Ed Mannery.

mirror performance and figure quality used in subsequent cast mirrors done in the RFCML. The delays did, of course, contribute significantly to deferral of access of ARC astronomers to the final product for observing.

7.4. Remote Observing

An important desire of the ARC consortium astronomers related to having control of observing time assignments, at the discretion of the individual institutions. This meant implementing the need for minimal presence by the night observer(s), on site; short scheduling cycles (quarterly); and the ability to switch observers from one institution to another within a single night, to take advantage of unique weather conditions or of rare TOOs (e.g., an SN, a GRB or a short lived, expected or unexpected, star flare).

When I left Princeton, the lead engineer, John Lowrance, suggested to me that a completely new technology and the improvements in communications likely to be on the horizon provided the opportunity for remote operations of the telescope. After due consideration of the ARC scientists, it was decided to implement this novel and doable suggestion. A research associate at UC, Dr. Robert Lowenstein (1946–2021), had already programmed operation for airborne instruments, and took on the job of implementing the special programs required for remote control of the 3.5 m telescope and the first instruments. I worked with him on designing the functioning of the software and the testing of the entire remote observing process. It was all in place when the telescope was commissioned in 1996 (Balick et al. 1988; Loewenstein & York 1986; Loewenstein et al. 1994; Gillespie et al. 1996).

Taking advantage of remote observing required that the instruments on the telescope be easy to switch to within a single night (15 minutes). They had to be ready to go in a very short time (e.g., cooled as necessary, and mounted). This desire was straightforward to implement for multiple, small instruments that could be mounted on the mirror cell (eight could be accommodated). The large echelle spectrograph was intended for single star spectroscopy and needed no rotation. It could be permanently mounted at one of the Nasmyth foci. Two intermediate sized instruments, the intermediate resolution optical Double Imaging Spectrograph (DIS) and an IR imager with grism spectroscopy (GRIM II) shared the other Nasmyth focus and could be rapidly interchanged. Each of the two had its own rotator.

Because of the many advantages of remote observing in terms of saved travel cost, saved travel time and scheduling flexibility, remote observing was used from the beginning for most observing programs. While observers can go to the APO site for traditional observing, almost all observers use remote observing routinely, when their program is compatible with an available instrument and does not require presence of the observer on site. As far as I know, the Apache Point telescope was the first major, ground-based telescope to provide this capability for all observers from home, both for operating the telescope and for having instantaneous access to the raw data obtained for use in modifying an observing program within a single night. Eventually, remote observing for most public, ground-based telescopes became routine.

One of the few limitations to remote observing as a main mode of observing arose with the use of flexible assignment of remote observing time for TOOs such as GRBs. The privilege of taking another observer's time for a desired TOO involved agreements that individuals asking for such time agree to reimburse the donating institution for the time taken. This became a little hard to negotiate in the case of GRBs once they were found to have optical/near-IR afterglows. The required time for the 3.5 m to make significant contributions to this field often approached a night or more per epoch of observation, owing to the typical magnitudes (22–24). Some observers were reluctant to give up as much time as needed, but generally the Director was able to facilitate arrangements for such situations. This difficulty, however, made it hard for APO observers to compete for time on GRB TOOs with Gemini North (located in Hawaii) and Gemini South (located in Chile) observers in combination with the better weather at those locations and the factor of six advantage in aperture.

Despite the constraints in the case of TOOs for GRB afterglows, the APO 3.5 m TOO observations of GRB afterglows contributed to the GRB field. Forty International Astronomical Union circulars and Gamma-Ray Burst Coordinates Network (GCN) notices were issued based on APO 3.5 m observations (e.g., Hearty et al. 2006a, 2006b), of which at least eleven contributed to the identification of the GRB afterglow or the host galaxy. Twelve scientific papers were published involving APO 3.5 m observations of GRB's (e.g., Reichart et al. 1999; de Ugarte Postigo et al. 2006). In addition, APO contributed 29 SDSS pre-burst observations of GRB fields.

One casualty of implementing remote observing was that a dark room originally built in the Donald R. Baldwin Operations Building at APO (dedicated 2003 June 9) for developing photographic plates was never used and was converted to a dark test facility for instruments. By the time the observatory was ready for use, digital detectors were available on all instruments.

7.5. First Instruments

The initial instruments for the telescope were built by founding members of the consortium. They were a modest resolution optical spectrograph, DIS; an echelle spectrograph (ARCES, the ARC Echelle Spectrograph); an IR imager/grism instrument, GRIM II; and an optical imaging camera (SPICAM).

DIS had provision for a $4\farcm5$ field for imaging, full rotation capability on one of the Nasmyth foci, and needed to be mountable and demountable in the same fifteen-minute interval as the planned small instruments (to be mounted on the 3.5 m mirror cell). Professor Jim Gunn and engineer Mike Carr (both at PU) designed and built DIS. DIS has a pixel scale near $0\farcs4$ pixel^{-1} in imaging or spectroscopic mode; provision for various filters and gratings; spectral coverage of 2000 pixels per channel at ∼0.6, 1.8 and 1.83 Å pixel^{-1} in the blue and 0.58 or 2.31 Å pixel^{-1} in the red; and various aperture selections. It became the most used instrument on the telescope.

Professor Al Harper led the design of the echelle structure for ARCES and Professor Lew Hobbs designed the optics. Professor Roger Hildebrand (1922–2021) and Shu-i Wang led the fabrication in the Chicago PSD and Yerkes shops (Wang et al. 2003). By consensus agreement, ARCES has been on the telescope since 1998. It is on the Nasmyth 1 focus. It has a 2048×2048 Tektronix/SITE CCD, 72 spectral orders and a resolving power of $R \sim 35{,}000$.

The third of the initial instruments was GRIM II constructed by Dr. Mark Hereld, Prof. Al Harper, Bernie Rauscher and Robert Pernic (Hereld et al. 1990), all at UC. It had three grisms ($R = 100$), three filters (J, H, K) and HgTl detectors (128×128). GRIM II was used interchangeably with DIS on the Nasmyth 2 focus. GRIM II was decommissioned when a more advanced IR instrument (NICFPS), built at the University of Colorado, Boulder, appeared.[15]

8. Origin and Construction of the Sloan Digital Sky Survey Project

8.1. The O'Hare Meetings and Expansion of ARC

Once the 3.5 m was well underway and the CCDs were proven as a big improvement over photographic plates for survey work, light-weight mirrors seemed to be on the horizon. This enabled a large reduction in costs of new telescopes, and community interest in large surveys of galaxies (millions of galaxies) ensued. The ARC consortium partners began to think about, and discuss, taking advantage of what we were learning from the 3.5 m experience. Realizing that the data reduction and analysis costs would be high and therefore that the total cost would still be large, we convened what became two "O'Hare meetings" including a group of astronomers[16] known to be interested in galaxy survey work to determine, in great detail, the hierarchical structure of the Universe. The meetings were convened by Professor Rich Kron (UC) and documented by him. Several projects involving traditional pointed telescopes were being considered, but a group of us decided, based on the consensus of these meetings, that, at the highest level, *the desire was to obtain very high precision spectra of 1,000,000 galaxies with associated photometric observations.*

The spectroscopy required using a 2.5–4 m telescope which would take about five years, assuming an adequately sized fiber spectrograph, a large survey camera to locate the galaxies and the required decent weather. The photometry of the galaxies in the same sky area that the spectroscopy would cover would require 20% of the 5 yr, assuming clear nights would yield high seeing quality. The balance of the time would be used for the spectroscopy. The target of 1,000,000 galaxy spectra was chosen simply because galaxy surveys using photographic plates were yielding surveys of tens of thousands of galaxies, but the precision and information being obtained were not felt adequate: a major step forward was needed.

The consensus reached by the assembled group of astronomers was that 1,000,000 galaxies would be a major step possible toward the goal; that working mainly above +30° galactic latitude would yield that number of objects and that the survey could be done from an observatory in the north; that a single dedicated new telescope was necessary, focused on the goal of obtaining spectra of ∼1,000,000 galaxies; that the technologies had advanced far enough that a telescope aperture of 2.5 m could probably accomplish the job in about five years; and that it would cost about $25 million dollars for the hardware, if enough CCDs could be procured to fill a three-degree focal plane camera for purposes of target selection (via photometry) to a limit near 21 mag in r-band.

Starting with these conclusions of the large group of some sixteen astronomers who participated in the O'Hare meetings, Jim Gunn, Rich Kron and I sat down to consider how to obtain the funds and to sharpen up the parameters of the nascent

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[15] The currently available instruments are listed at http://www/apo.nmsu/edu/arc35m/Instuments/DIS/.

[16] *Attendees at the O'Hare meetings.* 1. 1988 September 6–7. 2. 1988 December 2, 3. Rich Burg (STScI), Roger Davies (KPNO), Jim Gunn (Princeton), Al Harper (Chicago, part time), Steve Kent (CFA), Ed Kibblewhite (UC), David Koo (Santa Cruz), Rich Kron (UC), Bruce Margon (UW), John McGraw (UA), Pat Osmer (CTIO), David Schramm (UC & FNAL, part time), Pat Seitzer (STScI), Ed Shaya (Columbia), Anthony Tyson (Bell Labs), Don York (UC).

project. The individuals at the O'Hare meetings were approached to see if they thought their institutions would be interested. As it turned out, Chicago and Princeton expressed interest and optimism in acquiring the funds and enough resources were found to pay for a start on the project (thanks to a major gift from the Sloan Foundation and some additional, smaller, critical contributions). The telescope was eventually named the 2.5 m Sloan Foundation Telescope. The entire project is now known as the "Sloan Digital Sky Survey." A detailed plan for the survey was developed and the ARC consortium agreed to be the financially responsible party that would seek other partners and submit proposals to national funding agencies. The UW was already a member of ARC and joined what became the SDSS as well. Then JHU joined as did the U.S. Naval Observatory (USNO, Flagstaff). The Princeton IAS joined as well as Fermi National Accelerator Laboratory (Fermilab or FNAL) in Batavia, IL.

A *Principles of Operation* (POO) document was developed, under the leadership of Professor Jeremiah Ostriker of PU to govern data rights and responsibilities of SDSS member institutions, based on institutional contributions to the costs of the entire project, that governed the current and future members. Key principles adopted by the original and subsequent members of the project were that data rights were held by SDSS members, as a team, for two years, and that every two years, data would be reprocessed appropriately and publicly released. Upon that release, no restriction to use of the data would be imposed on non-members of the SDSS collaboration.

The subcommittee of the ARC Board, set up to guide the new project, nominated Jim Gunn as Project Scientist, Rich Kron as Survey Director and Don York as Project Director. The ARC Board approved. I was involved as Director in proposals for funding, recruiting institutions to join, setting up the initial scope of the project and in much of the early contracting work, from 1988 through the start of commissioning. The project involved many individuals, far too many to properly acknowledge here, but I have, I hope, provided adequate referencing for readers who want to know more. The project grew to encompass many unanticipated areas of astronomy, and I have taken the liberty, in the last few pages (sections 8.12, 8.13, 8.14 and 8.15) to elaborate on the impact of the SDSS project in selected science areas and on the culture of astronomy.

8.2. *Early Steps*

Much of the groundwork necessary to carry out the Survey was in place once the administrative apparatus noted above was worked out.

1. The engineers from the UW were contracted to take care of the details of the telescope itself and the enclosure (Hull et al. 1994a). FNAL led the procurement and programming of the computing infrastructure, and many SDSS scientists participated. The scientists and engineers at FNAL contributed heavily to the final design of the telescope control system and of the system for manually positioning 640 fibers on the targets chosen in a given field of sky, for spectroscopy.
2. The groundwork for the FNAL/SDSS collaboration had a long history, going back to 1982. Then Lab Director, Dr. Leon Lederman, and Professor David Schramm (UC/FNAL) set up an FNAL theory group on the early Universe. Once the Chicago/Princeton discussions on an observational survey of the Universe began, a meeting of key personnel from the FNAL computing division[17] took place at Chicago to discuss the scope of the FNAL involvement. A consensus was reached on a possible ultimate scope of the FNAL involvement. Steps were taken to involve existing FNAL employees in the project where they were interested and where their computing or engineering skills were appropriate.
3. Locations for additional telescopes had been built into the layout of APO (1985–1986), and the best of these was eventually selected for SDSS. Plans to add a new dorm and some smaller buildings for SDSS to the site, and to subcontract for the enclosure of the 2.5 m telescope (of an entirely different design from the 3.5 m enclosure) were laid out. Some re-arrangement of space in the APO Operations Building (The Donald R. Baldwin Operations Building) was made, to accommodate operating both the 2.5 m and 3.5 m telescopes from the same room (see Figure 2).
4. CCD purchases were arranged over several years. CCD groups moved from Tektronix Corporation to Ball Brothers Corporation, and 2×2 inch CCDs with 25 μm pixels became available (~4 million pixels per chip). Eventually, Ball Brothers sold the CCD fabrication operation to Scientific Imaging Technologies (SITe) located in Beaverton, Oregon. Eventually, ARC purchased, from SITe, 42 large CCDs (thirty for the Princeton Camera, four for the JHU spectrographs and spares), which were delivered to Jim Gunn at Princeton for integration into the camera and to Steve Smee at JHU for integration into the JHU spectrographs. The devices, on which the final SDSS design was based, were delivered to specification and on budget, though it took more time than expected.

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[17] There were numerous close associations of many years between FNAL staff, UC physicists and UC astronomers (mainly cosmologists). Interest by the previous director of FNAL, Leon Lederman, in public science education was clearly aligned with the SDSS goal of making all the SDSS data available and accessible to students. After the O'Hare meetings, a key meeting was held in the office of the Chair (Professor Don Lamb) of the UC Astronomy Department with a number of UC astronomers; the Director of FNAL, Dr. John Peoples; and a number of FNAL staff members, to explore the scope of involvement that Fermilab might participate in as an SDSS partner, to the benefit of both institutions. Discussions led to computer software, hardware at APO, involvement of then current FNAL staff and future FNAL hires, a much larger involvement than originally envisioned. Dr. Tom Nash chaired the meeting.

5. Designs for the wide-field $f/5$, 2.5 m telescope were based on the Las Campanas 2.5 m wide-field telescope, with modifications. The SOML (UA) had developed casting techniques for the 3.5 m mirror and a small spinoff company from UA, Hextek, was contracted to cast a 2.5 m honeycomb mirror (but not spun-cast). The Ohara E-6 glass used by Steward for the 3.5 m Angel mirrors was purchased as a long-lead item before the administrative arrangements noted above for the project were worked out, because the low expansion glass was scheduled to be discontinued by the company. Professor Harlan Epps, of Santa Cruz, designed and built optics for the spectrograph cameras and participated in polishing the secondary (and final laser etching work by Kodak).
6. A pre-proposal was developed by the scientists who were signing up to work on the project. It was further developed and submitted, in slightly different form, to NSF and to the Sloan Foundation in 1990 with Don York as Principal Investigator. Professor Gillian Knapp (PU) had a major impact on this effort.
7. Rich Kron, appointed by FNAL Director, Dr. John Peoples, as head of the new FNAL Experimental Astrophysics Group, hired Dr. Steve Kent to Head the FNAL effort on the data acquisition computers and software for the SDSS project. Early members of the group were Kron, Chris Stoughton (FNAL), Steve Bracker (FNAL), Dr. Tom Nash (FNAL) and Kent. Dr. Tom Dombeck (FNAL) was hired by me to be Project Manager. Dr. Bruce Gillespie (STScI) was hired by ARC as Manager of the APO Observatory (to build up the Observatory and manage integration of the facilities for the APO 3.5 m telescope and the SDSS project). These hires were made after our first proposal to the Sloan Foundation was accepted for the sky survey project, and we had a positive response to our NSF proposal.

8.3. Final Project Design Details

These aspects of groundwork enabled the following goals: (derived from a more detailed specification (Stoughton et al. 2002).

1. The main goal was to acquire 1,000,000 galaxy spectra and accompanying photometry in a nominal 5 yr period of elapsed time, for the main purpose of determining the large-scale structure of the Universe over the North Polar Cap for all types of galaxies, to the survey limit.
2. It was estimated this could be achieved from APO with a uniform photometric survey of galaxy images during moonless, photometric nights, for target selection with $0''.8$ FWHM stellar images to 1% photometric precision. The lower quality nights would be used for the spectroscopic survey, to 2% precision within a projected five-year period. The photometric survey was essential for the main spectroscopic survey.
3. The actual survey depth was limited by the sky brightness at APO, just slightly below, by 0.1 magnitudes, the best of the “dark sky sites” in the USA (Garstang 1989).
4. To fully characterize the galaxies, thirty 2 inch square CCDs, with 24 μm pixel sizes, were arrayed in five rows, each row with a different filter type (u, g, r, i and z). Data for each of the rows of five CCDs (color bands) were aggregated at the end of each drift scan segment.
5. Auxiliary science was to be done, without modification of the design parameters of the survey, as time was available, until the main survey was complete.

To meet these specifications, the telescope imaging camera had to be operated in time-delay-and-integrate (TDI) drift-scan mode (Schmidt et al. 1986), which limited the per-pixel integration time of the camera to 54.1 s of time. The setting of the specification on the mean image size for point sources in the survey and the various total survey times as estimated above were derived from the most extensive data on site seeing available (Beckers et al. 1979); from extensive wind tunnel studies by the UW engineering group (Comfort et al. 1994); and by strict adherence to nightly data on site quality to dictate periods of imaging operations. The information went into the detailed design of the 2.5 m enclosure: a roll-off building that left the entire telescope open to the air when rolled off for nighttime observing. To maximize image performance, a wind/light shield was mounted to the mirror cell of the telescope (see Figure 2), and judicious locations of heat sources below the telescope floor level were implemented to minimize air turbulence above the 2.5 m mirror.

8.4. Hardware Overview

A brief overview of the hardware, software and calibration aspects of the project as planned is given by York et al. (2000). A much more extensive view of the project may be found in Stoughton et al. (2002). The key subsystems are referenced below. The chief specification for the spectrographs used from 2000 to 2008 was to get spectra of 1,000,000 galaxies over 10,000 sq. degrees of sky in 5 yr. The various factual numbers in what follows refer to the spectrographs built to meet this goal. The rate of acquiring spectra, including target selection from the camera images, took more time than had been estimated, but the number of galaxy spectra obtained was finally 20% greater than our goal.

The partners in SDSS and the funding sources changed over time. The relevant information is included in the referenced papers. In 2009, upgraded spectrographs were deployed of similar design for enhanced extragalactic programs, mentioned later.

The hardware subsystems include the telescope: the camera: the fiber plug plates; two fiber-fed, double spectrographs; the

Photometric Telescope (PT), which supports real time standard star observations for calibration of the camera photometry; and a 10 μm cloud scanner, to evaluate photometric conditions.

8.5. The Telescope

The telescope is a modified two-corrector Ritchey–Chrétien optical design with a 2.5 m diameter honeycomb mirror made of low-expansion Ohara E6 glass ($f/2.25$) and a 1.08 m secondary producing 27% obscuration (Gunn et al. 2006). The final focal ratio is $f/5$ and the field of view is three degrees. In imaging mode, the telescope operates in TDI mode, enabled by very high precision motion control of the telescope. Optical distortion and smearing from the TDI scanning in imaging mode totals $\sim 1/4''$, a critical feature of the telescope. There is a Gascoigne astigmatism corrector used well in front of the focal plane (75 cm). There are two secondary correctors installed near the telescope focal plane, one used for imaging (in pristine conditions, $<1''$ seeing) and the other used for the spectroscopic mode, in less ideal conditions (average seeing, $1\overset{''}{.}5$–$1\overset{''}{.}7$).

The telescope is changed from imaging mode to spectroscopic mode by removing the imaging camera from the focal plane and placing a fiber plug plate with 640 fibers in the focal plane.

8.6. The Photometric/Astrometric Camera

The Photometric/Astrometric Camera (Gunn et al. 1998) contained an array of thirty 2048 × 2048 SITe/Tektronix CCDs, each 2 inches in physical size, arranged in six columns of five identically filtered CCDs (u, g, r, i, z) (Fukugita et al. 1996). The effective wavelengths of the respective filters and the FWHM (both in Å) were: u (3522, 634), g (4803, 1409), r (6284, 1388), i (7668, 1535) and z (9114, 1409), including the hardware in the optical path. Including the effects of the atmosphere of Earth all the numbers are a little different in the actual survey operation but the slight changes are corrected in the process of calibration, discussed in section 8.9. Each of the six sets of five CCDs were mounted in identical Dewars. Two additional Dewars contained eleven 2048 × 400 astrometric CCDs and a single focus chip. These two Dewars were mounted above (leading) and below (trailing) the six Dewars containing the larger CCDs. As the stars and galaxies drifted across the camera, each encountered the leading astrometric chips; the filtered CCDs in the order r; i; u; z; g; and the trailing astrometric chips. The sky was scanned along Great Circles at the sidereal rate along the six columns of photometric CCDs. The CCDs used for u-, g-, r- and i-bands were thinned, backside illuminated chips, while the z-band devices were thick, front side illuminated devices. The camera was built around the second (imaging) corrector of the telescope design, the filters were fastened to the back side of the corrector and the CCD Dewars were mounted to the backside, on rails. Continuous scanning in TDI mode along the six columns of CCDs, with each CCD having an active area of 49.15 mm^2 (13.52 arcmin^2), at the sidereal rate, produced six *strips* of color images, with gaps at the non-active CCD packaging, parallel to the scan direction. A second parallel scan of the camera across the sky, offset from the previous scan to fill the gap between adjacent CCDs, yielded six filled *stripes* in each of five colors spanning $2\overset{\circ}{.}5$ (with about $1'$, or 8%, of overlap along each edge).

The camera was read out continuously in TDI mode and typically ran for 8 hr on clear, dark nights at APO. Focus was maintained dynamically. The two astrometric Dewars each contained one focus chip and 11 smaller CCDs. These astrometric Dewars were arranged to lead and follow the bigger, photometric CCDs. The 22 astrometric CCDs in these two Dewars were filtered with r-band filters and 3 magnitude neutral density filters, and used to transfer bright astrometric standard star positions to the photometric images on the larger photometric CCDs.

The 24 μm pixels each covered $0\overset{''}{.}4$ on the sky. The integration time was 54 s per pixel. The time taken for stars to traverse a column of photometric chips was 342 s, so colors for stars included in one color of one strip were available within a 6 minute observing time window. Sharp cutoff passbands excluded the strongest night sky lines, such as O I (λ5577) and Hg I (λ5461). On the AB95 system (see later), the limiting magnitudes for corresponding detections are 22.1 in u-band, 23.2 in g-band, 23.1 in r-band, 22.5 in i-band and 20.8 in z-band, observing at an airmass of 1.4 at APO. A S/N of 50:1 (photometry at the 2% level) was reached at 19.1, 20.6, 20.4, 19.8 and 18.3 in u, g, r, i and z, respectively, for point sources (1 to 0.5 magnitudes brighter for typical galaxy images). In actuality, eight years of scanning the sky were required (using only moonless nights with pristine weather conditions) to complete the main scanning area of ∼10,000 deg^2 of sky plus the spectroscopy of the targeted objects in that area of sky.

At the end of each successful night, the data were couriered to FNAL. The good data were processed by automated pipelines to reduce all images of objects to individual stars and galaxies. Colors and morphologies of all objects were used to classify objects as candidate types to be confirmed by their spectra as types of objects (galaxies, quasars or stars, for instance) by observations with the two spectrographs described below.

The northern sky survey consisted of 45 great circle arcs laid over the minimal extinction contours of Schlegel et al. (1998) to minimize the effects of MW dust on the survey targets. When this area could not be accessed from APO, a set of three equatorial stripes were scanned for three months, one repeatedly (Stripe 82), for a SN survey, to find variable objects and to co-add the scans to go deeper than the SDSS survey of the North Polar Cap by 2 magnitudes (moonless nights). The three stripes (the southern survey) were ($\alpha = 20.^{\rm h}7$ to $4^{\rm h}.0$, $\delta = 0°$); ($\alpha = 20^{\rm h}.7$ to $4^{\rm h}.0$, $\delta = -5\overset{\circ}{.}8$) to ($4^{\rm h}.0$, $\delta = -5.^{\circ}8$); and ($\alpha = 22^{\rm h}.^{\rm h}$, $\delta = -8\overset{\circ}{.}7$) to ($2^{\rm h}.3$, $\delta = -13\overset{\circ}{.}2$). All science operations with the photometric camera were done with a 1370 × 1370 scanning 10 μm sky camera to assure the northern and southern surveys and the calibrations were carried out under photometric conditions (Hull et al. 1994b). Observations were terminated if the skies turned non-photometric on a given night.

8.7. The First Two Optical Spectrographs

The first two spectrographs (called the SDSS spectrographs) were identically specified, double, multi-object, fiber spectrographs that utilized a simple optical layout: reflective collimators; dichroic beam splitters (cross over at ∼6000 Å); grisms; all-refractive, $f/1.5$ cameras (eight optical elements); and state-of-the-art, thinned CCD detectors (the same type as were in the photometric camera). Each spectrograph had a blue and red channel with the above elements appropriately optimized. Each produced up to 320 spectra simultaneously on the two channels, so each spectrograph covered the near-UV (3900 Å, to include Ca II $\lambda\lambda$3933, 3969 absorption lines, and emission lines of O^{+1} near $\lambda\lambda$3727, 3729 from $z = 0$ galaxies) to the near-IR (9100 Å, to obtain spectra of the 4000 Å break at the highest z possible), with a resolving power $R = \lambda/\mathrm{FWHM} \sim 1800$ for 640 spectra. The spectra were 3 pixels wide, separated by 3 pixels on each side. Including the spectrograph optics and atmospheric transmission at APO airmass 1.2, the point source efficiency of the spectroscopic system was 10% at 4000 Å, 15% at 6000 Å, 17% at 7000 Å and 10% at 8000 Å. Flexure in the dispersion direction amounted to ∼20 $\mathrm{km\,s^{-1}}$ over 1 hr for a 15° motion of the telescope on the sky. Readout noise was 5 electrons for each pixel and the full well was 300,000 electrons (less in the u chips). Dark current was negligible (Smee et al. 2013).

8.8. Optical Spectrograph Upgrades

Upgrades for the spectrographs were made after the completion of the main galaxy survey goals. The upgraded spectrographs allowed higher redshift coverage of Luminous Red Galaxies (LRGs) to make a better BOSS and are referred to as the BOSS spectrographs. The prisms now use Volume Phase Holographic Gratings (VPHGs) sandwiched between two prisms instead of single 45° prisms in each channel with transmission gratings replicated on the prism hypotenuses. CCDs were replaced with devices with 4000 × 4000 pixels, 15 microns in size and better performance. The blue channels are now e2v CCDs and the red CCDs are Lawrence Berkley National Laboratory (LBNL) CCDs. The wavelength coverage was extended to cover 3560 to 10400 Å, allowing for improved performance in obtaining data in the blue on QSOs and allowing a deeper survey for redshifts of fainter LRGs, for cosmology studies. Using more and smaller fibers per plate (1000 instead of 640), reducing the S/N to 3–4 per pixel in i-band and accepting lower resolving power ($R = 1400$ in the blue, $R = 1400$ in the red), it was projected that 1.35 million LRG galaxies to $z = 0.7$ could be obtained in 5 yr. An additional 160,000 QSO spectra were expected to be obtained over the same time period. The upgrades were made at the end of 2008 (Smee et al. 2013). The upgraded spectrographs allowed an increase in the limiting magnitude in i-band to 19.9, maintaining the 1 hr integration time in ideal conditions. The details of these and other small changes are described by Smee et al. (2013).

8.9. Photometric Calibration

The photometric calibration is defined by Fukugita et al. (1996). The error goals for photometry for the primary standard stars are 1.5% in u, ⩽1% in g, r and i, and 1.5% in z, so the survey-wide root mean square (rms) errors in the final SDSS photometric catalog are 0.02 mag in r, 0.02 mag in $r - i$ and $g - r$, and 0.03 mag in $u - g$ and $i - z$. After the SDSS calibration status was established, the magnitudes were denoted u, g, r, i, z.

A set of 158 standard stars, known with high confidence to be non-variable in previous standard star programs (Smith et al. 2002) was adopted. A grid of patches containing the 158 standard stars, with r' magnitudes between 9 and 14, was established using the 1.0 m Ritchey–Chrétien telescope at USNO Flagstaff Station during the bright time of each lunation from 1998 March through 2000 January, with judicious avoidance of the Moon for standard stars fainter than $r' = 13.2$ (Smith et al. 2002; Hogg et al. 2001). The primary patch sizes for the USNO telescope were 11.′5 on a side, and multiple standards could sometimes be accommodated in single fields. Vega is the fundamental standard star and the magnitude system is known as AB95, in which the magnitudes are directly related to physical units. An asinh magnitude system was used to handle objects near the instrumental limit (Lupton et al. 1999).

Nightly extinction corrections and zero-points were established by observing primary standard patches (established by observations at USNO) with the PT (20 inch diameter) at APO, which the SDSS 2.5 m telescope observes over the preplanned course of the observing for the main photometric survey on a given night. The star BD+17°04708 was observed when it was available and was the fundamental standard for zero-points. The stars BD+26°02606 and BD+21°00607 were utilized when the main star was not available, but they are tied to the zero-point of BD+17°04708 as much as possible. The filters and extinction coefficients were slightly different for the USNO telescope and the SDSS PT telescope: hence the use of primed and unprimed filter systems. Eventually, all the photometry was placed on the natural system of the as-built APO 2.5 m telescope. Transforms between the Cousins system and the SDSS system are also published, and vice versa.

Secondary patches, $40' \times 40'$ in size, spanning each full stripe within the main survey data, were observed with the PT to calibrate SDSS stars to $r \sim 18$ in the patches (avoiding bright stars), at roughly 10 locations along every stripe of the main survey. The primary standard system initially set up with the PT was transferred to the full SDSS survey and eventually to the natural system of the SDSS telescope, filters and photometric APO sky.

8.10. Spectrophotometric Precision

Calibration of the observations with the spectrographs was obtained with F star flux standards included in the fiber hole layout for each plate. The 2% precision obtained depended on the light rays for each target being perpendicular to the plate at the position of each target on the plug plate. The plate was warped in the mounting structure for the plates during drilling, to make this so. Of course, the uniformity of the photometric precision over the entire survey depended on the uniformity of the observations of the standard stars over all the fields of the survey. As noted later, the value of the SDSS spectroscopic survey depended on the achievement of this precision for objects at the survey limit over the ∼1,000,000 objects over the nominal five-year period of the survey (actually finally accomplished over seven years); on using identical equipment; on constant checking of the hole drilling precision of the dedicated plate drilling machine; and on strict quality control of that process. The plates were drilled at UW and shipped to APO.

8.11. Software and Data Reduction Pipelines

Software to obtain and save the data recorded was developed for use at APO. The construction of that software went fairly smoothly. The data recorded at APO were archived on magnetic tape, used to monitor survey operations and shipped to FNAL by courier, daily. The transfer of data from the site was switched from mail courier to the internet as of 2006. The software to convert digits from the CCD camera to intensity units for display on the 30 TV monitors in real time was run at the APO site.

The extensive reduction done at FNAL for the photometric/astrometric survey needed for target selection for the spectroscopic surveys and for the spectroscopic data reduction itself involved a set of interlocking pipelines (Lupton et al. 2002), archiving procedures and bookkeeping procedures. Delays in the early planned surveys, owing to weather, led to a period of eight years during which this software was used. The first five years was called SDSS I and an extended period of about three years was called SDSS II, during which other surveys were carried out. The reduction steps used for those first *two* phases of SDSS are summarized here. (The text is written in past tense because use of the camera was discontinued, based on the brief summary by York et al. (2000).) The software described here for the early years was modified as necessary for the additional surveys described in section 8.12 below, but is not further described here. The software originally programmed for reducing the photometric and astrometric camera data to digital parameters in pipelines at FNAL (so the digital images could basically be reconstructed from the reduced data) took a much longer time than expected, because there were many decisions to be made and many revisions to allow the parameters to be extracted from the raw data to be done in the best way possible.

The *photometric pipeline* had many functions. It corrected the data for defects (interpolation over bad columns and bleed trails, identification and interpolation over "cosmic rays," etc.); calculation of overscan (bias), sky and flat field values; calculation of the PSFs as a function of time and location on the CCD array; finding of the objects detected; combining the data from the five bands; doing simple model fits to the images of each object; deblending overlapping objects; and measuring positions, magnitudes (including PSF and Petrosian magnitudes) and shape parameters for detected objects. The photometric pipeline used position calibration information from the astrometric array (reduced through the *astrometric pipeline)* and photometric calibration data from the PT (reduced through the *monitor telescope pipeline).* (The photometric telescope replaced the monitor telescope, but the name of the pipeline was not changed (Tucker et al. 2006).) Final calibrations were applied by the *final calibration pipeline,* allowing refinements in the positional and photometric calibration as the survey data were re-reduced for later data releases. The outputs, together with all the observing and processing information, were loaded into the *operational database*, which was the central collection of scientific and bookkeeping data used to run the survey.

To select the spectroscopic targets, objects were run through the *target selection pipeline* and flagged if they met the spectroscopic selection criteria for a particular type of object. The criteria for the primary objects (quasars, galaxies and LRGs) were not to be changed once the survey was underway. Algorithms for selection of serendipitous objects and samples of interesting stars could be changed throughout the survey (for instance, to test new selection criteria for newly discovered categories of objects). Holes for the selected objects were drilled in plug plates, subject to certain hole separation constraints, and the spectroscopic observations were made. The spectroscopic data were automatically reduced by the *spectroscopic pipeline*, which extracted, corrected and calibrated the spectra, determined the spectral types, and measured the redshifts. The reduced spectra were then stored in the *operational database*.

The contents of the operational database were copied at regular intervals into the *science database* for retrieval and scientific analysis. The science database was indexed in a hierarchical manner: the data and other information were organized spatially, into on-the-sky regions that could be divided and subdivided as necessary, (as opposed to the as-the-data-came-in organization of the operational database). This hierarchical scheme was consistent with those being adopted by other large surveys, to allow cross-referencing of multiple surveys. The science database also incorporated a set of query tools and was designed for easy portability.

The photometric data products of the original imaging and spectroscopic survey included a catalog of all detected objects, with measured positions, magnitudes, shape parameters, model fits and processing flags; atlas images (i.e., cutouts from the imaging data in all five bands of all detected objects, sized to enclose the area occupied by each object plus the PSF width, or the object size given in the ROSAT or Faint Images of the Radio Sky at Twenty-cm [FIRST] catalog); corrected images, binned 4×4, in u, g, r, i and z, with the detected objects removed; and masks of the areas of sky not processed (because of saturated stars, for example) and of corrected pixels (e.g., those from which cosmic rays were removed). The science database also included the calibrated, one-dimensional spectra, the derived redshifts and spectral types, and the needed bookkeeping information related to the spectroscopic observations. Also included were spectral images, calibrated and sky subtracted, with error and mask arrays; spectral parameters (redshifts, spectral types, detected lines); a GIF image of each spectrum; and auxiliary information, such as the number of objects in various databases, observing conditions, etc.

The pathbreaking software for internet-based scientific analysis was difficult to bring to satisfactory completion and basically was redone after the commissioning period began,[18] by Alex Szalay (JHU) and Jim Gray (b.1944–d.2007) of Microsoft. The original intent of the project was to release new data to the public on a two-year cycle, along with re-reduction of all previous data releases and upgrades of tools for display and preliminary science analysis. The mass of data that was eventually accumulated and the speed required to access and process the data became a very large challenge. An initial decision by the project to use an object-oriented database turned out to be inadequate because of failed expectations placed on the vendor. Gray was key to overcoming the previously perceived shortcomings of the alternate relational database architecture. This success led to the release of an analysis system referred to as the SkyServer, which was released with the SDSS First Data Release (Abazajian et al. 2003).

8.12. The Different Phases of SDSS

SDSS has far outlasted its intended purpose. The first five years of the main survey, which actually took 8 yr, was termed SDSS I. New discoveries from prior to and within SDSS I led to new funding opportunities and the project entered new phases. (Two examples of new discoveries that could not have been planned for pursuit in SDSS I were the discovery of Dark Energy,[19] just before SDSS was underway (Williams 2020), as the result of various, on-going SNe surveys, and the discovery of Baryon Acoustic Oscillations (BAO) from the big bang during SDSS I in the survey of luminous galaxies known as LRGs, out to $z \sim 0.35$.) New phases of the project, contemplated but not funded or planned for originally, were developed. To pursue the Dark Energy discovery, the original equipment of SDSS was fine. To pursue the baryonic oscillation issue, new equipment had to be built.

Weather prohibited the completion of the Northern Cap Survey (later known as the *Legacy Survey)* in the anticipated 5 yr. SDSS II was started late in 2005 to finish SDSS I; to initiate an SN survey (discussed later) in the southern sky; and to begin a program focusing on a variety of star types in the MW to exhaustively study the makeup of the parts of the MW that were not a priority in SDSS I, known as the *Sloan Extension for Galactic Understanding and Exploration* (SEGUE-I).

New spectroscopic equipment was constructed to pursue the BAO issue. When the imaging survey for the northern and southern skies was completed, the survey camera was retired, detailed below. Target selection needed for the new surveys was based on the imaging survey data collected in the first eight years. However, target selection software for new surveys was still needed and spectroscopic calibration and spectroscopic reduction were still required as were re-reduction of the photometric data from SDSS I and II with each new data release as small changes in the definition of the SDSS photometric system were made. The reduction software for the new surveys was modified as needed, based on new science goals and experience with reduction software used for SDSS I and II.

The spectrograph upgrades described earlier were performed in 2008 partially to augment the study of the acoustic oscillations by extending the observations of LRG from $z = 0.35$ to $z = 0.7$, to better determine the distance scale of the Universe at higher z. That survey was called BOSS, which started a new phase of SDSS (SDSS III). Each new phase included new funding partners and continued public distribution of regular SDSS data releases and improvements in software.

The Sloan data releases began with an Early Data Release (EDR) in 2001 (Stoughton et al. 2002). DR1 was in 2003. DR2 through DR6 (2004 through 2008) contained the increments of the main *Legacy Survey* described above, the Supernova survey and SEGUE-1. DR7 (2009) ended with release of all the data from SDSS I and SDSS II.

The photometric camera was decommissioned in the summer of 2008, when the *Legacy Survey* and SDSS II ended, and was placed in the Smithsonian Air and Space Museum in Washington, D.C. The upgraded spectrographs first produced data in 2009, marking the start of SDSS III, the BOSS survey of the higher z LRGs and a further search for new QSOs and black holes. SDSS III extended from 2009 to 2014 and

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[18] Jim Gray and Alex Szalay developed the SkyServer as part of a vision to make SDSS data accessible to, e.g., high school students. That is, the effort had a public outreach goal. It took a while for the professional community to start using it, but when professional astronomers did, it was realized how powerful it was, and it enjoyed wide amateur and professional use.

[19] Nobel Prize for the Discovery of Dark Energy, 2011, Brian Schmidt, Adam Riess and Saul Perlmutter.

included three other surveys beyond BOSS: SEGUE-2; the *Apache Point Observatory Galactic Evolution Experiment* (APOGEE); and a planet search experiment, the *Multi-object APO Radial Velocity Exoplanet Large-area Survey (*MARVELS). DR8 (2011) included all of SEGUE-1 and SEGUE-2 data and DR9 (2012) included the first BOSS data release. DR10 (2013) marked the first release of APOGEE data. A new spectrograph was built, APOGEE-I (Wilson et al. 2010; Wilson et al. 2019), to obtain high-resolution IR stellar spectra to derive abundances and stellar parameters of red giant stars at 11 μm (H-band), throughout the MW (insensitive to Galactic extinction and extending the reach of MW stellar studies). DR10 (2013) included the first data release of those data, plus more spectra for the BOSS survey.

SDSS III included a pilot program known as *Mapping Nearby Galaxies at Apache Point Observatory* (MaNGA), providing special new fiber bundles for use with BOSS blue and red spectrographs, along with new fiber carts. The goal was to obtain data cubes of the entire extent of ∼10,000 bright galaxies to study spectra of distributed light in bright galaxies. Each cart contained 17 bundles of fibers [for integral field spectroscopy (IFS)] with diameters from 12″ (19 fibers) to 32″ (127 fibers), totaling 92 science fiber bundles, that could be used at one time (typically for 3 hr), plus smaller ferrules for calibration spectra. A second pilot program, the *Sloan Extended Quasar, ELG (Emission Line Galaxies) and LRG Survey* (SEQUELS) was also started, within SDSS III, using the BOSS spectrographs to explore doing time domain studies of variable objects found in PanSTARRS-I[20] [called the *Time Domain Spectroscopic Survey* (TDSS)]. TDSS was a precursor to a further spectroscopic time-domain study of XR source spectra, the *SPectroscopic IDentification of eROSITA Sources* (SPIDERS), which became a major part of SDSS IV.

SDSS IV included an extension of BOSS (e-BOSS), SPIDERS and APOGEE (carried out from Las Campanas Observatory (LCO) with a spectrograph, APOGEE-II, nearly the twin of the one used at APO for APOGEE-1) and TDSS. DR16 is the final public release of SEQUELS data. DR17 is the final data release of SDSS IV.

A new phase of SDSS, SDSS V: *Pioneering Panoptic Spectroscopy* (Kollmeier et al. 2019; Almeida et al. 2023) began operation in 2021, with the APO 2.5 m telescope and the 2.5 m Dupont telescope near LCO, Chile, providing northern and southern sky APOGEE stellar spectra (300-fiber spectrographs) of a large sample of bulge, halo and MW stars. One of the BOSS 1000-fiber spectrographs was moved to the Dupont 2.5 m telescope so an all sky-survey called the *Black Hole Mapper* (BHM) could be carried out (along with the APO BOSS spectrograph), also utilized in conjunction with optical studies of some stars in parts of the MW stars probed by APOGEE-2. (The APOGEE-1/APOGEE-2/BOSS stellar survey within SDSS V is called *Milky Way Mapper*.) A robotic fiber positioner is replacing the plug plate system for fiber spectroscopy at both observatories.

Both 2.5 m telescopes and additional fiber spectrographs on smaller telescopes at APO and LCO are planned to provide IFS spectra of young star/ISM regions in the Local Group and nearby galaxies (using the MaNGA fiber carts), a survey called the *Local Volume Mapper* (LVM), to study large scale star formation. The first data release of SDSS V data occurred in 2023 (Almeida et al. 2023) and the next is anticipated to be in 2024. The SDSS data releases are cumulative and include corrected and augmented versions of previously released data (value added catalogs).[21]

8.13. The Success of SDSS

As of the middle of 2020, after ∼10 yr of operation of the SDSS equipment described earlier and 10 more years of extensions summarized in Section 8.12, the total number of refereed papers published with clear SDSS content reached over ∼10,000 and the number of citations to those papers reached ∼600,000. The impact covers much of the contents of modern astronomical research and far exceeds the original goals of the SDSS project. All the data are distributed through a public website on a regular basis to be used for research with no requirement that the original builders be included in the authorship of research papers that result. Many of the papers noted above were science papers not written by the original team that built the project, a result of the SDSS data release policy.

Much of the impact of the SDSS has come from (1) careful calibration of all products; (2) very large samples of uniformly measured images, selected by uniform criteria for spectroscopy, then uniform reduction of spectra, combined with surveys of large numbers of the same objects with other instruments (done with ground-based or space instruments, by other teams); and (3) a consensus behavior on the part of builders to execute the very best equipment and the most complete science analysis possible. With samples of hundreds of thousands to millions of objects from SDSS, combined with the timely appearance of large samples from other surveys (especially space projects), completely new samples of rare categories of objects have been identified.

The success of SDSS can also be measured by the growth in the number of participating institutions through the period of data releases. These are listed at the end of each data release paper. At the time of the EDR (Stoughton et al. 2002), the end of commissioning, there were 11 international participating

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[20] Panoramic Survey Telescope & Rapid Response System (PanSTARRS) is a facility in Hawaii for repeatably imaging the entire sky north of −47°.5 decl., available from Haleakala Observatory in Hawaii, multiple times, to find variable stars, SNe, comets, asteroids and Near-Earth Objects that might endanger Earth. It is equipped with SDSS filters and reaches objects as faint as 24th magnitude, north of −47°.5 latitude.

[21] All data are obtainable from https://www.sdss.org.

scientific institutions or consortia involved. At the time of the first data release in 2003, there were 13 involved (Abazajian et al. 2003). At the time of DR7 (2009), the end of SDSS I and II, the number was 24 (Abazajian et al. 2009). At the time of DR12 (2015), the end of SDSS III, the number was 23 (Alam et al. 2015). At the time of DR17, the end of SDSS IV, there were 37 institutions (Abdurro'uf et al. 2022). At the time of DR18, the beginning of SDSS V, there were 24 institutions (Almeida et al. 2023). In each case, some institutions dropped out and some new ones joined.

Several individuals or groups who played a major role in the project have been honored with national and international prizes since 2000. The following is a list of prizes that specifically refer to work of the mentioned individuals related to SDSS in the prize citations.

1. The ADM Sigmoid System Award (2021) to the SDSS, in particular, to thirty-one individuals[22] who assembled a database and software universally used to make the SDSS data available to thousands of professionals and amateurs alike. Citation: for "…an early and influential demonstration of the power of data science to transform a scientific domain."
2. The Ambartsumian International Science Prize (2021), Alex Szalay.
3. The R. M. Petrie Prize Lecture (2001); the Bruce Medal (2005); the Crafoord Prize (2005); The Gruber Prize (2005); the Joseph Webber Award for Astronomical Instrumentation (2002); the Henry Norris Russell Lectureship (2005); the Kyoto Prize (2019); and the National Medal of Science (2005), to James Gunn. The Crafoord Prize was awarded jointly to Gunn, James Peebles and Martin Rees.
4. The Dannie Heineman Prize (American Astronomical Society) (2021) to Robert Lupton and David Weinberg.
5. The George Van Biesbrock Award (American Astronomical Society) (2022) and The Royal Society Service Award (2019) to Donald York.
6. The Maria and Eric Muhlmann Prize (2005) to Robert Lupton.
7. The White House Champions of Change Award (2013) to Professor Jeremiah P. Ostriker recognizing the SDSS record of making data public for the public good (Open Science). See Figure 6.

Figure 6. Prof. Jeremiah Ostriker (center), Prof. Michael Strauss (top left), Al Sinisgalli (top center), Prof. Don York (top right), Prof. Gillian Knapp (bottom left) and Prof. James Gunn, (bottom right). When the picture was taken (2013), Don was at Chicago, while the others were at Princeton. Photo credit Anjelika Deogirikar and Michael Stebbins. The photo was taken on the occasion of the awarding of the White House Champions of Change Award to Jeremiah Ostriker.

8.14. Significant Impact on Several Astronomical Enterprises

SDSS had impacts on opening of participation in suitable SDSS projects to members of all SDSS institutions; by arousing new interest in funding of ground-based, astronomical projects [e.g., LSST; Dark Energy Survey (DES); Dark Energy Spectroscopic Instrument (DESI)]); and by policies that impact the way astronomy is carried out (e.g., complete and timely [approximately one to two year] provision of all the data to the public, via internet, for use by all; inclusion of project instrumentalists as well as scientist participants as a matter of policy in principal publications; and making all data and analysis tools accessible to students of all ages). The POO that laid out these policies for SDSS I were modified for each phase of SDSS II, SDSS III, etc., as the membership changed. The concept of a POO and the documents served the project well for 30 yr and was a pioneering practice in bringing heterogeneous international astronomy groups together. Professors Jeremiah Ostriker, Rich Kron and Don York formulated the initial draft of the first POO (SDSS I). Dr. John Peoples,

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[22] Michael Blanton, Adam Bolton, Bill Boroski, Joel Brownstein, Robert Brunner, Tamas Budavari, Sam Carliles, Jim Gray, Steve Kent, Peter Kunszt, Gerard Lemson, Nolan Li, Dmitry Medvedev, Jeff Munn, Deoyani Nandrekar-Heinis, Maria Nieto-Santisteban, Wil O'Mullane, Victor Paul, Don Slutz, Alex Szalay, Gyula Szokoly, Manu Taghizadeh-Popp, Jordan Raddick, Bonnie Souter, Ani Thakar, Jan Vandenberg, Benjamin Alan Weaver, Anne-Marie Weijmans, Sue Werner, Brian Yanny and Donald York.

Director of FNAL, over the course of the project, not only had a major impact on SDSS itself, but was instrumental in advocating for the involvement of the national Department of Energy (DOE) labs in cosmology research, in DOE funding of that research and in support from the various committees that advise DOE on funding future projects.

8.15. Selected Samples of Published Research from SDSS

SDSS provided publicly accessible data products to virtually all fields of astronomy. A few examples are given below. The selection of topics is based on my personal interests and is not meant to indicate the relative significance of the particular topics.

1. *The end of the dark ages.* In early searches for high redshift QSOs in the SDSS photometric camera scans, a number of objects were detected only in the SDSS z-band filter (8530–9730 Å). One of these turned out to be a $z \sim 5.8$ QSO (Fan et al. 2000). An extensive search of an additional 1550 square degrees of sky revealed three additional, similar objects which appeared in SDSS spectra to have a very strong blend of Lyα emission with nearby N^{+4} (N V) emission (a likely sign of a QSO) in the z-band at $z > 5.8$ (8530 Å–9730 Å). Extended continuum redward of 9730 Å in those four objects was seen in other instruments with appropriate sensitivity, but little or no flux in SDSS i-band (6880–8380 Å) or below (i.e., in the SDSS u-, g- or r-bands) was detected. The four objects were confirmed to be new high-z QSOs in follow-up studies using other telescopes, including the APO 3.5 m (Fan et al. 2001) and the Keck II 8.5 m (Becker et al. 2001). The dearth of flux in the i-band led to them being called i-band dropouts. These four objects showed strong Lyα forests (intergalactic neutral hydrogen clouds at $z < z_{\rm QSO}$) extending from shortward of Lyα emission at rest frame 1216 Å ($\lambda = 1216$ Å $\times (1+z_{\rm QSO})$) down to 912 Å rest frame ($\lambda = (1+z_{\rm QSO}) \times 912$ Å, the Lyman limit). This 300 Å region contains absorption from intergalactic hydrogen clouds between $z_{\rm QSO}$ and the Lyman limit. The redshifts of the three new QSOs were 5.82, 5.99 and 6.28. Observations of lower redshift Lyα forests in lower redshift QSOs showed that the amount of neutral hydrogen increased to higher z in the intergalactic medium (IGM) as anticipated as the hot gas from the big bang cooled and underwent recombination. (This would be better referred to as "combination" of electrons and protons). The resulting neutral hydrogen that was absorbing most of the light in the SDSS i-band in the new, higher z QSOs was evidently from the epoch of "combination" that followed the cooling of the hot hydrogen left from the big bang. The Lyα forest (known from previous QSO discoveries) dropped by a factor of 10 compared to the QSO continuum longward of Lyα emission for the $z = 5.3$ QSOs, by a factor of 20 for the $z = 6$ QSOs and by a factor of >100 for the newly discovered $z = 6.28$ QSO. As the redshift being probed by the QSOs was dropping, the neutral hydrogen from the period of the "Dark Ages" was thinning out, interpreted as the beginning of a period of reionization of the hydrogen, by radiation from newly formed galaxies and QSOs penetrating the thinning out region of neutral hydrogen.

   This was clearly the Gunn-Peterson effect predicted 16 yr earlier (Gunn & Peterson 1965), a boundary of the end of the Dark Ages as the Universe expanded (see Trimble 1999). The formation of UV and optical sources (i.e., galaxies and QSOs), made by clustering of matter that occurred in between the beginning of the Universe and the ionization of the recombined hydrogen at a time hundreds of millions of years later, created UV radiation that re-ionized the neutral hydrogen, reducing the opacity in the Lyα forest of lower z QSOs and their Lyman limits, allowing those sources to be seen at lower redshift. The "fog" that enshrouded the first newly formed galaxies and QSOs was dissipated and the new objects could be seen at lower redshifts. A key time in the evolution of the Universe was pinpointed.

   This discovery is an example of the power of SDSS to find very rare objects (high z QSOs) that could be observed with more powerful instruments to make the discovery predicted 35 yr earlier. The search for the very high z QSOs that enabled this discovery required separate searches of millions of false positive cosmic rays. Hundreds of cool dwarfs that also were i-band dropouts had to be definitively rejected as being QSOs to get the pure sample of four QSOs at high z (Knapp et al. 2004).
2. *Baryon acoustic oscillations (BAO).* The massive surveys of galaxies of different types by SDSS allowed clustering analysis of two very large, low-z samples from SDSS I. One was the LRG sample, with $z < 0.34$, the most massive galaxies, a sample of 58,000, with typical separations >0.1 Mpc, co-moving). The other was the main galaxy sample (MGS), $z < 0.15$, less massive galaxies, a sample of ∼285,000 <0.01 Mpc separation (Tegmark et al. 2006). For various reasons, the LRG sample was the most useful within SDSS I, the designation of the earliest galaxy survey by SDSS.

   Soon after SDSS went into operation, the Wilkinson Microwave Anisotropy Probe (WMAP) satellite (launched 2001 June 30, by NASA) began producing detailed maps of the fluctuations in the (CMBR), redshifted from $z \sim 1000$. On the scales of >0.1 Mpc (in co-moving coordinates), the WMAP maps of the power spectrum of radiation emitted by the gas that was forming into galaxies would be directly related to the

SDSS maps of the matter distributions of the visible galaxies at the late time to which the SDSS galaxy surveys refer, particularly, the large-scale structures of the LRG sample, $z \sim 0.35$ (Eisenstein et al. 2005).

Both the WMAP team and the SDSS team published numerous data and analysis papers between 2003 and 2014. The teams combined their data and results with other CMBR experiments (e.g., Hinshaw et al. 2013). The teams also compared their independent results with each other.

The importance of large-scale structure observations by SDSS lay in providing independent confirmation of the general outline of the early Universe model (Bennett et al. 2014), the sharpening of some of the details and the detection of the so-called BAO signal clearly echoing the structure of the CMBR data. Several key parameters that must be taken as priors from CMBR data can be refined from further large-scale galaxy structure surveys.

The galaxy clustering data also allowed a CMBR length scale corresponding to $z = 0.35$, the mean redshift of the 2006 LRG sample. Eventually, galaxy clustering at higher redshifts can tie down the geometry of the Universe in the region of space where the Dark Energy started causing acceleration of the Universe, around $z = 1$.

3. *The large Supernova Survey (SDSS II) and low-redshift acceleration of the Universe.* Just before SDSS went into operation (2000), surveys of SNe of Type Ia between $z = 0.16$ and $z = 0.8$, compared to SNe of the same type at $z < 0.16$ indicated that more distant SNe were fainter than expected from the widely accepted uniform expansion of the Universe. The apparent cause for the force driving the acceleration was termed Dark Energy, but other interpretations were possible including observational effects that might have introduced an apparent acceleration. The research groups involved concluded that Dark Energy made up a large portion of the total mass-energy of the Universe. Further confirmation of the surprising claim was necessary, and many more high z SNe needed to be observed. Several groups set out to get samples of hundreds of Type Ia SNe at high redshift to understand the effect in more detail. Key attributes of SDSS were recognized as being ideal to provide data on an under-observed redshift range between $z = 0.2$ to 0.4 (a remarkable coincidence). The normal operating procedures of the photometric camera were ideal for the needed repetitive, dark-time measurements over many weeks to follow the light curves of the SNe; the routine SDSS calibration technique was ideal and automatic; and four years of archived data for Stripe 82 were already available. Much of the needed software was available for obtaining the observations, but additional analysis software was needed. Three full seasons of observation ensued in 2005, dedicated to surveying the predefined equatorial Southern Stripe 82 for an expected 500 Type Ia SNe, when the North Polar Cap could not be observed from APO. The predefined stripe was $2\overset{\circ}{.}5$ wide, 300deg^2 in area and located at $\alpha = 20$h.7 to 4h, $\delta = 00°$.

   Over the course of eight years, the work of hundreds of researchers, involving over a dozen telescopes for auxiliary observations, resulted in the publication of a key paper on the results from SDSS and other SN surveys. Data from several SN teams were joined and analyzed together (Betoule et al. 2014): 374 SNe Ia from SDSS II ($0.05 < z < 0.4$) (Frieman et al. 2008—the SDSS sample); 239 SNe Ia from a second survey (largely from MegaCam on the Canada France Hawaii Telescope), that deals with higher z objects, called the SuperNova Legacy Survey (up to $z \sim 1$) (Conley et al. 2011); and 127 SNe from 7 less extensive SN distance projects, including nine from HST. The objects selected for the final sample, 740 SNe Ia [termed the Joint Light Curve Analysis (JLA)], were chosen to be as uniform as possible, with consistently fitted photometric light curves, recalibrated as necessary. All objects were spectroscopically verified to be Type Ia SNe (to minimize uncertainties from sample contamination). The critical fitting of the light curves (needed to derive the "standard candle" status of each source, essential to determining the distance to each source) was done in an improved and uniform manner (called SALT II) (Guy et al. 2007; Mosher et al. 2014). A few hundred objects had to be left out to satisfy these criteria.

   The analysis improved greatly on the uncertainties in the samples published to that time but did not change the conclusions of the 20th century discovery papers (Riess et al. 1998 (the High-z Supernova Search Team); Perlmutter et al. 1999 (the Supernova Cosmology Project)): the Universe is accelerating, is very close to being flat and has a cosmological constant.

   The SDSS Supernova Survey is an example of a timely survey of high community interest that could be carried out because the main features of the observations that were needed were built into the original plans for SDSS, before Dark Energy had been confirmed by the HST observing teams. Future results from the DES will involve a much higher number of sources and a wider range of redshifts and will be built on the legacy of the analysis techniques developed since 1998 by SDSS and the collaborating teams.

4. *The study of QSOs was completely changed by SDSS, quantitatively and qualitatively.* Before the SDSS project began, 1549 QSOs had been cataloged (Hewitt & Burbidge 1980). The number of QSOs with absorption lines, generally thought to arise in foreground galaxies (referred to as "intervening" galaxies) of even a few elements, numbered only one hundred eleven in the Hewitt and Burbidge catalog. After five years of the SDSS survey

beginning formal operations, 300,000 photometric QSOs were cataloged, and spectra existed for 100,000, thanks to the QSO target selection procedures described by Richards et al. (2002). After ∼10 yr, there were 1 million photometric quasars known (Richards et al. 2009) and the 105,000 spectroscopic quasars had been reduced and published (Schneider et al. 2010), with high enough quality to detect absorption lines of Mg II from intervening galactic material in front of 33,000 QSOs.

These absorption features and accompanying lines of other elements of the periodic table are of great interest for studying the evolution of elements in galaxies to the redshifts of the faintest known QSOs at the highest redshift to $z = 0$. After the emphasis on QSO spectra increased with the SDSS phases through SDSS IV, the total number of spectroscopically confirmed QSOs grew to ∼750,000.

The large sample of QSOs from SDSS I and II was enough to define several special types of QSOs (such as various varieties of BAL QSOs and time variable QSOs). The very large number of intervening absorbers combined with the stacking of spectra of a well-defined set of 800 QSOs in the redshift range 1 to 2 (York et al. 2006), all with $z_{\rm gal} < 0.04 \times z_{\rm QSO}$, led to showing that the depletion pattern that most characterized the gas (Zn/Mg) in the intervening systems (galaxies) had many properties in common with galaxies found within the Local Group. The systems found to have C IV absorbers are often close to the QSOs themselves ($z_{\rm C\ IV} \sim z_{\rm QSO}$ presumably, circum-QSO gas) and may have other characteristic abundance patterns.

The QSOs themselves were found, after further study, to include examples of variability on timescales of days to years. Regions near the QSO outflows containing BALs sometimes showed spectral variability in outflows on timescales of days (Lundgren et al. 2007). Later work indicated variations in the BALs on timescales up to hundreds of years (Filiz Aket al. 2012) and complete disappearance of BAL features on timescales of thousands of years (Filiz Aket al. 2013). A picture emerged in which most massive galaxies have QSOs ($>10^8$ solar masses) or AGNs (with $<10^7$ solar mass black holes) at their centers.

The number of visible QSOs beyond redshift 7 is tiny (<10) (Lyke et al. 2020). The number of detectable QSOs seen in SDSS peaks near $z = 2$, but below $z = 0.2$ and above $z = 7.0$, the number of known QSOs in all of SDSS appears to be well below 5% of the peak. If most galaxies had massive black holes at some point in their lifetimes, they have presumably burned out or are currently in quiescent states. But the statistics of the occurence of the objects associated with objects at $z > 7$ is changing rapidly due to new observations.

The study of the QSOs is an example of discovering much greater diversity of classifications of a particular type of object when the sample size is increased by a factor of more than 100.

5. *Star streams.* During the commissioning period for the SDSS project, with all the equipment fully operational and a provisional set of data visualization software, numbers of QSO candidates were identified based on their spectral energy distributions. A number of the redshifts taken to confirm the objects were not consistent with the redshifts of QSOs and the follow-up spectra showed they were MW stars of type A to F. Furthermore, many of these were shown to have variability properties consistent with those of RR Lyrae stars, variable stars long used for determining stellar distance. This set of objects was much more distant MW halo stars than most well cataloged RR Lyrae stars before the year 2000. They allowed probing deeper and more completely into the Galactic halo than could be done previously (because of their initial selection as faint QSO candidates). Rockosi et al. (2002) identified a stream of RR Lyrae and other stars emerging from a globular cluster, Pal 5, presumably showing the gravitational dispersal of the cluster. The stream-like shape reflected the fact that the velocities of the stars in the cluster orbit were disturbed into the shape of a stream, along the orbit of the cluster in the MW. Many such streams were subsequently found (Belokurov et al. 2006). Evidently, most stars in the halo originated in old star clusters, disrupted over millions of years in the gravitational field of the MW halo.[23]

   Many other examples of far-reaching research results developed from the results of the discovery of halo RR Lyrae stars originally misunderstood as QSOs in SDSS photometric images until SDSS spectra were available.

6. *Matching of SDSS objects with surveys in other wave bands.* For large, uniform samples of certain astronomical classes of objects, recorded with the same equipment, it can be very useful to observe the same sample in other energy bands, in order to make more focused samples for further exploration. An example is the SDSS data set of XR sources from the ROSAT satellite (Anderson et al. 2007). Most of the ROSAT detections are broad line QSOs or Seyfert 2 galaxies in the range 15 < mag < 21. Rare types of XR sources continue to be found, among the 7000 ROSAT sources matched with SDSS sources, including BL Lac objects (266 optical continuum sources

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[23] As this research emerged, I thought often of my wonderings about the origin of the halo stars, which I often observed in my IS studies based on the IS lines that appeared in spectra of high-latitude halo stars. Lyman Spitzer (1956) had formulated his prediction that IS clouds at high latitude implied the existence of hot gas in the halo that might produce O VI absorption from a pressure confining medium.) When I came to Chicago in 1982, the origin of the halo stars was my first question of astrometrist Professor Kyle Cudworth. Where did they come from? He confessed that this was an important ambiguity in his field. Now, I knew the answer. Kyle became involved in the subsequent SDSS research on the subject.

with few emission line indicators) and narrow line Seyfert 1 galaxies (∼774 candidates). The nature of the sources assures there can be few misidentifications, so subclasses from such an investigation are likely to reveal even smaller subclasses with unique and tell-tale features. Optical sources within SDSS that match positions of ROSAT sources to the ROSAT accuracy of ∼30″, that have unusual SDSS colors and which also coincide with a FIRST radio source position, are reliable as detections of XR sources. Algorithmic matching is done with the photometric and spectroscopic parameters from SDSS and from ROSAT measurements of the XR sources. Then every source is checked by hand, for completeness, to make sure very few matches have been missed.

Other rare matches include XR AGNs with multiple peaked emission lines and Seyfert galaxies with a mixture of broad and narrow emission lines. Many of the matches are bright enough to be investigated with the new generation, spectroscopic XR telescopes.

7. *Cross-identifications in multiple wave bands.* Obrić et al. (2006) carried out similar matching efforts with a sample of 99,088 SDSS galaxies from DR1 from the SDSS MGS (2003) and seven smaller data sets [Galaxy Evolution Explorer (GALEX) (UV), Two Micron All Sky Survey (2MASS) (near-IR), Infrared Astronomical Satellite (IRAS) (mid/far IR), Green Bank GB6 survey (6 cm), FIRST (20cm), NRAO VLA Sky Survey (NVSS) (20cm) and Westerbork Northern Sky Survey (WENSS) (92cm)]. The position error circles for these surveys are all smaller than the ∼30″ ROSAT error boxes. The number of sources with high reliability matches with SDSS ranged from 132 (GB6) to 19,184 (2MASS) for the seven surveys. (Only 30 ROSAT matches were found in this early survey, compared to the 7000 in the Anderson et al. survey noted above.) This Obrić et al. study depended, as did the Anderson et al. ROSAT study, on the large parameter set from the automatic SDSS reductions (Lupton et al. 1999), the high-quality follow-up spectra of SDSS and multiple follow-up studies from SDSS on measurements of emission lines, galaxy masses and other SDSS analyses of the properties of the matched objects.

   Despite the small sample of overlapping matches for the seven surveys with SDSS sources, the results provided an early panchromatic view of the Universe of galaxies and a preview of techniques and results that could be reasonably expected as the SDSS sample of galaxies grew from future data releases.
8. *Solar System Asteroids.* SDSS discovered hundreds of thousands of asteroids in the solar system. They were easy to spot in the main survey data (Ivezić et al. 2002) because of their high proper motions, detectable as blurred images on single CCDs with ∼1 minute integrations. Stars appear as point sources because their proper motions are undetectable in the image shapes in single exposures, owing to the TDI scanning mode used by SDSS. The high proper motion asteroids thus stand out from stars because their images produce "star trails," since they move with respect to the stars. The asteroids found in this way turned out to be grouped in certain color classes defined with the SDSS filter system. Since they all reflect the same solar spectrum, the color differences are clearly due to different surface properties.

9. Involvement with STEM Education

I was co-Founder, with UC Director of Neighborhood Relations, Duel Richardson, of the Chicago Public Schools/University of Chicago Internet Project (CUIP) circa 1996. The project focused on producing a sustainable internet culture in 33 public schools in the neighborhood of the UC. Our activities included infrastructure development (wires, power, computers, wireless), teacher training, system management and classroom integration of technology. From 1996 to 2016, we developed and operated a digital library for K-12 students (called *e-CUIP*); an edited, standards-based list of internet references for teachers (*websift*); a set of classroom instructional modules for teachers in Chicago Public Schools based on the collections of Chicago museums *(Chicago Web Docent, CWD*); and instructional modules based on scientific careers of notable astronomers. For the last years, we continued our program of the previous years, helping nine school principals become owners of sustainable technology systems that did not depend on our team to maintain them. The project was terminated in August 2020

10. Travels

I had extensive opportunities for travel to foreign countries in conjunction with the research projects described in sections above; to diverse science conferences; and to planning meetings for major astronomical projects. My wife accompanied me on many of the more exotic trips.

The first of these opportunities was a long trip through the Soviet Union, in conjunction with speaking engagements on the early results from Copernicus, which took us to Azerbaijan, Georgia and Armenia. We visited Academician Viktor Ambartsumian at Burakan Observatory on that trip. I had only finished my Ph.D. three years before and mainly knew graduate school astronomy and the key aspects of research on IS gas. I still recall how much he knew about the impact of saturation of IS lines and how much it impacted the conclusions of the Copernicus studies of deuterium in space. This interpretive issue is one of the main issues limiting our knowledge of the ISM today.

I worked on definition studies of the FUSE satellite, which took me to Canberra and Sydney, Australia; to England; and to Rome.

I attended assorted science conferences throughout Europe, and spent many weeks with colleagues Alfred Vidal-Madjar and Claudine Laurent in Paris, writing papers on deuterium in space, and in Marseilles, working on absorption lines in QSOs with Celine Peroux.

Pushpa Khare and Anand Srianand hosted Anna and I in Pune, India, for conferences on intergalactic gas.

In addition, I traveled often to China for many reasons: I convened a large conference aimed at six thousand Chinese high school students on the history of astronomy; organized a research prize contest on modern cosmology research for Chinese scientists; organized an essay contest for Chinese students; and consulted on the LAMOST project. I also had a very small part to play in defining a search for very fast transients at Dome A in Antarctica, with Lifan Wang from Texas A&M University. The first activity resulted in a book, *The Astronomy Revolution: 400 Years of Exploring the Cosmos. Eds.,* D. York, O. Gingerich, & S.-N. Zhang (2012). The associated travels and the activities for Chinese scientists, Chinese students and international speakers and awardees were all sponsored by the John Templeton Foundation.

On my twelve trips to China, I was hosted at different times by Zhao Gang, Deputy Director General of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) and lead scientist of the Stellar Abundance and Galactic Evolution group at NAOC, in Beijing; Xue Suijian, NAOC Assistant Director for Science and Project Planning and International Cooperation Affairs; and Cui Xiangqun, Director of the Nanjing Institute of Astronomical Optics and Technology and Chief Engineer of LAMOST. Anna and I had several opportunities to travel extensively in China, including visits to the Tibetan Airshower Array, a solar eclipse in western China and to various historical sites in western China, including the Caves of the Thousand Buddhas (the Dunhuang Caves), on the Silk Road, and various points on the Great Wall of China.

I am most grateful to those who hosted us in these places and shared the rich cultures of their countries with us.

Acknowledgments

I gratefully acknowledge discussions with the following individuals in putting together this set of reminiscences. They are listed by the main institution that the individuals were at when we worked together.

Kurt Anderson (NMSU), Scott Anderson (UW), Nancy Chanover (NMSU), Mike Evans (UW), Josh Frieman (UC/FNAL), Priscilla Frisch (UC), Bruce Gillespie (APO), Carol Grady (GSFC), Jim Gunn (PU), Al Harper (UC), Tim Heckman (JHU), John Hill (UA), Lew Hobbs (UC), Ed Jenkins (PU), Steve Kent (FNAL), Bill Ketzeback (APO), Ed Kibblewhite (UC), Rocky Kolb (UC/FNAL), Rich Kron (UC/FNAL), Don Lamb (UC), Don Long (APO), Britt Lundgren (UC/University of North Carolina at Ashville), Ed Mannery (UW), Bruce Margon (UW), Buddy Martin (UA), Don Morton (PU), Takeshi Oka (UC), Jerry Ostriker (PU), Pat Palmer (UC), Alim Patton (UW), John Peoples (FNAL), Jordan Raddick (JHU), Gordon Richards (UC), Blair Savage (UWis), Steve Smee (JHU), Walter Siegmund (UW), William H. Smith (PU), George Sonneborn (GSFC), Ted Snow (PU), Chris Stoughton (FNAL), Michael Strauss (PU), Alex Szalay (JHU), Alfred Vidal-Madjar (Institute d'Astophysique, Paris), Dan Welty (PU, UC, STScI), Adolf Witt (University of Toledo), Jennifer Woods (UC) and Brian Yanny (UC/FNAL). For technical and editing assistance and great patience, I thank sons Sean, Maurice, Chandler and Jeremy, and wife, Anna.

I am especially grateful to my very close colleague, Dr. Dan Welty, now at STScI, who worked with me at Princeton and Chicago for a total of fifty years,from whom I learned so much. He participated in many of the accounts of research recorded here.

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