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FINAL REPORT

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To Isolate and Examine all Significant Phenomena Associated with the Yellow Coronal Line at 5694 A.

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I. SUMMARY OF RESEARCH UNDER THE CONTRACT

INTRODUCTION

Research under the yellow line contract may be divided conveniently into three phases, of which each phase was under the supervision of Dr. W. O. Roberts, Director of the Observatory. In the first phase, Roberts was assisted by F. P. Dolder and Bruno Witte in conducting the research and by D. E. Billings in preparing publication of the results. In the second part, Roberts was assisted by Billings, R. H. Cook, D. H. Liebenberg, and R. Grenchik. Work under the third phase of the program was carried out by Roberts, Billings, and C. W. Pecker.

In the following paragraphs research done under each of the phases is described in detail. The numeral notations refer to the publications listed by number under the section, "Reports Issued".

PHASE I. YELLOW CORONAL LINE, FLARES, AND ACTIVE PROMINENCES

Dolder and Witte first made a careful examination of all Climax and Sacramento Peak spectrograms to identify all cases of the rarely-observed yellow line. They tabulated all instances of the emission line together with position angles and intensities. Next they prepared a catalog in which the yellow line intensities were plotted as a function of angle along the solar limb. In addition the coronal red line and coronal green line isophotes were plotted for the active regions in which the yellow line emission appears; flares were indicated, and a print of the prominence on the limb at the time and place of yellow line emission was included. All of these data were included in a single composite diagram for each yellow line case.

Two analyses were next applied to the accumulated yellow line data.[1] The first was a study of the relationship of yellow line emission to solar flares at or near the limb at the time of yellow line emission. The study showed clearly that there was a high correspondence, far too great to be the result of chance, between yellow line emission and flares occuring within one day and within five degrees of the point on the limb at which the yellow line was observed. The correspondence was so high, as a matter of fact, that it is quite likely that there is a one-to-one correspondence between limb flares and yellow line emission.[2,3] This possibility must be considered, however, in the light of the fact that there has been only a very limited number of hours of observation of the yellow-line and its time and position-associated flares.

The second analysis involved a study of the characteristics of the prominences associated with yellow line emission. Prominence films from the High Altitude Observatory were analyzed in detail, and a list of prominence characteristics were evaluated with respect to their relative importance in describing the prominence corresponding to each yellow line case. The study showed that the characteristics of yellow line prominences

were those that had previously been associated with active sunspot regions: matter forming in space and following sharply curved trajectories downward, broken knots of matter, focussing of matter, and surges. The features were in general those that indicate large electric and magnetic fields in the solar atmosphere.[4]

PHASE II. STRUCTURE OF THE SOLAR CORONA

Results obtained under the first part of the yellow line program had suggested magnetic fields extending outward from regions of sunspot and flare activity. In the second part of the program we analyzed the effect such fields would have on: (a) the emission line corona, in directing matter outward from active centers to form regions of high red line and green line emission[5]; and (b) the white light corona in forming coronal streamers. In part (a), Roberts was assisted by Cook, Billings, and Liebenberg; in part (b) by Billings and Grenchik.

In the study of the emission-line corona, several regions in the corona were selected that maintained their identity as sources of red and green emission over a period of several solar rotations. From a study of the detailed behavior of these regions we were able to say that the evolution of a typical coronal region probably develops along the following pattern: After intense flare activity, the coronal region becomes significantly brighter in both red and green line emission. During the ensuing several weeks, the total emission in both lines declines, but the ratio of green to red line emission increases.[6] Furthermore, the isophotal contours of both red and green emission spread outward with a velocity of the order of one kilometer per second. Our interpretation of these phenomena is that matter is ejected outward from the active center at the time of great flare activity and that it spreads outward slowly from this center.[7,8] Data for this study were coronal spectra taken at Climax and Sacramento Peak.

The study of the white light corona was based on photographs and sketches of coronal rays and streamers that have been observed at eclipses over many years. We investigated the possibility that the formation of the streamers resulted from the focussing of matter by various combinations of magnetic fields: (1) by the interaction of like fields from two active centers, (2) by the interaction of active-center fields and a general solar magnetic field. As a result of these studies we concluded that no simple magnetic focussing by active centers was adequate to explain the detailed shape of the coronal streamers but that the shape could be explained by considering an interaction of the mechanical energy of matter ejected from the sun with active-center and general magnetic fields.[9,10]

PHASE III. LINE PROFILE ANALYSIS OF ACTIVE CENTER PHENOMENA AND IDENTIFICATION OF YELLOW CORONAL LINE

The apparent increase of the ratio of green to red line emission in

coronal regions, noted in our description of the second part of the yellow line program, implies a gradual increase in the temperature of the coronal regions. In attempting to find a source of energy to explain this heating, we made a detailed study of the shape of coronal lines in the active centers, using the new HAO electronic null-method microphotometer. The study developed into two distinct progress: (a) a study of the Doppler distortions of the red coronal line in centers of great activity; and (b) a study of the profile of the yellow line, and of a companion line at λ 5446, for identification of the atom responsible for the yellow line.

From the red line study we found that most red line emission gave a line profile from which the computed coronal temperature agreed very closely with that found by Lyot and Dollfus, about two million degrees Kelvin. In certain exceptional cases, however, the red line undergoes a great distortion, implying either isotropically distributed mass-motion velocities of up to 60 km/sec. or temperatures as high as fifteen million degrees. We also noted a curious correlation between broadening of the red coronal line and broadening of the prominence lines, H α and helium D_3.[11]

The work on the identification of the yellow line fell, in turn, into two parts. The first part involved a study of the line profiles of the yellow line in one case in which this line was of sufficient intensity for precise microphotometry. From profiles of the yellow, red, and green lines on several spectra photographed on the same day, and making the assumption that the three lines originated from gas at the same temperature, we determined that the atomic weight of the atom emitting the yellow line was approximately 40—the atomic weight of calcium. In the second part of the study we looked for and found a companion to the yellow line, previously reported by Waldmeier at λ 5445. By the use of careful microphotometric techniques we were able to measure the intensity of this line, finding it about 2/3 as intense as the yellow line. This was within the range of intensities that had been predicted for the companion of the yellow line, provided that the two originated from Ca XV—Edlen's original identification of the line.[12]

Our evidence supporting the Ca XV identification of the yellow line and its apparent co-existence with the red and green lines raises an important question, since the ionization potential of the Ca XV ion is several times higher than that of the Fe X and Fe XIV ions which emit the red and green lines respectively. An important question is raised by this result and by the apparent correlation between the broadening of the red coronal line with that of the prominence lines, which arise from atoms that are ionized at only a few volts. The question is this: Is it possible for an aggregate of ions to exist for a short time (one or two hours) at temperatures too high for those ions to remain (because of ionization or recombination) for longer periods of time? The question can be answered only by further knowledge of the collisional properties of the ions. Such knowledge is not available from laboratory experimentation, since the states of ionization with which we are dealing exist at temperatures of several million degrees. The phenomena we have observed in our Yellow Line program, however, may yield fundamental knowledge about the nature of highly ionized atoms in general.

II. APPLICATIONS AND DIRECTIONS OF FUTURE RESEARCH

Through the Yellow Line project we have made a number of important and interesting contributions to the body of knowledge concerning the solar corona. We have also uncovered a host of new questions, even more important and interesting than those that confronted us at the beginning of the project. We have developed microphotometric techniques that make accessible to us a vast body of information in our library of coronal spectrograms. It is our opinion that a project for attacking these new problems, using the new techniques, will be extremely fruitful in developing interpretations of active-region phenomena at the solar surface and in the corona. These active-region phenomena, in turn, are closely related to practical problems of ionosphere and upper atmosphere.

The work done under the contract, and that suggested in broad terms for the continuation under ONR auspices of a related project, embraces, in the strict sense of the word, basic research. It is basic in the sense that our effort under this program is directed toward an enlargement of our understanding of solar processes, toward the development of theories that explain the physical relationships that exist among diverse solar phenomena. On the other hand, even though our approach involved strictly basic research, the results achieved represent very important progress toward the solution of problems of practical significance.

The identification of the yellow coronal line as Ca XV suggests temperatures and pressures in active regions of the corona well above those that were previously believed to exist. Our theory of coronal formation, moreover, postulates a continuance of these conditions in an active region over a time period very much longer than the life of the solar flare that we presume to be associated with the physical process involved in heating the corona. This indicates the possibility that increases in D-region ionization resulting in complete radio fade outs are caused by X-rays from the corona itself since such increases are also longer lived than the flare. Rocket observations made by Chubb and others at NRL, furthermore, suggest changes of X-ray intensity near 5 Angstroms by factors as large as several hundred.

The coronal-formation theory postulates, as we have explained before, that hot coronal gases diffuse slowly out (approximately 1 km. per second) from an active center. Solar radio-noise observations tend to support the view that magnetic fields extend at right angles to the surface of the advancing front of coronal gas. There is a possibility the magnetic fields associated with active regions can be roughly determined by constructing a plot of coronal-intensity contours - something we are already doing on a routine basis in our data-reporting program. This would represent a research development of great importance, especially since at present it appears virtually impossible to measure directly the magnetic fields in the solar atmosphere above active areas.

If we have information on active-center magnetic fields, we will probably be able to say something more definite about the magnetic

focussing of corpuscles ejected by the active regions. This question becomes one of special importance near sunspot maximum when the active regions themselves appear to be the major factor in the production and ejection of corpuscular particles. Thus we appear to have developed an approach, that merits intensive further study, to the question of prediction of corpuscular outbursts during high-activity levels of the spot cycle. This in turn may be very important in prediction of the planetary geomagnetic index, K_p, and thus of ionospheric storms in the F region as well as disturbances in the "corpuscular E region" in polar latitudes.

III. REPORTS ISSUED

A. A number of papers, arising directly out of the work of the contract, have been published in the technical journals, and, in addition, we have issued both technical and special reports under the contract. A list of the papers and reports follows:

1. Dolder, F.P., "Solar Activity and the Yellow Coronal Line 5694 A", HAO Technical Report, 10 November 1952.

2. Roberts, W.O. and Dolder, F.P., "Solar Limb Flares and the Yellow Coronal Line"(A), Astron. J. 58, 37, 1953.

3. Dolder, F.P., Roberts, W.O., and Billings, D.E., "Solar Flares and the Yellow Coronal Line", Ap. J., 119, 120, 1954

4. Dolder, F.P., Roberts, W.O., and Billings, D.E., "Active Region Prominences and the Yellow Coronal Emission Line", Ap. J., 120, 112, 1954.

5. *Roberts, W.O., No Title, HAO Solar Research Memorandum No. 7, 10 October 1953.

6. *Billings, D.E., "Evolution of Red and Green Line Emitting Coronal Regions", HAO Solar Research Memorandum No. 17, 28 May 1953.

7. *Billings, D.E., Roberts, W.O., and Liebenberg, D.H., "Expanding Gas Model of the Corona", HAO Solar Research Memorandum No. 19, 24 August 1953.

8. Billings, D.E., Liebenberg, D.H., and Roberts, W.O., "Evolution of Coronal Regions"(A), Astron. J. 58, 211, 1953.

9. *Roberts, W.O., Grenchik, R., and Billings, D.E., "Origin of White Light Coronal Streamers", HAO Solar Research Memorandum No. 20, 1 September 1953.

10. Roberts, W.O., Grenchik, R., and Billings, D.E., "Origin of White-Light Coronal Streamers"(A), Astron. J., 58, 225, 1953.

11. Billings, D. E., Pecker, C., and Roberts, W. O., "Study of the Broadening of Coronal Lines in Active Regions", HAO Solar Research Memorandum No. 23, 3 March 1954. Also published in Comptes Rendus, 238, 1194, 1954.

12. Pecker, C., Billings, D. E., and Roberts, W. O., "Identification of the Yellow Coronal Line 5694.4", HAO Solar Research Memorandum No. 22, 24 February 1954. Also published in Comptes Rendus, 238, 1101, 1954 and submitted to Ap. J.

*Note:

The reports designated by an asterisk are HAO Solar Memoranda, which are informal and preliminary reports drawn up for distribution on a limited basis primarily at HAO, Harvard, and Sacramento Peak (UARO). In general the memoranda have as their subject new ideas, or hypotheses, that have not yet been fully tested for conformance with the observed facts or for consistency with the established theoretical structure. This makes possible detailed criticism of the proposed new work direction before there is a large investment in research time. These criticisms serve to indicate to us whether or not the new hypothesis merits further study. Because this is the purpose of the memoranda, it is not appropriate to give them wide circulation, even though many later form the basis of publications in the technical literature. We are, however, for the sake of completeness, listing herein the HAO Solar Research Memoranda that have arisen under the Yellow Line contract. One copy of each Memorandum is attached.

B. Status Reports.

Five Status Reports (four quarterly and one semi-annual) were issued covering all contract operations for the period from 1 February 1952 through 30 September 1953. This report, the Final Report, summarizes the work of the entire contract period from the inception of the contract through termination.

IV. ACKNOWLEDGEMENT

We wish to express our deep gratitude to the Office of Naval Research for making this work possible.

Respectfully submitted,

Robert J. Low
Administrative Officer

4 October 1954