2. SOLAR AND STELLAR CORONAE

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GORDON NEWKIRK Jr

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GORDON NEWKIRK'S CONTRIBUTIONS TO CORONAL STUDIES

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1. Brief Biography

Gordon Allen Newkirk, Jr. was born in West Orange, New Jersey June 12, 1928 and died in Boulder, Colorado December 21, 1985 at age 57. He was graduated from Harvard University in 1950 and in 1953 earned a Ph.D. in astrophysics from the University of Michigan. In 1955, after service in the Signal Corps of the U.S. Army he took a position at the High Altitude Observatory in Boulder where he worked the remaining thirty years of his life. For 11 of those years (1968-1979) he was director of the observatory and associate director of the National Center for Atmospheric Research. He was also active as a teacher and from 1965 through 1985 was an adjoint professor at the University of Colorado. From 1972 through 1975 he served as Chairman of the Solar Physics Division of the American Astronomical Society and from 1976 through 1979 as President of Commission 10 (Solar Activity) of the International Astronomical Union.

On April 11, 1956 Dr. Newkirk was married to Nancy Buck in Boulder and together they built a home in Sunshine Canyon and reared their family of three daughters. Gordon loved the mountains and knew them well. He was an active outdoorsman and naturalist for whom backpacking and skiing were important family endeavors. His scientific life, as his private one, was characterized by a lifelong fascination with nature and a skilled and patient approach in learning its secrets and mastering its ways.

2. The Nature of Newkirk's Research

Although a scientist of broad interests Newkirk's particular interest was the corona of the sun and fully half of the papers he published dealt with coronal physics. Through his work and his influence on others the High Altitude Observatory became known during his tenure there as the world leader in optical studies of the extended corona. He was by nature a methodical and deliberate scientist whose career was focused on a few fundamental problems, which he followed, patiently, hand over hand to their conclusion, until he became the master of every detail that was involved. This was the pattern of his coronal research, and it led to pioneering achievements.

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Newkirk's research in coronal physics was directed at four fundamental problems:

- o the development of a model of the electron corona;
- o the perfection of the coronagraph;
- o studies of the structure of the corona; and
- o an uncompleted study of the propagation of cosmic rays in the corona.

2.1 A MODEL OF THE ELECTRON CORONA.

In a paper published in 1959 (1) Newkirk developed a coronal model that is still used to describe the electron density of the corona. To do this he took on the task of interpreting measurements that had been made routinely since 1956 at the Climax station of HAO with the K-coronameter --- a photoelectric coronagraph that had been developed there by Gérard Wlérick and James Axtell (2). The instrument was designed to distinguish the outer electron corona on the basis of the linear polarization of the K-component, and it provided useful data, under the best conditions, to a distance of about 1 radius above the solar limb.

Newkirk's model, fitted empirically to the Climax data, was of especial value in solar radio astronomy, which in the 1950's was a particularly active field. To this end he employed the model in conjunction with models of the chromosphere and of a plage to develop intensity profiles of the solar disk as they should be seen in various radio frequencies, and to demonstrate that the "slowly varying" component of coronal radio emission was due solely to density enhancements (3).

2.2 PERFECTING THE CORONAGRAPH

The optical coronagraph, developed by Lyot in 1929 (4), had by 1955 become an instrument of routine --- fundamentally limited, in terms of spectral data, to bright coronal features within about 0.5 R_o above the limb of the sun, and to white-light polarimetric observations extending somewhat higher but of much coarser resolution. Moreover, the K-coronameter observations of the intermediate corona were secured at the expense of long integration times. Images of the corona with detail sufficient to identify changes in fine scale structure were restricted to a narrow range of the brightest inner corona, extending but a few arc minutes above the limb. The dimmer intermediate and outer corona --- seen so clearly in fleeting moments of natural eclipse --- lay just beyond the reach of ground-based, Lyot coronagraphs (5). It is fair to say that images from coronagraphs were, to any who had seen the extended beauty of the corona at eclipse, at best a tantalizing substitute for the real thing.

From the day that Newkirk joined HAO he bent his efforts to perfect the 25-year old instrument to the point where the full extent of the corona might be captured outside of eclipse. It was a challenge that would test his patience and tax his skill as an experimentalist for almost 20 years.

He found success, as had Lyot, by returning to basic principles: first in the physics of scattering and sky brightness, then in optics and optical design, and last in adapting the instrument for remote operation above the atmosphere.

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Newkirk had begun the quest during his military service, when on special assignment he measured the brightness of the high altitude sky near the sun from altitudes of 5000 to 13000 ft., from Colorado mountaintops that he sometimes reached by ski-lift (6). For this, he used a portable photographic sky photometer that had been designed earlier at HAO by Jack Evans (7). The Evans photometer was a portable Lyot f/100 coronagraph, modified to be externally occulted, and used to make broad-band measurements of the brightness of the sky near the limb of the sun. A 1.6 cm external occulting disk at the solar end of a meter-long stem blocked direct sunlight from reaching the 1.5 cm objective lens, with a considerable reduction in instrumentally-scattered light. Evans had developed the instrument to evaluate potential coronagraph sites for a U.S. Air Force solar observatory that was eventually built on Sacramento Peak in New Mexico. He had also attempted sky measurements with the instrument from the open hatch of a propeller-driven military aircraft in an early attempt to measure the brightness of the near-sun sky above the ground.

In 1959 Newkirk tried the Evans sky photometer as a true coronagraph, in a manned balloon flight to an altitude of about 40,000 ft, launched from the "Stratobowl" --- a natural depression in the Black Hills of South Dakota from which earlier manned balloon flights had been made. On board as pilot was Cdr. Malcolm Ross, USN, who held the altitude record for manned ascent, and Robert Cooper, a technician at HAO who endeavored to point the occulting photometer/coronagraph at the sun from the balloon gondola in the cold air of the tropopause, in the hope of capturing photographs of the outer corona in the field of view of the photometer. It was not a successful experiment: Cooper's heroic measurements were severely contaminated by the radiance introduced by the scattering of sunlight from everpresent, local clouds of water particles from his and Ross' exhalations.

Newkirk learned from the experience (8). The manned balloon measurements were followed by a series of unmanned flights to explore sky brightness as a function of angle and of wavelength. For this, he employed the "Stratoscope" gondola that had been developed at Princeton by Martin Schwarzschild in the late 1950's to secure high-resolution, white-light photographs of sunspots and solar granulation (9). This necessitated the design of a new and larger version of the external-occulting photometer and the perfection of skills and auxiliary equipment for remote operation. In the autumn of 1960, Newkirk's balloon-borne "Coronascope", launched from an airfield near Minneapolis, succeeded in securing measurements on two flights into the stratosphere, to an altitude of about 80,000 ft. These were followed by papers that interpreted these pioneering measurements of the solar aureole to derive the particle size distribution as a function of height in the upper atmosphere, using the theory of Rayleigh and Mie scattering (10-15). These studies also established for the first time the near-sun sky brightness that fixed the limits of observation of the corona outside of eclipse, as a function of wavelength and altitude above the ground.

This done, Newkirk turned to the next step in the challenge: that of developing a coronagraph to operate in the stratosphere that was sufficiently improved over Lyot's original design to take full advantage of the much-reduced sky brightness, and thus be capable of detecting the intermediate and outer corona. He had found that at an altitude of 80,000 ft. the near-sun sky brightness had fallen enough (in the photographic infrared) to equal the

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brightness of the outer corona, or about $10^{-8}B_o$, in units of the brightness of the solar disk. To photograph the corona to at least $6R_o$ required that the instrumentally scattered light in the coronagraph be at least an order of magnitude lower than this, or about 10^{-9} B_o. The level of scattered light in Lyot's coronagraph --- in which instrumentally scattered light had been reduced by at least a factor of 100 below that in the best simple telescopes --- was about 5×10^{-5} B_o. The challenge Newkirk faced was to improve the Lyot design by a further factor of 1000!

And he did it. Newkirk first considered a reflecting coronagraph as a possible solution (16), but returned instead to a more conventional instrument that was externally occulted in the manner of the Evans sky photometer. Newkirk found, upon measurements, that the limit of detection in the Lyot coronagraph was set principally by body-scattering in the singlet objective lens: a fundamental property of the glass itself. The way around this was to shade the lens from direct solar light, by employing an external occulter at the cost, however, of the innermost corona. The height above the limb at which the corona could be imaged with an external occulting coronagraph was fixed by the aperture of the objective and the distance between the occulter and the lens that it shaded. Newkirk adopted $0.5R_o$ above the solar limb as a workable inner limit, to overlap with the range available in conventional Lyot coronagraphs. This required a separation of 2.3 m between the occulting disk and the 3.3 cm objective lens. He achieved further reductions in scattered light by suppressing diffraction at the edge of the occulting disk through principles of "apodization" --- in this case the use of multiple, co-aligned external occulting disks (17,18).

Newkirk launched his new coronagraph in the old Stratoscope gondola from Palestine, Texas, in 1964 (19) and succeeded in recording the form of the intermediate and outer corona on infrared film, on the first try, from an altitude of about 80,000 ft. (20). Following these successes, he turned immediately to the challenge of adapting the external occulting coronagraph for use on orbital platforms, where sky brightness was no longer a factor. This, too, he passed on as observatory director to other hands (21). These efforts, guided by Robert MacQueen, reached fruition in 1973 with the launch and successful operation of the Skylab manned spacecraft, which carried, as one of its primary observatory instruments, a three-meter Newkirk coronagraph. The instrument recorded the intermediate and outer corona on photographic film that was returned to earth with each of the three teams of Skylab astronauts (22). On these film were the first high-resolution records of temporal changes in the intermediate and outer corona, including the first clear looks at the birth, development and expulsion of a new class of solar features that came to be known as "coronal transients".

2.3 THE STRUCTURE OF THE SOLAR CORONA

In the years that Newkirk was perfecting the coronagraph for orbital use he worked as well on the general question of coronal structure: a problem that led him to develop a new camera for securing photographs of unprecedented quality of the corona at natural eclipses.

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2.3.1 A CORONAL ECLIPSE CAMERA

Since 1851, astronomers had made broad-band photographs of the corona at eclipse --- but almost never bringing back on plates or film the wonders they had seen in fleeting moments by eye. The obstacle, Newkirk recognized, was the steep brightness gradient of the white-light corona --- falling 5 orders of magnitude from the innermost corona to visible limits of coronal streamers. The great dynamic range of the dark-adapted eye was able to accommodate the full range; photographic emulsions, with a dynamic range of typically two and at most three orders of magnitude could capture but a part of the corona in a single exposure. The best photographs of the corona made at eclipse showed in exquisite detail either the innermost corona and imbedded prominences, or an equally restricted glimpse of some part of the more ethereal outer corona, extending above an indistinguishable, over-exposed glare of the inner and brighter region. The problem had come home to Newkirk in 1963, when for a laboratory exercise he had dispatched graduate students with simple coronal cameras to a line of stations along the path of totality of the Alaskan-Canadian eclipse of that year. The goal was to search for temporal changes in the corona, by post-eclipse comparison of photographs taken at different stations and hence at separated intervals of time. The experiment failed. Key stations were beclouded and pictures from successful sites were inadequate for the task.

Newkirk attacked the problem by designing and having built a radially-graded neutral filter, of deposited metal on glass, to be placed immediately before the focal plane of the telescope. The circularly-symmetric density gradient of the filter was designed to compensate for the brightness gradient of the average corona. The film at the focal plane saw a flattened gradient of coronal brightness that was well within its range. To ensure that the remainder of the system would not further degrade the result, Newkirk worked with Lee Lacey of the HAO engineering staff to design and build a new, single-purpose eclipse telescope whose focal plane was driven, west to east, to compensate for the opposite motion of the sky. The telescope itself (f/15 with 11 cm aperture) was mounted rigidly in a fixed position and hence extremely stable.

In the autumn of 1966, Newkirk and Lacey took their new coronal camera to Pulacayo on the altiplano of Bolivia to try it at the November 11 total eclipse of the sun --- at a site not far from where Schaeberle had gone, 73 years before, to test his 40-foot camera at the 1893 eclipse in Chile (23). The result, as for Schaeberle, was the finest photograph ever taken of the solar corona, by anyone, anywhere. Far more, the 1966 photograph had captured for the first time on film, the essential structure of the entire corona. Additional exposures were made through polarizing filters for quantitative analyses of the corona. But the unpolarized, radially-graded picture was worth a thousand words, and more, for it revealed associations that had never before been seen; oft reprinted, it guided a fresh understanding of the solar corona as the product of magnetic forces and the outward flow of the solar wind. It made the field lines that hold the corona together at once visible throughout the coronal form, giving to coronal physics what x-rays had once given to medicine. It was bad news, however, for romantics, for it bettered what could be seen by eye or through any simple telescope. After

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105 years of repeated attempts, photography had finally gained the upper hand in recording the coronal form.

Newkirk took his coronal camera, with results equally fine, to Oaxaca in Mexico for the 1970 eclipse (24), and, thwarted by clouds, to the Gaspe Peninsula for the eclipse of 1972. It was his last expedition, for by then, as observatory director he felt that he could go no more. Since that time, the Newkirk camera has been taken, with always good results, to total eclipses in Africa, Australia, India, Siberia, Java, and in 1988, to the Philippines, compiling an unequalled record of the changing corona through a complete Hale cycle of 22 years.

2.3.2 INTERPRETIVE STUDIES

Newkirk used the 1966 eclipse photograph as an aid for a seminal review of coronal structure that was published the following year (25). This led in turn to papers with Altschuler, Harvey, Howard and others on the relationship between magnetic fields and the structure of the corona (26-35). These demonstrated a remarkable correspondence between calculated force-free fieldlines derived from photospheric magnetograms and the white-light structure of the corona revealed in Newkirk's remarkable eclipse photographs.

In intervening years, while he was almost fully occupied as director of HAO Newkirk become heavily involved in studies of solar activity (36,37)--- *coincident with and following his term as president of Commission 10 of the* IAU. This included directing a planning project for NASA in 1980 on the study of the solar cycle from space (38), a study in the same year of the faint early sun paradox and of solar activity on time scales of 10^5 yrs and longer (39), an exhaustive review in 1983 of solar luminosity variations (40), and a venture in 1984 into the use of ice-borne ^{10}Be as a tracer of solar activity in the past (41), in connection with a sabbatical year in Zürich.

The last of these brought home to Newkirk that much more needed to be known about the mechanism of the solar modulation of the incoming galactic rays that produced ^{10}Be and ^{14}C in the atmosphere. This led him, in turn, to a fourth fundamental problem regarding the extended corona of the sun.

2.4 PROPAGATION OF GALACTIC COSMIC RAYS IN THE CORONA

Newkirk had made earlier, preliminary studies of this problem with Wentzel (41), with Hundhausen and Pizzo (42), and with Lockwood (43). These inspired him to tackle, alone, the fundaments of the problem, in his typical, methodical manner --- first collecting all relevant data, as he had done 30 years before when he took up the backlog of early K-coronameter measurements. This time he would harness the power of computers to trace the paths of incoming particles through the corona. As his health began to fail, he attempted to work the data from a remote terminal in his home.

Life did not give Gordon time to complete the study, though we should wish that it had --- for without a doubt he would have followed this tangled, still-unresolved problem through to its very end, as was his way with all he ever touched.

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