FINAL REPROT

TO THE

NATIONAL AERONAUTICS and SPACE ADMINISTRATION

For Research Conducted Under

Contract NASw-66

STELLAR SPECTROPHOTOMETRY IN THE FAR ULTRAVIOLET

Submitted By

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I. Introduction

The program of research carried out during the period July, 1959 to December, 1963 under NASA contract NASw-66 was directed toward the study of stellar spectrophotometry in the vacuum ultraviolet. The early phases of this work were directed toward the design of a small 300-pound satellite for ultraviolet spectrophotometric measurements. This study provided the basis for the design of a larger Wisconsin experimental package for the Orbiting Astronomical Observatory. In the course of this work laboratory instrumentation was developed for testing and calibrating vacuum UV optical equipment and for the fabrication of UV interference filters and mirror coatings. The latter phases of the research carried out under this contract included the design and construction of a stable platform for use in the X-15 rocket plane in order to conduct ultraviolet measurements with the aircraft. During the course of this research several theoretical studies were undertaken. These programs are described in greater detail in the following sections.

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II. Study Report

1. Feasibility study of an ultraviolet spectrophotometric satellite:

The feasibility study was initiated by delineating the various study areas and by starting a program of laboratory work. Investigations of stellar energy distributions in the ultraviolet were carried out by A. D. Code and the results of this study were published in a paper entitled "Stellar Astronomy From a Space Vehicle". A tabulation based on "Model Stellar Atmospheres of the Ultraviolet Magnitudes of the Brightest Stars" was conducted by Philip Solomon. This compilation appeared as a Space Astronomy Laboratory report and was incorporated in Mr. Solomon's master's thesis for the University of Wisconsin in 1960. A study of the possible spectral lines

in the UV and infrared in diffuse nebulae, planetary nebulae and interstellar space was carried out by Professors D. E. Osterbrock and A. D. Code. A part of these results is contained in the previously mentioned paper. C. R. O'Dell conducted a study of the effects of librations on the satellite's stability and an extensive investigation of temperature stabilization was carried out by Mr. Duane A. Williams. D. A. William's report on "Temperature Control of an Earth Satellite", September, 1959, provided considerable insight into the thermal problems to be encountered in the design of an astronomical satellite. Martin Burkhead and D. J. Schroeder conducted studies of the reflectivity of surfaces in the ultraviolet and Donald J. Taylor investigated the electronic circuitry employed in the University of Wisconsin meteorological satellites and carried out a complete design for the control electronics and associated signal-handling electronics in a four-color UV photometer satellite. During this period laboratory work was conducted on the solar aspect cells to be used in providing information on satellite orientation. A remote slewing control study was conducted and a prototype inertial wheel slewing system was operated on the end of a 50-foot torsion pendulum. Laboratory investigations were also made of the operation of the yo-yo type inertial unloading devise. During this period of time our first vacuum test system was constructed. The results of these studies led to a preliminary design of a four-color UV satellite. Drawings of both the structure and electronics for this simple 300-pound satellite were completed and submitted to NASA for consideration. The background gained in this study was indispensable when our emphasis was turned towards the OAO concept.

2. Studies resulting in the proposal for the Wisconsin Experimental Package in the Orbiting Astronomical Observatory: As a result of the initial studies described above, the University of Wisconsin Space Astronomy Laboratory prepared an experiment description outline for an ultraviolet photometer suitable for use in the Orbiting Astronomical Observatory. This OAO experiment description outline was prepared by Drs. T. E. Houck, J. F. McNall and A. D. Code and submitted to NASA in February, 1961. The document described the scientific background and experiment objective and the details of the hardware and suggested mode of data processing. On the basis of this document an Industries Conference was called in which the nature of the Wisconsin experiment was described. Following this presentation detailed specifications were prepared and bids solicited. At the time of selection of the subcontractor, Cook Research Labs of the Cook Electric Company, the OAO program was divorced from the research contract NASw-66 and placed under the contract NAS5-1348 with the Goddard Space Flight Center.

3. Ultraviolet Interference Filter Fabrication: It was recognized that filter photometry in the ultraviolet would require the study and development of suitable filters and detectors to isolate the relevant spectral regions. Since no commercial firm was manufacturing interference filters for the vacuum ultraviolet, we undertook the fabrication of such filters ourselves. For this purpose a vacuum evaporator was constructed which would provide means of accurately monitoring the thickness of coatings during the evaporation and permit control of shutters and motion of sample wheels in the vacuum. This vacuum evaporator was completed and on the basis of computer programs for interference filters, fabrication of UV interference

filters was undertaken by Dr. Daniel J. Schroeder. The technique is described in Dr. Schroeder's publication in the Journal of the Optical Society of America. We have fabricated all of the necessary filters for the Wisconsin Experimental Package in the OAO as well as providing filters for a number of other flight experiments both within our group and for others. In addition filters have been provided for the Goddard Space Flight Center and the University of Arizona for laboratory investiation and flight packages.

4. Vacuum Calibration: In order to select detectors for the ultraviolet and to provide for energy calibration of complete UV optical systems a vacuum calibration tank was constructed that incorporated a 12-inch reflecting collimator and sufficient volume to accomodate any of the individual telescopes or optical modules contemplated in our OAO program, X-15 program and rocket program. The monochromatic light source was provided by means of a Jarrell-Ash vacuum monochromator coupled to the 12-inch collimator. The monochromatic flux in the collimated beam was calibrated by means of detectors which in turn were calibrated by reference to tungsten ribbon filament lamps and a fundamental platinum black body. This vacuum collimator and calibration tank was used for the calibration of the OAO Wisconsin experiment and for X-15 and Aerobee rocket modules. The calibration facility is completely described in the Space Astronomy Laboratory report by Daniel Schroeder. Difficulties were encountered in obtaining a uniform collimated beam. The principal source of difficulty was in the monochromator and we have since designed a more satisfactory calibration tank facility.

5. Research With the X-15 Rocket Plane: In view of the contradictory data that had been obtained on the energy distribution of stars in the ultraviolet prior to 1960 the University of Wisconsin Space Astronomy Laboratory suggested utilizing the manned X-15 rocket plane for obtaining photographs of selected regions of the sky in the ultraviolet. The use of photographic techniques it was thought would provide a sufficiently different basis for the determination of stellar energy distribution to help in resolving the contradictions. A rather complete description of the scientific objectives and experimental technique to be employed with the X-15 was contained in the Space Astronomy Laboratory report on Stellar Astronomy From High Altitude Aircraft prepared by A. D. Code and T. E. Houck. The first step in a flight program with the X-15 consisted of a photoelectric survey of the daytime sky brightness in the ultraviolet. This was carried out by replacing one of the bug-eye movie cameras in the X-15 with a photoelectric photometer incorporating a band pass in the normal photographic region and a band pass at about 2500 Angstroms where the maximum ozone absorption occurs. The principal objective was to determine whether or not it was possible to see bright stars in the ultraviolet against the daytime sky background at X-15 altitude. Five flights were obtained with this unguided sky brightness photometer, a description of which is contained in the SAL report of March 24, 1962, "The X-15 Bug-Eye Photometer" by William N. Reining. The experimental data in the photographic region were utilized by Northrop Aircraft's Nortronics Division as part of a study on the daylight sky for star tracker purposes and are described in Northrop Nortronics Report at the ninth National IRIS Symposium, Dallas, May 8, 1963, "High Altitude Sky Luminance Measurement", by W. M. Clark and H. A. Muldoon. The ultraviolet data

has been discussed by Dr. Martin Burkhead and formed a part of his Ph.D. thesis at the University of Wisconsin. The results of this study suggested the brighter stars could be observed at altitudes in excess of 200,000 feet. In order to carry out observations of individual stars and individual star fields it was necessary to design a three-axis stabilized platform to be mounted in the instrument elevator of the X-15 airplane. Preliminary designs of such a stable platform were carried out at the laboratory along with studies of satisfactory designs for wide-angle cameras in the ultraviolet. It was initially decided to construct four off-axis Schmidt cameras corrected for the region between 3,000 and 2,000 Angstroms and fabrication of such cameras was undertaken. It later proved that the resolution of these cameras is not sufficient to give the contrast necessary between the star and the sky background unless altitudes in excess of 250,000 feet could be achieved. In order to stabilize and point the gimbaled platform at a particular star a prototype star tracker was constructed along principles suggested by T. E. Houck and A. D. Code. This star tracker uses a rotating polaroid and a fixed-quadrant mosaic polaroid material in order to achieve a large field and tracking on the photo center of that field. At this stage it appeared desirable to subcontract to industry for detailed design and construction of a stable platform. In April of 1961 a subcontract was awarded to Astronautics Corporation of America in Milwaukee, Wisconsin for design studies of a stable platform. The design of a three-axis gyro stabilized platform in which a star tracker may provide an error signal was completed and ACA was awarded a second subcontract for construction of the three-axis stabilized platform in June, 1961. This platform is capable of a pointing accuracy of one minute of arc and of carrying an instrument load of approximately 50 pounds.

ACA was subsequently awarded a prime contract by NASA for integration and test and field services on the present platform and the construction of a second three-axis platform for the X-15. Additional laboratory and construction work in connection with the X-15 program were carried on at the Space Astronomy Laboratory. These included many tests on characteristics of film in the ultraviolet and calibration of the photometric equipment. The construction of the control and timing circuitry to operate the cameras was then undertaken. In order to provide higher resolution, design studies were instigated for lens type cameras and ultimately four ultraviolet lenses were purchased from Barnes Optical. At this point the X-15 program was transferred to a research grant, NSG 618.

III. Other Studies

During the course of the work described above various theoretical investigations were undertaken which were directly related to problems of ultraviolet spectroscopy. Philip M. Solomon undertook an investigation of the absorption coefficient of quasimolecular hydrogen and extended this to an investigation of the opacity of light molecules in astrophysics. It had been suggested that the apparent defficiency in radiation in the ultraviolet as observed by rockets might be due to a new source of opacity. Discussions by Solomon indicated that this was an unlikely explanation. The opacity of light molecules in astrophysics constituted Mr. Solomon's Ph.D. thesis completed in 1964 and a discussion of the absorption coefficient of quasimolecular hydrogen was published in the Astrophysical Journal. George W. Collins investigated the continuous spectrum from rapidly rotating stars and came to the conclusion that different orientations of rapid rotators can cause large effects in the ultraviolet. Other

investigations that were made possible by the computing facilities provided by the Space Astronomy Laboratory consisted of Eugene Cappriotti's investigation of the hydrogen radiation spectrum in gaseous nebulae; Harland W. Epps' discussion of physical models for rapidly rotating early type stars; and Dr. Robert A. R. Parker's paper on the spectrum of the nebulae under conditions of collisional excitation and ionization. All of the reports and papers that have been referred to in this section are listed in the publications listing at the end of this report.

IV. Facilities

The Space Astronomy Laboratory is presently housed in a rented building provided by the University at 35 North Park Street. The first temporary offices of the lab were located at 1118 West Johnson Street. Later facilities were moved to Sterling Hall and then on a permanent basis to our building on Park Street.

A detailed listing of capital equipment is contained in the quarterly reports and an inventory of all equipment is maintained by the University Purchasing Department.

The research programs carried out under this contract have proved to be a very effective educational tool. Undergraduate students have been employed on these programs and the experience they have gained has been helpful in their later employment. Approximately 15 of these students are now employed by NASA or in the Aerospace Industry.

The vacuum system purchased under this contract includes two chambers, one to allow manufacturing of filters and plating, the other to facilitate vacuum calibration of optical instruments. A Jarrell-Ash vacuum monochromator for use in calibration was also obtained. These facilities are presently being used in the OAO program.

Computing facilities have been provided through the rental of one-third of an IBM 1620. Data reduction for most of the reports and papers generated by this project were run on these machines. Also a great deal of time was used by astronomy graduate students for unsupported research.

An electronic lab was started with an oscilloscope, several oscillators, and meters, and sundry small equipment. Electronic support was provided in the areas of instrumentation and flight hardware. Several undergraduate engineers were hired and furnished help while gaining knowledge.

A mechanical shop was established which supported both the electronic and optical areas. Most equipment for the shop was obtained through the University's acquiring surplus equipment.

V. Publications

Burkhead, M. S. "Ultraviolet Measures of the Day Sky and Observations of Bright OBA Stars for Space Astronomy Applications", Ph. D. Thesis, University of Wisconsin.

Capriotti, E. R. "The Hydrogen Radiation Spectrum in Gaseous Nebulae", Ap.J. 139,225, 1964.

Clark, W. M., and Muldoon, H. A. "High Altitude Sky Luminance Measurements", Northrop Nortronics Report, 9th National IRIS Symposium, Dallas, May 8, 1963.

Code, A. D. "Stellar Astronomy From a Space Vehicle", Ap.J. 65,278, 1960.

Code, A. D., and Houck, T. E. "Stellar Astronomy From High Altitude Aircraft", Space Astronomy Laboratory Report.

Collins II, G. W. "Continuim From a Rapidly Rotating Stellar Atmosphere", Ap.J. 138,1134, 1963.

Epps, H. W. "Physical Models for Rapidly Rotating Early-type Stars", Ph.D. Thesis, University of Wisconsin, 1964.

Houck, T. E., and Code, A. D. "OAO Experiment Description Outline", Feb., 1961

Osterbrock, D. E., and Code, A. D. Expected UV Spectrum of a Planetary Nebula", 1959.