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RESULTS OF CORONAL HOLE RESEARCH: AN OVERVIEW

By Robert M. Wilson
Space Sciences Laboratory

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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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16. ABSTRACT

An overview of the last 10 years of coronal hole research, in particular since 1970, is presented. The findings of the early investigations and the more recent results obtained with Skylab/Apollo Telescope Mount instrumentation are discussed.

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RESULTS OF CORONAL HOLE RESEARCH: AN OVERVIEW

I. INTRODUCTION

Coronal holes are usually defined as large-scale and long-lived regions on the solar disk and at the poles, where the extreme ultraviolet (EUV) and X-ray emissions are reduced relative to quiet Sun values. Coronal holes are also observed at visible-light and radio wavelengths, they appear as open features (unipolar) bounded by apparently divergent coronal loop structures, and they may be the source of high-velocity streams in the solar wind. Furthermore, coronal holes appear to rotate more as a rigid body rather than sharing in differential rotation and to be regions characterized by low densities and temperatures. Thus, in many ways, coronal holes are the "antithesis of active regions."

The "Skylab Solar Workshop Series A on Coronal Holes," cosponsored by NASA and National Science Foundation and managed by National Center for Atmospheric Research/High Altitude Observatory, has brought together a number of investigators to discuss and deduce the nature of coronal holes. As part of this workshop study, this report is an attempt to summarize the observational and theoretical results of the last 10 years of coronal hole research, particularly the time period since 1970. This report does not attempt to summarize any of the results of the Workshop, although many rather revealing findings have already been determined.

II. DISCUSSION

Coronal hole research extends back more than a decade. Early observations, performed using EUV and X-ray rocket experiments, indicated the presence of coronal holes (although the term "coronal hole" had not been applied) as darkened areas near the poles [1-6]. Withbroe et al. [7] appear to be the first to apply the term "hole" to these darkened, low-emission areas, although it should be noted that Waldmeier [8] lays claims to this honor. In 1957, Waldmeier coined the term "Löcher" (which means "holes") and applied it to low-emission regions that were identified on several consecutive rotations in a study of the morphology of the monochromatic corona using synoptic charts of green-line intensity. In any event, the term "coronal hole" became the accepted description in the literature after 1971.

Based on an analysis of daily Mg X (625 Å) spectroheliograms acquired by the Harvard College Observatory (HCO) experiment on the Orbiting Solar Observatory (OSO)-6 spacecraft for a 28-day period centered on March 7, 1970 (the dates of well-observed total solar eclipse), Withbroe et al. [7] have constructed maps of the variation across the solar disk of the electron density at the base of the corona. Their major finding was that a correspondence existed between low-density regions and reduced-emission regions as observed in white light and Mg X. Hence, coronal holes are observed to be not only reduced-emission areas, but also areas of low electron density.

Krieger et al. [9] have reported results of X-ray rocket observations (November 24, 1970) of large-scale coronal structures. In particular, they investigated the relationship between X-ray coronal holes and chromospheric and magnetic-field observations. Many of these early studies, performed by American Science and Engineering, have been summarized by Vaiana et al. [10]. They found little correlation in the X-ray structure of the coronal hole with either the H-alpha or Ca K observations. Indeed, the network elements appeared little different from those present in other quiet-sun areas. The magnetic-field configuration, however, was more distinctive. It was found that in the center of the hole the photospheric field is weak. Surrounding this area were regions of stronger fields of the same polarity which, in turn, were bounded by similarly intense fields of opposite polarity. The proximity of other X-ray structures, i.e., arcades of close loop structure, gave the appearance that the hole was "open." Very little evidence of any coronal X-ray emission from the hole itself could be seen; however, the presence of faint limb brightening indicated the presence of at least some coronal material within the hole. They concluded that coronal holes are the product of solar magnetic-field configuration, their formation requiring low photospheric-field strengths and diverging coronal fields of predominantly one polarity.

Altschuler and Perry [11] found from K-coronameter data for several time periods large coronal regions of negligible electron density, as had previously been reported by Withbroe et al. [7] in Mg X at the base of the corona. Thus, they concluded that there are coronal holes of relatively negligible electron density which extend out from the base of the corona to at least 1.5 $R_\odot$, where $R_\odot$ is the solar radius. Further, they felt that perhaps there is no "homogeneous corona," but instead only a corona associated with active regions and coronal magnetic fields.

Munro and Withbroe [12] were among the first to study in detail the properties of coronal holes. Using OSO-4 EUV data, they investigated a large, elongated coronal hole (November 9, 1967) which extended from the northern polar region downward across the equator into the southern hemisphere. The hole was particularly visible in the coronal lines of Si XII (499 Å) and Mg X (625 Å). It was found that a coronal hole is characterized by significant deficiency in the intensity of coronal emission lines, yet there is little change in lines and continua formed below 8×10^5 K, except for the He I (584 Å, 504 Å) and the He II (304 Å) emission features. Also, it was found that as the ionization potential of the coronal ions increases, the hole becomes more pronounced. Further, they constructed models for the chromospheric-coronal transition and coronal layers for the hole and areas representative of average quiet regions to deduce any observable differences between the two types of regions. It was found that the electron pressure in the center of the hole was reduced by a factor of 3, the coronal temperature was lower by 6×10^5 K, and the temperature gradient in the transition layer was less steep by an order of magnitude. Furthermore, since both the conductive flux from the corona to the chromosphere and the coronal temperature in the hole were below normal, it appeared that the coronal heating in the hole was lower than in the surrounding areas. Data further indicated that the electron density in the hole was lower than elsewhere on the disk, with some areas in the hole having densities a factor of two to three lower than normal quiet regions. The model indicates that in a coronal hole the electron pressure at the top of the chromosphere is lower than normal and that less heat is deposited there by conduction from the corona. It was concluded that EUV coronal holes are, in a sense, the "antithesis of active regions" because, while active regions display coronal electron pressures and temperatures and temperature gradients in the transition layer larger than in normal areas, coronal holes appear to have smaller quantities than in quiet regions. Furthermore, in active regions the chromospheric EUV emission is enhanced, while in holes this emission is less than or equal to that in normal quiet regions. Also, the appearance of a hole in coronal lines is attributed primarily to the decrease in pressure, but ions with higher ionization potentials are additionally affected by the drop in the coronal temperature.

Because coronal holes appear to be areas in which the coronal gas pressure is significantly lower than surrounding areas, the coronal magnetic field undoubtedly plays an important role in maintaining pressure equilibrium in these regions. Altschuler et al. [13] have studied the relationship between holes and coronal magnetic geometry as computed from measurements of the photospheric magnetic field using a technique developed by Altschuler and Newkirk [14], i.e., calculated current-free (potential) coronal magnetic field. Their investigation of the coronal holes associated with the November 12, 1966 eclipse data indicated that holes generally occur over quiet chromospheric regions where there is usually a weak and diverging magnetic field. Further, it was suggested that coronal holes are regions of reduced chromospheric and coronal heating and predicted that the chromospheric fine structure underlying them would be found to differ from that of the normal quiet chromosphere.

Withbroe and Wang [15], based on an analysis of OSO-4 EUV spectroheliograms [in particular Si XII (499 Å) and Mg X (625 Å)], have investigated changes in the appearance of the corona near the south pole during the period October 25-November 29, 1967. On the basis of their data, they found that throughout the period of interest a large area existed at the south pole where the emission from EUV coronal lines was lower by a factor of 4 or more than the mission in surrounding areas. While major temporal changes in the coronal EUV emission occurred, the change in the polar emission was much less pronounced for lines formed primarily in the transition layer, such as O VI (1032 Å) and Ne VIII (770 Å). To explain the observations, a simple model consisting of two types of regions was used. The first had a temperature-density structure similar to that in models developed for typical equatorial quiet areas. The second had a corona in which the temperature and density were a factor of two lower and the chromospheric-coronal temperature gradient was less steep by a factor of four. The analysis of the EUV data indicated that a major factor causing the low coronal emission in the polar hole was the low electron density in the region, verified by K-coronameter observations. The physical conditions in the polar coronal hole were found to be similar to those in another somewhat larger equatorial hole whose observations have been reported by Munro and Withbroe [12]. The authors reiterated a previous conclusion that the low coronal temperature, coronal pressure, and conductive flux in coronal holes imply a reduced coronal heating in these areas as compared with normal quiet areas. Furthermore, the low coronal pressure and reduced deposition of energy into the chromosphere by conduction from the corona appear to affect conditions in the upper chromosphere, especially as evidenced by the deficiency in the He I and II emission in these areas.

Withbroe and Gurman [16], using HCO OSO-6 EUV data, have constructed models of the chromosphere-corona transition region and lower corona. The resulting models were used to determine how coronal temperature and the conductive flux from the corona to the chromosphere vary as a function of the electron pressure. The authors found the coronal temperature to range from 10^6 K in coronal holes to 2.5×10^6 K in active regions. They also found the conductive flux to vary approximately as $P^{1.8}$, where P is electron pressure, for $P \leq 3.0 \times 10^{15}$ and to remain constant at a value of approximately 6×10^6 erg cm^{-2} s^{-1} for $P > 3.0 \times 10^{15}$.

Efforts at a more quantitative description of the temperature and density structure of coronal holes have been made by Pneuman [17], who explains coronal holes as regions of "open" magnetic-field configuration, while the field lines in surrounding regions are "closed." Pneuman found significant differences between the temperature and density distributions of open-field and closed-field regions. As a result of his calculation, he concluded that coronal holes are not necessarily locations of reduced mechanical heating and alternatively suggested that coronal holes are regions of open magnetic-field lines being continuously drained of energy content by the solar wind expansion and outward thermal conduction.

Additional theoretical studies aimed at explaining coronal holes have been performed by Noci [18], who explored the relationship between the upward mechanical energy flux into the corona, the downward heat flux through the transition region, and the pressure at the base of the corona. His important conclusion was that there must be a greater flow of energy into the solar wind from coronal holes than from nonhole regions. Hence, coronal holes appear to be sources of very strong solar wind.

In addition to the observational evidence that coronal holes seem to occur between the sector boundaries, where the solar wind is known to originate preferentially [18], Krieger et al. [19] deduced that the source of a high-velocity stream of solar wind observed in interplanetary space was probably located within a coronal hole. X-ray images taken during a sounding rocket flight on November 24, 1970 indicated the presence of a magnetically open structure (i.e., a coronal hole) in the lower corona which extended from the northern hemisphere to the south pole. Their analysis indicated a lower-limit temperature within the hole of 1.3×10^6 K and a density/scale-height within the structure a factor of two less than in the surrounding large-scale magnetically closed regions which is consistent with Pneuman's [17] predictions. Using coronal magnetic maps based on the potential-field approximation of Altschuler and Newkirk [14], Krieger et al. showed the basic magnetic configuration surrounding the hole to be divergent, a result also supported by their X-ray images. Magnetograms further suggested low photospheric-field strength within the hole. Using a method of instantaneous ideal spirals to extrapolate the solar wind bulk velocity back to the Sun, it was found that the peak of a conspicuous high-velocity stream originated within the coronal hole. Additional coronal mapping and a review of solar wind data contained in the Solar-Geophysical Data for other time periods indicated a strong possibility that these were recurrent features, thus adding further weight that coronal holes may very well be the source of the solar wind high-velocity streams. Krieger et al. concluded that solar wind bulk velocity and photospheric magnetic-field data from the period 1962 through 1970 indicate the possible extension of their result to the interpretation of long-term variations in the solar wind pattern.

The major success of Skylab offered two great advantages over previous rocket and spacecraft experiments designed to observe the Sun. First, it provided a highly stable platform from which investigations of the Sun could be conducted over a long period. Second, and perhaps more critically, it provided a platform for a number of large instruments with high spatial and temporal resolution. These two criteria provided the means whereby an effective study of the variety of solar features, from the chromosphere through the transition region into the corona, could be accomplished. (For a description of the Skylab/Apollo Telescope Mount and its observing programs, see Schneider and Green [20, 21] and Reeves et al. [22].) Goldberg [23] has reviewed solar research using satellites, in particular the ATM, and discussed, in part, some of the results relative to coronal hole investigation. Other papers which describe some of the first results of the Skylab/ATM data as related to coronal hole research include Vaiana et al. [24, 25], Tousey et al. [26], Huber et al. [27], Lundquist [28], and Reeves and Dupree [29].

Goldberg [23] has reiterated some of the observed characteristics of coronal holes; i.e., (1) they are large, extended areas in which coronal emission is either very weak or absent, (2) they were first observed on the solar disk in rocket photographs and are now recognized also as gaps in the white-light corona seen above the limb, (3) they last at least as long as one solar rotation, (4) they are magnetically open features, usually found above regions of weak longitudinal magnetic field, and may be sources of high-velocity enhancements in the solar wind, (5) they are plainly visible in soft X-ray images and certain EUV spectroheliograms and have recently been observed in the light of the helium D_3 line, (6) they contain X-ray and EUV bright points and large spicules (called "macrospicules"), and (7) they, as compared with normal quiet regions of the corona, have electron temperatures reduced by a factor of approximately 1.6, electron densities reduced by a factor of nearly 3, and temperature gradients lower by a factor of 3 to 10 with a correspondingly thicker transition region [16].

Huber et al. [27] have investigated, based on EUV spectroheliograms obtained by the HCO ATM experiment, the intensity distribution in cells and boundaries of the chromospheric network (and its extension into the transition region) within and outside coronal holes and found that, although the hole boundary is obvious only in Mg X (625 Å), Ne VIII (780 Å), and Ne VII (465 Å), a careful inspection reveals that coronal holes manifest themselves in all layers of the upper solar atmosphere. Further, it was found that all lines have weakened network boundaries within the coronal hole. Histograms representing areas within the coronal hole were found to exhibit a higher and narrower peak than those representing areas outside the hole, suggesting that the intensity is more uniform in the hole than outside. In addition, histograms outside holes exhibit a pronounced tail extending to higher intensities, which can be attributed to the emission network. The weakening of the tail in the histograms for holes suggests that the network weakens in holes more than do the internetwork areas. Huber et al. also found the intensity decrease of Mg X (625 Å) inside the hole to be a factor of 5 and confirmed the finding of Munro and Withbroe [12] and Vernazza and Noyes [30], respectively, that the electron density inside the area covered by a hole is somewhat lower than outside a hole and that the color temperature of the Lyman continuum is approximately 400 K higher within the hole than outside. They also verified a report by Tousey et al. [26] that there is an increase of the limb-brightened ring over holes in Ne VII (465 Å) and found that the height of emission of transition-region lines is greater in the hole by an amount that increases smoothly with increased temperatures of formation.

Continuing investigations into the relation between coronal holes and high-velocity solar wind streams, Kreiger et al. [31] have reported results based on an analysis of X-ray images obtained from the American Science and Engineering experiment onboard Skylab and a comparison of these images with Interplanetary Monitoring Probe (IMP)-H data. They identified 13 coronal holes and 10 possible candidate holes which lay within 20° of the center of the solar disk (in the X-ray images) during the period May 28, 1973 through February 2, 1974. Of the 13 definite coronal holes, 11 had associated solar wind data, 7 were associated with a high-speed stream, and 4 were not. Of the 10 possible candidate holes, 7 had associated solar wind data, 3 were associated with a stream, 2 had a possible association with a stream, and 2 had no apparent stream associated with them. Of the 8 peaks observed in the IMP-H data with radial velocities exceeding 600 km s^{-1}, 6 were associated with coronal holes (the IMP-H measurements were plotted against an assumed departure point on the Sun which was calculated by the constant velocity approximation of Snyder and Neugebauer [32]), 1 was possibly associated with a candidate hole, and 1 was clearly not associated with any hole or candidate hole. Four minor peaks (radial velocity less than 600 km s^{-1}) were also observed in the IMP-H data, all being associated with either definite holes or candidate holes. With the statistics available in only 4-1/4 solar rotations, Kreiger et al. concluded that the association between coronal holes and high-speed solar wind streams is strong but not absolute. Most high-speed streams are associated with coronal holes, and most coronal holes are accompanied by high-speed streams. In particular, they found a strong association between the most prominent coronal hole of the ATM period (denoted coronal hole 1 or CH1) and the most prominent, recurrent high-speed stream.

Roelof [33] has made an in-depth review of coronal structure and the solar wind. He discussed the relation between "open coronal structure and geomagnetic disturbance," "open coronal structure and general coronal emission," and "open coronal structure and the interplanetary field." He also touched upon "nonstatistical indicators of coronal structure" and "high coronal plasma longitudes: the EQRH results" (i.e., extrapolated quasiradial hyper-velocity), and closed with a discussion of "high coronal plasma longitudes: plasma, field and energetic particles."

Harvey et al. [34, 35] have reported results of a comparison of Skylab X-ray images (American Science and Engineering experiment) with ground-based helium D_3 (587 Å) observations. They found that coronal features, such as coronal holes and bright points, are identified in helium pictures with sufficient confidence that ground-based helium observations should be valuable for the study of their evolution. They found good correlation between large coronal holes and D_3 observations. The north polar pole was visible in both; however, the south polar pole, because of the computer enhancement technique, was not visible in the D_3 observations. Further, they pointed out that even small X-ray coronal holes are always associated with abnormally weak D_3 absorption. They concluded that, while it is not possible to identify all coronal holes on D_3 observations, He I (10830 Å) observations do provide a much improved signal-to-noise ratio that allows essentially unambiguous identification of even small coronal holes.

Timothy et al. [36, 37] have addressed the long-term development of the large-scale corona and the structure and evolution of coronal holes based on X-ray filtergrams obtained by the American Science and Engineering telescope aboard Skylab for the period May 28 through September 20, 1973. They found coronal holes permanently in existence over both poles, with two holes extending southward from the north polar hole to latitudes of approximately 20° S. One of these (CH1) was discerned to be very similar to a feature observed on November 24, 1970 [19]. A third hole was also reported to have formed approximately 5 to 10° north of the equator (CH2). They followed the evolution of CH1 as a function of time to ascertain its rotational characteristics at latitudes ranging from 20° S to 50° N, and they explored the relationship between CH1 and a recurrent high-velocity solar wind stream. Their preliminary investigation revealed the following results: (1) coronal holes form in bands of a unipolar magnetic field which are bounded by areas of opposite polarity, resulting in a characteristically divergent magnetic-field configuration; (2) coronal holes have lifetimes in excess of 5 solar rotations, which is in agreement with the typical lifetime of large-scale magnetic features; (3) coronal holes are formed when patterns of emerging active region flux result in the appropriate large-scale field pattern and die when this large-scale pattern is distorted; (4) observations of CH1 showed that while large-scale fields with which the hole was associated displayed differential rotation, the hole itself rotated almost as a rigid body, having a mean synodic rate of $(13.25 \pm 0.03) - (0.33 \pm 0.09) \sin^2 \Phi$ deg day^{-1}, where Φ is the heliographic latitude; and (5) CH1 was the source of a recurrent high-velocity solar wind stream. Timothy et al. proposed that coronal holes are, to some extent, self-propagating structures whose original diverging magnetic-field configuration gives rise to a high-velocity solar wind stream which then causes closed boundary loop structures that have migrated into the hole to become open, thus retaining the original open form of the hole. The structure remains until new protruding field configurations arrive with sufficient energies to produce large-scale loop structure and which are also sufficiently strong to withstand the force of the streaming plasma.

Bell and Noci [38] have statistically studied coronal holes as M-regions [33], correlating them with solar wind disturbances. They compared OSO-6 Mg X (625 Å) spectroheliograms with Pioneer VI solar wind velocity data and the daily K_p geomagnetic index. The results tended to support the coronal hole-high velocity solar wind connection but were hampered by a reduced number of clear coronal holes present on the Sun during the period covered by OSO-6 (August 1969 through April 1970) and by a high noise level in the statistics because of the presence of active regions at the same longitude as the hole. Since M-regions become more conspicuous only late in the solar cycle, the authors undertook a second investigation [39] using OSO-7 Fe XV (284 Å) spectroheliograms, Pioneer VI and IX solar wind velocity data, and the geomagnetic daily sums index K_p published in the Solar-Geophysical Data for the period April 29, 1972 to August 31, 1973. Their results indicate the existence of recurrent disturbances with a 27-day period, based on an examination of the autocorrelation curves for K_p and for corrected solar wind velocity, and a statistical association between coronal holes and these solar wind disturbances, some of which persisted for up to 5 rotations. Bell and Noci concluded that in coronal holes the magnetic field is diverging, which causes a continuous escape of high-velocity solar wind particles. A "normal" solar wind originates in other solar regions of a weak magnetic field where field lines have been opened at some height. An additional source of high-velocity streams may be flares which, by disrupting the equilibrium of the configurations, produce blasts of high-velocity particles.

Drago [40], using Skylab X-ray images (American Science and Engineering), OSO-7 Fe XV (284 Å) EUV spectroheliograms, and Nançay interferometer radio observations (408 and 169 MHz), has attempted to deduce the physical parameters of the large coronal hole CH1 whose central meridian passage took place on May 31, 1973. He found the hole to be visible at both radio frequencies, but because of the higher resolving power, the hole was much more evident at 408 MHz. Because of the lack of north-south resolving power in the radio data, a satisfactory determination of the physical parameters of the hole could not be ascertained. Assuming an average coronal temperature within the hole(T_H) of 1 to 1.5×10^6 K, the results included: (1) an average coronal temperature just outside the hole(T_A) of $T_H \leq T_A \leq 1.1\ T_H$, (2) an average emission measure in the hole of $2.2 \times 10^{23}\ (T_H)^{-1/2}$, (3) an average emission measure just outside the hole between $3.7 \times 10^{23}\ (T_H)^{-1/2}$ and $3.7 \times 10^{23}\ (1.1T_H)^{-1/2}$, and (4) assuming hydrostatic equilibrium, a ratio of electron densities just outside the hole to inside the hole of approximately 1.3.

Palagi et al. [41] have reported evidence that a coronal hole may have been observed twice at a time interval of 1 solar rotation with the "North Cross" Radiotelescope (Bologna, Italy) in observations made during the period December 14, 1973 to January 24, 1974. Unfortunately, they could not give detailed quantitative results.

Gurman et al. [42] have compared EUV data (i.e., Mg X, 625 Å) spectroheliograms) from the HCO experiment on OSO-6 with photospheric magnetograms (Fe I, 5233 Å) from Kitt Peak. Their results indicate a bipartite relationship between values of the longitudinal field strength B and Mg X intensity I averaged over the 35 × 35 arc s raster areas during the period February 27 to March 7, 1970. The relationships were for quiet regions $|B| \sim I^k$, where k is a constant between 0.0 and 0.3, and for active regions $|B| \sim I$. From these relationships, the authors inferred that $|B| \sim n_e^{2k}$, where n_e is the electron density, in quiet regions and $|B| \sim n_e^2$ in active regions. In addition, the authors examined the photospheric field beneath a coronal hole and found it to be virtually identical to that beneath normal quiet regions.

Dulk and Sheridan [43] studied the middle corona from Culgoora 80 and 160 MHz radioheliograms. They mapped the brightness distribution of the quiet Sun at the aforementioned frequencies and found features that are both brighter and darker than average. The "dark" regions in the radiograms were found to be well correlated with dark regions on EUV spectroheliograms (Fe XV, 284 Å). The "bright" regions were found to be associated with quiescent filaments and not plages or bright regions on microwave (Fleurs 21 cm and Stanford 9 cm) or

EUV maps. The authors suggested that these "bright" regions resulted from "coronal helmets," while the "dark" regions resulted from coronal holes. Based on observations between July 13 and 21, 1973, in particular July 20 and 21, 1973, the authors estimated the density and brightness temperature within and near the coronal holes. They found the brightness temperature at 80 MHz outside the hole to be approximately 1×10^6 K and inside the hole approximately 8×10^5 K. At 160 MHz, these values were approximately 1×10^6 K outside the hole and approximately 6×10^5 K inside the hole. The authors deduced the density inside the hole to be approximately one-quarter of that in Newkirk's [44] model of the spherically symmetric corona. The authors also compared the Culgoora observations with those made by the High Altitude Observatory Manua Loa K-coronameter and found good agreement between the radio and optical curves.

Brueckner and Bartoe [45] have reviewed the results of a rocket study (January 15, 1974) of the fine structure of the solar atmosphere based on high-resolution spectroheliograms in the EUV emission lines of He I (584 Å), He II (304 Å), O IV (554 Å), O V (630 Å), and Ne VII (465 Å). They also obtained simultaneously broad-band filterheliograms of the EUV corona and compared the spatial distribution of the EUV emission with H-alpha filterheliograms. They found that there is a very sharp boundary between coronal holes and the regular corona when observed in the coronal EUV lines. They saw no difference in the appearance of O IV and O V EUV emission centers within the coronal hole and within the regular corona, and noted a very slight depression of Ne VII in the hole, as well as an obvious depression of the He I and He II emission centers (in the polar cap). They found no difference in the number or appearance of dark H-alpha mottles when they compared a coronal hole with the regular corona. Also, they found the structure of coronal loops to be perpendicular to the solar surface at the polar caps and were able to recognize a sudden change from a vertical magnetic field structure to a more tilted one at the boundary of a coronal hole. Further, they noted that the He-spicules, called "macro-spicules" [26, 46] appeared to be taller in coronal holes. They suggested that in the temperature range of coronal holes, i.e., 2×10^5 to 1×10^6 K, fine structures such as clouds might be dominant and that the observation not only of a slight depression of the Ne VII emission over coronal holes but also its extension further into the corona might well imply the presence of Ne VII clouds high above coronal holes. Also, they concluded that the "filled-in" network, which marked the boundary of the south polar cap, might indicate low-lying, horizontal magnetic fields outside the hole near its boundary.

Neupert and Pizzo [47] have discussed solar coronal holes as sources of recurrent geomagnetic disturbances, based on an analysis of OSO-7 Fe XV (284 Å) spectroheliograms and superposed-epoch analysis of geomagnetic activity deduced from Application Technology Satellite 1 and Pioneer IX observations for the period January 1972 through January 1973. They investigated both bright coronal regions (associated with solar activity) and regions of less than average brightness (coronal holes). They found that a significant enhancement in geomagnetic activity occurred 2 to 3 days after central meridian passage of large coronal holes that extended to within 5° of the solar subearth point when they were on the meridian (the authors call these "near-equatorial holes" and those not within 5° of the solar subearth point "nonequatorial holes"). Further, they found that neither bright coronal features, sunspots, or bright calcium plage regions showed such a correlation. They noted that the large near-equatorial coronal holes were frequently long-lived features and that they appear to satisfy the requirements for "M-regions," which were hypothesized by Bartels [48] to be responsible for recurrent geomagnetic disturbances. They concluded that if solar wind high-speed streams originate preferentially in coronal holes, the velocity at the base of the corona will be substantially higher than that expected from an axisymmetric solar wind model.

Henze et al. [49] have observed the large August 1973 coronal hole (CH1) on radio maps obtained at 2.0 cm and 8.6 mm wavelengths by the La Posta Astrophysical Observatory and compared the radio coronal hole to that of the X-ray coronal hole as observed by the Skylab/ATM X-ray experiments. They found that the hole decreased in brightness temperature on the order of 50 to 100 K relative to the quiet chromosphere and that the position of the radio coronal hole appeared to superpose the X-ray coronal hole.

Nolte et al. [50] have extended the study by Krieger et al. [31] of the relationship between high-velocity solar wind streams and coronal holes observed in soft X-rays during the period of Skylab observations (approximately 9 solar rotations). They identified eight different coronal holes near solar equatorial latitudes, seven of which recurred for more than 1 solar rotation. One hole was present throughout the mission. Solar wind data from IMP-7 and 8 and Pioneer 6, 7, 8, and 9 were used to identify long-lived, high-velocity solar wind streams. The authors reported that apparently stable, recurrent, high-velocity streams were observed during the Skylab period, three of which were clearly associated with the central meridian passage of well-established, long-lived, elongated (along the meridian), recurrent coronal holes.

Liebenberg et al. [51] have analyzed solar wind development in the middle corona. They compared observed emission-line profiles from above the limb during the 1965 total solar eclipse with computed line profiles from an optically thin corona and found that the picture of solar wind flow from regions outside large coronal streamers is consistent with recent suggestions of solar wind flow from coronal holes.

Fisher and Musman [52] have detected coronal holes from Fe XIV (5303 Å) coronal green-line observations during the period May 23 through 28, 1973. The hole selected in their study was one that lay between NOAA active regions AR118 and AR119 [24] and was also simultaneously observed by the OSO-7 spacecraft. They used Sac Peak photoelectric measurements of intensity to estimate the distribution of volume emissivity in the coronal green-line over the solar surface. Based on this distribution and a calculated dependence of emissivity as a function of temperature and electron density, they were able to estimate a coronal density distribution. Assuming temperatures of 1.4×10^6 K and 1.8×10^6 K, they deduced electron densities in an average coronal hole to be 8.0×10^7 cm^{-3} and 6.8×10^7 cm^{-3}, respectively, which is to be compared with electron densities based on Mg X (625 Å) observations inferred by Withbroe et al. [7] of 2×10^8 cm^{-3}. Also, assuming an electron density for the hole equal to one-third that obtained for the average equatorial region (as suggested by the Mg X data), the authors deduced hole temperatures in the range of 1.15 to 1.23×10^6 K.

Bohlin et al. [53, 54] have reported observations of large He-spicules, called "macrospicules," in the He II (304 Å) EUV spectroheliograms taken with the Naval Research Laboratory (NRL) slitless spectrograph aboard the Skylab/ATM [26, 45]. These macrospicules occur at the Sun's polar limb and somewhat resemble H-alpha spicules, except that they are larger (ranging from 5 arc s to more than 60 arc s in length and 5 arc s to 30 arc s in width), more long-lived (from 5 to over 40 min), and occur only within the chromospheric boundaries of coronal holes. Further, they are observable only in the He II (304 Å) line and only rarely in the transition line of Ne VII (465 Å). At no time are they visible in H-alpha. The authors have noted that Jordan [55] has shown that He II forms in the temperature region 5 to 12×10^4 K, with a maximum at approximately 8×10^4 K at the base of the transition layer or the uppermost chromosphere, which differs markedly from the temperatures deduced by Beckers [56, 57] for H-alpha spicules of approximately 1.6×10^4 K. The authors feel that the physical driving mechanism for macrospicules, whether it be a shock wave [58], a Rayleigh-Taylor instability due to downward conducted energy flux from the corona [59], or one of the theories incorporating interactions of opposite magnetic fields (see Reference 57, for example), must somehow account for this highly selective influence on a very thin layer of the solar atmosphere. The authors concluded that macrospicules are most easily visible over the solar poles due to the coronal holes normally present there; thus, they may be another manifestation of coronal holes. Also, they are much less frequently observed at lower latitudes during limb passage of relatively rare, low-latitude coronal holes.

Bohlin et al. [60] have also discussed the sizes, evolution, and phenomenology of the Sun's polar coronal holes during the Skylab mission. They found that during the Skylab mission period (May 1973 through January 1974), the poles were characterized as permanent coronal holes and that a number of phenomena could be associated with the polar cap region: (1) "marcospicules" in chromospheric He II (304 Å), (2) "polar plumes" in coronal lines forming at 0.7 to 1.1×10^6 K, (3) a wider, elevated, limb-brightened ring in the upper transition-region line Ne VII (465 Å), and (4) a decreased intensity and general loss of definition of the chromospheric network in He I (584 Å) and He II (304 Å).

Gold et al. [61] have investigated the interrelationships among solar wind streams and quiet-time fluxes of energetic solar protons, helium, and medium ($Z \geq 3$) nuclei near Earth for the Skylab mission period by comparing IMP-7 and 8 data with Skylab (American Science and Engineering) X-ray images. They found that large recurrent equatorial coronal holes previously identified as sources of high-speed solar wind also developed recurrent helium and medium energetic particle streams. They note, however, that coronal holes are not the only sources of quiet-time helium and medium energetic particle fluxes. They observed that one coronal hole with its associated solar wind and energetic particle streams disappeared and two holes were born that subsequently developed into high-speed solar wind and helium and energetic particle sources. They further noted that these low-intensity, quiet-time streams are clearly different from flare events and that their coronal ordering suggests that they may be more representative of quiet solar processes.

Mariska and Withbroe [62], based on HCO ATM observations, have constructed limb-brightening curves of EUV resonance lines of C III, O IV, O VI, Ne VII, and Mg X from spectroheliograms of a quiet limb region and a polar coronal hole. They note that a simple model for the transition region and corona fails to account for the observed emission just off the disk; therefore, they include the effects of spicules that extend into the transition region and contribute only a small fraction of their total emission to account for the discrepancy [63].

Wagner [64, 65] has examined Fe XV (284 Å) OSO-7 EUV spectroheliograms during the period May 1972 to October 1973 to determine solar rotational periods for low-emission coronal-hole features. Based on an autocorrelation technique, he deduced synodic rotational periods for coronal holes, which lasted at least 1 solar rotation, for each of seven latitude zones. The zonal rotation periods in days were found to be (1) 80° - 60° N: 27.5 ± 0.1,

(2) 60° - 40° N: 27.1 ± 0.3, (3) 40° - 20° N: 27.1 ± 0.2, (4) 20° N - 20° S: 27.0 ± 0.1, (5) 20° - 40° S: 27.3 ± 0.2, (6) 40° - 60° S: 27.6 ± 0.2, and (7) 60° - 80° S: 28.0 ± 0.4. He also compared the coronal-hole rotation period with those of some other solar features, in particular the photospheric plasma [66], photospheric magnetic field [67], recurrent sunspots [68], and coronal green-line features lasting more than 11 rotations [69]. More recently, Foukal [70] has examined HCO ATM spectroheliograms and Mt. Wilson magnetograms and determined spectroscopic evidence for a higher rotation rate for the magnetic network — approximately 2 percent — than the general photosphere and has found evidence that the flux tubes accelerate the local plasma of the network boundaries. Wagner found that, at the equator, coronal holes corotate with the faster phenomena such as recurrent sunspots, photospheric magnetic fields, and green-line structures. Also, beyond 20° latitude (north or south), the coronal holes exhibit more rigid rotation than most of the other phenomena and closely match the green-line, long-lived quiet regions or the single-rotation, green-line features found during years of declining solar activity. Wagner also noted that, at least in the data of the 18 months under investigation, coronal holes were distributed along four longitudes centered near 0°, 90°, 180°, and 270°. He found coronal holes to wax and wane and later reappear at the same locations. In general, only one or two coronal holes were detected on the Sun at any given time, with two exceptions occurring in January and May 1973 when all four longitudes were sites of holes simultaneously.

Zirin [71,72] has reported observations of the solar chromosphere at the limb as seen in the helium D_3 line taken with the Big Bear telescope during the period August to November 1974. He observed the chromosphere to be easily visible around most of the limb while disappearing in various regions, particularly the poles. He has suggested that these reduced-emission D_3 regions are coronal holes, a suggestion which is confirmed by K-coronameter and He I (10830 Å) data. The author noted that Athay and Menzel [73] have determined the height of the D_3 maximum emission to be at 1150 km and the He II (1640 Å) maximum at 1500 km above the photosphere. Zirin measured the normal D_3 chromospheric brightness to be 0.2 times the brightness of the disk just inside the limb, as seen through the Big Bear universal birefringent filter, and noted the D_3 emission inside the holes to be reduced by a factor of 2 or 3 from the normal chromosphere. He explained the D_3 observations, as well as those of He I (10830 Å) and He II (1640 Å), by means of photoionization by coronal back-radiation. He found that a Chapman-type layer [74] is formed and its height is determined by absorption, with $N(He)H = 5 \times 10^{17}$ near $\tau = 1$ in the He I and He II continua, where H is the scale height, N(He) is the number density of the helium atoms and ions, and τ is the optical depth. He concluded that the chromospheric emission or absorption is weak in coronal holes because there is no coronal back-radiation.

Feldman et al. [75] have examined the line profile of the He II (1640 Å) line obtained with the NRL EUV spectrograph experiment aboard Skylab and have compared the observed profiles with those derived assuming collisional excitation [55] and radiative recombination [72, 76]. The He II multiplet is composed of seven lines, and their wavelengths have been accurately calculated by Garcia and Mack [77]. Also located in the vicinity of the He II (1640 Å) line are lines of Fe II (1637.40 Å, 1640.15 Å, 1643.58 Å) and a Si (1641.3 Å) line. The authors have calculated relative intensities of the He II line as a function of altitude above and below the solar limb for a representative quiet-Sun region and a polar coronal hole. Their findings indicated that, for the quiet-Sun region, the He II intensity peaked at approximately 2 arc s above the limb and, for the coronal hole, the peak intensity occurred at approximately 3 arc s above the limb. They also noted that the coronal-hole intensities were approximately a factor of 4 less than the quiet-Sun intensities and the width of the coronal-hole He II line was approximately 20 percent less than the width measured from the quiet-Sun region. Finally, they found that the helium emission extended with appreciable intensity out to 6 arc s above the limb, an observation difficult to explain using a homogeneous model in which the helium emission is confined to an extremely narrow layer in the transition region.

Jordan [55] has investigated the absolute and relative intensities of helium lines in the solar EUV spectrum, in particular the He I (537 Å, 584 Å) and He II (256 Å, 304 Å, 1640 Å) lines. She noted that the lines of neutral and singly ionized helium in the solar EUV spectrum have anomalously high intensities when compared with lines of other ions at similar temperatures and suggested that the observed absolute and relative intensities, and also line widths, can be accounted for if a mechanism that causes the helium atoms and ions to be excited by electrons with temperatures greater than the ionization equilibrium value is operating. Further, she suggested that the observed decrease of He line intensities in coronal holes, with the apparent little or no change in other transition lines, might be accounted for either by the reduction of the enhancement mechanism in coronal holes and/or by the reduced temperature gradient in the hole region.

Adams and Sturrock [78, 79] have continued investigations into the modeling of coronal holes. They suggest a model that has an energy source which injects a certain constant flux into the base of the corona, an energy outflow from the corona due to conduction of heat downward into the transition region, an energy outflow from the corona due to particles flowing out into the solar wind, and an empirical relation between the temperature and density at the base of the corona. The authors compared the results of their calculations with observations reported by Munro and Withbroe [12], and found reasonable agreement, exceptions being in absolute flux values and flux decrease factors.

(Munro and Withbroe reported a decrease of flux by a factor of 8 from 1×10^6 to 1.3×10^5 erg cm^{-2} s^{-1} within the hole; Adams and Sturrock only see a decrease by a factor of approximately 2 from 1.7×10^5 to 7.9×10^4 erg cm^{-2} s^{-1}.) Adams and Sturrock concluded that the diverging-field pattern associated with coronal holes can, indeed, bring about reductions in the temperature and density at the base of the corona comparable to those observed in coronal holes.

The intensities and profiles of selected EUV transition-region lines for a quiet-Sun region and a polar coronal hole have been investigated by Feldman et al. [80]. The spectra were obtained from the NRL slit spectrograph onboard Skylab on August 14, 1973 (coronal hole) and August 27, 1973 (quiet-Sun region) and covered a region from 12 arc s inside the limb to 20 arc s above the limb. The lines selected for comparison included O II (1666.15 Å), O IV (1399.77 Å, 1401.16 Å), O V (1218.41 Å), N IV (1486.50 Å), N V (1238.82 Å, 1242.80 Å), S IV (1406 Å), Al III (1854.72 Å), and Si III (1298.9 Å), which are formed at temperatures in the range from 0.36 to 2.2×10^5 K. The authors found that lines of the higher temperature ions (e.g., O V) are significantly less intense in the coronal hole, while lines of lower temperature ions show little change. The profiles of optically thin transition region lines (O V, N IV, and O III) were found to be equal to within 10 percent, and nearly the same for both the quiet-Sun region and the coronal hole, being somewhat broader than expected assuming ionization equilibrium. Also, the authors showed the line profile and width for the chromospheric line of O I (1355.60 Å) to be significantly different from the aforementioned lines, but again they were the same whether inside the coronal hole or quiet-Sun region. Further, they deduced bulk velocities of 28 km s^{-1} (O V), 24 km s^{-1} (N IV), and 20 km s^{-1} (O III) for the aforementioned transition-region lines, based on their line widths, and concluded that there appears to be little, if any, statistically significant difference in the velocities obtained from the quiet-Sun region and the coronal hole.

Doschek et al. [81] have investigated limb brightening of selected EUV transition lines in the quiet-Sun and the south polar coronal hole, based on observations obtained with the NRL ATM spectrograph on August 14, 1973 (coronal hole) and August 27, 1973 (quiet-Sun region). The lines included those lines identified in Feldman et al. [80] and O IV (1407.39 Å), S IV (1416.94 Å), and Si III (1303.32 Å), as well as O I (1355.6 Å). These lines are emitted from ions formed within the temperature range from 1×10^4 to 2.2×10^5 K, and the limb-brightening curves covered a region from 4 arc s inside the limb to 20 arc s above the limb. The authors compared data from 0 to 20 arc s with predictions based on both homogeneous and inhomogeneous models of the transition region and concluded that O I is formed in spicules, while the limb brightening curve of the He II (1640.4 Å) is consistent with a temperature of formation of approximately 4 to 9×10^4 K.

Roelof et al. [82] have reexamined the problem of the relationship between coronal optical emission — the green-line of Fe XIV (5303 Å) — and interplanetary plasma measurements from a statistical point of view that emphasizes causal relationships that are shorter than 1 solar rotation. The authors computed cross-correlation functions based on Kislovodsk green-line intensity measurements and Vela solar wind velocity data for the period January through June 1967. The cross-correlation functions were calculated separately for east and west limb observations in 5° latitude increments, and the solar wind velocities were correlated at their estimated emission times by correcting for the plasma Earth-Sun transit time using the observed velocities. The authors found cross-correlation patterns that appeared to be dominated by two competing effects: (1) a tendency of quasistationary green-line emission and solar wind velocity to "anticorrelate" and (2) a tendency of transient green-line emission and solar wind velocity enhancements to correlate "positively." The authors also noted evidence for simultaneous (same-day) emission brightenings over 2 to 4 limb quadrants.

Pope and Schoolman [83] have investigated the height of emission of the D_3 line in the chromosphere. Using a specially designed, double-peaked birefringent filter, they obtained simultaneous filterheliograms of the limb in D_3 and the nearby continuum. They observed the D_3 chromosphere to be a shell which is separated from the limb by a gap, the height of maximum D_3 contribution occurring at approximately 1350 km above the limb and being independent of intensity, which ranged between 1 and 10 percent of the intensity at disk center. They interpreted this gap as the height to which coronal EUV radiation is capable of penetrating the atmosphere. The authors suggested that the area of very low D_3 emission, noted in some of their filterheliograms, was probably coincident with coronal holes.

Fürst and Hirth [84] have observed a coronal hole at 10.69 GHz (2.8 cm) with the Bonn 100 m radio telescope on July 24, 1973, and noted the difference of the brightness temperature between outside and inside the hole to be approximately 400 to 500 K. They noted that the lack of emission within the coronal hole could be explained by an electron density at the bottom of the corona to be between 2 and 3×10^8 cm^{-3}, densities which agree with those derived from limb-brightening observations at 5 GHz by Chiuderi et al. [85].

Lantos and Avignon [86] have investigated the quiet-Sun at 169 MHz (1.77 m) from 1957 to 1970 using the Nançay interferometer. The time period of observation includes the maxima of two solar cycles (Nos. 19 and 20) and the minimum between them. The authors compared their data with other radio and UV observations and also with the Munro and Withbroe [12] model, and concluded that the radio quiet-Sun corresponds to the coronal holes. The authors noted that the physical condition in the coronal holes did not vary systematically with the cycle of activity, as indicated by the approximate constancy of the brightness temperature, being about 7.5×10^5 K. A comparison of their model with that of Munro and Withbroe [12], for coronal holes, yielded values that were somewhat lower; e.g., a temperature of 9×10^5 K as compared to 1.05×10^6 K, a flux of 7×10^4 erg cm^{-2} s^{-1} as compared to 1.25×10^5 erg cm^{-2} s^{-1}, and an electron density of 1.2×10^8 cm^{-3} as compared with 3×10^8 cm^{-3}. The authors suggested that the absence of variation in the coronal heating in the holes is primarily constant with the cycle of activity and, correlatively, that the heating is local and, to a first approximation, independent of the surrounding active regions. Finally, the authors suggested that the conditions described by Vaiana et al. [10] as being necessary for the formation of coronal holes, i.e., that they are the product of specific solar magnetic-field configurations (e.g., the absence of strong magnetic fields, the presence of surrounding regions of opposite polarity, and the divergence of the magnetic fields), are not the basic conditions of their formation, rather they may only be reasons which may explain the absence of loops over them, loops being associated with the active regions of the Sun.

Avignon et al. [87] have also reported observations of the flux of the quiet-Sun and its brightness temperature at 408 MHz (73 cm), derived from measurements with the E-W Nançay interferometer and the E-W arm of the Medicina North Cross for the periods March 1973 to October 1974 and December 14, 1973 to January 24, 1974, respectively. They found that the lowest envelopes, which define the radio quiet-Sun, correspond to transits of extended coronal holes across the Sun's disk. They deduced the central brightness temperature for the quiet-Sun, which is the value to be applied to the coronal hole, to be 4.6×10^5 K.

Withbroe and Jaffe [88] and Withbroe et al. [89] examined two macrospicules in a coronal hole at the north pole on December 11, 1973 using the Harvard instrument onboard Skylab. They constructed contour maps from the C III (977 Å) EUV spectroheliograms and observed the features to shoot upward to a maximum height of 3.5×10^4 km above the limb and then fall back into the chromosphere, reaching terminal velocities of approximately 140 km s^{-1}. They observed the maximum diameters of these features to be approximately 5 arc s, or approximately 3.6×10^3 km. The authors calculated the total EUV flux of these features when they were at maximum height for Lyman-alpha (1216 Å), C II (1335 Å), C III (977 Å), O IV (554 Å), and O VI (1032 Å) and found them to be in the range of 5.5×10^{20} to 3.3×10^{23} erg s^{-1}, dependent on which of the two macrospicules was under discussion and which wavelength was of interest. They also plotted the variation of intensity with time at several heights above the limb for one of the macrospicules in C II (1335 Å) and Mg X (625 Å) and found the Mg X intensity to be reduced when the C II intensity was at its greatest value, attributing this to absorption by the macrospicule of coronal radiation from behind the macrospicule. On the basis of a model developed by the authors from the EUV measurements (i.e., a cylindrical macrospicule with a cool core surrounded by a transition sheath in which the temperature increases radially outward to the coronal value of 10^6 K; most of the mass of the macrospicules is contained in the cool core), they found that the energy required to produce the macrospicules was approximately 3×10^{26} ergs, which is approximately 2 orders of magnitude more than that required to produce an ordinary spicule and indicates that macrospicules may be an important factor in the energy balance of the chromosphere and corona.

A number of atlases of coronal hole observations have been generated over the years. These include the one of Reeves and Parkinson [90], who discuss OSO-4 coronal hole positions; Wetherbee and Reeves [91], who discuss ATM/S055 EUV coronal hole observations; Bohlin [46], who cross-references the ATM/NRL and American Science and Engineering observations; Nolte et al. [92], who discuss ATM/S054 X-ray coronal hole boundary observations; Underwood and Broussard [93], who discuss coronal hole boundary observations prior to Skylab; and Wilson [94], who discusses ATM/S056 X-ray coronal hole observations. Also, a compendium of coronal holes within ±30° of the solar equator for Carrington rotations 1601 through 1610, an association of coronal holes and solar wind streams for the same period, and a table of average properties of four high-speed streams have been generated.[1] Finally, in addition to those papers already cited, a number of other articles including in part Goldberg et al. [95], Krieger et al. [96], Underwood [97], and Livingston et al. [98], while not discussing coronal holes per se, do show coronal hole imagery and may be of interest to the coronal hole investigator.

It is to be emphasized that this report only presents results already reported in the literature and, hence, does not include the most recent findings of the "Skylab Solar Workshop Series A on Coronal Holes" which will publish its proceedings later. The Workshop has been investigating the correlation of various satellite, rocket, and ground-based (visible light and radio) observations of coronal holes and the interplanetary medium to deduce the morphology and evolution of coronal holes and the relation between holes and the solar wind. In addition, Workshop participants have generated physical models of holes from the Sun's surface all the way to the Earth and beyond in attempts to understand the basic solar physics of coronal holes. Some of these initial findings have been reported in the Skylab Solar Workshop Newsletters and in contributions submitted to the Workshop.

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1. See Skylab Solar Workshop Newletter, vol. 1, no. 3, March 1976, pp. 5-12.

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APPROVAL

RESULTS OF CORONAL HOLE RESEARCH: AN OVERVIEW

By Robert M. Wilson

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

ANTHONY C. DeLoach
Chief, Solar Sciences Branch

WILLIAM C. SNODDY
Chief, Astronomy and Solid State Physics Division

CHARLES A. LUNDQUIST
Director, Space Sciences Laboratory

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