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# THE WISCONSIN EXPERIMENT PACKAGE (WEP) ABOARD THE ORBITING ASTRONOMICAL OBSERVATORY (OAO-2)

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**Abstract:** On 7 December 1968, NASA's Orbiting Astronomical Observatory (OAO-2) was launched into space. Roughly ten years in development, the OAO carried two sets of experiments, each designed to conduct the first extended observations of the sky at ultraviolet wavelengths. One experiment package was designed by the University of Wisconsin; the other by the Smithsonian Astrophysical Observatory.

Remote operation of the OAO, especially the WEP's narrow-field photometric instruments, demanded a complex stabilization and control system that could point the spacecraft towards any desired object with an accuracy of better than one arc-minute. A host of other calculations were performed to ensure that the instruments were never pointed within a fixed number of degrees of the Sun, Moon, or even the Earth.

During its 50 months of operation, WEP successfully observed more than a thousand celestial objects. It was the first true stellar space observatory, whose operations represented a greater technological leap forward in its day than did the Hubble Space Telescope (HST), launched in 1990.

At the same time, OAO-2 marked a significant turning point in the way astrophysical research was conducted. OAO scientists' dependence upon high-speed, digital techniques of data acquisition, storage, transmission, and reduction, not only presaged but also influenced the universal adoption of such techniques throughout the astronomical community. The OAO spacecraft was a significant bellwether of the transition to an era of digital data manipulation that occurred well *before* the impact of the personal computer and the charge-coupled device (CCD).

**Keywords:** Orbiting Astronomical Observatory, Wisconsin Experiment Package, Space Astronomy Laboratory, University of Wisconsin-Madison, Arthur D. Code, ultraviolet astronomy

## 1 INTRODUCTION

Creation of the Space Science Board (SSB) of the National Academy of Sciences (NAS) in 1958 proved a decisive step towards opening the space frontier for future astronomical as well as astronautical exploration. The SSB's first meeting (27 June) was held before the International Geophysical Year (or IGY, stretching from 1 July 1957 to 31 December 1958) had officially ended. Geophysicist Lloyd V. Berkner (1905–1967), formerly of the Department of Terrestrial Magnetism at the Carnegie Institution of Washington, was elected Chairman of its fifteen-member panel. Berkner's appointment to the SSB stemmed from the guiding roles he had played in creation of the IGY itself, where he served as President of the International Council of Scientific Unions (ICSU) and Vice-President of the Comité Spécial de l'Année Géophysique Internationale (CSAGI), which coordinated the scientific efforts of more than sixty nations. Historian Allan A. Needell has demonstrated Berkner's central role behind the 1954 decisions by the International Union of Geodesy and Geophysics (IUGG), and the CSAGI, to request the launch of one or more scientific satellites (Needell, 2000: 325).[1] Berkner also served as IGY reporter for rockets and satellites, which put him in close touch with planned spaceflight developments, particularly the American Vanguard project (Bulkeley, 1991; Chapman, 1959; Green and Lomask, 1971; Sullivan, 1961; Wilson, 1961).

One of the principal motivations that led to the SSB's creation was its anticipated advisory capacity to "… provide help and advice … [to the] possible new civilian space agency ..." (the future National Aeronautics and Space Administration, or NASA) then being established by the U.S. Congress (SSB, 1958a: 3), whose transformation from the prior National Advisory Committee on Aeronautics, or NACA, became official on 1 October 1958 (McDougall, 1985).[2] But over the next two years, tensions frequently arose between NASA and the SSB over matters of authority in establishing future directions of the emerging space science program. By 1960, however, NASA was well-positioned "… to direct American achievements in space during the ensuing decade." (Hetherington, 1975: 107; Newell, 1980, 205-214).

After the first SSB meeting, Berkner sent telegrams (on 3 July) to a number of prominent U.S. astronomers, asking for their suggestions regarding future satellite experiments. Among those receiving these requests was Arthur D. Code (b. 1923), newly-appointed Director of the Washburn Observatory at the University of Wisconsin-Madison.[3] This was an opportunity for which Code was well prepared, and in which he would distinguish himself and his institution in coming decades.

Code, a native of Brooklyn, New York, entered the University of Chicago in 1940, but his education was interrupted by the Second World War. Widely experienced in radio communications and their associated technologies, Code enlisted in the U.S. Navy, where he received advanced training in electronics in the Chicago area before being stationed as an instructor at the Naval Research Laboratory in Washington, D.C. During the War, he gained extensive

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practical experience with the design and construction of technical equipment that served him well in years ahead. He also took coursework in physics at George Washington University, receiving instruction from Russian émigré physicist George Gamow (Code, 1982). Though he never received a formal bachelor's degree, Code was admitted to Chicago's graduate program in 1945. At the Yerkes Observatory, he design-ed and constructed an improved amplifier for the tracings of coude spectrograms obtained at McDonald Observatory (Osterbrock, 2003). In 1950, he was awarded his Ph.D. for a theoretical study of radiative transfer in O- and B-type stars, directed by Subrahmanyan Chandrasekhar (Code, 1950). Following a one-year appointment at the University of Virginia, Code was hired onto the faculty of the Department of Astronomy at the University of Wisconsin-Madison (1951-1956), where he specialized in photoelectric photometry. There, he and Albert E. Whitford (1905–2002) built a one-channel scanning spectrophotometer that was used at the Mount Wilson Observatory. In 1956, however, Code was hired away by Caltech's Department of Astronomy, then chaired by Jesse Greenstein (1909–2002).

In the autumn of 1957, Code and Caltech colleague Donald E. Osterbrock (b. 1924) both observed the passage of *Sputnik I* over Pasadena—an event that left a lasting impression upon the former. As Code later related to Osterbrock, the sight of *Sputnik* brought to him the realization that humanity would at last be able to measure the ultraviolet fluxes of stars (and other celestial objects) from above the Earth's atmosphere. Thereupon, Code privately resolved that he would attempt to conduct those measurements from an orbiting spacecraft (Osterbrock, 2003).

In his 1960 chapter on "Stellar Energy Distribution", published within the volume *Stellar Atmospheres* (edited by Greenstein), Code reiterated the problem that had always thwarted ground-based astronomical observations, namely, that the atmosphere's opacity to short-wavelength radiation represented "... the greatest single limitation on our knowledge of the spectral energy distribution of stars." (Code, 1960a: 50). In that same year, he published a cogent essay, "Stellar Astronomy from a Space Vehicle", that presented a host of critical observations that could be made from beyond the atmosphere, and likewise offered the prediction, strongly borne out in coming decades, that "... astrophysical investigations [conducted] throughout the entire electromagnetic spectrum, ... cannot fail to have a tremendous impact on the future course of stellar astronomy." (Code, 1960b: 278).

## 2 OPPOSITION TO SPACE ASTRONOMY

Yet, among many senior members of the American astronomical community, notable opposition arose to the growth of Federal support being awarded to the advent of space astronomy. Although difficult to understand today, this attitude was especially prevalent among the more elite institutions and personnel of west-coast observatories. Cost considerations stood among the principal sources of contention; some tens of smaller, ground-based telescopes could be built, it was argued, for the cost of a single, large space telescope (Smith, 1989: 44-48).

In the immediate post-war period, only a handful of American astronomers foresaw the potentials of spaceflight upon their discipline and pursued an active research interest (slanted toward measurements of the solar ultraviolet spectrum) through the launch of specially-instrumented V-2 rockets at White Sands, New Mexico (DeVorkin, 1989; 1992). But growing awareness of the very limited returns in useable data, combined with the inherent risks of failure, significantly dampened the spirits of this group, and soon spread to colleagues elsewhere.[4] At the same time, completion of the 200-inch reflector on Palomar Mountain was eagerly anticipated, and was viewed as the primary tool with which significant new discoveries in the coming decade (and beyond) would likely be made. Despite the limitations of slower photographic plates and long exposure times necessary, such traditional observing techniques were well-understood and accepted among the community as defining what it meant to be an astronomer (McCray, 2004).[5]

Opposition to space astronomy also reflected a generational issue, especially among researchers who had established their institutional homes and careers before the Second World War. The creation and continued support of leading ground-based observatories still highlighted the pinnacles of pre-war astronomical patronage, wherein many of the discipline's leading discoveries about the nature of the Galaxy and the expansion of the Universe had been accomplished. As a result, elder practitioners of the discipline exhibited a reluctance to support expenditures for newer types of research that strayed away from traditional problems that were to be investigated through continued usage of large ground-based optical telescopes.

An example of this type of thinking is displayed in the 1960 response of Mount Wilson and Palomar Observatory astronomer Horace W. Babcock to a request for ideas regarding possible development and launch of astronomical satellites, posed to him by University of Michigan astronomer Leo Goldberg (1913–1987), then Chairman of the ad-hoc Committee on Optical and Radio Astronomy that reported to the Space Science Board. Strongly evident among Babcock's argument was the feeling that events of the Space Age were moving far too rapidly to permit a proper assessment of pending and future research needs and opportunities. He judged that "The greatly condensed time schedules and the 'crash' nature of many of the developments ..." would likely prove quite inefficient, and "... can hardly be justified ..." by standards of traditional astronomical research. Babcock lamented that "... the immense expenditures being made and planned for 'space research' ..." had arisen not from scientific motives, but instead seemed "... in large part the result of popular demands for [improved] national prestige ..." in the aftermath of *Sputnik* and other Soviet space initiatives. He objected that such funding decisions retained a strong political component, and questioned whether such initiatives would remain "... dependent on the varying trends of mass psychology." Nonetheless, and speaking more directly as a scientist, Babcock admitted that "... if large satellite vehicles are to be launched in the coming years, [then] astronomers have a distinct obligation to exploit the opportunities [presented] for the advancement of science." (Babcock, 1960). He did not seem to

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realize, however, that such a moment was already at hand.

## 3 CODE'S RETURN TO WISCONSIN

What happened next, with regard to Code's subsequent career trajectory, must be regarded as a mixture of fortunate timing, opportunity, and reward; but at the same time, reflected the somewhat unusual and potentially risk-filled decision to leave a tenured position at Caltech and return to the University of Wisconsin-Madison (effective 1 July 1958) as a full Professor and Director of the University's Washburn Observatory. This relocation had been made possible by the concurrent appointment of former Washburn Director, Whitford, to the Directorship of the Lick Observatory of the University of California (Osterbrock, 1976; 2004). As a strong incentive to bringing Code back to their institution, the University of Wisconsin administration expressed its commitment to the rapid enlargement of its astronomy department and the establishment of a full graduate-level program—steps previously recommended by Whitford. As evidence of that commitment, the Department of Astronomy (on 30 June 1958) dedicated its state-of-the-art 36-inch (0.9 m) reflector at the Pine Bluff Observatory located west of Madison, during the 100th Meeting of the American Astronomical Society. Superseding the historic 15.6-inch (0.4 m) Clark refractor of the original Washburn Observatory, the new reflector was optimized for research in photoelectric photometry and spectrophotometry (Bless and Lattis, 2000).

At the same time, it was no secret that Code's Caltech supervisor, Jesse Greenstein, had no fondness for the possibilities of spaceborne astronomical observations (McCray, 2004). Indeed, Greenstein continued to champion the superiority of ground-based optical telescopes, especially Caltech's 200-inch reflector, that made his facility the world's premiere astronomical research institution. The prestige of a Caltech appointment, and assurance of future research opportunities that it afforded, were no small matter for Code to walk away from. But the Wisconsin position offered him the autonomy and the opportunity to pursue research in space astronomy that would almost certainly be lacking, were he to remain at Caltech under Greenstein (Code, 1982). Those crucial factors undoubtedly cast the difference in favor of Code's return to the smaller Washburn Observatory, which nonetheless possessed a distinguished history of scientific and technical innovation in the development of photoelectric photometry, achieved under the tenures of Joel Stebbins (1878–1966) and Whitford (DeVorkin, 1985; Hearnshaw, 1996; Leibl and Fluke, 2004).

By October 1958 Code was invited by Berkner to become a member of the ad hoc SSB Committee on 'Optical and Radio Astronomy' chaired by Leo Goldberg, which first met at Ann Arbor, Michigan, on 6 October 1958 (Berkner, 1958; SSB, 1958b).[6] There, Code presented one of ten informal 'proposals' which described possible measurements of radiation densities (chiefly in the UV) that might be accomplished from a 100 pound satellite. Code was subsequently named a coordinator of such proposals in stellar astronomy (SSB, 1958b: 5, 6, 9). Along with other proposals made in areas of fundamental physics, solar, and radio astronomy, these were utilized by the Goldberg Sub-Committee in its drafting of a "… primer of astronomical research from space vehicles …" that was to be delivered to the Space Science Board early in 1959 (Goldberg, 1958: 1).

Berkner's solicitations of suggestions for satellite experiments netted roughly two hundred responses from the astronomical community (Berkner and Odishaw, 1961; Hetherington, 1975; Smith, 1989).[7] Yet, the number of core groups wishing to pursue these matters quickly dropped to four or five, once it was learned that more formal proposals would be requested. Those who were most seriously committed formed the basis of NASA's Space Science Working Group (SSWG), whose meetings commenced in February 1959 (DeVorkin, 2005). With a decided emphasis upon UV astronomy, SSWG members began to develop their proposals for the first 'Orbiting Astronomical Observatories'. The institutions, principal investigators, and names of the experiment packages eventually flown by these core groups are listed in Table 1.

Table 1. Original NASA SSWG

| Institution | Principal Investigator | Instrument Package |
|---|---|---|
| Wisconsin | Arthur D. Code | WEP, on OAO-1 and OAO-2 |
| SAO[a] | Fred L. Whipple | Celescope, on OAO-2 |
| Goddard | Albert Boggess III | GEP[b] (OAO-3; launch failure) |
| Princeton | Lyman Spitzer, Jr. | PEP[c] (OAO-4) |
| Michigan/ Harvard | Leo Goldberg | OSOs[d] |

[a] Smithsonian Astrophysical Observatory

[b] Goddard Experiment Package. This group began as the astronomical branch of the Naval Research Laboratory, Washington, D.C., but was moved to the Naval Ordnance Laboratory, Anacostia, Maryland (Code, 2003), and later became re-organized as the Goddard Space Flight Center (GSFC).

[c] Princeton Experiment Package. Renamed Copernicus.

[d] Orbiting Solar Observatories. Partly due to the radically different thermal requirements of the OSOs, solar astronomers removed themselves from the SSWG (Roman, 1972).

## 4 FOUNDING OF THE SPACE ASTRONOMY LABORATORY (1959)

In 1959, Code and then Assistant Professor Theodore E. Houck (1926–1974) established the Space Astronomy Laboratory (SAL) within the Department of Astronomy at the University of Wisconsin-Madison (Code, 1982). SAL was the first of several notable startups in Code's career, which came to include the OAO spacecraft and the Space Telescope Science Institute (Code, 1997). Houck had earned his Ph.D. in 1956 under Whitford (only the third Wisconsin doctorate awarded in astronomy) with a thesis on early-type stars (Houck, 1956). He was originally appointed an Instructor (1956-1959) and had chosen the site for the Department's new Pine Bluff Observatory.

Also joining SAL was Robert C. Bless (b. 1927), a recent Ph.D. from the University of Michigan, who had completed a thesis under William C. Liller on the photoelectric spectrophotometry of A-type stars (Bless, 1959). While still at Michigan, Bless and several other students, along with Leo Goldberg, had observed *Sputnik* in the fall of 1957, which whetted both men's appetites for space astronomy. Originally, Bless came to Wisconsin on a temporary two-year research appointment that was extended to three years (1958-

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1961); he then became a permanent faculty member, achieving Assistant- (1961), Associate- (1963), and full Professorships (1969). The fourth original member of SAL was John F. McNall (1930–1978), who had earned bachelor's (1953), master's (1956), and doctoral degrees (1960) in electrical engineering (computer science) from the University of Wisconsin. Starting in 1960, McNall became a Project Associate with SAL and later was appointed an Assistant Professor of Computer Science (1963).

The Space Astronomy Laboratory was first housed in Sterling Hall on the Wisconsin campus, but with the reassignment of astronomy faculty (from offices in the overcrowded Washburn Observatory), SAL was moved to the basement of a house owned by the University, and then to a vacant warehouse on North Park Street in Madison, before acquiring a permanent home in Chamberlin Hall. Despite these somewhat adverse operating conditions, the four researchers nonetheless developed a camaraderie that possessed a number of advantages. In contrast to the larger team assembled by the Smithsonian Astrophysical Observatory (SAO), the smaller SAL team proceeded without much evidence of a hierarchy. The relative absence of bureaucratic 'red tape' (in those early days) contributed to a free flow of scientific ideas. Ironically, the loose-knit organization of SAL proved somewhat suspect to NASA officials, who urged them to be more hierarchical and to emulate the Smithsonian (Bless, 2003).

Well before the OAO satellites were constructed, SAL personnel (along with other SSWG members) requested financial support from NASA to fabricate and test several smaller, less sophisticated devices as a means of demonstrating their capabilities under near-spaceflight conditions (Smith, 1989: 40). In 1961, a weather balloon carrying a small UV-sensitive photometer (for measuring sky brightness) was launched from the Madison campus and recovered by an Illinois farmer. Prototypes of the photometer assemblies being prepared for the OAOs were flown by SAL scientists aboard Aerobee sounding rockets, starting in 1962. Additional instruments, including a camera, photometer, and spectrograph, were tested aboard several flights of NASA's X-15 rocket plane (Code, 1982; Bless and Lattis, 2000).

Code has described the initial excitement, the team spirit, and 'can-do' attitude that dominated the early days of SAL. Great satisfaction came from reliance upon the self, rather than an outside agency. Also characteristic of the startup was the newness, the curiosity, which accompanied the dawning Space Age. Awareness and opportunity of setting an important scientific precedent furnished additional rewards to the team. Finally, there was the attendant joy of communicating their findings to peers. All of these things Code has likened to cross-country skiing on a field of virgin snow (Code, 2003).

## 5 NASA'S ORBITING ASTRONOMICAL OBSERVATORY (OAO) SERIES

Due to launch vehicle capabilities extant at the end of the IGY, SSWG teams were initially restricted in the expected weights of their payloads to approximately 100 pounds. But from rapid developments in rocket booster technology, created in response to the coming era of manned spaceflight, that weight restriction was soon substantially raised. By the third meeting of Goldberg's Optical and Radio Astronomy Committee (on 26 February 1960), there was foreseen a "... jump in payload from about 150 lbs. to about 5000 lbs. in the not too distant future." (SSB, 1960: 2). This anticipated outcome bore significant consequences for the creation and operation of much larger scientific payloads, and led NASA to attempt a much bolder step in spacecraft design than was first envisioned by the SSWG teams.

Seemingly the most important decision made regarding these future astronomical satellites was NASA's adoption of a 'modular' approach, or 'standardized platform', for containment of the individualized experiment packages. As Nancy G. Roman, former Chief of Astronomy and Relativity Programs at NASA from 1959 to 1979, has explained, "Because of the common pointing requirements, it was decided early on that a standard spacecraft design would serve each experiment ..." with only minor modifications expected for individual payloads (Roman, 2001: 523).[8] At the first meeting of SSWG members in February 1959, the notion of a standardized platform was announced as being applicable to a wide variety of scientific payloads (DeVorkin, 2005: 245). Not all SSWG members, however, were enthusiastic about NASA's mission-oriented approach, which seemingly threatened their individual autonomies.

The standardized platform that NASA envisioned was to consist of a single, ten-foot-long tube that was approximately forty inches in diameter. Outside of this framework would be attached the arrays of solar panels and other instruments. Thus, for the smaller experiment packages (those designed by the University of Wisconsin and the Smithsonian Astrophysical Observatory), it was recognized that the expansive payload container would "... require the efficient combination into one large package of compatible experiments." (SSB, 1960: 2). But how was this to be accomplished? When management officials at the GSFC first proposed to cluster the Wisconsin and Smithsonian packages within the same tube, objections were immediately raised. In its place, Code and Houck suggested that the two packages be separated and placed at opposite ends of the tube, allowing views in different directions. Reportedly, Goddard engineers at once declared such an idea to be impossible to execute from the operations standpoint. But only two weeks later, the idea of a double-ended spacecraft had become an accomplished fact (Code, 1982; Code, 2006). Such a turnaround in thinking evidently recognized that Code and Houck's proposal represented the *optimal* solution to the problem of combining the two experiment packages (Figure 1). Today, a full-scale engineering model of the OAO spacecraft is displayed at the University of Wisconsin's Space Place at 2300 South Park Street, Madison, Wisconsin.

NASA's OAO series comprised more than just a scientific showpiece; it was also a political tool selected to enhance the nation's prestige. Still smarting from the blow to U.S. pride felt in the wake of *Sputnik*, President Eisenhower welcomed the counsel of his Scientific Advisor, George B. Kistiakowski, who informed him about the "... potential gains in national prestige if we establish the first astro-observatory on a satellite ..." (quoted in Smith, 1989: 37; see also

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Dickson, 2001; Divine, 1993; Killian, 1977; Launius, Logsdon, and Smith, 2000). Representing an enormous technical advance over previous IGY experiments, these instruments would become the largest, heaviest, and most sophisticated unmanned satellites yet launched. Through its demonstration that the U.S. had acquired both launch and scientific capabilities comparable to those of the rival Soviet Union, NASA hoped that the public's image of the American space program would itself be strongly boosted. Yet, by the time of their earliest successful launch (almost ten years later), the OAOs were largely overshadowed by the achievements and goals of the manned spacecraft program.

### 5.1 Challenges of Remotely Operating an Orbiting Telescope

Accompanying NASA's development of the OAO spacecraft as a full-fledged astronomical observatory in space were a number of critical operations capabilities that would determine its ultimate success or failure as a scientific instrument; most importantly, the ability to move efficiently from one target star to another. As GSFC scientist Paul B. Davenport wrote, the OAO demanded a "... complex stabilization and control system ..." that could point the spacecraft toward any desired object "... with a high degree of accuracy ..." and maintain that orientation for the duration of the observations (Davenport, 1963: 1). This overall task was envisioned by NASA as comprising at least four principal subtasks: (a) maximization of sunlight on the arrays of solar cells that provided the spacecraft's power; (b) generation of slewing commands that enabled the spacecraft's attitude (i.e., orientation) to be changed, usually by the most efficient route (unless dictated by other constraints); (c) determination and maintenance of the satellite's orientation by means of six gimbaled star trackers; and (d) calculating when an object would be observed near to, or occulted by, the Sun, Moon, and (most frequently) the Earth (Davenport, 1963: i; see also Jenkins, 1970; Lynn, 1970; Purcell, 1970).

To ensure the safety of its on-board equipment, the optical axis of the OAO could never be pointed within 45° of the Sun. Light reflecting from the Moon, and especially from the fully-illuminated Earth, could (and in one case did) cause serious damage to one of the SAO's UV-sensitive cameras (vidicons). Sunshades were designed to automatically close if the optical axis came too near the Sun's position. A further observing restraint was that imposed by the so-called South Atlantic Anomaly (SAA), a region over the South American continent and southern Atlantic Ocean where the Van Allen radiation belts descend relatively closely to the Earth's surface. Passage of the spacecraft through this region sometimes caused the production of secondary electrons that interfered with operation of its photomultiplier tubes. The necessary calculations concerning these restraints were first performed on the ground and then relayed in advance to the orbiting satellite. Such "... computer-assisted advanced planning [was] mandatory ..." for conducting these operations efficiently (Purcell, 1970: 43).

The mathematical theory behind those subtasks of OAO operations was furnished by Davenport (1963). One fundamental coordinate system, centered on the Earth and defined by its equatorial plane, provided the basis for specifying the positions of all celestial objects, including the Sun, Moon, and stars, along with the spacecraft's location in its orbit. A second fundamental coordinate system was that centered upon the OAO itself, whose optical axis coincided with the positive x-axis, and around which the rotational motion known as 'roll' was defined. Two remaining orthogonal axes (y-axis and z-axis) corresponded to the rotational motions known as 'pitch' and 'yaw', respectively. The ever-changing relationships between these two coordinate systems, and the transformations that were necessary whenever the spacecraft was slewed from one target object to another, demanded solutions employing matrix multiplications (and a high number of logical decisions). Before additional constraints were imposed, as many as twenty-four possible solutions (though in practice only twelve principal solutions) existed for each desired slewing sequence. All spacecraft slews were restricted to angles of less than 30 degrees. This condition was imposed by the relatively limited fields of view of its six gimbaled star trackers (two for each axis). Determination of the gimbal angles for each star tracker was another of the tasks to be performed by the OAO operating system. Related calculations and logical decisions were necessary in repositioning the OAO's solar panels at the end of each slewing sequence. Unless the spacecraft were kept in observing mode on a round-the-clock basis, it would eventually lose its stability and pointing capability (Code, 1982). The OAO's best observing time usually occurred during its passage through the Earth's shadow, where it spent roughly 30 minutes out of each 100-minute orbit.

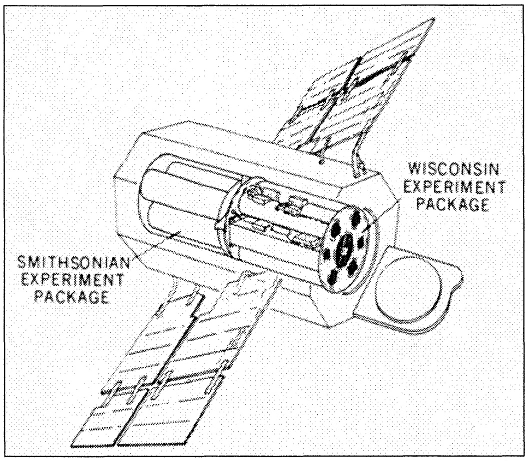

Figure 1: Phantom view of OAO-2 spacecraft, showing the Wisconsin and Smithsonian experiment packages. (Reproduced from *Publications of the Astronomical Society of the Pacific*, 81, p. 477 (1969), by permission of the author and the Editor, Astronomical Society of the Pacific).

To support those calculations used in operating the Wisconsin package, a computer program was written by University of Wisconsin-Madison graduate student Harry C. Heacox, Jr., and which earned him an M.S. degree from the Department of Astronomy (Heacox, 1970; Heacox and McNall, 1972). Heacox's FORTRAN program, dubbed HARUSPEX (Heacox's Answer to a Request for Unparalleled Superiority in Programmed EXperimentation), was run on the IBM

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360/65 mainframe computer at the Goddard Space Flight Center. Heacox's principal advisor was SAL scientist John F. McNall.

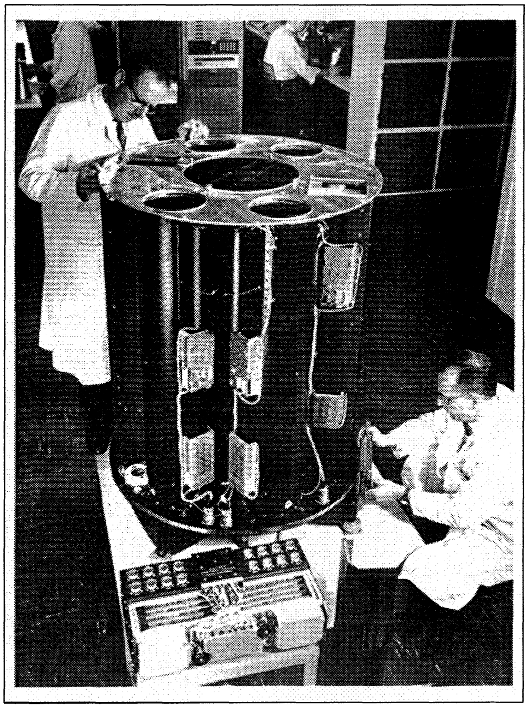

Figure 2: Wisconsin Experiment Package (WEP), undergoing assembly at Cook Technological Center. Courtesy, Space Astronomy Laboratory (SAL) Archives, University of Wisconsin-Madison.

Heacox described HARUSPEX as a "... large, complex computer program intended for use by personnel who are not computer-oriented." In attempting to maximize the "... ease, simplicity, and convenience of use ..." of the program by SAL personnel, both "Extra programming effort and some degree of machine inefficiency ... " were deliberately built into the programming structure. Wherever possible, the machine's output was presented in 'graphic form', which then meant using a line printer as a plotter, although tabular output was frequently employed. One of the principal tasks of HARUSPEX was the preparation of a tentative WEP observing schedule that might typically extend for a week. The proposed schedule was then subjected to more rigorous testing before its commands were folded into the OAO's own command-and-control system (overseen by the GSFC) and communicated to the spacecraft. In Heacox's judgment, HARUSPEX functioned like a "... very simple monitor system ..." in which the mainline program played the part of an executive, while 'major tasks' were accomplished "... by means of large subroutines." An 'extensive library' of sub-routines performed the necessary 'trigonometric manipulations' and other 'utility functions' (Heacox, 1970: 2, 3, 4).

HARUSPEX also provided an interface to the Wisconsin team's Ground Operating Equipment (GOE) station, structured around a smaller Digital Equipment Corporation (DEC) PDP-8 minicomputer containing 32K of storage and operated by teletype. This system routinely displayed the status of the Wisconsin equipment including filter positions, gains, voltages, and temperatures of all seven telescopes (described below). If an emergency arose, a command generator within the GOE could issue instructions directly to the OAO during an interval when the ground station was in contact with the spacecraft.

An important distinction, however, must be drawn between the SAO and WEP packages aboard the OAO-2. The SAO experiment package (termed Project Celescope) consisted of four UV television cameras used in conjunction with relatively wide-angle Schwarzschild reflecting telescopes. Its mission was to capture two-by-two degree UV images of celestial objects, whose photometric characteristics were later analyzed (Anonymous, 1962; Davis, 1972; Davis, et al., 1972; Rogerson, 1963; Watts, 1968). The SAO package required far less precision in the spacecraft's pointing system for capturing those images. By contrast, the WEP consisted of seven, narrow-angle reflecting telescopes that fed five filter photometers and two scanning spectrometers. To succeed, these required a much higher pointing capability—better than one arc minute accuracy—that necessitated a high-performance and -flexibility operating system that was furnished by HARUSPEX and Goddard's command-and-control system. No operating system of this sophistication had previously been developed for remotely operating an orbiting satellite.

For this reason, the OAO spacecraft represented a greater technological leap forward (in its day) than even the Hubble Space Telescope, when launched more than two decades later. The bulk of this accomplishment was centered around the remote operating systems that were necessary to point, slew, and control the spacecraft while in orbit. This small-scale astronomical observatory could neither achieve the same light gathering power nor angular resolution as the HST's larger 94-in. (2.4 m) primary mirror. But for the first time, it enabled extended observations to be made across the ultraviolet spectrum, for periods of time far in excess of those glimpsed from sounding rockets. Whether used for purposes of imagery (in the SAO/Celescope experiment), or to obtain photometric and spectrophotometric data (in the WEP), the OAO represented a milestone in the advent of space astronomy.

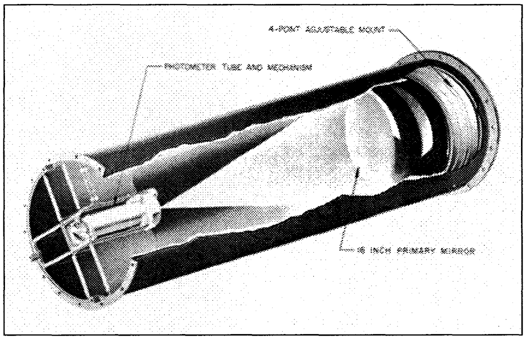

Figure 3: Sixteen-inch aperture nebular photometer, that occupies the central portion of the Wisconsin Experiment Package (WEP). Courtesy, Space Astronomy Laboratory (SAL) Archives, University of Wisconsin-Madison.

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## 6 THE WISCONSIN EXPERIMENT PACKAGE (WEP)

The adoption of a standardized platform, around which the OAO spacecraft was constructed, led to other important decisions (plus a division of labor) within NASA and its various centers that became operational during the 1960s. The OAO spacecraft was managed by the Goddard Space Flight Center (GSFC), Greenbelt, Maryland. The Grumman Aircraft Engineering Corporation (later renamed the Grumman Aerospace Corporation), Bethpage, Long Island, New York, was chosen as prime contractor for the platform that housed the twin experiment packages. The launch vehicle, a two-stage Atlas rocket, was managed by NASA's Lewis Research Center, Cleveland, Ohio, though actual launch operations were conducted from the Kennedy Space Center, Cape Canaveral, Florida. Five data acquisition stations were united under the Satellite Tracking and Data Acquisition Network (GSFC, 1969).

Minus the twin scientific packages, the OAO spacecraft had a weight of roughly 3,400 pounds. An additional one thousand pounds was allotted to scientific experiments; each team's payload was thus restricted to half that amount. Although the spacecraft itself was operated on some 420 watts of power, the WEP was restricted to no more than thirteen watts! In addition, the OAO data storage units were extremely limited; maximum memory capacity was 4,096 25-bit words (in redundant mode), or twice that amount in non-redundant mode (ibid.).

Neither the Wisconsin nor the Smithsonian teams possessed in-house resources needed to design and construct the experiment packages themselves. Each solicited and accepted bids from outside professional contractors. But here again, substantial differences are apparent in the teams' organizational styles and resulting choice of contractors. Nine contractors submitted bids to construct the WEP; these included a joint proposal from the Grumman Corporation (builders of the OAO 'platform') and the Perkin-Elmer Corporation (future contractor of the optical system for the Hubble Space Telescope).[9] But the Wisconsin team was reluctant to place its investment into a large, bureaucratic organization that was located perhaps one or two thousand miles away. Instead, it selected the much smaller and nearer Cook Technological Center located at Morton Grove, Illinois (a division of the Cook Electric Company, Chicago) because, according to Bless, "... we thought we'd have more control ... and you could also drive down there in two hours." (Bless, 2003). The principal electronic engineer at Cook was Curtis B. Bendell. As a result, the Wisconsin team chose a smaller, regional company that more nearly matched its own, less-formal organizational style. While Cook designed and tested all of the electronic circuitry that was used in the WEP (Figure 2), actual construction of the electronics was performed by the SAL team at Madison (Code, 1982).

For the twin reasons of redundancy (to minimize potential losses in the event of equipment failure) and to maximize coverage over the broadest UV spectral ranges (without constructing a single, all-purpose instrument), the WEP consisted of seven co-aligned scientific instruments of three different types. Yet, all reflected the long tradition of photoelectric photometry conducted at the Washburn Observatory. The largest instrument, which occupied the central portion of the five foot-long cylinder, was a sixteen-inch aperture, f/2 reflecting telescope equipped with a photoelectric photometer at the prime focus (Figure 3). This 74-pound telescope was designed to examine nebulae and other extended objects over a wavelength range from 2000 to 3300 angstroms. Four different filters, each with a bandpass of roughly 300 angstroms, could be selected by ground command. Two diaphragms provided viewing fields of 30 or 10 arc minutes. Because none of the UV interference filters could then be obtained from commercial suppliers, they were all fabricated at SAL, according to techniques developed by Daniel J. Schroeder (b. 1933) and implemented by Timothy Fairchild (Code, 2006).

Surrounding the sixteen-inch reflector were four identical eight-inch aperture eccentric-pupil (off-axis) telescopes, each equipped with a photoelectric photometer at their f/4 prime focus (Figure 4). These 28-pound instruments, used for stellar observations, were equipped with four filters covering bandpasses between 1000 and 4250 angstroms. Having narrower fields of view (either 2 or 10 arc minutes), these telescopes were capable of observing sources as faint as visual magnitude 12 or 13. Similar photometers were employed on both the eight- and sixteen-inch telescopes, which by design of the amplification system (or gain), enabled a range in sensitivity of between four and six orders of magnitude. SAL scientists also undertook the absolute calibrations of all photometers, using the synchrotron radiation storage ring at the UW Physical Sciences Laboratory, Stoughton, Wisconsin (Code, 1982).

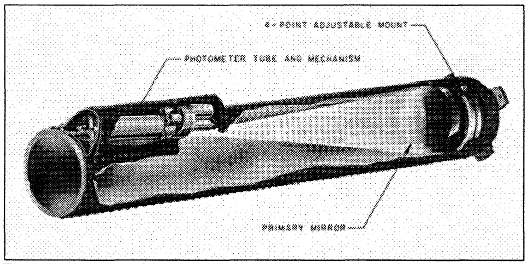

Figure 4: One of the four eight-inch aperture (off-axis) stellar photometers aboard the Wisconsin Experiment Package (WEP). Courtesy, Space Astronomy Laboratory (SAL) Archives, University of Wisconsin-Madison.

The final instruments aboard the WEP were a pair of nearly identical scanning spectrometers (Figure 5). These devices resembled the technique of objective-prism spectroscopy pioneered by Harvard College Observatory Director, Edward C. Pickering (1846–1919). Each spectrometer contained a six-by-eight-inch plane epoxy replica grating held on a pyrex base. Light from a star first struck this objective grating and was dispersed into its component colors. A parabolic mirror, with a 32-inch focus, reflected the light back through a small hole at the center of the grating and onto a slit at the entrance to the spectrometer. One of these devices examined the UV spectral range from 1000 to 2000 angstroms, while the other performed measurements across the 2000 to 4000 angstrom range. During the course of operation, a drive motor tilted the grating in order to scan the entire spectrum in 100 steps of 10 or 20 angstroms each, respectively. These instruments produced a highly accurate series of

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measurements of the source's intensity across its entire spectral range—the same result as if its UV spectrum had been recorded 'photographically' and later scanned to produce an intensity profile. More than any other OAO instruments, these scanning spectrometers (technically speaking, spectrophotometers) enabled Code and his colleagues to measure the UV fluxes of stars that he had first envisioned in the wake of *Sputnik* (Code, 1969; Code et al., 1969; Code et al., 1970; Code, 1972; Watts, 1964).

Nonetheless, inclusion of the scanning spectrometers on the WEP became an item of controversy. Earlier, the team responsible for constructing the larger Goddard Experiment Package (GEP), which was renamed OAO-3, intended to equip its own instrument, a 36-inch (0.9 m) UV telescope, with higher-resolution scanning spectrometers. The Wisconsin team had to convince NASA of the desirability of installing its lower-resolution spectrometers aboard the WEP, under the argument that they would provide a backup data collection system to the four eight-inch WEP filter photometers (Bless, personal communication). A final irony was realized, however, because the Goddard package suffered a complete failure when its protective shroud did not detach during the 30 November 1970 launch of OAO-3. Thus, data obtained by the WEP spectrometers was not superseded until the successful deployment of the Princeton Experiment Package (PEP) and its 32-inch (0.8-m) UV telescope as OAO-4, renamed Copernicus, launched 21 August 1972.

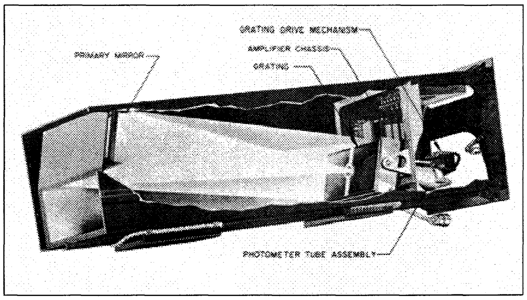

Figure 5: One of the two eight-inch aperture scanning spectrometers aboard the Wisconsin Experiment Package (WEP). Courtesy, Space Astronomy Laboratory (SAL) Archives, University of Wisconsin-Madison.

## 7 OAO FAILURE; THEN SUCCESS

By 1966, the WEP had passed all pre-flight inspections and was readied for launch; the SAO's Project Celescope, however, remained incomplete (from holdup of the vidicons). On account of this "... delay of the Whipple experiment ..." NASA was forced to come up with a "... hasty substitution for the SAO experiment." (Roman, 2001: 524). MIT physicists, William L. Kraushaar (b. 1920), who had previously worked on the OSO-3 and Explorer 11 satellites, along with George W. Clark (b. 1928), were appointed co-principal investigators behind a "... 50-100 MeV gamma ray experiment ...", while Lockheed Missiles and Space Systems physicist Philip C. Fisher (b. 1926) and GSFC physicist Kenneth J. Frost, were named principal investigators on "... two soft (2-150 KeV) X-ray experiments." (Leverington, 2000: 292; Code, personal communication). Kraushaar later joined the University of Wisconsin-Madison Physics Department.

As the launch date of the first (OAO-1) spacecraft drew near, members of the Wisconsin team assisted with pre-launch operations from the GSFC, but were forced to go on virtually no sleep, as the first five or six launch attempts were all scrubbed. Bless (2003) later recalled, "As soon as one launch [date] was canceled we had to start working on the next." At last, on 8 April 1966, the spacecraft was finally placed into orbit by an Atlas-Agena D launch vehicle. But major difficulties soon beset the spacecraft's power and guidance systems; one of its batteries may have exploded, and after two days, contact with the spacecraft was permanently lost. It was a devastating blow to the Wisconsin team, whose particular timing, Bless later realized, was marked by a perverse symbolic coincidence: "It turned out that OAO-1 ascended on Good Friday and died on Easter Sunday." (Bless, 2003). In retrospect, NASA's Associate Administrator, Homer E. Newell, remarked that the OAO "... was a good example of the kinds of trouble one could get into by trying to force too big a technological step." (Newell, 1980: 165).

Following an overhaul of the OAO project within NASA's management structure, a newer and more conservative objective was at first announced: instead of one year in space, only one hundred hours of successful observations would be attempted. But now Goddard scientists, who nominally were 'next-in-line' to launch their own experiment package, fought against such a measure, and argued that cumulative expenditures for the OAOs demanded a far greater return (in data acquisition) than that permitted by the one-hundred-hour goal (Bless, 1983). As a result, NASA reversed its decision concerning the one-hundred-hour restriction. But more importantly, and in light of the availability of another full-scale prototype model of the OAO spacecraft, NASA resorted to its original flight schedule (as if OAO-1 had never happened) and determined to make a second launch effort (to be known as OAO-2) that would finally unite the Smithsonian and Wisconsin experiment packages (Code, 2006; Bless, personal communication). That decision likewise kept the Goddard and Princeton experiments (to be known as OAO-3 and OAO-4) in the usual pipeline. Accordingly, the SAL team was asked to construct a duplicate experiment package, which occupied them for the next two-and-one-half years. By the end of 1968, they were poised to try their payload again. And this time, the WEP was accompanied by the SAO's now-completed Project Celescope (Figure 6).

The OAO-2 spacecraft was successfully launched by an Atlas-Centaur rocket on 7 December 1968, and placed into a roughly circular orbit 480 nautical miles high, inclined 35 degrees to the Earth's equator (GSFC, 1969; Code et al., 1970). Therein, the WEP began a remarkably successful 50-month period of gathering photometric and spectrophotometric data on stars, nebulae, galaxies, and even planets and comets.[10] The OAO's early accomplishments were summarized in a letter (3 July 1970) from Code to Jesse Mitchell, Director of NASA's Astronomy and Physics Branch, wherein Code proclaimed that "OAO II is a fantastically successful spacecraft from both the scientific and engineering standpoints. No other observatory on the ground or in space, to my knowledge, has contributed so much to astronomy in its first 18 months of

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operation." (Code, 1970). Unlike its SAO counterpart, whose cameras were shut down in April 1970 after only sixteen months of operation, the WEP spectrometers showed "... no significant degradation over a 3-year period." (Code and Savage, 1972: 213). Yet, a notable failure did occur (after only 2.5 months) in the circuitry that controlled the stepper motor which drove the filter wheel on the 16-inch nebular photometer; this action permanently positioned the calibration source in front of the photomultiplier tube and eliminated all further data acquisition with the WEP's largest instrument.

Over the course of its mission, political rather than technical problems posed the most significant threat to the WEP's longevity. Fears that the OAO-2 spacecraft could be prematurely terminated first arose among the Wisconsin astronomers during Christmas break of 1970 (Bless, personal communication), and grew to a climax in the spring of 1971. As the manned Apollo program was beginning to wind down, and prospects for the coming era of the Space Shuttle were growing, NASA's priorities were shifting rapidly (and its Congressionally-approved budget was facing some of its first-ever declines). Termination of the OAO-2 spacecraft, on 30 June 1971, was seemingly viewed as a possible 'cost-saving venture' on NASA's part for fiscal year 1972 (Code, 1971a).[11]

In April 1971, as Congressional debate over NASA's budget for the upcoming fiscal year approached, the Wisconsin astronomers launched an intensive lobbying effort that sought immediate help (in the form of letters and phone calls) from colleagues. On behalf of the OAO satellite, these combined appeals were directed to various U.S. senators and congressmen, and especially toward the NASA administration (specifically, John Naugle, Associate Administrator for Space Sciences and Applications, with copies to be sent to Homer Newell, Jesse Mitchell, and also to Joseph Karth, Chairman of the House of Representatives Subcommittee on Space Science and Applications) (Code, 1971a; 1971c). In addition, Code (1971b) forwarded a copy of the planned OAO-2 observing program for the latter half of 1971 to Naugle. The effects of this lobbying effort were swift and decisive. On 30 April 1971, and again on 10 May, Naugle sent (combined) telegrams to at least 33 individuals, affirming that "... funds have been reprogrammed and NASA will continue to provide support for the OAO-2 mission through December 1971." Naugle admitted that the lobbyists' effort "... expressed by letter ... was a consideration in making this decision." (Naugle, 1971a; 1971b). Never again was funding for the OAO-2's mission threatened.

On 14 February 1973, the WEP's power supply failed, and the mission was finally terminated. Having exceeded its anticipated lifetime of one year by *more than four times*, WEP completed observations of more than a thousand celestial objects. This feat was deemed a "... superior engineering accomplishment ..." by Cook Technological Center engineer, Curtis B. Bendell (1972: 23).

## 8 SCIENTIFIC RESULTS FROM WEP

Roughly six months after OAO-2 was launched, Wisconsin astronomers Code, Bless, and Blair D. Savage (b. 1941) gave presentations on their preliminary results at International Astronomical Union (IAU) Symposium No. 36, held at Lunteren, The Netherlands, between 24 and 27 June 1969 (Houziaux and Butler, 1970). Yet, only a brief synopsis of WEP measurements and discoveries can be recounted below. Apart from the principal monograph and review paper already cited (Code, 1972; Code and Savage, 1972), findings from the OAO spacecraft have mainly appeared as a series of forty-one successively-numbered research papers, published chiefly in the *Astrophysical Journal*, extending from that of Code et al. (1970)[12] to that of Davis et al. (1982). Various catalogues of OAO data have likewise been issued; most recently that of Meade (1999). At NASA's request, Bless also delivered a series of lectures (1969-1970) at eighteen institutions (Bless, 1969; 1970; 1983), which doubled as a public relations and polling opportunity for the Agency (Anonymous, n.d.).

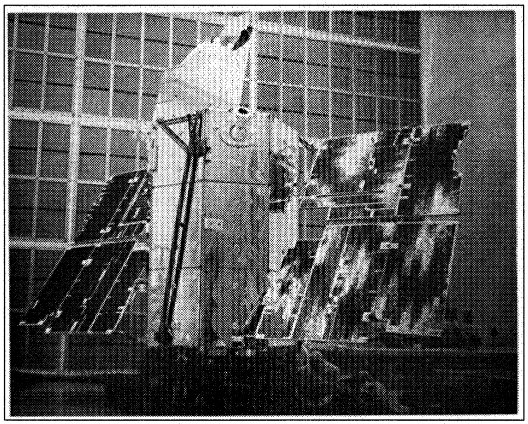

Figure 6. OAO-2 spacecraft undergoing preparations in a clean room at Cape Kennedy before launch. (Reproduced from *The Astrophysical Journal*, 161, Plate 1, f.388 (1970), by permission of the author and the American Astronomical Society).

The principal scientific mission of the WEP was to measure the spectral energy distributions of stars in the ultraviolet, using both filter photometers and spectrometers. Data obtained from a wide variety of stars led to more precise determinations of stellar effective temperatures and chemical compositions. Among O- and B-type stars, as was expected, strong absorption features were associated with the Lyman-alpha line (1216 angstroms), while the presence of silicon and carbon (as resonance lines) was readily confirmed. One fundamental result was a better match to theoretical predictions than could be obtained from the visual spectral region alone; the previous temperature scale was found to be too low. By correcting for the scanner's sensitivity across the UV spectral range, absolute luminosities of roughly 150 stars could be derived to an accuracy of ten percent.

Roughly a quarter of the O- and B-type stars observed by WEP proved suitable for the derivation of interstellar extinction in the Galaxy, based upon measurements from the filter photometers. Although difficulties were encountered in attempting to separate interstellar from stellar absorption features, overall results offered independent confirmation that the derived densities of interstellar hydrogen were not at variance with those obtained from 21-cm wavelength measurements.

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Ultraviolet emission lines were observed in the spectra of a number of peculiar stars. Those lines supported the notion of expanding shells of material surrounding these objects, which has aided our understanding of the processes of mass-loss in highly-evolved stars.

Observations of Nova Serpentis (1970) revealed that its UV brightness continued to increase, even as its visual brightness decreased. This finding argued for the rapid evolution of an optically thick shell surrounding the star, that behaved somewhat analogously to the evolution of planetary nebulae seen around lower-mass stars.

A majority of 'dark' nebulae appeared brighter, at wavelengths below 1,600 angstroms, than do many diffuse nebulae when examined in visible light. This finding suggested that interstellar dust grains have significantly higher UV albedos than was expected. The measured peak on the interstellar extinction curve, at 2,200 angstroms and possibly signifying graphite, was judged "... perhaps the most interesting ..." result from the OAO-2's extensive data collection (Roman, 2001: 524). Such a discovery stood to revise understandings of the interstellar medium and the processes of star formation.

WEP provided unambiguous evidence that galaxies on average are systematically brighter in the UV than was expected from the known main sequence stars that comprise them. Disk populations of O- and B-type stars are thought to contribute those added fluxes, which are modified through processes of interstellar absorption.

Within our own Solar System, the Wisconsin package discovered a vast hydrogen cloud surrounding the nucleus of Comet Tago-Sato-Kosaka (1969g). Originally predicted by astronomers L. Biermann and E. Trefftz, the cloud was detected through its strong Lyman-alpha emission. The feature was confirmed around Comet Bennett (1969i), whose cloud extended roughly 100,000 kilometers from the nucleus. These and other observations provided strong support that water ice is a dominant component of the material in a comet's nucleus, which undergoes photo-dissociation when it becomes active.

The presence of ozone in the Martian atmosphere was another unexpected discovery made by the WEP. Subsequent reanalysis of data collected by *Mariner* spacecraft confirmed this finding, which offered important clues to the chemistry and evolution of that planet's atmosphere.

## 9 THE WISCONSIN APT: A GROUND-BASED ROBOTIC TELESCOPE

Between launches of the OAO-1 and OAO-2 spacecraft, SAL scientists Houck, McNall, Terrell L. Miedaner, and Donald E. Michalski also demonstrated the capabilities of the first computer-controlled telescope at the department's Pine Bluff Observatory. This instrument was later dubbed the Wisconsin Automatic Photoelectric Telescope, or APT (Code, 1992). Houck first obtained the surplus mounting, designed for an aircraft guidance system, and suggested its use in collecting atmospheric extinction data. The device carried a WEP 8-inch off-axis reflecting telescope and photoelectric photometer, whose operations were essentially identical to those employed on the OAOs. The original analog control system was found to possess serious mechanical difficulties, but McNall added shaft encoders and stepper motors as a means of providing digital pointing and control functions. A PDP-8 minicomputer, having a memory of only 4,096 12-bit words, and similar to that used by the Wisconsin team's Ground Operating Equipment station, was reprogrammed by Miedaner. Even the small shed-like observatory, which sported a roll-off roof, was automated. Published accounts of the telescope's capabilities noted that the instrument represented an 'offshoot' or 'spinoff' from the nation's space program that stood to benefit contemporary ground-based astronomy—a tremendous understatement, in retrospect (Miedaner and McNall, 1967; NcNall, Miedaner, and Code, 1968).

Code (1992) later noted three levels or operative criteria which have emerged and that roughly characterize the enormous diversity of telescope control systems employed by today's professional astronomers. (a) The simplest of these is called *remote observing* (and was originally called 'remote control' —Maran, 1967). Here, commands are issued (usually in real time) from a control center, located some distance away from the observatory, to direct the telescope's functions. Remote observing, by definition, requires active input from a human being, who monitors and adjusts the subsequent operations. (b) *Automatic operation* consists of a set of pre-programmed instructions that enables a device (such as a telescope) to perform a set of operations without direct assistance or intervention from a human being. However, no deviation from the pre-programmed sequence of commands is allowed. (c) Finally, a *robotic* (or intelligent) system performs a set of logical decisions, based upon all forms of input to the system, and then executes a series of automatic commands, ranging from the mundane to the highly sophisticated (e.g., star acquisition and subsequent collection of photometric data). The 8-inch ground-based telescope fashioned by McNall and his colleagues satisfied all three of these functionality criteria, and thus "... the Wisconsin APT can quite properly be called a robotic telescope." (Code, 1992: 8). Later cannibalized for its parts, the robotic telescope no longer exists.

Might some (or all) of these criteria perhaps be applied to the OAO-2 spacecraft itself? By observing from above the Earth's atmosphere, OAO-2 was unquestionably a "... remotely operated observatory ..." (Code, 1970: 381). Further, its principal operations, such as slewing from one star to another and automatic collection of photometric data, were performed under the controls of computer programs such as HARUSPEX. However, OAO-2 (and WEP) could do nothing without those pre-programmed instructions that were supplied on a continuing basis from the Ground Operating Equipment station. Moreover, all of the safety checks (i.e., logical decisions) that accompanied each spacecraft maneuver and observing sequence were programmed in advance before they were transmitted to the satellite (Bless, personal communication). As a result, the third and final criteria associated with the label, 'robotic telescope', cannot be assigned to the OAO-2.

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## 10 CONCLUSIONS

A number of important 'firsts' may be attributed to the OAO-2. It was the first true stellar space observatory that embodied both remote and automatic modes of operation, before those attributes were widely applied to the control of large and small ground-based optical telescopes. While the OAO-2 spacecraft cannot be called a robotic telescope, the concurrent development of a ground-based, automatic photoelectric telescope (or APT) was successfully undertaken by members of the Wisconsin team and described as a 'spinoff' from the nation's space program.

OAO-2 (and especially WEP) played an important role in the field of space astronomy; its large collection of UV data (acquired by filter photometers and scanning spectrometers) marked the first significant opening of the electromagnetic spectrum in wavelengths shorter than visible light—a trend that has characterized much of astrophysics in the latter half of the twentieth century. Perhaps the best analogy of that accomplishment is one supplied by Bless, who has likened the whole of the electromagnetic spectrum to the sounds produced by a symphony orchestra. Having long been restricted to observing through the narrow window represented by visible light, ground-based optical astronomers were in effect only able to hear but a few notes of the entire symphony (Bless, 2003).[13] Space-based astronomy has removed that limitation and contributed to a full investigation of the electromagnetic spectrum, ranging from high-energy gamma rays to long-wavelength radio waves. OAO-2 observations enabled data to catch up with, and in some cases to supersede, existing theories of stellar atmospheres and the ISM.

The design, construction, and operation of OAO-2 appears to have marked another, and more significant, transition in the development of late-twentieth century astrophysical research. That trend has been the growing reliance placed upon digital means of data acquisition, storage, transmission, and reduction that is now practiced throughout the discipline. While the tremendous advantages conferred by such techniques are unquestioned assumptions today, that was far from the case, prior to the launch of OAO-2. From the demands imposed by remote, automatic operations above the Earth's atmosphere, both Wisconsin and Smithsonian scientists were forced to adopt the (mainframe) digital computer as the only means of achieving the necessary speed, accuracy, and control over the OAO-2 spacecraft. As Code (1969: 292) presciently observed, "… high-speed computers are essential to the astronomer …" for carrying out these multiple tasks.

That is not to say that digital computers had not gained widespread usage in astronomical applications; just the opposite was true. For example, three of the leading U.S. centers for astronomical computations, namely, (a) the United States Naval Observatory, Washington, D.C.; (b) the IAU's Central Bureau for Astronomical Telegrams, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts; and (c) the Minor Planet Center, Cincinnati Observatory, Cincinnati, Ohio, had all pioneered the use of digital computing techniques, some even predating the Second World War (employing analog means). Such facilities were routinely used in the production of the *American Ephemeris and Nautical Almanac* (*AENA*), and the calculation of orbital elements and ephemerides of newly-discovered comets and minor planets, respectively. The point, however, is that these digital tools were largely restricted to the solution of routine, computational problems in practical astronomy and were not employed in the *collection* and *analysis* of observational data, which remained chiefly optical and analog in nature (i.e., long-exposure images recorded on photographic plates).[14]

Electronic devices themselves were nothing new to astronomers of this era. Photoelectric cells and photomultiplier tubes saw widespread application to the study of point-source phenomena, especially after the Second World War (DeVorkin, 1985). Related devices were applied to the measurement of intensity profiles of stellar and galactic spectra. Wisconsin astronomer, John F. McNall, and his colleagues at the Lick Observatory, Mount Hamilton, California, developed a new electronic detector and amplifier system; namely, the image-intensifier image-dissector scanner (McNall, Robinson, and Wampler, 1970; Robinson and Wampler, 1972). More broadly, steps were taken toward fabrication of an electronic camera, first envisioned by French astronomer André Lallemand (1936), whose development was intensified by wartime research (Wlérick, 1987). And yet, all of these systems, which displayed increased sensitivity and decreased exposure times (in comparison to photographic plates), were to pale in comparison to the forthcoming universal adoption of the charge-coupled device (CCD)—itself a product of industrial-scale research-and-development (Smith and Tatarewicz, 1985; 1995).

It is no surprise, therefore, that the WEP arose from an institution that had *avoided* photographic research methods, and which instead had pioneered the techniques of photoelectric photometry to analyze the properties of stars and the interstellar medium (DeVorkin, 1985; Hearnshaw, 1996; Liebl and Fluke, 2004). In that regard, the Wisconsin package may be seen as a natural extension of those earlier techniques, once the technology of spaceflight was achieved and the long-standing barriers to investigation of the electromagnetic spectrum beyond the Earth's atmosphere were at last removed.

As demonstrated by the WEP and OAO-2 spacecraft, a transition to digital data acquisition and analysis, which occurred within the context of mainframe (and mini) computing environments, nonetheless took place well *before* the 1970s advent of the personal computer and the charge-coupled device (CCD). Personal computers and their accompanying software programs eventually brought more sophisticated and flexible computing powers to researchers, along with graphical interfaces, plus the added convenience of the individual user's desktop. Superior networking technologies have enabled personal computers to remotely operate even the largest and most sophisticated of today's astronomical instruments and observatories (McCray, 2004). Succeeding generations of astronomers have adopted the computer as perhaps the single most important tool in their arsenal, after the telescope or spacecraft itself. Along with opening the field of UV space astronomy, OAO-2 was a bellwether of the equally-important transition to

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digital data acquisition and analysis strategies employed universally today.

## 11 NOTES

1. Needell (2000: 319-320) has argued that the satellite proposals 'transformed' the IGY from a scientific program "... into a watershed in the relations between science, technology, and the American federal government."
2. The SSB was also expected to provide advice to the National Science Foundation (NSF) and the Advanced Research Projects Agency (ARPA) (SSB, 1958a).
3. Neither the original telegram from Berkner, nor Code's response, has been preserved, although Code's response was acknowledged by R.C. Peavey, Secretary, SSB (Telegram, Peavey to Code, 5 August 1958, ADC Papers, SSB Folder). Code (2005; 2006) has further recalled that he received a 'letter' from Berkner, evidently prior to the SSB's first meeting, soliciting suggestions for "... a 100 pound satellite." This opportunity proved influential in Code's decision to return to the University of Wisconsin-Madison. Berkner's letter has not been located; nor has it been described by Needell (2000).
4. DeVorkin (1989: 73) writes: "Most astronomers were simply not comfortable with the degree of funding and manpower commitments required to pursue active experimental programs with rockets, nor were they comfortable with the style of research which required a high dedication to building devices that were likely to be destroyed upon use." For a broader assessment of astronomers' responses to the advent of Federal support after World War II, see DeVorkin (2000).
5. McCray's first chapter, "Leo and Jesse's Changing World" (pp. 13-49), examines the profound differences in viewpoint between astronomers Leo Goldberg and Jesse Greenstein over the approaching Space Age and the expected role of Government patronage in the support of public vs. private research institutions.
6. Goldberg's Committee was originally titled, "Astronomy and Radio Astronomy," but afterwards its name was changed to the less redundant, "Optical and Radio Astronomy."
7. Berkner and Odishaw (1961: 432) report that some 200 proposals were assessed, whereas Hetherington (1975: 104) states that, from over 150 telegrams sent out in July 1958, "... some one hundred replies ..." were received by the SSB. Smith (1989: 37) notes that "... approximately two hundred replies ..." came to the Academy. This higher number evidently reflects the additional responses made to Berkner's earlier letter.
8. Roman does not say with whom the modular approach originated. Homer E. Newell, NASA's former Associate Administrator, has written that Abe Silverstein, then Director of Space Flight Development and (Acting) Director of the Beltsville Space Center (later renamed GSFC), "... favored the development of large, observatory-class spacecraft ..." under the assumption that "... larger spacecraft would probably give more science per dollar than smaller ones." (Newell, 1980: 207). Rosenthal (1968) offers no direct guidance on this question.
9. In response to the University of Wisconsin Request for Quotation 31-1360-0, dated 10 May 1961, bids were received from the following: Grumman Aircraft Engineering Corporation and Perkin-Elmer Corporation; McDonnell Aircraft Corporation; Space Technology Laboratories, Inc.; Texas Instruments, Inc.; Control Technology Corporation; AC Spark Plug Division of General Motors Corporation; Bendix Corporation; Astronautics Corporation of America; and Cook Technological Center (Box 21/84, "Univ. of Wisconsin/Space Astronomy Lab/WEP Bids," SAL Archives).
10. For the most detailed recollections of actual day-to-day operations of OAO-2, and the numerous problems encountered by the Wisconsin team, see Bless (1984).
11. Code (1971a) stated that, as Principal Investigator on OAO-2, he had "... received no formal notification of the proposed shutdown of the satellite ...", nor had he "... been invited to participate in any NASA consideration of the OAO-2 termination."
12. A draft of the Code et al. (1970) paper is preserved in ADC Papers, OAO - Ap.J. Paper 1 Folder.
13. Of course, this claim unfairly excludes the accomplishments of more than a generation of radio astronomers, particularly after the Second World War, and similarly neglects the achievements of early infrared observations conducted with ground-based instruments.
14. From the beginning, radio astronomy likewise demanded the use of electronic equipment (originally analog, and later digital) for the reception, recording, and analysis of all incoming signals. Such observations were made with single, fixed or steerable antennas and later employed the signal-combining capabilities of very-long-baseline interferometry (VLBI).

## 12 ACKNOWLEDGEMENTS

Anyone attempting to write a well-balanced account of the OAO-2 spacecraft will encounter a nearly-complete lack of documentary materials available at the Goddard Space Flight Center (GSFC), which nonetheless managed the project (R.W. Smith, personal communication). As a result, the story must be pieced together from a variety of other sources, including published and unpublished accounts, meeting minutes, conference presentations, and especially oral history interviews with the leading participants.

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The following abbreviations are used:

AAS = American Astronomical Society
ADC = Arthur D. Code Papers, 1958-1985, Memorial Library Archives, University of Wisconsin-Madison
GSFC = Goddard Space Flight Center, Greenbelt, Maryland
SAL = Space Astronomy Laboratory Archives, Department of Astronomy, University of Wisconsin-Madison
SSB = Space Science Board, National Academy of Sciences

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