HIGH ALTITUDE OBSERVATORY
of
Harvard University and University of Colorado

TECHNICAL REPORT

Part I
Expanding Gas Model of the Corona

by
DONALD E. BILLINGS, WALTER ORR ROBERTS,
and DONALD H. LIEBENBERG

Part II
Origin of White Light Coronal Streamers

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WALTER ORR ROBERTS, RAYMOND GRENCHIK,
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20 November 1953

ONR Contract Nonr-393(02)
Project NR 046-721/9-22-52

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INTRODUCTION

During the summer of 1953 the High Altitude Observatory provided half-time stipends to two students recommended by their home institutions to work on research projects under the subject contract. Mr. Raymond Grenchik, a graduate student from the University of Indiana and Mr. Donald Liebenberg, an undergraduate student from the University of Wisconsin, participated in the Observatory program of research from the end of June through the end of August. The results of their work circulated within the Observatory in the form of research memoranda and are reproduced here to form this technical report. The work was supervised by Drs. Donald E. Billings and Walter Orr Roberts, who appear as co-authors of the reports along with Mr. Liebenberg and Mr. Grenchik.

The work of Liebenberg was a direct outgrowth of previous work by Billings, Cook and Roberts on the formation of the solar emission line corona. The conclusions of the previous efforts to work on a diffusion, or expanding gas model of the corona and to compute expansion rates for the corona are brought together in this report. In preparation for the summer work Billings and Liebenberg developed a new index of coronal activity that not only played an important role in the evaluation of the evolution of the coronal regions but also may have later applications in solar-terrestrial research.

The research carried out by Grenchik is related to the emission line coronal work in a less direct way and represents an effort on the part of High Altitude Observatory to develop a self-consistent hypothesis explaining the distribution and form both of emission line corona and of the white-light coronal streamers seen at eclipse. The work on the white-light coronal streamers is still in very qualitative and tentative state, but is reported here in order to present a statement of our present thinking on the question.

Part I

Expanding Gas Model of the Corona

by

Donald E. Billings, Walter Orr Roberts
High Altitude Observatory

and Donald H. Liebenberg
University of Wisconsin.

In a preliminary draft of a prepared paper some months ago, W. O. Roberts[1] suggested a model of the emission-line corona, with, as a basic concept, gas expanding or diffusing outward with a velocity of about one km/second from centers of sunspot-prominence and flare activity, carrying with it the atoms that emit the coronal spectrum lines. This concept is very different from the temperature model suggested by Waldmeier,[2] Alfven,[3] Kiepenheuer,[4] Woolley and Allen,[5] and Woolley and Gascoigne,[6] in which the coronal regions, i.e., the regions of high intensity line emission near active centers (called "C-regions" by Waldmeier[7]) differ from the rest of the corona in that they are of a different temperature. We should note, however, a certain resemblance of the expanding model to the suggestion of Wolley and Gascoigne[6] that radioactive atoms of almost every kind from the solar interior may penetrate the chromosphere and heat the corona. The expanding gas model agrees in some detail with one formulated very recently by the Australians, Piddington and Davies[8] on the basis of solar radio noise observations.

In a later memorandum,[9] Billings presented the results of a study of the variation with successive limb passages of the red-line and green-line emission from a number of coronal regions. He estimated the emission by measuring the high-intensity and low-intensity areas of our "Weekly Charts of Solar Activity," and applying an arbitrarily defined index. The study indicated two characteristics of coronal regions; (1) a close correspondence between coronal emission and flare activity; (2) a clear-cut tendency for the ratio of red to green line emission to decline during the whole history (including the rise and decline) of a coronal region.

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[1] Preliminary Draft of Paper, "Formation of the Solar Emission Line Corona", 20 January 1953.

[2] Experientia 2, 12, 1946.

[3] Cosmical Electrodynamics, Cambridge University Press.

[4] M.N. 106, 515, 1946.

[5] M.N. 108, 292, 1948.

[6] M.N. 106, 113, 1946.

[7] Ap. J. 101, 117, 1945.

[8] Nature 171, 692, 1953.

[9] High Altitude Observatory Solar Research Memorandum, "Evolution of Red and Green Line Emitting Coronal Regions," 28 May 1953.

We felt that these results are of sufficient interest to justify our carrying the investigation further. First, we sought to establish an index with a sounder physical basis to use in estimating total emission in a given line in the coronal regions that could be derived from the spectra taken at one height from the solar limb in the regular daily photographic survey made at Climax and Sacramento Peak.

We defined such an index after obtaining special spectra from Climax taken at different heights above the solar limb over coronal regions. From such spectra, on successive days of limb passage of two coronal regions, we were able to build up a three dimensional model of the density distribution of emitting atoms giving the total number (a quantity proportional to it) of emitting atoms in each vertical column of the region as a function of the intensity observed at the base of each region and the distance (longitude and latitude) of that region from the center of the coronal region.

Our routine readings of coronal plates are made at 5° latitude intervals, each day. Hence, during the several days required for a coronal region to pass over the limb we acquire a two-dimensional array of intensity readings near the base of the corona. For the study discussed here, we converted these readings into a measure of the total number of emitting atoms from the whole coronal region by multiplying each reading by the appropriate factors determined from the three-dimensional model studies, then summing for the entire limb passage.

We realize that the coronal index thus defined is based on much too limited evidence. In order to build a reliable three-dimensional model of each coronal region we need, at the least, spectra taken at several heights for each of three successive days when the region is on the limb. Since we started this investigation the scarcity of strong coronal regions and rather intermittent observing conditions have limited the data for building such models. Since the monochromatic photographs of Lyot show much variation in the form of the emission corona, we make a questionable assumption when we consider two regions to be typical of all regions. Fortunately, the results which we obtain are not too highly sensitive to the index used.

The index which we used tends to emphasize the higher readings over the lower, and those near the center of the coronal region as compared to those on the outside. It gives results which are not greatly different either from those given in the earlier memorandum, or from those obtained by a simpler and quicker method we also have used: merely summing the highest intensity readings each day for the limb passage. The history of a coronal region is not so sensitive to the index chosen as to variations in observing conditions. Hence, although we feel that further investigation of the index is desirable, we do not think that modifications of it on the basis of subsequent investigations can change by any large extent the results we have obtained.

Liebenberg computed the index discussed above for each limb passage of seven coronal regions, and the short method index for eight regions.

These fifteen comprised all regions from January 1, 1951 to the present, for which we had also rather complete data and which were sufficiently removed from other regions that we could unambiguously identify the coronal emission in each with a given active sunspot center. We then plotted coronal index against time for each of these regions. A study of these plots revealed the following characteristics.

(1) The variation of the red index is more erratic than that of the green index.

(2) The green index follows flare activity more clearly than the red, but on some occasions the red index appears to respond to an outburst of flare activity with more sensitivity than the green index does.

(3) Red and green index maxima do not always coincide, but do coincide with a much higher frequency than we would expect as a result of chance. (See Fig. 1.)

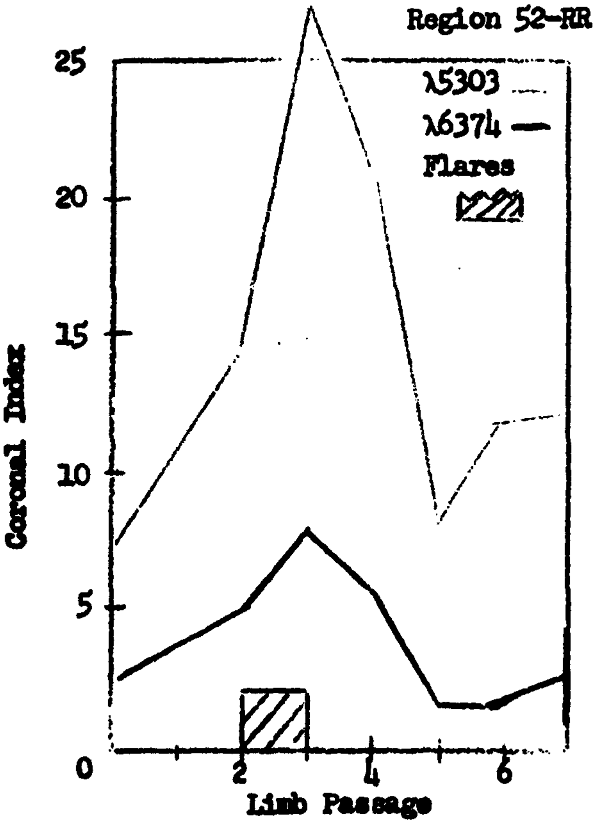

Figure 1

(4) Some regions had a long and complex history which, in certain cases, could be broken into two or more clear-cut events — each consisting of a rise and subsequent decline of coronal activity.

We were able to distinguish eighteen such clear-cut events in the histories which we studied. We then computed the logarithm of the ratio of red index to green index at each limb passage for each event, and plotted this ratio as a function of time. An analysis of the resulting plots showed them to fall into the following classes:

No. of events	Trend — Red to Green ratio
2	Upward
6	Downward
3	Going through a maximum
3	Going through a minimum
4	Random

These results are less confusing if we add to them the observations that all six events in class 2 referred to truly new regions — i.e., regions occurring on portions of the sun which previously had been free of spots — and that there were only three other new regions and they all fell in class 4. In other words, all building up of coronal activity from an inactive sun that we studied was accompanied by a drop in red to green ratio. In most of the cases this drop continued even during the subsequent decline of coronal activity, although in some cases the ratio rose again toward the end of the event.

We feel that the temperature model of a coronal region is inadequate to explain the unidirectional changes in red to green ratio during a rise and fall in coronal activity. The following argument explains why. Let us consider the schematic diagram Fig. 2. This shows, in a general way,

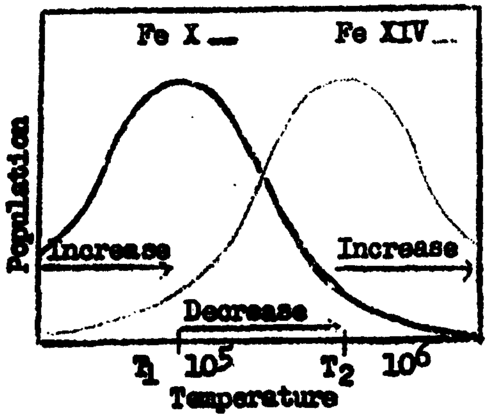

Figure 2

how we might expect the population of the Fe X ions (which emit the red coronal line) and the green Fe XIV ions (which emit the green coronal line) to vary with temperature. We have also indicated on the figure how the ratio of red to green would vary with temperature for each of the temperature ranges shown. We see that it is impossible to carry out any succession of temperature changes which will cause a unidirectional change in red and green ratio and at the same time return the temperature to its original value.

From a consideration of cases of unidirectional change of red to green ratio we have formulated the spreading gas hypothesis in the following form:

(1) Yellow, red and green line emission (λλ5694, 6374 and 5303) in a coronal region becomes pronounced with the infusion into the corona of gas of considerably higher density than that of the corona prior to the infusion.

(2) The infusion takes place from the active center during periods of flare activity.

(3) The gas infused into the corona spreads out through the corona along magnetic lines of force at a sufficient rate to replace the entire corona in any region in about one to two weeks.

(4) As the gas spreads out its temperature rises slowly.

(5) The resulting temperature and density conditions are such that yellow line emission persists for a few hours, red line emission for a few days, green line emission for a week or two.

(6) The coronal region disappears when the gas has diffused to a low density. The corona then becomes too faint for us to observe the change of ratio of red to green intensities during the return of the temperature to normal.

This hypothesis, though admittedly crude and qualitative, explains the unidirectional change in the red to the green ratio. Shortly after the gas is infused into the coronal region we see bright filaments of red emission. The brightness indicates that the density is high. From Fig. 3, the increase in density prior to the increase in temperature causes the red line emission to become intense and we recognize a coronal region. The temperature rises slowly during the spread of the gas, however, and the green line emission becomes dominant. As the activity from the center subsides the continued spreading of the gas lowers the density until the region is no longer recognisable. We do not here postulate what the mechanism for heating the corona may be. Perhaps it is from magnetohydrodynamic waves, perhaps mechanical energy is ultimately converted into thermal energy. Occasional Doppler

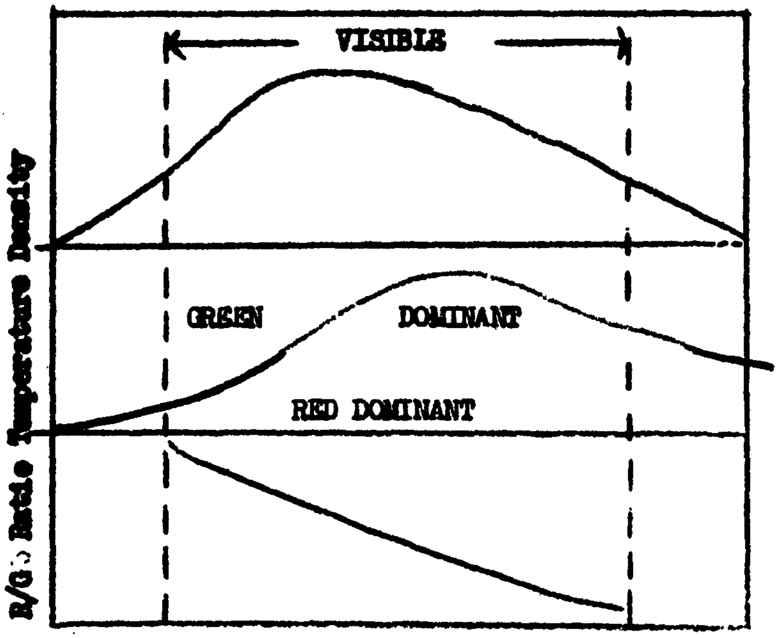

Figure 3

shifts in the red line in the vicinity of active prominences[10] indicate that the red line filaments can exhibit mass-motion kinetic energy, though this is the exception, rather than the rule. The detailed physics of the situation has not, so far as we are aware, been explained, but deserves a theoretical attack.

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[10] Roberts, Ap. J. 108, 523, 1948.

Part II

Origin of White Light Coronal Streamers

by

Walter Orr Roberts, Donald E. Billings
High Altitude Observatory

and Raymond Grenchik
University of Indiana

The shape of the solar corona, its relationship to the more readily observed sunspots, and possible connections between the corona and geomagnetism have occupied the attentions of many astronomers. Even before the end of the last century such people as Ranyard, Lockyer, and Hansky successfully related the changing form of the white corona seen at eclipse to changes of the phase of the sunspot cycle.

Ludendorff 1) in the twenties studied large numbers of coronal isophotes, and found a statistically significant relationship between solar cycle phase and the ellipticity of the corona. Bergstrand 2) in 1930 suggested that the white light corona consisted of two components: (1) a polar corona that dropped off rapidly, and (2) an equatorial halo that was seen at large radius projected above the pole, and that dropped slowly. However, it was van de Hulst and Allen, 3) 4) building on the work of Grotrian and many others, who explained the components of the white light corona in a way that seems entirely satisfactory and makes clear the separation into a truly solar "electron corona" and a "diffraction corona" from interplanetary particles.

The shape variations of this electron corona still present major problems, some of which we have attacked in our present work with the support of the Office of Naval Research. Some of the ideas in this study are several years old, in their most qualitative form; others stem specifically from the summer program of work of the High Altitude Observatory. The specific problem we tackled was the shape of the coronal rays. Roberts had developed some preliminary ideas to explain the pronounced inflections so often found in the streamers and rays. We sought at the outset simply to test these.

The first figure summarizes and also somewhat idealizes, the principal observed characteristics of the white light corona seen at eclipse. A substantial number of observed facts are of interest, and any satisfactory

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1) Sitz.d. Preuss. Akad. Wiss. (Phys-Math) Vol. 16, 1928.
2) Ark. f. mat. astr. o. fys. Vol. 22A, No. 1, 1930..
3) Ap. J., 105, 471, 1947.
4) M.N., 106, 137, 1946.

white light coronal theory must explain them:

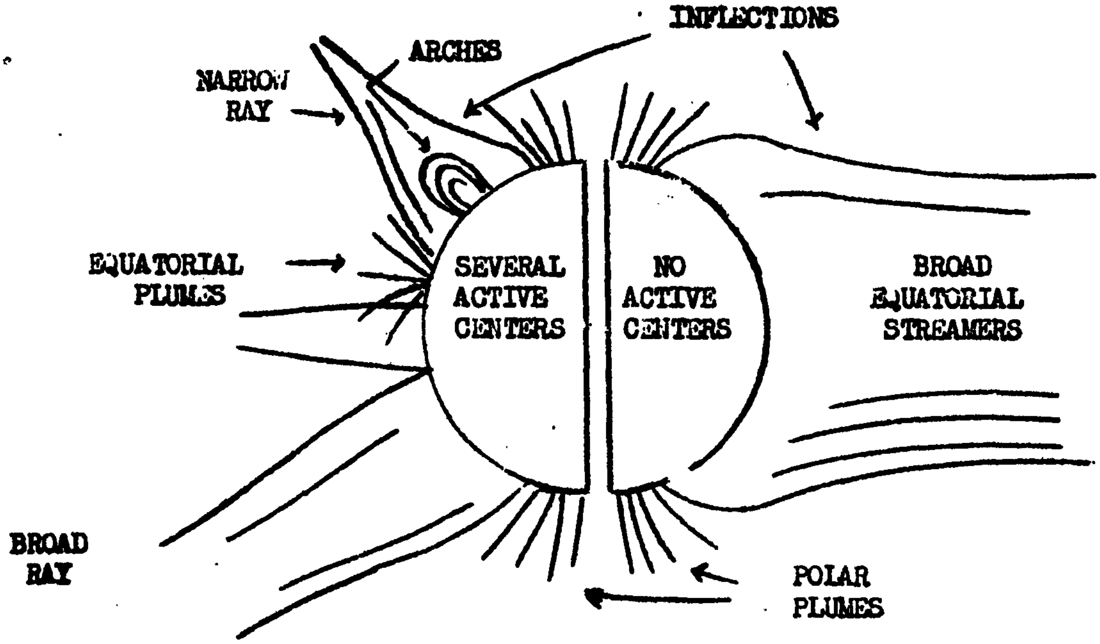

Figure 1

(a) The broadness of the equatorial streams when the sun at eclipse has a large spot-free region near the limb.

(b) The polar plumes, so often used as evidence of a general solar magnetic field. Van de Hulst has shown that they fit reasonably well a dipole of length about 2/3 of a solar diameter, lined up with the rotation pole.

(c) Parallelism of the high latitude boundaries of the streamers and rays with the polar plumes.

(d) The inflections in the streamer and ray boundaries.

(e) The more complex high-spot-activity forms, with numerous narrow and broad rays, as shown.

(f) Equatorial plumes at active sunspot regions, very similar in appearance to trajectories of sunspot prominences. Boundaries of the rays and streamers are parallel to these plumes where they join.

(g) The arches under the rays. Quiescent prominences are usually found there.

Enormous progress towards a self-consistent picture of the relationships among these characteristics was made in 1944 by C. W. Allen,[5] with important contributions also by K. O. Kiepenheuer.[6] Allen proposed that the extension of the white light coronal streamers cause the important geomagnetic and auroral activity that recurs with 27-day periodicity near the minimum phase of the spot cycle. This is the terrestrial activity for which Bartels [7] in 1932 postulated the existence of solar "M-regions," based on the fact that the storms recurred with the solar rotation period.

Allen [5] also showed that the streamers tend to avoid the sunspot regions, and called upon this to explain the well-known cone of about 40° "avoidance" between sunspots and geomagnetic disturbance of M-region type.

Our first effort was directed towards explaining this "cone of avoidance", and the other features of the formation of coronal streamers in a simple static model of the corona, as follows: We sought to identify the shape of the coronal streamers with the shape of the net magnetic fields resulting from interaction of fields of sunspot groups or of spots and the solar dipole -- noting that the field strength of both could be so low as to be undetected by Zeeman effect.

We assumed that neutral ion clouds (electrons and protons) would move along the field, and be funnelled into regions of space defined by the net field.

We pictured the net spot magnetic field at some distance up in the solar atmosphere as like that of isolated single pole. We assumed an excess of flux of one pole to emanate from the spot group, giving a symmetrical field about the spot, of appreciable magnitude to a large distance -- say 250,000 kms from the spot. Equatorial plumes, and the trajectories of "coronal sunspot" prominences in our conception, define the field shape near the spot. This assumed unipolar character, by the way, accords nicely with the recent findings by the Australians Payne-Scott and Little [8] that severe radio noise storms at 97 mc/sec originating in coronal gas well above sunspot groups exhibit polarizations corresponding to a single magnetic polarity for each group, generally to the polarity of the largest individual spot of the group.

From tracings of prominence trajectories for a well-defined example of this phenomenon by Matsushima [9] we derived the general shape of the unipolar spot field, assuming that the trajectories defined the field. We then extrapolated this field, obtaining the approximate shape shown in Figure 2. We postulated as the initial condition for the formation of a narrow coronal streamer, the existence of two similar poles, at some arbitrary distance along the solar surface, as shown. The shape of the net field resulting from the addition of these fields in this plane at least, suggested the shape of the coronal streamers. Interaction with the

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6) Jour. Geophys. Res., 57, 113, 1952.
7) Terr. Mag. 37, 1, 1932.
8) Australian Journal of Scientific Research, 5A, 32, 1952.
9) Unpublished work at High Altitude Observatory, 1951.

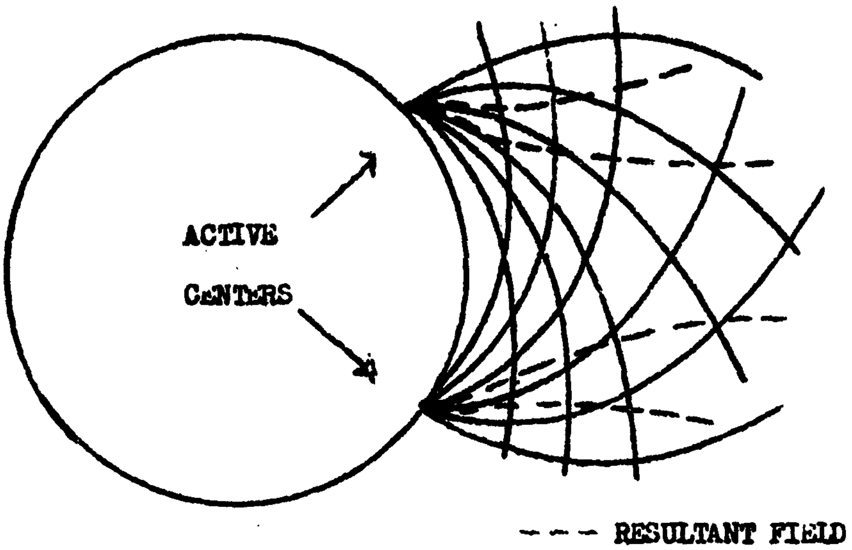

Figure 2

solar dipole field, on the assumption of comparable field strengths, we took as a cause of the high latitude coronal streamers and rays. The hypothesis nicely explained the inflection and suggested that M-regions required spot pairs — and that the ionic cloud (protons and electrons) required for the terrestrial magnetic effect could be gathered up from the whole solar surface between the focussing spots — i.e., from ion spicule and granule jets.

Three facts caused us to abandon this hypothesis: (1) it offered no possibility of explaining the broad equatorial streamers that occur in the absence of sunspot activity; (2) the focussing situation seemed favorable only in the plane including the two sunspots and the radius vectors through them; and (3) the detailed shape of the net field resulting from the interaction of the general magnetic dipole and a spot field could not at any separation be made to fit the appearance of the high latitude rays. Moreover, it seemed unreasonable to ignore the distorting effects of the particle energies on the field itself.

Our next step, therefore, was to look at the possibilities of explaining the streamer shapes as the result of the following two factors: (1) a tendency for net spot-fields of opposite sign to combine to form an "umbrella" over the intervening space; and (2) the distorting effect of particle motions on the net field, causing it to be carried outwards. In this conception, also, the particles comprising the white light corona are ejected over the whole solar surface and are swept into streamers, rays, or plumes. The observed changes of coronal shapes and intensity distributions at different phases of the solar activity cycle follow simply from this hypothesis.

So far, we have examined this idea only in rather qualitative fashion, but it seems to avoid the troubles of the static model at the cost of slightly added complexity. It offers a number of attractive possibilities, as follows:

(a) It explains the general shape both of the no-sunspot corona and of the sunspot corona forms, including the inflections.

(b) It explains the equatorial plumes; and the fact that active regions "repel" the coronal streams is then a logical consequence of the mechanism.

(c) It explains why the lower latitude boundaries of the streamers are always active regions as Bugoslavskay's 10) detailed drawings and interpretations show. It suggests also that the outbreak of sunspots at the base of M-region streamers should cause their disruption, as experimental evidence indicates to be the case.

This conception of origin suggests that the emission line corona and the bases of white light streamers should be mutually exclusive. This, therefore, explains the statistically well-established tendency of the M-region type magnetic storms to occur when the brightness of the emission corona is great three days east of the central meridian for the storm date, a fact reported by Shapley and Roberts 11) in 1945 and recently confirmed by Muller. 12) However, it fails to explain why a similar active center, with strong emission corona, is not found somewhere west of central meridian at the same time. More detailed observational effort will be required, of a sort not now being done at any coronagraphic stations, to settle the important question of the longitudes of the white light coronal streamers.

The theory suggests that the transit time ascribed to M-region particles by Allen 5) and by Kiepenheuer 6) (approximately three days) may be seriously in error. The times could be very much slower than three days. Longitude studies of the locations of the streamers near the sun, and times of the M-region storms at the earth should, however, give us some idea of the curvature, if any, of the M-region coronal streamers as they go far out from the sun.

We call attention to the fact that since the emission corona is related to spot groups, this paper suggests a relationship between the white light corona and the emission corona in contradiction to that described by Waldmeier 13) where M-regions were identified with bright coronal emission regions. The relationship, however, fits very nicely the main conclusions and hypotheses advanced by Allen.

The present state of the problem suggests that a most important

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10) Structure of the Solar Corona, Works of the State Astronomical Institute of P.K. Sternberg, 1950.

11) Ap. J., 103, 257, 1946.

12) Observatory, 73, 75, 1953.

13) Zs. f. Ap., 27, 42, 1950.

theoretical study should be undertaken by someone who is qualified to solve it. The problem is to predict the steady-state density distribution for a uniform cloud of electrons and protons, ejected isotropically, along radii, from the solar surface, on the assumption that the sun has a dipole field, of the shape given by van de Hulst and a field strength of 1 gauss at the pole. If solution of this problem gave shapes suggestive of the no-sunspot corona, it would be strong evidence in support of the hypothesis stated here, and would lead directly into similar consideration for the case of the interaction of the polar field and a sunspot field of the type we have discussed. We therefore sincerely hope that someone will take up the problem and solve it using the Chapman-Ferarro 14) or Alfven 15) or some new approach.

END

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14) Journ. Geophys. Res. 57, 15, 1952.
15) Cosmical Electrodynamics, Oxford Press, 1950.