FINAL REPORT ON NASA GRANT No. NGR 05-020-330

Administered by NASA Headquarters

as part of their Physics and Astronomy Program

Dynamics of the Solar Wind and its Interaction with Bodies in the Solar System

This grant supported research at Stanford University over a four and a half year period commencing April, 1, 1969. During the active lifetime of this grant, 18 quarterly progress reports were transmitted to NASA Headquarters describing the accomplishments and work in progress in each of these periods. This report summarizes the work of the entire period, and is brief because the principal results of the research are all reported in the 13 papers, 2 Ph.D. dissertations, 1 Engineer's degree thesis, and 8 talks at national or international scientific meetings, as reviewed below.

As will become evident from the positions of the personnel associated with the work, this project was conceived and carried out as a collaborative effort between personnel at Stanford University and Ames Research Center; and most of the resulting papers were coauthored by members of both institutions. There has, furthermore, been a flow of the younger personnel from Stanford to NASA Ames Research Center. It has been the feeling of all involved that this project was a fine example of NASA-University cooperation with numerous benefits accruing to both partners. Although lack of funding has greatly curtailed the research of the Principal Investigator in the general field of Solar-Terrestrial Physics, similar cooperative efforts with NASA Ames are currently being carried out in other fields of study.

The total extent of this grant consisted of four one-year grants with a budget of $110,000, extending over the period from April 1, 1969 to March 31, 1973. A six month's extension without additional funds was then requested

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and granted. Because several parts of the project were unfinished at the close of the period funded, and further funding was not forthcoming from NASA at that time, application was made to the National Science Foundation for a one year grant. Their grant of $20,000 for an 18 month period starting March 15, 1973 has enabled several individual efforts then in progress to be completed.

The first paper to be produced with the support of this grant was entitled "Hydromagnetic Aspects of Solar Wind Flow Past the Moon" by John R. Spreiter, Principal Investigator, and Clive M. Marsh and Audrey L. Summers. It was published as the lead-off article in the new journal Cosmic Electrodynamics, 1, 5-50 (1970). Mrs. Summers is a permanent member of the Theoretical Studies Branch of the Space Sciences Division, and Dr. Marsh was a National Academy of Sciences NASA Postdoctoral Research Associate in the same branch at Ames Research Center. He has since returned to his native England.

Attention was next turned from the Moon to our nearest planetary neighbors, Venus and Mars; and resulted in the paper "Solar Wind Flow Past Nonmagnetic Planets - Venus and Mars" by John R. Spreiter, Audrey L. Summers, and Arthur W. Rizzi, published in Planetary and Space Science, 18, pp. 1281-1299 (1970). This was the first paper participated in by Dr. Rizzi at the beginning of his Ph.D. studies at Stanford. Those studies culminated with his dissertation "Solar Wind Flow Past the Planets Earth, Mars, and Venus" completed in 1971. Upon graduation, Dr. Rizzi joined the Computational Fluid Dynamics Branch of NASA Ames Research Center as a National Academy of Sciences NASA Postdoctoral Research Associate. Subsequently, he was appointed to a regular civil service position, in which he remains today.

A review entitled "Solar Wind Flow Past Objects in the Solar System" by

John R. Spreiter and Alberta Y. Alksne summarizing much of what was known about that subject was published in the Annual Review of Fluid Mechanics, 2, pp. 313-354 (1970). This represents an extended version of the invited lecture "Solar Wind Flow Past the Earth, Moon, and Planets" presented at the January 1971 annual meeting of the American Institute of Aeronautics and Astronautics in New York, and is closely related to the invited summary paper "Fluid Aspects of Solar Wind Interaction with the Earth, Moon, and Planets" presented at the General Scientific Assembly of the International Association of Geomagnetism and Aeronomy in Madrid, Spain in September 1969. Mrs. Alksne was a member of the Theoretical Studies Branch of NASA Ames Research Center at that time, but has since retired, completed a two year appointment in the Peace Corps teaching mathematics in Kenya, and is now a consultant on a NASA grant from Ames Research Center to Stanford University to determine appropriate boundary conditions to be applied at the top of the Venusian atmosphere.

While the above was being done, John R. Spreiter and Arthur W. Rizzi returned their attention to the Martian interaction with the solar wind and produced a paper entitled "The Martian Bow Wave - Theory and Observation" published in Planetary and Space Science, 20, pp. 205-208 (1972). In this paper they showed that the theoretical predictions for the location of the bow wave were in almost perfect agreement with the actual observations provided the calculations they previously described in a general way were made using the best information available for the conditions and direction of the incident solar wind at the time of the direct measurements by Mariner 4.

Studies more directly related to the solar wind, and to a lesser extent the Sun itself, were carried out during about the same time and resulted in a paper entitled "Shock Waves in the Solar System" by John R. Spreiter and was

published in Astronautica Acta, 17, pp. 321-338 (1972). This paper provided the written version of an invited lecture presented at the session on Cosmic Phenomena at the Third International Colloquium on Gasdynamics of Explosions and Reactive Systems in Marseille, France, in September 1971. Immediately preceding this event, the Principal Investigator participated in the Summer Advanced Institute on Earth's Particles and Fields in Cortina, Italy.

During this same time period, Dr. Joan Hirshberg was an active participant in the research project. The resulting publications were "Observations of a Solar Flare Induced Interplanetary Shock and Helium Enriched Gas" by Joan Hirshberg, Alberta Y. Alksne, D. S. Colburn, S. J. Bame, and A. J. Hundhausen in the Journal of Geophysical Research, 75, pp. 1-15 (1970); "Helium Enriched Interplanetary Plasma from the Proton Flare of August/ September, 1966" by Joan Hirshberg, J. R. Asbridge, and D. E. Robbins in Solar Physics, 18, pp. 313-320 (1971); and "Solar Flares and Solar Wind Helium Enrichments, July 1965 - July 1967" by Joan Hirshberg, S. J. Bame, D. E. Robbins in Solar Physics, 23, pp. 467-486 (1972). These papers amplified greatly the contents of a paper entitled "Helium Enriched Interplanetary Medium and Solar Flares" Dr. Hirshberg presented at the 1970 fall meeting of the American Geophysical Union in San Francisco; and formed much of the basis for the paper entitled "Solar Wind Helium Enhancements following Major Solar Flares" presented by her at the First Asilomar Solar Wind Conference in March 1971. Her coauthors, Drs. Asbridge, Bame, Hundhausen and Robbins were of the Los Alamos Scientific Laboratory; Dr. Colburn was of NASA Ames Research Center. After the support for Dr. Hirshberg's participation could no longer be maintained, she joined NASA Ames Research Center as a National Academy of Sciences NASA Senior Postdoctoral Research Associated. She is now with the High Altitude Observatory of the National Center for Atmospheric

Research in Boulder, Colorado.

In addition to the above works aimed directly at various aspects of the solar wind and its interaction with bodies in the Solar System, certain supporting studies of basic plasma phenomena were carried on in collaboration with Dr. Shigeka Morioka of Osaka University during his tenure as a National Academy of Sciences NASA Senior Postdoctoral Research Associate at Ames Research Center. This resulted in the publication of 3 papers authored by Shigeki Morioka and John R. Spreiter entitled "The Effect of Finite Larmor Radius on the Perturbation Flow Mixing of a Collisionless Plasma" in the Journal of Plasma Physics, 4, pp. 403-424 (1970); "Effect of Dissipation due to Firehose Instability on Perturbation Half-Jet Flow of a Collisionless Plasma" in the Journal of Plasma Physics, 4, 629-641 (1970); and "Effect of Dissipation due to Firehose Instability on Half-Jet Flow" published in the Proceedings of the IUTAM Symposium on Dynamics of Ionized Gases (1971). The latter provides the written version of an invited lecture given by Dr. Morioka at the International Union of Theoretical and Applied Mechanics Symposium in Tokyo in September 1971.

Still another piece of supporting work in plasma physics was that performed by Mr. Earl Knechtel, a graduate student in the Applied Mechanics Department and research worker at NASA Ames Research Center, for his Stanford thesis entitled "Gas-Surface Momentum Accommodation for Conditions Simulating Near-Earth Satellites" submitted in January 1972 in partial fulfillment of the requirements for the degree of Engineer, a degree midway between the M.S. and Ph.D. degree at Stanford. Many of the results of this study were reported by him at the XXII International Aeronautics Federation Congress in Brussels, Belgium in September 1971 in a paper entitled "Measured Normal and Tangential Momentum Accommodation on Aluminum of N_2^+ at and Above

Earth Satellite Speed".

In 1972, the Principal Investigator and Dr. Arthur W. Rizzi of NASA Ames Research Center prepared an invited general lecture entitled "Interplanetary Space - A New Laboratory for Rarefied Gasdynamics" for the Eighth International Symposium on Rarefied Gasdynamics held at Stanford in July of that year. The abbreviated text of that paper has recently appeared on pages 497-521 of Rarefied Gas Dynamics published in 1974 by Academic Press.

The final publication resulting from the research project is entitled "Aligned Magnetohydrodynamic Solution for the Solar Wind Flow Past the Earth's Magnetosphere" by John R. Spreiter and Arthur W. Rizzi published in Acta Astronautica, 1, pp. 15-35 (1974). In it are presented the results of an exact magnetohydrodynamic, as opposed to gasdynamic, solution for solar-wind flow past the Earth. This provides the most accurate representation for this problem yet published anywhere.

In addition to the above items described above, the Ph.D. dissertation of Mr. Charles K. Lombard, a student in the Applied Mechanics Department of Stanford, entitled "Termination of the Solar Wind in the Hot, Partially Ionized Interstellar Medium" has just now been completed. A copy of that work is attached to this report. This study provides the most complete analysis to date of the interaction of the solar wind with both the ionized and neutral components of the interstellar medium, allowing in considerable detail for the effects of ionization by both photoionization and charge exchange of the interstellar neutral gas as it flows through the ionized solar wind plasma. Until May 1973, Mr. Lombard received his financial support for graduate studies from this grant. Since then, he has assisted on an unrelated project and continued to work to complete his solar wind studies for the Ph.D. He has now completed all requirements for the degree, and has commenced an

appointment as a National Academy of Sciences NASA Research Associate in the Computational Fluid Dynamics Branch of NASA Ames Research Center.

Two other research efforts nearing completion for the Ph.D. degree have been supported to a minor degree by this grant. One is the work of Mr. Richard Desautel, a Lockheed employee now teaching part time at San Jose State University, on the dynamical behavior of the magnetosphere tail in response to solar wind disturbances. The other is the work of Mr. J. T. Lee, formerly of United Technology and now of Sandia in Los Alamos, on the topic of the behavior of atmospheric plumes. Both students have been self-supporting; only the research supervision and incidental expenses have been borne by the grant. Both projects are nearing the final typing stage; and both students have met all other requirements for the degree.

In addition, supervision of the work of Mr. Joseph Reagan, a graduate special student at Stanford and a Lockheed employee, on a Ph.D. dissertation topic concerned with energetic particle access into the magnetosphere from the solar wind was instituted near the end of the grant period. This work is continuing without financial support at the present time, although a research proposal to support a more intensive effort was submitted to NASA Headquarters about half a year ago.