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ANNUAL REPORT ON AERONOMY RESEARCH
AT RICHLAND, WASHINGTON

R. J. Hoch

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**ANNUAL REPORT
ON
AERONOMY RESEARCH
AT RICHLAND, WASHINGTON**

By

R. J. Hoch

**Mathematics and Physics Research Department
Systems and Electronics Division**

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**BATTELLE MEMORIAL INSTITUTE
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- Page 12, line 1: "Approximate" should be "Appropriate"
- Page 12, line 11: "Chander" should be "Chandra"
The same change in the 8th reference on p. 179 is required.
- Page 19, footnote: 4π should be $(4\pi)^{-1}$, 2 places
- Page 24, fig. 3-2: delete (2106 PST), the UT entries are accurate.
- Page 71, line 1: "approximate" should be "approximated"
- Page 90, line 4: "Norten" should be "Norton"
- Page 113, lines 6 and 13: A should be A
- Page 115, line 12: " $4\pi \times 10^6$ " should be " 10^6 ". The subsequent results are therefore a factor of 4π too low. This error effects the remainder of the ensuing discussion, but the general conclusions are believed to be valid. They are valid because rather coarse "worst case" estimates were used up to the point of the mistake and when these estimates are refined one can still arrive at about the same result by the tighter argument.
- Pages 128-130: Add to captions of Fig. 7-5a, b, c, respectively, the dates: 27/28 Feb. 68, 20/21 Mar. 69, 8/9 Mar. 70.
- Page 180, insert: *Frank, L. A. Explorer 12 Observations of the Temporal Variations of Low-Energy Electron Intensities in the Outer Radiation Zone During a Geomagnetic Storm, J. Geophys. Res., 71 19, 4631, 1966*

Foreword

Attention was focussed this year on the analysis and interpretation of the data. This task was facilitated by the automatic digital equipment that came into operation early in the year. Though this automatic equipment was designed to reduce and display data on-line in real time, we arranged it so we could also recycle data that had been accumulated in the past through the equipment. From the beginning of the investigation in 1967, we had kept a parallel record of all raw data on punched paper tape in addition to the analog record we had been using for analysis "by hand." Thus when the digital equipment was ready to operate the old data were all ready in appropriate digital format and we were able to feed the relevant backlog through the equipment with only minor editing.

It would be difficult to over-estimate the impact the high speed digital equipment has had on the research. It reduced days of handwork to minutes and made it possible to have a complete overview of the results in such a short time that we could focus attention on the physical processes involved. It also provided the luxury of being able to try out an idea without great expense or loss of time; for example, trying a new altitude assumption, or a new magnetic field configuration.

The results of this are that we have been able to present this year what we believe to be definitive answers on the cause of the stable auroral red arcs that occur at mid-latitudes. The report is directed entirely toward the progress made in explaining the physical phenomena under investigation. The progress is summarized in the abstract and in the final section of the report.

It is gratifying to be able to describe even in outline what the essential processes are in the formation of the glowing red rings that occur in the mid-latitude zone of our planet but the understanding brings to the fore new scientific problems.

We find, for example, that although we can explain how the mid-latitude arcs arise from the ring current in the magnetosphere, it is not known why the ring current itself develops during a magnetic storm. However, we believe that on the basis of the work done so far, we have a new experimental approach for the ring current problem.

We have found that the arcs provide a way to monitor the position and radial movement of the ring current region and we've also found that the behaviour seems to be closely connected to the position and motion of the plasmopause. Our optical monitoring technique apparently provides a very useful tool for studying these fundamental structural features of the magnetosphere provided we can establish how the arcs are located with respect to these features under a range of conditions.

The optical monitoring technique is not as direct an approach to studying the magnetosphere as *in situ* measurements by satellite, but it is complementary to the satellite measurements and has the advantage of being continuous rather than intermittent. Furthermore, we can scan a large fraction of the field line intersections with the atmosphere at one time whereas the satellite takes data only at successive points along its line of flight. We have inferred the correlations of the arcs with magnetospheric features by finding a few cases where we and the satellites made simultaneous measurements.

There is actually a ground-based technique for measuring the position of the plasmopause by monitoring proton whistlers - more precisely, by monitoring magnetic micropulsations which are interpreted in terms of whistlers. Since we have inferred that the arcs and presumably the ring current develop where the plasmopause is located, then what ought to be done is to measure the arc positions and plasmopause position simultaneously from the ground. This will tell us whether the detailed behaviour of these two features is precisely correlated and, by inference, whether the ring current follows the plasmopause too.

We have made arrangements to borrow the micropulsation apparatus to start making plasmopause measurements simultaneously with the optical observations. In the coming year we will attempt to initiate these simultaneous measurements to the extent possible within budgetary constraints.

This report, though written by one of us (R.J.H.) summarizes research in which several have participated. The participants were: Mr. C. R. Batishko (now with the Kitt Peak Observatory in Tucson, Arizona), Mrs. F. I. Carver, Dr. K. C. Clark, of the University of Washington, Mr. R. W. Owen, Dr. F. E. Roach, (consultant to the program), Mr. L. L. Smith, Mr. R. L. Skaugset and the author, R. J. Hoch. Except as noted, the participants are Battelle-Northwest staff.

ANNUAL REPORT ON AERONOMY RESEARCH
AT RICHLAND, WASHINGTONAbstract

A brief history of research on Stable Auroral Red (SAR) arcs is presented. Results of observations of SAR-arcs from Richland, Washington, during the period September 27, 1967, through March 31, 1970, are described. Twenty-three events are divided into 15 definite and eight probable SAR-arcs. Typical features and behavior of the SAR-arcs are described and the location of 14 arcs is shown. A record of all observations, visibility and geomagnetic activity is appended. A first estimate of probability of SAR-arc occurrence on a given night is 0.09.

The ratio of [OI] 6300A/ [OI] 5577A was determined in one intense SAR-arc (3.5-4 kR) to be 26. An analysis of the process of excitation of atomic oxygen by electrons shows that the observed arc would be produced by electrons with a characteristic temperature of 4200° K and lower than normally assumed density. In addition, a very small high energy tail on a Maxwellian distribution of electron energies is required.

The ratio of [NI] 5199A/ [OI] 6300A in another intense SAR-arc observed by others [*Carleton and Roach*, 1965] is subjected to similar analysis in terms of electron excitation. The electron temperature and density requirements found in the preceding ([OI] 6300A/[OI]5577A) analysis are found to be required in this second case also. The high energy tail is not needed but may be present.

The resulting electron spectrum, density and temperature are consistent with other's observations [*Carleton and Roach*, 1965; *J. R. Roach*, 1963; *Norton and Findlay*, 1969] though not with other's assumed values for

calculations [*Walker and Rees*, 1968; *Roble*, 1969]. The electrons seem to bear evidence of being heated from the topside of the atmosphere.

The possibility of the SAR-arcs being excited by the magnetospheric particles that cause the main phase decrease of the geomagnetic field is investigated. Evidence of the spatial and temporal coincidence of intermediate energy magnetospheric particles with the SAR-arcs is found and reviewed. The energy content and loss rate measured are found to fit the requirements of SAR-arc production. The excitation of the SAR-arcs is examined in terms of the behavior of the incoming charged particles and secondaries traversing the atmosphere.

With a connection between the SAR-arcs and the magnetosphere established, the position of many SAR-arcs is then traced back along field lines to investigate the internal structure of the magnetosphere. The motion of the arcs is found to be traceable to a characteristic azimuthal asymmetry of the plasmasphere. It is suggested that the particles that cause the main phase decrease and cause the SAR-arcs must share this **asymmetry**.

The physical conditions at the interface of the plasmasphere and the source region of the SAR-arcs are examined and it is found that it is plausible that a supra-thermal electron distribution should be formed at the interface. Followed down field lines to earth, this electron anomaly seems to correspond approximately to one which has been observed by satellites contemporaneously with a SAR-arc occurrence.

A simple model of the magnetosphere is formulated and an analysis of the behavior of longitudinal hydromagnetic (hm) waves in the region of

the plasmopause is undertaken. It is found that the plasmopause is an unstable region. In this region longitudinal (hm) waves can develop and propagate freely. Wave energy is dissipated preferentially at the boundary. This localization of heating might, it is suggested, give rise to the distribution of particles that cause the main phase field decrease and excite the SAR-arcs.

Table of Contents

Foreword	iii
Abstract	vi
List of Figures	x
List of Tables	xv
Introduction	1
History of the Problem	8
Occurrences of Stable Auroral Red-Arcs	18
Ratio of [OI] 6300Å/ [OI] 5577Å and Estimate of Electron Temperature	33
Expected Ratio of [NI] 5199Å/ [OI] 6300Å	67
Identification of the Particles that Excite the SAR-Arcs	91
Mapping of SAR-Arcs into the Magnetosphere	119
The Heating Mechanism	145
Summary and Conclusions	172
References	179
Appendices	184-217
Biographical Note	218

List of Figures

<u>Figure</u>		<u>Page</u>
3-1	Position of the SAR-arc at 0745 UT (2345 PST) September 29, 1967	22
3-2	SAR-ARC southward drift illustrated by positions at one-hour intervals as observed from Richland station.	24
3-3	Daily and three-hour planetary magnetic indices for several days near time of SAR-arc occurrence	25
3-4	Occasions on which SAR-arcs have been recorded at Richland, Washington, from late September 1967 through March 1970.	27
3-5	Maps of SAR-arcs. The shaded region (PA) marks the portion of the sky in which [O I] 6300 Å from the poleward aurora was brighter than the region of the SAR-arc. The intensities shown are rough averages of the brightest region taken along the length of the SAR-arc. Each map covers a circle approximately 3000 km in diameter. Geographic coordinates of the center of the maps are 46° 25'N and 119° 38'W.	28
4-1	Photometric intensity (scale deflection units) in azimuthal scans at 10° and 50° elevation, 8/9 March 1970, 1950 PST	36
4-2	Energy level diagram of O I 2p ⁴	42
4-3	Cross sections for electron-induced excitation of atomic oxygen from <i>Smith, Henry and Burke</i> [1967]. Also shown are linear segments used to approximate the cross sections.	47
4-4	The red-green ratio $\rho(h, T)$ for a range of T and several values of h.	50
4-5	The value of the red-green ratio $\rho(T)$ weighted to account for the altitude dependence of the volume emission rate.	53
4-6	Electron temperature versus altitude in a SAR-arc according to the calculations of <i>Roble</i> [1969].	54
4-7	The effect of shifting the SAR-arc downward on the red-green ratio $\rho(T)$.	57

<u>Figure</u>		<u>Page</u>
4-8	Joining a high energy tail onto the main Maxwellian distribution. On a linear (l.h.) scale the difference between the high energy distribution and the original one is very small (lowest curve). On a logarithmic (r.h.) scale the difference is apparent.	60
4-9	[OI] 6300Å intensity from a SAR-arc as a function of electron temperature at 400 km, from calculations of <i>Roble</i> [1969].	63
4-10	Composite electron energy spectrum consisting of a 4200°K Maxwellian distribution (0, 1.96eV) and a 9000°K Maxwellian tail above 1.96 eV.	65
5-1	Energy level diagrams of oxygen and nitrogen.	69
5-2	Cross sections for electron induced excitation of oxygen and nitrogen. From <i>Smith, Henry and Burke</i> [1967].	72
5-3	Plot of the ratio $g(T) = \frac{a_4 s^2 D}{\alpha_3 p^1 D}$ as a function of temperature.	74
5-4	Density of the several species used in calculation of $\rho(h,T)$.	76
5-5	$\rho(h,T)$ as a function of altitude for several temperatures of the electrons (NO QUENCHING).	78
5-6	The ratio $\rho(h,T)$ as a function of altitude in cases of quenching by electrons according to two electron distributions used by others and in the case of no quenching (upper limit).	80
5-7	Variation of $\rho(h,T)$, ($h=400$ km), according to the electron density assumed at 400 km.	82
5-8	Time variation of [OI] 6300Å intensity during measurement of <i>Carleton and Roach</i> [1965].	84
6-1	Illustrating the "normal" (upper half) and "heated" (lower half) configuration of the inner part of the geomagnetic field.	94
6-2	Detection of the "ring current" during the magnetic storm of early November 1961, from <i>Frank</i> [1966].	96
6-3	L-dependence of peak count rate on 1 October 1961 from Explorer 12 measurements after <i>Frank</i> [1966].	98

<u>Figure</u>		<u>Page</u>
6-4	Position of the brightest region of a SAR-arc recorded 7/8 November 1961 at Fritz Peak, Colorado, after <i>Marovich</i> [1966]	99
6-5	Contours of constant proton ($200 \text{ eV} < E < 50 \text{ keV}$) energy densities on 9 July 1966. From a report by <i>Frank</i> [1967] on the measurement of the extraterrestrial ring current during geomagnetic storms. The point of closest approach $\lambda_m \sim 55^\circ$ ($L \sim 3.04$) according to Frank.	102
6-6	Distribution of position of SAR-arcs during geomagnetic storms compared to position of the ring current tip reported by <i>Frank</i> [1967] for 23 June 1966 ($L \sim 4$) and 9 July 1966 ($L \sim 3$). The dashed line is only meant to suggest the trend toward higher L with weaker storms. $\bar{A}_p$'s are averages during the SAR-arcs and the vertical bars indicate the drift of the SAR-arcs.	104
6-7	Variation of the horizontal component of the geomagnetic field. These are combined data presented by <i>Frank</i> [1967] from several low and mid-latitude stations.	105
6-8	Intensity of a SAR-arc as a function of top-side energy flux (at 1000 km) according to the calculations of <i>Roble</i> [1969].	107
6-9	Illustrating the top-side surface at 1000 km altitude used for calculation of incoming energy.	108
6-10	Meridian spectrogram and densitometer tracing from north to south along the 6300A line, 23/24 March 1969, 2023 PST, <i>Richland</i> station. Note that the H_α emission is a few degrees above the north horizon and has only slight altitude extension. The 6300A emission in the SAR-arc peaks about 20° south of zenith.	110
6-11	Meridian spectrogram, 25 min. 23/24 March 1969 0307 (start) MST, Banff. Note that the H_β emission extends over most of the meridian. The H_α emission is obscured by bands of molecular nitrogen.	111
6-12	Position of the H_α and H_β emitting regions determined by triangulation. The extent of the emitting volume (at half-maximum) is indicated. The position of a SAR-arc recorded at <i>Richland</i> is shown at an (assumed) altitude of 400 km.	112

<u>Figure</u>		<u>Page</u>
7-1	Mapping of the SAR-arc into the magnetosphere.	121
7-2	The three steps in the transformation of coordinates illustrated schematically.	122
7-3	Illustrating the distortion of the westward (l.h.) side of the SAR-arcs toward higher L's.	124
7-4	Plots of quadratic functions obtained by least squares analysis for separate regions of the SAR-arc.	127
7-5 a, b, c	SAR-arc positions transformed to the magnetic equatorial plane.	128
7-6	Azimuthal configuration of the plasmasphere exaggerated for clarity, from "Physics of the Earth in Space", page 84, National Academy of Sciences report (1969).	131
7-7	Plasmasphere density and RC energy density versus L according to <i>Taylor, et al.</i> , [1968] and <i>Frank</i> [1967].	133
7-8	Illustrating the energy density anomaly at the interface of the plasmopause and the RC distribution.	134
7-9	Energies required of plasmasphere protons to remove the density anomaly.	136
7-10	Electron density at approximately 2000 km on 28/29 September 1967 from <i>Norton and Findlay</i> [1969].	138
7-11	Electron temperature at approximately 2000 km on 28/29 September 1967, from <i>Norton and Findlay</i> [1969].	139
7-12	Position as a function of time for several SAR-arcs in the meridian plane.	141
7-13	Distribution of SAR-arcs transformed to magnetic equatorial plane.	143
8-1	Alfven velocity in equatorial plane.	149
8-2	Plasma density in equatorial plane.	151
8-3	Nature of the longitudinal wave.	154
8-4	Radial dependence of k_i and k_r .	159

<u>Figure</u>		<u>Page</u>
8-5	Change in wave energy in the region of the instability ignoring reflections.	163
8-6	Simple analog illustrating the function of the knee.	165
8-7	Waves in which $\vec{k} \perp \vec{B}$ but $\vec{k}$ not $\parallel$ to $\vec{r}$	168
8-8	Compression of the magnetosphere versus field increase at sudden commencement, after <i>Hess</i> [1968]	169
9-1	Suggested experiment.	177

List of Tables

<u>Table</u>		<u>Page</u>
3-1	Occasions of definite and probable SAR-arcs observed at Richland, Washington	26
4-1	Observed intensities, kilo Rayleighs	38
4-2	Corrected intensities (kilo Rayleighs) with correction factors and the final intensity ratios	40
4-3	Coefficients for evaluation of equation 4-15	49
5-1	Coefficients for evaluation of equation 5-6	73
5-2	Comparison of ρ for several cases	86

ANNUAL REPORT ON AERONOMY RESEARCH
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1. Introduction

In Section 9 (the last section) the results of this research that are believed to be novel are listed. In this first section the intention is to place the work in perspective with other research and explain the motivation for the investigation undertaken.

At altitudes of 250 to 700 km above the earth the predominant neutral component of the atmosphere is atomic oxygen. The actual peak in the atomic oxygen density lies in the 100 to 120 km range which is where most of the oxygen atoms are produced by photo-dissociation of the O_2 molecule. The so-called E region of the ionosphere near 100 km, and the region just below it is a highly active part of the atmosphere in terms of optical transitions. It is in this region that most of the familiar visible auroral displays have a peak intensity, and it is also the location of the ever present [O1] 5577A airglow layer. Most studies and analyses of auroral phenomena are thus naturally focused on the 100 km altitude region. This study, however, is concerned with a less well-known subvisual auroral phenomenon which begins at about 300 km, reaches a peak intensity at about 400 km, and extends to 600 or 700 km.

In several ways the atmosphere is simpler above 250 km than it is in the 100 km region. To a good approximation one may assume that the neutral constituents are in diffusive equilibrium above 250 km. But, even more helpful is the fact that from 300 to 700 km the neutral atmosphere is practically pure atomic oxygen. The presence of this lightweight gas at great altitudes is to be expected on the basis of a Boltzmann statistical

distribution or equivalently on the basis of the barometric law. The absence of a comparable concentration of atomic nitrogen which is even lighter and might therefore be expected in the same region is due to the relative difficulty of dissociating a diatomic nitrogen molecule by the same processes that rather easily dissociate molecular oxygen. Thus, the concentration of N is low at high altitudes because few N atoms are formed from N_2 . The reasons for the relative stability of N_2 are quite interesting but we will not be able to cover that topic. The little bit of atomic nitrogen that is present above 300 km, ($n(N)/n(O) \sim 10^{-2}$) and which may or may not be excited when oxygen is, can serve as a kind of indicator to the analyst to distinguish between excitation mechanisms. For example, excitation to the first excited state induced by electron collision would be expected to occur with comparable specific probabilities for the O and N atoms; but in chemical reactions in the atmosphere, O and N behave very differently. These ideas are considered in more detail later, in context of the investigation of the phenomena called Stable Auroral Red (SAR)-arcs which are the primary subject of this study.

During times when the magnetic field of earth has been disturbed by variations of the solar plasma flux, a pair of localized zones encircling the earth at mid-latitudes in the 250-700 km altitude region begin to emit the 6300-6364A radiation of atomic oxygen. On a world-scale these zones are rather narrow; the north-south width is some two or three hundred km between half-maximum intensity points. Though they span only 3 or 4 degrees of latitude, and might be called narrow, they do not seem narrow to a ground-based observer for whom the emitting zone may extend over most of the sky. The emitting regions follow lines of constant

magnetic latitude rather than geographic latitude, but they deviate slightly from perfect magnetic alignment. This deviation, which first appears to be a troublesome complication, has an important significance which will be described. The deviation is not great enough to mask the fact that to first order the emission is magnetically localized and therefore truly an auroral form as opposed to airglow or something yet unnamed. The two emitting zones encircling the earth are magnetically conjugate, i.e., symmetrically located with respect to the magnetic equatorial plane.

To the physicist, one of the most striking observational facts is that the [OI] 5577Å emission from the 1S state of oxygen is usually entirely absent in the 6300Å emitting zone or at least it is below the detection threshold of the instrumentation. This infers that the excitation mechanism can raise the neutral oxygen atom to its first (1D) excited state (1.96 eV) from which a 6300Å photon will be emitted in the decay to the 3P ground state, but the excitation mechanism does not usually raise the atom to its second (1S) excited state (4.17 eV) from which 5577Å photon will be emitted in the transition to the 1D state. When cross-sections and quenching of these metastable states are considered, this stringent restriction on the excitation mechanism still remains in force. This aspect of the problem is treated in some detail in this study both in regard to the experimental determination of the 5577Å emission and in the implications of the result.

Compared to the northern or southern polar auroras (aurora borealis and aurora australis), the mid-latitude auroral arcs have been relatively rarely detected. During years of high solar activity polar auroras occur

virtually every night. In this research it has been found that even as far south as Banff, Alberta, Canada, polar auroras occur on about half the nights during years of high activity. By contrast, the mid-latitude arc has been detected only some 80 times since its discovery 14 years ago and during the last minimum of solar activity it seemed to stop occurring entirely. To illustrate the frequency of detection, photometric observations for this study were made all night, every clear moonless night, beginning in September 1967. In addition, automatic spectographic equipment which operated continuously was used. From September 1967 to March 1970, 23 mid-latitude arcs were recorded, some 15 of which were sufficiently well defined and uncompromised by clouds that they are suitable for detailed analysis. We have come to realize the importance of making a careful distinction between frequency of detection and frequency of occurrence. Estimates of frequency of occurrence are discussed later.

With one exception, the mid-latitude arcs that have occurred recently have had volume emission rates on the order of $20 \text{ photons cm}^{-3} \text{ sec}^{-1}$ in the brightest region. The corresponding flux at the ground is about $3.15 \times 10^{-12} \text{ watts cm}^{-2} \text{ steradian}^{-1}$. This is well below the visual threshold at 6300Å, consequently the arcs have been termed "subvisual". During the decline of the previous (and much stronger) solar maximum some mid-latitude arcs which approached the visual threshold were recorded but apparently none were ever perceived from the ground. The visual observation would be difficult in any event because of their diffuse morphology. One arc in which the volume emission rate was approximately $300 \text{ photons cm}^{-3} \text{ sec}^{-1}$ occurred recently.

The mid-latitude arc has been called by several names including:

1' Arc Monochromatique, M-arc, SAR-arc (Stable Auroral Red-arc), and other permutations of the adjectives. The name "SAR-arc" is descriptive, short and presently the most used, so we have adopted it too.

It is not known from direct measurements that the SAR-arcs are present on the day-side of earth. It would be a very difficult observation to make because of the bright background. On the basis of the explanation to be presented here, the SAR-arcs ought to encircle the entire earth but to date the evidence that they do is still indirect.

The general picture of the SAR-arc phenomenon is now more complete than the one available at the outset of this investigation four years ago. A significant part of the new information presently available on the phenomenon including the measurements of height, east-west extent and magnetic conjugacy has resulted directly or indirectly from this investigation.

Up to the present what might be called the major question about the SAR-arcs has remained unresolved. That is, simply, "Why do these two rings sometimes occur around the earth when the solar plasma flux varies?" There were several competing hypotheses at the outset of the investigation but experimental progress was at a standstill because the phenomenon itself had apparently stopped occurring. The experimental apparatus for this investigation was set up on the basis that it was statistically likely that the SAR-arcs would re-occur as solar activity increased. It was hoped that additional experimental evidence might suggest the cause. This proved to be a well-advised procedure; the data were obtained and in the process of accumulating results and continually reviewing the data there gradually emerged a concept of how the phenomenon occurred. If there was a single key point it was the realization that the data showed the arcs to be occurring

during the time when the magnetic field underwent a prolonged decrease. That fact had been reported soon after the discovery of the arcs [Rees and Akasofu, 1963] and the recent data redirected attention to it. The implication was that 'the SAR-arcs, which were observed to occur in unison with the field decrease, were either causally related to the decrease itself or both effects could be traced to a common cause. The evidence now points to the latter and the description of the sequence of events which terminates in a pair of SAR-arcs is the main theme of this dissertation. It was found that parts of the consistent explanation had been treated by others, and in assembling this material an effort has been made to acknowledge such debts.

Certainly the first debt is to the discoverer of the SAR-arc, Daniel Barbier, and then to all the others who gathered information on the SAR-arc phenomena during the last solar maximum. The next section attempts to allocate credit properly in the context of a brief history of work on the SAR-arcs. Following that section, a summary of the data gathered at Richland, Washington, is presented. Then four sections, each dealing with a particular experimental aspect of the investigation and an analysis of the implications, follow. The process by which the energy of the solar plasma may be distributed in the magnetosphere is treated in the next to the last section and that treatment is primarily theoretical. Lacking an experimental basis it is necessarily the most tentative part of the work. The final section summarizes the research and synthesizes the several results into a consistent picture.

The line of logic that connects the five sections (3 through 8) between the "history" and the "conclusions" is the following:

- (i) The observed nature of the phenomenon - when and where it occurs (Section 3).
- (ii) The spectral data and analysis supporting the hypothesis that electrons excite the atomic oxygen (Sections 4,5).
- (iii) Identification of the locus in the magnetosphere of the particles that deliver energy to the SAR-arcs (Sections 6,7).
- (iv) A mechanism by which the magnetospheric particles can be energized. (Section 8).

In a final overview, one of the main results of the research may be that the SAR-arc is found to be more than just a minor peculiarity of the upper atmosphere. The phenomenon marks the position of a primary structural feature of the inner magnetosphere. The investigation shows that the power and advantage of the optical technique used in this study is that it can provide continuous and detailed information on physical processes far from earth that are difficult to monitor by intermittent satellite passes or one point whistler measurements.

2. History of the Problem

Parallel developments in several different research areas have established the ground work on which this investigation is based. We draw upon experimental data and/or theory from atomic physics, hydro-magnetics, the space exploration programs and, of course, from the early observations and analyses of SAR-arcs. In this section attention will be directed primarily to the history of the thing to be explained: the SAR-arcs. References to other material will be provided as it is called upon in the text.

Some historical information on the SAR-arcs has been summarized by others [*Roach and Roach*, 1963], [*Cole*, 1965], [*Roble*, 1969].

The date of the first SAR-arc reported is 10 March 1956. *Barbier*, conducting observations at the Haute Provence Observatory in southern France ($5^{\circ} 43'$ E long., $43^{\circ} 56'$ N lat.), recorded some 30 SAR-arcs from 10 March 1956 to 29 September 1957. He reported these observations in early 1958 [*Barbier*, 1958]. Photo-electric photometers equipped with narrow pass-band filters were used. Most of *Barbier*'s observations were made by rotating a photometer through 360° in azimuth at an elevation angle of 15° above the horizon. Intensity measurements at the zenith and celestial pole were also taken. For the azimuthal scan, *Barbier*'s record showed two intensity peaks, one west of magnetic north, the other east of magnetic north. The separation between the two peaks generally increased slowly during the night. *Barbier* interpreted the peaks as the places where the photometer cut across the legs of an arc-like form shaped something like a rainbow to the north. The changing separation between the peaks

was attributed to a slow drift of the arc which was usually southward.

Barbier recorded a SAR-arc on the night of 28/29 September 1959 and on that same night, what turned out to be a SAR-arc was recorded at Fritz Peak, Colorado, in the U. S.. When the data from Haute Provence and Fritz Peak were compared they strongly suggested that a single arc had been detected extending from France across the Atlantic and over the United States [Roach and Roach, 1963]. This was the first evidence of the worldwide extent of the phenomenon.

When Barbier's results became known, emphasis in the United States was directed toward detection of the SAR-arcs with existing scanning photometers at Fritz Peak, Colorado, and Rapid City, South Dakota. Publications by *Barbier* [1958, 1960] and by Roach and *Marovich* [1959, 1960] summarized part of these early observations and described the main features of spectral purity, stability, north-south width, the characteristic sluggish motion and the correlation of occurrences with high magnetic activity.

On 8/9 July 1958 arcs were observed at Haute Provence and Fritz Peak in the northern hemisphere and in the southern hemisphere at Camden, Australia [Roach, *et al.*, 1962]. The observations did not overlap in time because of the longitudinal separation of the observatories but the possibility that world-scale conjugate pairs of arcs occurred was clearly inferred.

The fact that the brightest region of the typical SAR-arc was at about 400 km was established by Roach, *et al.* [1960] and by Moore and *Odenchantz* [1961]. *Tohmatsu and Roach* [1962] described the typical cross-sectional distribution of intensity and *Marovich and Roach* [1963] summarized the

latitudinal distribution of SAR-arcs.

O'Brien, et al. [1960] noted that on 28 November 1959 the Geiger counters aboard the Explorer VII satellite showed a very high count rate crossing field lines which led to a SAR-arc.

J. R. Roach [1963] reported that radio wave scintillation was enhanced for waves propagating through the SAR-arc. He inferred that a lower than normal electron density prevailed in the SAR-arc.

Carleton and J. R. Roach [1965] analyzed a long exposure (75 minutes) photographic spectrogram of a bright SAR-arc and reported a slight enhancement of [NI] 5199-5201Å emission in the region of the arc. They estimated the intensity of the [NI] emission to be such that the line of sight flux ratio of [NI] 5199-5201Å/[OI] 6300Å would have been about 0.025. A pair of parallel arcs occurred during this observation.

As solar magnetic activity declined following the 1957-8 maximum, the frequency of recorded SAR-arc occurrences also declined. During the peak of solar activity the frequency was about 12 per year; by 1961 it had declined to 5. Then there was a lapse of 24 months when none were reported until Marovich observed an arc on 22/23 September 1963. Occurrences then seemed to stop entirely for the next four years.

Rees and Akasofu [1963] noted that there had been a correlation between the times when the arcs appeared and when the magnetic field decreased.

A rather complete summary of the facts known about the arcs before the solar minimum was given by *Roach and Roach* [1963]. *Marovich* [1966] published a catalog of the intensity and positions of all SAR-arcs observed from Fritz Peak before 1965.

As the characteristics of the arcs became known, several ideas about

possible excitation processes were published. These fall approximately into the following three categories with some overlapping: (1) Electric fields that accelerate charged particles exist. (2) An influx of heat or of charged particles causes the excitation indirectly. (3) It is basically a chemical reaction between constituents of the atmosphere.

King and Roach [1961] suggested that a reaction of the third category occurred

followed by

This would give rise to oxygen atoms excited to the ^1D state (1.96 eV) but not to the ^1S state (4.17 eV). The problems with the idea are that (i) far more than the expected concentration of N_2 in the SAR-arc region is needed (about 400 x), (ii) the last reaction does **not** conserve spin [Dalgarno and Walker, 1964], and (iii) the reaction rate called for by the authors would deplete the electrons of the F region far faster (~ 30 x) than observed Rees [1962]. King *and* Roach advanced an ad hoc argument to obtain the required N_2 but the problems with spin and electron depletion were pointed out later and effectively negated the hypothesis.

Perhaps because the elongate SAR-arc shape suggests an electric current flow as in a tubular fluorescent lamp, the idea that the SAR-arc could be excited by an electric field normal to the magnetic field has received considerable attention [Rees, 1961] [Megill *et al.* 1963] [Megill and Carleton, 1964] [Megill and Van Zandt, 1964] [Walker and Rees, 1968]. There has been much discussion of how appropriately intense fields might arise to move the ambient charged particles and of what magnetic fields

should then appear under the current region. Approximate magnetic fields were not observed but discussion continued until the idea was recently dealt a fatal blow for a different reason which follows. *Walker and Rees* [1968] showed that the E-field would heat the ions of the ionosphere more than the electrons. Specifically they showed that the ion, electron temperature ratio T_i/T_e ranges from about 4 to 9 as the E-field varies from the weakest SAR-arc to the strongest. The heating of the ions would occur at an altitude well below the arcs because of the relatively low altitude of ion peak concentration. At 150 km for example $T_e \sim 1200^\circ\text{K}$ implies $T_i \sim 5000^\circ\text{K}$ for a faint arc. Until recently the ion temperature was not known but *Chander* [1969] now has shown ion temperatures in the SAR-arc to be far lower than would be expected if there were an E-field.

Dalgarno [1964] and *Cole* [1965] have proposed related ideas. Dalgarno suggests a flux of soft electrons flows into the SAR-arc region and heats ambient electrons sufficiently to excite the lowest state of oxygen. Cole suggests the conduction of heat into the SAR-arc region to elevate the ambient electron temperature. *Walker and Rees* [1968] suggest that the electron flux proposed by Dalgarno ought to have particles of energy less than 15 eV rather than the 400 eV Dalgarno originally suggested but the idea remains the same.

Cole, in invoking the concept of heat flowing into the region, circumvents the question of whether a few relatively high energy particles have the energy or whether there occurs primarily a transfer of translational kinetic energy among ambient particles. He suggests a combination, but mostly the latter. In any case, he is able to calculate the energy requirements without detailed information on the energy spectrum. The question of

how the energy is distributed becomes an experimental problem which may be investigated (as we have done) by estimating the relative population of excited states of neutral atoms.

Cole's hypothesis goes further suggesting that "ring currents" are the source of the heat which is conducted along field lines to the SAR-arc region. The name "ring current" has come to stand for the body of energized particles that cause a characteristic decrease in the geomagnetic field during times of perturbation. A great current loop could cause the observed reduction and such a ring current was an early suggestion. It has been shown [Dessler and Parker, 1959], [Parker, 1962] that it is only necessary to increase the general kinetic energy of an azimuthal zone of plasma, to obtain the source field decrease. It is now quite certain [Frank, 1967] that just such a hot zone exists but it is still being called the "ring current" even though it does not really flow around earth.

The fact that the SAR-arcs occur in unison with the field decrease and hence with the ring current lends strong support to Cole's theoretical suggestion that the ring current is the energy source for the arcs. But the problem of how the "ring current" particles become energized is a matter of hot dispute. Cole has suggested the "pumping" of hot ambient plasma inward from the outer part of the magnetosphere by means of electrostatic fields associated with geomagnetic field fluctuations. Noisy fluctuations of the geomagnetic field are experimentally observed and Cole therefore starts with observations as a given fact. Others have informally suggested the ring current particles are "injected" from the solar plasma but the arguments are still quite tentative. (In section 8 of this document a simple heating mechanism is explored.)

Calculations by *Roble* [1969] starting with a flow of heat into the topside of the arc verify the development of an arc as Cole suggested. Roble also measured the atomic oxygen temperature and found it to be low ($\sim 1250^\circ\text{K}$) which suggests excitation induced by low energy electron-oxygen collisions.

Since the field lines passing through the SAR-arcs extend out some three earth radii from the center of the geomagnetic dipole, and it is clear from the outset that the SAR-arcs are somehow connected with the large scale perturbations of the magnetosphere, the physical conditions in the magnetosphere itself which have been measured in the space exploration program are pertinent to the explanation of the SAR-arcs. Several recent technical summaries of data gathered in the space program are given in the references [*Hess*, 1968], [*Matsushita and Campbell*, 1967]. Some of the relevant ideas are the following.

The overall picture that has emerged is that the dipole-like configuration of the magnetic field is approximately valid for those "loops" which extend out less than 8 or 10 earth radii (R_E) in the magnetic equatorial plane. Larger loops are swept back into an extended "tail" behind the earth by the flow of conductive solar plasma.

In the closed or "inner" magnetosphere (where the dipole picture is approximately valid) the ambient plasma is electrically neutral consisting almost entirely of electrons and protons above about 1000 km altitude. However, the distribution of high energy component of the plasma in terms of the directional flux of the protons or the electrons, is highly organized in some regions such as the radiation belts. The overall density of particles at a given energy is not generally a simple function of radial

distance and information is the most complete on the distribution of the high energy (MeV) particles. A main feature of the low energy plasma density is a characteristic step or "knee" between 3 and 5 earth radii where the plasma density drops sharply. The drop marks the plasmapause, the outer boundary of the plasmasphere.

The overall picture is far from complete - particularly with respect to the distribution of low energy (< 1 keV) particles. Although these 'thermal' particles most of which have energies of less than 10 eV account for all but a few percent of the mass of magnetospheric plasma, it is only recently that detectors with thresholds as low as 200 eV have been used successfully. Most "space" experiments have dealt with particle energies well over one keV. In terms of understanding the dynamic behavior of the magnetosphere, information is also incomplete. For example, how the radiation belts happen to have such high energy particles is not known, and in terms of the magnetosphere, the causal mechanism of the familiar polar auroras is still not understood. On the positive side of the ledger, the information that has been accumulated on intermediate energy particles (~ 1 keV) [Frank, 1967] has been extremely valuable in this investigation of the SAR-arcs; for these intermediate energy particles populate the "ring current".

In addition to the history that has been summarized above, a few paragraphs on the local history of this investigation are inserted below.

In Seattle, in 1965, the author was involved in the construction of a pair of meridian auroral spectrographs when Dr. K. C. Clark mentioned the SAR-arc problem to him. Encouraged also by the late Dr. Boris Jacobsohn, a study of the literature of the phenomenon was made. From this,

it was realized that on a statistical basis the eastern Washington desert was a prime site for the observation of the SAR-arcs. Arrangements were then made to set up one of the new University of Washington meridian spectrographs near Richland in March of 1966. Soon thereafter the Division of Research of the US AEC began to support this research.

Even at that time there was some question as to whether the SAR-arcs had actually stopped or whether they were occurring either very faintly or out of range of the Fritz Peak, Colorado station which was the only United States station known to be making observations.

The new meridian spectrograph at Richland, which was sensitive enough to detect even one of the fainter SAR-arcs that had been reported previously, showed no evidence of an arc in all the spectrograms made from March 1966 to September 1967.

During these first observations at Richland, Dr. Franklin Roach, who had played a major role in the initial investigation of the SAR-arcs from the United States, supplied generous encouragement and advice. In the summer of 1967, Dr. Roach made arrangements to loan Dr. Clark and the author a nearly completed photoelectric scanning system. This system would provide about a 20-fold increase in sensitivity at 6300A over the spectrograph plus the advantage of all-sky coverage. Within a week after the new photometric apparatus was set into operation at Richland a distinct SAR-arc too faint to be detected by the spectrograph was recorded at the site.

Thus the reappearance of the SAR-arcs was established on 28/29 September 1967, ten years to the day after the first arc was detected in the United

States. Since then some 23 SAR-arcs have been detected, only two or three of which were not recorded at the Richland site.

In 1968 the reappearance detected at Richland was reported [Hoch *et al.*, 1968] and in late 1968 informal communication of the Richland data to Dr. Jacques Blamont of the Institute of Astrophysics in Paris prompted review of the OGO-B satellite 6300A topside data. It was established that the polar orbiting satellite had detected the 28/29 September 1967 arc, that a conjugate arc was present and that the arcs spanned the entire dark side of the earth [Reed and Blamont, 1968]. These facts which were previously implied by ground based data now were confirmed directly.

Norton and Findlay [1969] reported measured electron density and temperature above a SAR-arc partly with the help of ground based observations. They found a severe depression of electron density and a sharp peak in temperature in the general region of the arc. Glass *et al.* [1970] have described a SAR-arc recorded with airborne equipment in the southern hemisphere calling attention to the significance of the systematic magnetic misalignment of the arc. Recently, Cole [1969] has introduced the concept of a "thermal aurora" in which the emission is excited by the heating of the ambient environment rather than by direct bombardment by energetic particles. The SAR-arcs, according to Cole, are examples of such thermal auroras and he suggested that possibly the high altitude 6300A poleward auroras may be thermal auroras as well.

3. Occurrences of Stable Auroral Red-Arcs

In this section recent observational evidence of the SAR-arc phenomenon is presented without detailed analysis. The purpose is to document where and when the SAR-arcs were observed. It may be noted that the data presented are but a small number of measurements distilled from a program of synoptic monitoring.

A relatively detailed description of one occurrence of a SAR-arc is presented and the description is then generalized for other events.

Observational Arrangement

Photoelectric scanning photometers are operated during clear moonless night hours at a station on Rattlesnake Mountain near Richland, Washington. Altitude of the site is 1100 m and coordinates of the station are $52^{\circ} 51'N$, $298^{\circ} 51'E$ Geomagnetic. The remote desert locale of the station provides relatively clear viewing conditions and a low stray light level. The McIlwain's L coordinate associated with the site (2.9 at altitude 400 km)* locates it near the middle of the zone where SAR-arcs were observed with highest statistical frequency before the last solar minimum [Roach and Roach, 1963].

The sky is routinely scanned with the photometers every five minutes by a sequence of five almucantar sweeps and a zenith reading. The sweeps

* A precise definition of the L is given in the references [Hess, 1968] and [Matsushita & Campbell, 1967]. Basically the L value labels the family of field lines that would intersect the magnetic equatorial plane at a geocentric distance of L earth radii in a dipole model. Thus, the field line passing through the zenith 400 km above the Richland station would (in an ideal dipole) extend to a radial distance of $2.9 R_e$ in the magnetic equatorial plane.

are spaced to give approximately even coverage of an imaginary surface at 300 km altitude. A 5° field of view is used in the photometers and the data of each sweep are recorded in analog and digital form. The digital data are divided into 432 samples which are recorded together with time, angular coordinates, and other data for data processing. Narrow pass band interference filters (10-20Å) are used to select the wavelength to be mapped. The filters are kept at constant temperature to assure stability of transmission characteristics. One photometer monitors only 6300Å while another maps 4278, 5577 and 6300Å sequentially. A third photometer maps 5350, 6080 and 7150Å sequentially to provide data on the underlying continuous spectrum of the airglow, zodiacal, stellar, galactic and man-made light.

Sensitivity of the equipment is such that a region that is 25 Rayleighs (R) brighter than its background will be delineated on the sky maps.* Extraction of galactic, stellar, and zodiacal background light and correction for geometrical effects are done numerically by high speed electronic data processing. For objects at 400 km altitude, the circle of coverage is approximately 3000 km in diameter.

This photometric installation has been in essentially continuous operation during clear weather moonless nighttime hours since late September of 1967. Weather has permitted approximately 40% of these moonless hours to be monitored. Some data were obtained on 53% of the nights on which

* The Rayleigh unit is conventionally used to describe photon flux in auroral investigations. It is simply the flux (number/cm² sec ster.) in units of $4\pi \times 10^6$ photons. Thus $1R = 4\pi \times 10^6$ photons/cm² sec ster.. The rationale for adoption of the unit is found in *Hunten, Roach and Chamberlain* [1956]

observations were scheduled but sometimes observations were stopped after part of a night because of decreasing visibility. Backup data for hours when the moon is up and the photometer is not operated are provided by a pair of meridian spectrographs, one at Rattlesnake Mountain and one at Banff, Alberta, Canada. These spectrographs are of the type described by *Clark and Romick* [1959]. The spectrographs provide a check of whether or not any bright SAR-arc occurred on a clear night when the photometers were not operated because of moonlight. One such arc was recorded by the Richland spectrograph when the moon was up on the night of 23/24 March 1969 and the photometers were not being operated. On the night of 8/9 March 1970 a SAR-arc was recorded by the Richland spectrograph and by the photometers as well. From the Richland site, triangulation on a SAR-arc can be accomplished in cooperation with the Fritz Peak, Colorado station. Geomagnetic latitude and longitude are 48.7° N, 316.2° E for Fritz Peak.

Observations

On 28/29 September 1967 a SAR-arc appeared and data from the Richland and Fritz Peak stations were combined. The occurrence of a SAR-arc on the night of 28/29 September 1967 marked the definite reappearance of the phenomenon after an apparent absence of four years. An earlier SAR-arc may well have occurred on 2/3 May 1967 according to almucantar scans of 6300A intensity made by Marovich at Fritz Peak but records of 28/29 September are more complete and permit unambiguous identification of the reappearance.

At each station, a record of incident intensity of 6300 A radiation as a function of azimuth and elevation angle was recorded. These stations

are separated by 1480 km, and an auroral form 400 km above one station is seen at almost 10 degrees elevation from the other. Thus, a relatively unambiguous determination may be made of the position of an emitting region simultaneously within the lines of sight of both stations.

The position of the maximum intensity region of the 28/29 September SAR-arc at 0745 UT is shown in Figure 3-1. Average altitude of the sector within the line of sight of both stations was determined to be 400 km.

The altitude during a one-hour interval when the arc remained relatively motionless was determined by plotting the position of the arc as recorded from both stations for a number of assumed altitudes. The plots of the arc from the two stations were found to coincide in the region of mutual observation at the assumed altitude of 400 km. Uncertainty in the altitude determination was estimated to be about 30 km because of the diffuse distribution of the emitting region.

Since only angular coordinates were available on extreme sectors of the arc recorded from only one or the other of the stations, the altitude of these end sectors could not be determined directly. For purposes of mapping, it **was** assumed the end sectors were at the same altitude as the average for the middle sector. The overall curvature suggests this assumption is reasonable. Total length of the sector of the arc covered by these combined records is 4170 km.

As shown in Figure 3-1, the SAR-arc was approximately parallel to lines of constant L. The latitude of the arc changed during the night, as described in the following, but rough alignment with lines of constant L was maintained.

During the night the arc moved southward across the zenith of the

Figure 3-1 Position of the SAR-arc at 0745 UT (2345 PST) September 29, 1967.

Richland station at 0645 UT (2245 PST) and passed over Fritz Peak at 0940 UT. At 1050 UT, the arc reached its most southerly position when it passed approximately 2° south of the Fritz Peak zenith. It then reversed direction and, by 1125 UT, drifted northward about 100 km at which time sunrise precluded further observation. The altitude during the time when the arc was drifting rapidly southward could not be reliably determined from the mutual observations because motions of the arc during the 5-minute interval required to complete a sky map acted to compromise resolution of position. The southward drift is illustrated by the sequence of arc positions shown in Figure 3-2. The described drift and alignment depend only slightly on arc altitude, taken to be constant at 400 km in the analysis.

All-sky maps of the intensity of 5577A light, recorded from Fritz Peak when the SAR-arc was present, showed no arc-like structure in the 5577A emission in the region of the SAR-arc. Meridian spectrograms made at the Richland station provided qualitative agreement that the SAR-arc was predominantly the 6300-6364A emission of neutral atomic oxygen.

Average intensity was about 150 R in the brightest region of the arc. At any given time intensity along the length of the arc was nonuniform varying by about a factor of two. There were also sluggish temporal variations of about the same magnitude, apparently not correlated from place to place along the arc. Unobserved faint cloud patches possibly could have compromised observations of intensity. The maximum intensity recorded was 300 R in one bright region of the arc at 0745 UT. Width of the arc measured in the north-south sense was determined to have been approximately 160 km between half-maximum intensity regions.

Figure 3-2 SAR-ARC southward drift illustrated by positions at one-hour intervals as observed from Richland station.

The SAR-arc occurred during a time of increased magnetic activity as shown in Figure 3-3. There was an intense poleward auroral display all during the night the SAR-arc was recorded. There was also a poleward auroral display the night before (27/28 September). No SAR-arc appeared to accompany the 27/28 September display though it was as intense as the poleward display of the night of 28/29 September.

Figure 3-3 Daily and three-hour planetary magnetic indices for several days near time of SAR-arc occurrence. (Data from IER-FB Solar Geophysical Data of ESSA Laboratory, Issued November-December 1967.)

Table 3-1 lists nights on which SAR-arcs were definitely recorded at Richland, Washington, along with other nights on which there is some evidence of a SAR-arc but some circumstance such as poor weather or faintness of the emission makes the identification uncertain.

TABLE 3-1 Occasions of definite and probable SAR-arcs observed at Richland, Washington.

<u>Occasions of Definite SAR-arcs</u>	<u>Occasions of Probable SAR-arcs</u>
28/29 Sept 67	3/4 Nov 67
30/31 Dec 67	1/2 Mar 68
2/3 Jan 68	2/3 Mar 68
27/28 Feb 68	17/18 May 69
28/29 Feb 68	11/12 June 69
30/31 Oct 68	13/14 June 69
31 Oct/1 Nov 68	16/17 June 69
19/20 Mar 69	13/14 July 69
20/21 Mar 69	
23/24 Mar 69	
24/25 Mar 69	
14/15 May 69	
14/15 Sept 69	
7/8 Mar 70	
8/9 Mar 70	

A SAR-arc typically persists for several hours and the identifications in Table 3-1 are based on some three hundred and fifty sky maps of the SAR-arcs. The occasions of recorded SAR-arcs are displayed along a time axis in Figure 3-4.

The position of the brightest region of 14 definite SAR-arcs at the time each was best defined on our records is shown in Figure 3-5. One of the 15 arcs listed as definite (23/24 Mar 69) was recorded only spectrographically in the meridian plane. Thus no map is available for that event.

On every occasion of a SAR-arc there has been a polar auroral display to the north of the arc. 6300A emission was almost always more intense in the northward auroral display than in the brightest region of the SAR-arc. The only exceptions have been cases in which the polar aurora was almost out of range. The figures show the area of the sky (marked PA) where the polar aurora was brighter than the brightest region of the SAR-arc.

Figure 3-4 Occasions on which SAR-arcs have been recorded at Richland, Washington, from late September 1967 through March 1970.

Figure 3-5 Maps of SAR-arcs. The shaded region (PA) marks the portion of the sky in which [01] 6300A from the poleward aurora was brighter than the region of the SAR-arc. The intensities shown are rough averages of the brightest region taken along the length of the SAR-arc. Each map covers a circle approximately 3000 km in diameter. Geographic coordinates of the center of the maps are 46° 25'N and 119° 38'W.

The distinct SAR-arcs observed have the general characteristics described in the introduction and history (Sections 1 and 2). In brief summary the characteristics are:

- SAR-arcs occur equatorward of the usual polar auroras.
- In the octave of visible radiation SAR-arcs consist predominantly of the 6300 - 6364Å red emission lines of atomic oxygen (but none of the arcs ever recorded is believed to have been bright enough to be visible to the unaided eye).
- The arcs are magnetically controlled, appearing during times of high magnetic activity.

They are aligned approximately parallel to lines of constant L.

- The brightest region is near 400 km altitude and they typically extend several hundred km in altitude and in north-south width.
- They are quite stable though a motion (often equatorward) of the whole arc is often observed.

Rather than describe each arc, we will discuss some features and results that seem to us to add something new or help resolve a questionable point.

Occasionally the suggestion has arisen that the SAR-arcs are simply the topmost part of a normal auroral display and that there only appears to be a separate arc from the vantage point of the observations. Figures 3-5 b, f, g, k, m, and n show this not to be the case. On these maps the SAR-arc is plotted when it was overhead or south of the station while the auroral display was to the north of the station. This situation occurred

on several other nights as well when the SAR-arc passed over the station. The maps shown were selected on the basis of when the arc was best defined which is not necessarily the time when the arc was overhead or south of the station.

Thus, the SAR-arc and the auroral display are spatially separate. We often "see" the SAR-arc to our south or overhead while the polar aurora is to our north. However, we know of no instance in which there was a SAR-arc without a poleward aurora occurring simultaneously. Therefore, although the SAR-arc is definitely not the top part of a polar aurora, the data allow the possibility of a connection between these two phenomena.

There appears to be no lower limit to the intensity of a SAR-arc. In some cases repeated scans show that there is a systematically brightened arc-like zone of 6300Å emission south of the main aurora but on a single map the arc would be difficult to discriminate from noise. For example, Figure 3-5 b shows a SAR-arc of only 50 R. It would appear possible that there is usually (perhaps always) an incipient or faint arc equatorward of the polar aurora but that the arc is often too faint to be detected by present instrumentation.

In 14 of the SAR-arcs no enhancement of [OI] 5577 could be found in the region of the SAR-arc. In the last arc which was far brighter than the rest, a definite enhancement at [OI] 5577 was detected. The interpretation and analysis of this is the subject of the next section. Spectrographic records of SAR-arcs were obtained on 23/24 March 1969 and 7/8 March 1970. These records show no emission other than [OI] 6300 doublet enhanced in the region of the SAR-arc but the spectrographs are less sensitive than the photometers. The spectrographic records are illustrated

in Section 6.

Several SAR-arcs with intensity greater than one kR were recorded before the solar minimum, but many fainter ones were also recorded. A comparison of the records of recent arcs with ones recorded during the last solar season show no apparent differences between the recent SAR-arcs and the ones recorded before the minimum except, as mentioned, we have recently delineated some arcs which are fainter than those reported in the past.

Some of the arcs shown in Figure 3-5 were so far north at the time they were best defined that they would not have been easily observed from the established stations southward of ours. Fritz Peak is the most northerly of those stations which were operated routinely during the solar minimum. The SAR-arcs shown in Figure (3-5) a, b, e, f, g, i, j, k, m and n were definitely within range of Fritz Peak. The circumstance, of location of our station coupled with the tendency of auroral phenomena to occur generally nearer the poles during times of low activity and also coupled with the fact that we began recording SAR-arcs occasionally as soon as we set up equipment northward of other stations, leads us to suggest that it is not at all certain that the SAR-arcs stopped occurring during the solar minimum. The arcs may simply have been very faint and/or out of range during the solar minimum.

In summarizing the optical data it is concluded that while SAR-arcs may be very subtle in intensity, at least 15 distinct arcs have occurred since 27/28 September 1967. Evidence that SAR-arcs did not occur during the solar minimum is at best inconclusive. The nature of the connection between SAR-arcs and polar-type auroras deserves further investigation

because the two phenomena are temporally connected in that a polar aurora always seems to accompany a SAR-arc. However, it is not clear whether a SAR-arc always accompanies a polar aurora and if it does, it must be very faint. The main regions of [OI] 6300Å emission of the SAR arcs and polar type auroras are spatially separate. The fact that the major spectral emission of a SAR-arc in the visual wavelength region is the 6300-6364Å doublet has been checked spectrographically.

In Appendix 0, a record of observations, visibility, and geomagnetic activity for the period 27 September 1967 through 31 March 1970 is presented. For a total of 918 nights observations were scheduled on 486 nights. Weather permitted observations on 259 of these. Of this 259, a definite or probable SAR-arc was detected on 23 nights. Thus an arc bright enough to detect occurred on almost 9% of the nights monitored photometrically.

4. Ratio of [01] 6300A/ [01] 5577A and Estimate of Electron Temperature

This section and the following section are directed toward investigating the hypothesis that in the SAR-arc atomic oxygen is excited by ambient electrons which have become heated by some topside source which (for these two sections) is undefined. The temperature of the ambient electrons in the SAR-arc region can be estimated from the measured ratio of intensity of emissions from the first and second excited states of the oxygen atoms. Fundamentally, it is possible to deduce from the intensity ratio only integrals of the relative population of electrons (weighted by excitation cross-sections) at or above the threshold energies for excitation of the two excited states. Thus, to estimate electron temperature, a population distribution in energy for the electrons must be assumed. It will first be assumed that the distribution is Maxwellian. Thus, the temperature that results from this Maxwellian assumption might properly be called an "effective temperature" meaning the equivalent temperature of the assumed Maxwellian distribution. The assumption is then subject to review on the basis of the results calculated.

Carleton [1965] suggests that the assumption of a Maxwellian distribution of electrons at a temperature higher than the neutral gas should be "a very good approximation at these altitudes". He estimated $T = 2700^\circ$ yields $R_{6300} \sim 100R$ and $T = 3800^\circ$ yields $R_{6300} \sim 10 \text{ kR}$. These estimates are in substantial agreement with similar ones by *Cole* [1965] and *Roble* [1969].

Observations

A SAR-arc was detected on the nights of March 617, 7/8. 8/9, 1970[†]. It is likely that it was one persistent arc lasting the three nights and occurring in unison with the main phase of a single geomagnetic storm. On the first two nights the [01] 6300A emission was only a few hundred Rayleighs and the [01] 5577A emission from the arc, if it were present, was too faint to be detected in the presence of the 5577A air-glow and the 55776 emission of the rather dynamic visible polar auroral display. The visible auroral display was poleward but well within optical range of the Richland station on 7/8 and 8/9 March 1970. On 8/9 March, the polar display was noticeably fainter than on the preceding night and less active but the SAR-arc intensity had risen to the unusually high value of 3.5 to 4.0 kilo Rayleighs at the commencement of observing at 1940 PST (end of astronomical twilight). The enhancement of [01] 55778 radiation in the region of the SAR-arc could then be discriminated from background and the results presented here are based on observations made between 1950 and 1953 PST.

The fact that the SAR-arc was very intense compared to other recent arcs leads to concern over the possibility that the [01] 6300A/ [01] 5577A ratio might also be atypical. The [01] 6300A/ [01] 5577A ratio has been estimated to be 80:1 or higher in the usual SAR-arc. [F. E. Roach, 1970]. The 80:1 ratio was measured for a 10 minute period by Barbier [1960]. More recently, Schaeffer [1969] has measured possible

[†]The observations of 6/7 March were made by Hernandez at Fritz Peak, Colorado. Clouds precluded observations at Richland that night.

short term 5577A enhancements in at least two faint SAR-arcs and he concludes that the [01] 6300A/ [01] 5577A ratio is greater than 10:1 and 4:1. His work involved measurement of very small and somewhat sporadic enhancements of 5577A in high background conditions. Thus, we do not feel his lower bounds of 10 and 4 should be considered definitive estimates at this time. An unusually high 5577A emission could occur if, for example, the electron temperatures were higher than usual. The main point is that detectable enhancements of [01] 5577 are occasionally observed and should be understandable in terms of the excitation process. However, caution in generalizing these results for a specific SAR-arc to other SAR-arcs would appear appropriate.

Figure 4-1 is a plot of the photometric intensity recorded by sweeping the sky in a series of almucantars as described in Section 3. The [01] 6300A and [01] 5577A records shown were made simultaneously with separate photometers on the same mount. The intensities of the [01] 5577A and [01] 6300A emissions in the SAR-arc are determined by underdrawing the peaks and scaling the deflections.

Calibration of intensity to absolute units is accomplished by:

- (1) Routine checks of instrument response to a standard C¹⁴ light source.
- (2) Checking response of the equipment when a star of known color and brightness is crossed. This also provides data on the relative extinction of light according to atmospheric conditions

The known standard values of the intensity of zodiacal and galactic light backgrounds as a function of wavelength, angular coordinates and

Figure 4-1 Photometric intensity (scale deflection units) in azimuthal scans at 10° and 50° elevation, 8/9 March 1970, 1950 PST

time permit extraction of these extra-planetary components as a further guide to underdrawing.

Records of low activity nights before and after the active nights were used to check **airglow** distribution and to double check the zodiacal light. The values of the red and green enhancement from the arc given in Table 4-1 were thus **determined**. The green enhancements in the west side of the arc were distinct but misaligned with the red peak. Thus we suspect the red and green emissions are not from a common volume element in the west and will not use the values in computing the ratio.

Assuming a constant height of 400 km for the photometric center of the arc, extinction and geometrical corrections are made for each slant path through the atmosphere. The extinction corrections used are

$$I_s = I_a \left[\exp (-\tau_\lambda m(z)) \right] V(z,h)$$

where I_s and I_a are respectively intensities at the station and in the arc, where

$$\tau_{6300} = 0.113$$

$$\tau_{5577} = 0.185$$

and where $m(z)$ is the number of air masses traversed by the light incident at a zenith "distance" (angle) z equal to $(90^\circ - \text{elevation angle})$. To a first approximation,

$$m(z) = 0.885 \sec(z)$$

but at large z , corrections for curvature are introduced. The 0.885 factor is an altitude correction for the decreased air mass at the station

Elevation angle	10°E	15°E	20°E	30°E	50°E	50°W	30°W	20°W	15°W	10°W
$I_s(5577)$	0.164	0.226	0.184	0.160	0.144	-	-	~0.10	~0.08	~0.04
$I_s(6300)$	5.89	6.73	6.37	5.23	3.67	3.31	4.14	3.81	3.62	3.24

TABLE 4-1 Observed Intensities, kilo Rayleighs

relative to sea level. The geometrical correction $V(z,h)$ for lengthening of the emitting path in the arc off zenith is an obvious one.

The resulting corrected values of the emissions are given in Table 4-2. The contributions of stellar and zodiacal light, airglow and scattered light have been effectively eliminated in the process of underdrawing the peaks and therefore we may now compute the average ratio of [OI] 6300Å/ [OI] 5577Å from the arc. The result is:

$$\frac{[\text{OI}] 6300\text{\AA}}{[\text{OI}] 5577\text{\AA}} = 26 \pm 3$$

Next we infer from this measurement a volume emission ratio which leads to an electron temperature.

Analysis

With $n(e)$ electrons per unit volume having a normalized velocity distribution function $f(v)$, the probability per unit time of an atom in state i undergoing a collisionally induced transition $i \rightarrow j$ is $\alpha_{ij} n(e)$ where

$$\alpha_{ij} = \int_0^\infty f(v) v Q(i \rightarrow j) dv \quad (4-1)$$

and $Q(i \rightarrow j)$ is the velocity dependent cross-section.

If, after being excited to state j , the atom decays to k with transition probability A_{jk} , then the volume emission rate of photons from the $i \rightarrow j \rightarrow k$ sequence is

$$F_{jk} = \alpha_{ij} n(e) n(O_i) A_{jk} \left(\sum_{\ell} A_{j\ell} + \sum_x \beta_{jx} n(x) \right)^{-1} \quad (4-2)$$

Elevation angle	10°E	15°E	20°E	30°E	50°E	50°W	30°W	20°W	15°W	10°W
$I_a(5577)$	0.153	0.176	0.138	0.129	0.142	-	-	-	-	-
$I_a(6300)$	3.88	4.09	3.99	3.71	3.32	3.00	2.94	2.39	2.20	2.13
$\exp(\tau_{\lambda}^m(z))$	$\lambda=5577$	2.48	1.87	1.61	1.39	1.24	1.24	1.39	1.61	1.87
	$\lambda=6300$	1.75	1.46	1.34	1.22	1.14	1.14	1.22	1.34	1.46
$h = 400 \text{ km}$ $V(z,h)$	2.66	2.40	2.14	1.72	1.26	1.26	1.72	2.14	2.40	2.66
$\frac{I_a(6300)}{I_a(5577)}$	25	23	29	29	23	-	-	-	-	-

TABLE 4-2 Corrected intensities (kilo Rayleighs) with
correction factors and the final intensity ratios

where β_{jx} is the specific rate coefficient for quenching of state j by species x .

For a case in which the state j is populated by another process in addition to electron induced excitation, one, must add the appropriate rate to the $[a_{ij} n(e) n(O_i)]$ factor.

The energy level diagram of atomic oxygen which shows the relevant transitions is shown in Figure 4-2.

Applying equations (4-1) and (4-2) to the ($^1D \rightarrow ^3P$) and ($^1S \rightarrow ^1D$) transitions we have

$$F_{^1D^3P_2} = \frac{(\alpha_{^3P^1D} n(e) n(O^3P) + F_{^1S^1D}) A_{^1D^3P_2}}{A_{^1D^3P_1} + A_{^1D^3P_2} + \sum_x \beta_{^1D^x} n(x)} \quad (4-3)$$

$$F_{^1S^1D} = \frac{(\alpha_{^3P^1S} n(e) n(O^3P) + \alpha_{^1P^1S} n(e) n(O^1D)) A_{^1S^1D}}{A_{^1S^1D} + A_{^1S^3P} + \sum_x \beta_{^1S^y} n(y)} \quad (4-4)$$

It may be possible to simplify equations (4-3) and (4-4) by neglecting relatively small terms. In particular, the quenching terms may be negligible in the mid-region of the SAR-arc.

The 1D state of oxygen is known to be quenched according to the concentration of the N_2 molecule [Hunten and McElroy, 1966] [Peterson and Van Zandt, 1969] with $\beta_{^1DN_2}$ in the range $(5 \text{ to } 10) \times 10^{-11}$. We adopt the value $\beta_{^1DN_2}$ a 7.5×10^{-11} . The concentration of N_2 is approximately $4.46 \times 10^{11} \times 10^{-h/100}$ where h is in km. This value is based on work to be presented in the next section. At 400 km,

Figure 4-2 Energy level diagram of OI $2p^4$

$\beta_{1D} N_2 n(N_2) = 3.4 \times 10^{-3}$. Thus, using the following values (*Chamberlain*, 1961)

$$\begin{aligned}
 A_{1D} 3P_2 &= 0.0069 \\
 A_{1D} 3P_1 &= 0.0022 \\
 A_{1S} 1D &= 1.28 \\
 A_{1S} 3P_1 &= 0.078
 \end{aligned}
 \tag{4-5}$$

we estimate,

$$\frac{\sum_x \beta_{1D} x n(x)}{A_{1D} 3P_2 + A_{1D} 3P_1} = \frac{3.4 \times 10^{-3}}{9.1 \times 10^{-3}} = 0.37 \quad \text{at 400 km}$$

It is concluded that the quenching term is significant for the $1D$ state.

Since only N_2 is involved the summation term may be rewritten

$$\sum_x \beta_{1D} x n(x) = 7.5 \times 10^{-11} n(N_2)$$

where $n(N_2)$ is the concentration of N_2 at h.

For quenching of the $1S$ state, the quenching species is also thought to be N_2 but the rate is very low. *Hunten and McElroy* [1966] indicate a laboratory measured value of $\beta_{1S} N_2 < 10^{-15}$, thus as an estimate

$$\frac{\sum_y \beta_{1S^y} n(y)}{A_{1S^1D} + A_{1S^3P_1}} \sim 10^{-8} \quad \text{at 400 km}$$

and the last term in the denominator of equation (4-4) can be neglected.

Forming the quotient $F_{1D^3P_2} / F_{1S^1D}$ yields

$$\frac{F_{1D^3P_2}}{F_{1S^1D}} = \left(1 + 1.06 \left[\frac{\alpha_{3P^1D}}{\alpha_{3P^1S} + \alpha_{1D^1S} \frac{n(O^1D)}{n(O^3P)}} \right] \right) \frac{6.9}{9.1 + 7.5 \times 10^{-8} n(N_2)} \quad (4-6)$$

Here the numerical values of the transition probabilities (4-5) have been inserted. The result is the [01] 6300A/ [01] 5577A volume emission ratio. Knowing the experimental results, it may be noted in advance that the factor in square brackets must be of order 10^2 . Although $n(O^1D)$ would be expected to be less than $n(O^3P)$ one can not at this stage justify dropping the term involving the ratio of densities. The α_{1D^1S} term may be large because the cross-section for the transition is significant. Thus, the concentration ratio $n(O^1D)/n(O^3P)$ must be estimated. This is done in Appendix 1. It will result that the term $\alpha_{1D^1S} n(O^1D)/n(O^3P)$ could safely be dropped but we retain it temporarily to illustrate how it may be treated.

The concentration ratio is given approximately by

$$\frac{n(O^1D)}{n(O^3P)} \sim \frac{\langle n(O^1D) \rangle}{\langle n(O^3P) \rangle} \sim 3.9 R_{6300} \times 10^{-8} \quad (4-7)$$

Putting this value in equation (4-6) it is found that the red-green ratio given by (4-6) is therefore approximately

$$\frac{F_{1_D 3P_2}}{F_{1_S 1_D}} = \rho(h, T) \sim m(h) \left(1 + 1.06 \left[\frac{\alpha_{3P_1 D}}{\alpha_{3P_1 S} + \alpha_{1_D 1_S} 3.9R_{6300} \times 10^{-8}} \right] \right) \quad (4-8)$$

where we have introduced the symbol $\rho(h, T)$ for the ratio and where $m(h)$ is given by

$$m(h) = \frac{6.9}{9.1 + 7.5 \times 10^{-8} n(N_2)} \rightarrow 0.76 \text{ as } n(N_2) \rightarrow 0 \text{ at high altitudes}$$

The T dependence is in the a 's.

The electron velocity distribution of equation (4-1) is conventionally written

$$dv f(v) = \left(\frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} 4\pi v^2 dv \quad (4-9)$$

It is convenient for calculational purposes to transform equations (4-1) and (4-9) to energy units. Equation (4-9) becomes

$$dE f(E) = \frac{E^{1/2}}{\pi^{1/2} (kT)^{3/2}} e^{-E/kT} dE \quad (4-10)$$

and (4-1) becomes

$$\alpha_{ij} = \frac{1}{(kT)^{3/2}} \left(\frac{2\pi}{m} \right)^{1/2} \int_0^\infty EQ(E, i \rightarrow j) e^{-E/kT} dE \quad (4-11)$$

Calculated cross-sections for the ($^3P \rightarrow ^1D$), ($^3P \rightarrow ^1S$), ($^1D \rightarrow ^1S$) transitions are shown in Figure 4-3 [Smith, Henry and Burke, 1967]. From equation (4-8) it is noted that the a's occur in both numerator and denominator hence all terms outside the integral of (4-11) will cancel. The dimensions of the Q's are of no concern for the same reason. Thus, we let $Q = G\pi a_0^2$ where G is a dimensionless factor given numerically by the ordinate of Figure 4-3.

Next we fit each region of the cross-sections by a straight line segment so that

$$G_{ij} = a_{ij}E + b_{ij} \quad (\text{in a certain range of } E) \quad (4-12)$$

The error introduced in the integrals by this approximation should be acceptable in view of uncertainties in the experimental results being checked.

Then from (4-11) the integrals are

$$a_{ij} \propto \int_E^{\bar{E}} E \{a_{ij}E + b_{ij}\} e^{-E/kT} dE \quad (4-13)$$

in the energy range $[E, \bar{E}]$. Evaluation of (4-13) can now be done analytically yielding

$$\alpha_{ij} \left[\int_E^{\bar{E}} \right] \propto \left[-a_{ij}kT E^2 e^{-E/kT} - (2kTa_{ij} + b_{ij}) \left\{ (kT)^2 e^{-E/kT} \left(\frac{E}{kT} + 1 \right) \right\} \right] \Bigg|_E^{\bar{E}} \quad (4-14)$$

for the range of the straight line segment between E and $\bar{E}$.

Figure 4-3 Cross sections for electron-induced excitation of atomic oxygen from *Smith, Henry and Burke* [1967]. Also shown are linear segments used to approximate the cross sections.

It is to be understood that the contributions from each energy range are to be added together to obtain the final value of a_{ij} . The more complicated looking notation that would be needed to indicate such summation is omitted.

Again, noting that only a ratio of a's is needed we may divide out $(-kT)$ and rearrange (4-14) obtaining

$$\alpha_{ij} \int_{\underline{E}}^{\bar{E}} a_{ij} (-\underline{E}^2 e^{-\underline{E}/kT} + \bar{E}^2 e^{-\bar{E}/kT}) + (2kTa_{ij} + b_{ij}) \times \left\{ (\bar{E} e^{-\bar{E}/kT} - \underline{E} e^{-\underline{E}/kT}) + kT(e^{-\bar{E}/kT} - e^{-\underline{E}/kT}) \right\} \quad (4-15)$$

Table 4-3 gives the values of coefficients needed to evaluate (4-15).

A final calculation indicates the cross-sections above 13.6 eV can be set equal to zero with no effect on the results because of the very low electron population above 13.6 eV for reasonable temperatures.

The variable parameters are h and T and the calculational program is now to select T and evaluate equation 4-15 for each a_{ij} (summing the results for each of the energy ranges). The resulting net a_{ij} 's for each T are then to be substituted into equation (4-8) at which time h is selected. The result is the red-green ratio $\rho(h,T)$ for a particular SAR-arc intensity R_{6300} . These steps were programmed for automatic machine computation. The resulting intensity ratio as a function of electron temperature and height is shown in Figure 4-4.

In the final calculation it was found that the R_{6300} term was insignificant for all reasonable SAR-arc intensities and thus the final ratio equation may be written

E	α_{3P^1S}		α_{3P^1D}		α_{1D^1S}	
	a_{3P^1S}	b_{3P^1S}	a_{3P^1D}	b_{3P^1D}	a_{1D^1S}	b_{1D^1S}
0 $\rightarrow$ 1.96	0	0	0	0	0	0
1.96 $\rightarrow$ 4.17	0	0	.173	- 340	0	0
4.17 $\rightarrow$ 5.40	.0284	-.1189	-.012	443	.103	-.432
5.40 $\rightarrow$ 5.60	.0284	-.1189	-.012	443	-2.44×10^{-3}	.138
5.60 $\rightarrow$ 13.60	$-.125 \times 10^{-3}$	.047	-.012	443	-2.44×10^{-3}	.138
13.60 $\rightarrow$ ∞	0	0	0	0	0	0

Table 4-3 Coefficients used in evaluation
of equation 4-15.

Figure 4-4 The red-green ratio $\rho(h, T)$ for a range of T and several values of h .

$$\rho(h, T) = m(h) \left(1 + p \frac{\alpha_{3P_1D}}{\alpha_{3P_1S}} \right) \quad (4-16)$$

where

$$m(h) = \frac{A_{1D^3P_2}}{A_{1D^3P_2} + A_{1D^3P_1} + \int_x \beta_x 1_D n(x)} = \frac{6.9}{9.1 + 13.8 \times 10^{3-h/100}} \quad (4-17)$$

(Here we have used the analytical expression for $n(x) = n(N_2)$ mentioned after equation 4-4.)

where

$$p = \frac{A_{1S^1D} + A_{1S^3P_2}}{A_{1S^1D}} = 1.06 \quad (4-18)$$

and where α_{ij} is given by equation 4-15.

To compare the result to the experimental result it is necessary to consider the value of the ratio $\rho(h, T)$ given by (4-16) along a line of sight through a SAR-arc. The value for comparison is given by

$$\rho(t) = \frac{\int_0^\infty \rho(h, T) F_{1D^3P_2}(h) dh}{\int_0^\infty F_{1D^3P_2}(h) dh} \quad (4-19)$$

or if $T \neq T(h)$ we may write

$$\rho(T) = (1 + p \frac{\alpha_{3P1D}}{\alpha_{3P1S}}) \frac{\int_0^\infty m(h) F_{1D3P2}(h) dh}{\int_0^\infty F_{1D3P2}(h) dh} \quad (4-20)$$

The integrals of equation (4-20) may be evaluated numerically using the measured value of $F_{1D3P2}(h)$ given by *Tohmatsu and Roach*, [1962]. It should be borne in mind that the result is valid only in the constant temperature approximation. The resulting value of $\rho(T)$ is shown in Figure 4-5. The main effect of the integrations of (4-20) is to reduce the red-green ratio ρ to 0.6 of the value of p at the altitude of the peak volume emission rate of 6300Å. The reason the ratio is reduced is that the lower part of the arc is relatively "greener" than the upper part on account of the quenching of the $O(^1D)$ at low altitudes, and the integration through the arc brings this relatively green region into the line of sight average. The intensity profile determined by Tohmatsu and Roach is shown in Appendix 1.

It is noted from Figure 4-5 that in this constant temperature approximation, the experimentally determined ratio (26 ± 3) implies an electron temperature of approximately 9000°K which is more than twice the temperature others (e.g., Carleton) might have anticipated.

This result seems rather high. *Cole* [1965] and *Roble* [1969] have calculated the intensity of SAR-arcs expected on the basis of different electron temperature profiles in altitude. Results from Roble's calculations are shown in Figure 4-6. Substituting values of (T,h) scaled

Figure 4-5 The value of the red-green ratio $\rho(T)$ weighted to account for the altitude dependence of the volume emission rate.

- (a) PROFILE FOR A 1.6 kR SAR ARC
(b) PROFILE FOR A 3.7 kR SAR ARC

Figure 4-6 Electron temperature versus altitude in a SAR-arc according to the calculations of *Roble* [1969].

from (b) of Figure 4-6 into equation (4-16) yields a function $\rho(T, h)$ which when integrated in (4-17) gives a result $\rho(T) > 10^3$. This very high red-green ratio was to be expected when these relatively low temperatures of Figure 4-6 were put into equation (4-17).

The discrepancy between the 9000°K result and the 2400-4000°K range shown in Figure 4-6 can not be resolved just by adding in a reasonable electron temperature gradient. It is true that allowing temperature to increase with altitude gives some additional excitation and emission from the 1S state at high altitudes. But it is found by trial calculations that even using a rather high temperature of 5000°K at 300 km and a very large gradient of 20° K/km, the resulting $\rho(T)$ from equation (4-17) is about 60 rather than the 26 observed. Furthermore, a 5000°K temperature at 300 km and 20° K/km gradient would, according to the calculations of Roble, yield an arc more than an order of magnitude brighter than the one observed.

The red-green ratio ρ is effected by the altitude distribution of the [O1] 6300Å emission which so far has been assumed to be the distribution determined by *Tohmatsu and Roach* [1962]. It is of interest to see what effect changing altitude will have on ρ . A direct method of checking to re-evaluate equation (4-16) for the same shaped distribution translated to lower altitudes. A computation was made for the distribution shifted downward in increments from zero to 100 km. This makes a physically unrealistic situation (since the shape should change) but it is a valid way to check the sensitivity of ρ to a variation of

the height parameter. The results are plotted in Figure 4-7 where it can be seen that even if the SAR-arc were lower in altitude by 100 km, the electron temperature still would correspond to the temperature given by $\rho \sim 43$ in Figure 4-5. Thus, the temperature implied is about 7500°K .

It has thus been seen that neither adjusting the temperature gradient nor the height of the SAR-arc has a substantial effect in resolving the discrepancy between the effective temperature implied by the observed ratio and what the temperature should be to produce an arc of the intensity actually measured. The possibility that the quenching coefficient is incorrect has also been checked by changing it and examining the results. It was found that, like the height variation, the effect was significant but entirely insufficient to reduce the implied temperature by more than about 1000°K for any reasonable choice of β_{1Dx} . The basic problem is apparent in Figure 4-5; namely, that to obtain a temperature in the 3000°K range, the ratio of red to green ought to be more than an order of magnitude higher than observed. Even the ratio 80 observed by Barbier implies $T \sim 6000^\circ \text{K}$. In reviewing the literature we find that apparently no one who discussed using a Maxwellian distribution of electrons ever said explicitly that the intensity 5577A line would be anything but "very low" or "insignificant" at the electron temperatures of $2000\text{--}4000^\circ \text{K}$. Now we have found that, in some observations at least, there is sufficient 5577A emission that additional explanation is needed. It is suggested that the way out of the apparent dilemma is to modify one of the first assumptions.

Figure 4-7 The effect of shifting the SAR-arc downward on the red-green ratio $\rho(T)$.

Suppose the ambient electrons are in a quasi-steady but nonequilibrium state due to the fact that they are being heated from above. Then the energy distribution of the electrons can not be precisely Maxwellian. In particular, there must be a high energy tail. That is, the population toward the high energy side of the peak of the thermal distribution would be expected to be slightly greater than in a Maxwellian distribution. Such a skewed distribution is to be expected during heating and the low red-green ratio observed apparently provides evidence of the high energy component.

The task of deciding on a theoretical basis the proper analytical form expected of the electron energy distribution, appears to be too formidable to take on at this stage. The nature of the energy source (number density, energy spectrum and spatial distribution) is not at all well known. Even if it were, the description of the slowing-down process in a realistic atmosphere is a non-trivial problem.

If there is some heating, then the electron density may be effected as well as the energy spectrum. There seem to be two ways to interpret the data at this stage. First we may take it that the slope of the electron energy spectrum above 2 eV corresponds to a 9000° K Maxwellian distribution but the amplitude at 2 eV corresponds to a lower, say 3000° Maxwell distribution. By this means a first estimate could be made of the high energy tail by joining a 9000° K tail onto the 3000° Maxwellian distribution at 2 eV. (The amplitude of the tail must be adjusted to match). Then the difference between the new tail and the

3000" K tail would yield a first estimate of the additional high energy population. This procedure is shown schematically in Figure 4-8 and the analysis will be illustrated.

The second interpretation is that the distribution is actually approximately **Maxwellian** at about 8000" K and, the reason the **6300A** emission from the SAR-arc is not many times brighter than observed is ~~that~~ the electron density that others, e.g., Roble, Cole and **Carleton** have assumed is much higher than the actual density. The **6300A** intensity is approximately proportional to the electron density and the fact that the density was low would permit a higher temperature.

In short, the first interpretation is that there exists a high energy tail on an otherwise normal electron distribution; the second interpretation is that the distribution is much hotter than normal but the electron density is low. The ideas are definitely not mutually exclusive. The density may actually be somewhat lower than normal, the distribution can also be somewhat hotter than normal and there can be a high energy tail as well.

Independent reasoning based on the ratio of the **[NI] 5200A/ [OI] 6300A** emissions (presented in the next section) suggests that the electron density in a SAR-arc is in fact lower than others have assumed by about a factor of 10. This result, in addition to being compatible with a top-side heating process, agrees with the result of a high altitude satellite measurement and with qualitative inferences drawn by others. The observations are discussed in the next section. However, a very high electron temperature and very low electron density cannot be the complete answer

Figure 4-8 Joining a high energy tail onto the main Maxwellian distribution. On a linear (l.h.) scale the difference between the high energy distribution and the original one is very small (lowest curve) On a logarithmic (r.h.) scale the difference is apparent.

because many attempts to record the 5577A emission in SAR-arcs have failed to yield a 30:1 red-green ratio or even an 80:1 red-green ratio when the arc was so bright that such an enhancement of 5577A would have been detectable *Roach*, [1970]. Observational experience thus suggests that relatively strong green enhancement is much more sporadic than the characteristic persistent and stable 6300A emission of the SAR-arc. The work of *Schaefer* [1970] mentioned previously, indicated somewhat sporadic emission of [O I] 5577A. The suggestion therefore emerges that the occurrence of a small high energy tail may also be comparably sporadic to the 5577A emission. The main body of ambient electrons may have a relatively stable energy distribution and therefore the 6300A emission will be acceptably stable.

We have combined these ideas to arrive at what seems to be a reasonable electron distribution consistent with the experimental facts. The temperature of the basic Maxwellian is elevated as permitted by the lower electron density and by the observed 6300A intensity. A tail is then added to give the red-green ratio observed. The description is developed in quantitative terms as follows:

$$\text{Let } n(e,400)_0 = 1.3 \times 10^6 \text{ cm}^{-3}$$

This is an electron density at 400 km on which detailed 6300A intensity calculations have been based *Roble*, [1969].

$$\text{Let } n(e,400)_5 = 1.3 \times 10^5 \text{ cm}^{-3}$$

This is the approximate electron density deduced in Section 5. Then, if the density had not been lower than normal, the SAR-arc intensity R'_{6300} would have been much higher than the actually measured R_{6300} , the relation being at least

$$R'_{6300} = R_{6300} \frac{n(e,400)_0}{n(e,400)_5} \sim 3.0 \times 10 \text{ kR} = 30 \text{ kR}$$

(using a conservative 3kR for the intensity of the SAR-arc). From Figure 4-9 in which SAR-arc intensity is plotted as a function of electron temperature at 400 km (from calculations of *Roble*, [1969]) we note that $R'_{6300} = 30 \text{ kR}$ implies that the temperature of the ambient electrons at 400 km would be 4200° K . Thus we assume a basic Maxwellian distribution of the ambient electrons denoted symbolically $f^m(E, 4200^\circ \text{ K})$. This characterizes the bulk of the ambient electrons which give rise to the stable 6300Å emission of the arc.

From Figure 4-5 we have seen that measured red-green ratio of 26 implies an electron temperature of 9000° K . This result is independent of electron density. Although it has not been discussed, quenching of the oxygen states by electrons is insignificant in this problem hence variations in electron density cause no problem because of quenching. Following the procedure described in Figure 4-8 and the discussion pertaining to it, we join a 9000° K Maxwellian tail $cf^m(E, 9000^\circ \text{ K})$ to the basic distribution at 1.96 eV. Then, the final distribution is

Figure 4-9 [01] 6300Å intensity from a SAR-arc as a function of electron temperature at 400 km, from calculations of *Roble* [1969].

$$f(E) = \begin{cases} f^m(E, 4200^\circ \text{ K}) = E^{1/2} e^{-E/4.2k \times 10^3}, & (E < 1.96 \text{ eV}) \\ cf^m(E, 9000^\circ \text{ K}) = 0.083 E^{1/2} e^{-E/9k \times 10^3}, & (E > 1.96 \text{ eV}) \end{cases}$$

Finally, the relative increase in population above 1.96 eV due to the high energy tail may be described

$$\begin{aligned} \frac{\Delta f(E)}{f^m(E, 4200^\circ \text{ K})} &= \frac{cf^m(E, 9000^\circ \text{ K}) - f^m(E, 4200^\circ \text{ K})}{f^m(E, 4200^\circ \text{ K})}, \quad (E > 1.96 \text{ eV}) \\ &= \frac{0.083 e^{-E/9k \times 10^3} - e^{-E/4.2k \times 10^3}}{e^{-E/4.2k \times 10^3}}, \quad (E > 1.96 \text{ eV}) \\ &= 0.083 e^{1.47E} - 1, \quad (E > 1.96 \text{ eV}) \end{aligned}$$

In Figure 4-10 the resulting electron spectrum and the composite parts of the spectrum are illustrated. Although the modification to the spectrum looks radical on a logarithmic scale it is actually quite small. For example, given a Maxwellian distribution (4200° K) of 10^2 electrons, moving one electron out to 4 eV would give approximately the modification suggested.

Conclusions

This investigation of electron temperature suggests that the assumption of a pure Maxwellian distribution and normal electron density is not entirely valid. A simple Maxwellian distribution at a temperature

Figure 4-10 Composite electron energy spectrum consisting of a 4200°K Maxwellian distribution (0, 1.96eV) and a 9000°K Maxwellian tail above 1.96eV.

that gives the correct 6300A intensity implies a 55778 intensity far lower than observed in some arcs. Assuming the cross-sections are not grossly incorrect, the adjustment to the electron distribution required is one that adds to the high energy population of the distribution. The basic Maxwellian distribution can be slightly hotter than others have assumed because the electron density is lower than normal. The need to add to a high energy component to the energy spectrum as well as the lower than normal electron density seems to imply a nonequilibrium state, in particular, a state in which heating is in progress. The result is compatible with the idea that there is a reservoir of rather high energy particles above the SAR-arc. In Section 6 the results of a search for these particles are presented.

Finally, it might be mentioned that the development of a proper theoretical solution to what the high energy tail should look like should not forever be avoided as has been done here. It appears to be a tractable if formidable problem and plans to investigate it further in the near future have been laid.

5. Expected Ratio of [NI] 5199A/ [OI] 6300A

This section is similar to Section 4 in that the problem is to calculate the intensity ratio of a pair of spectral lines under the conditions 'expected in a SAR-arc. The purpose is to show that observational data are compatible with and even suggest a process of excitation of the SAR-arc by ambient electrons. The difficulty with the detailed shape of the electron energy spectrum which was encountered in the last section may be expected to be less severe because in this case the excitation potentials for the excited states being compared are much closer to each other.

The calculation may be developed to a certain stage independently of a particular atmospheric model and the results are then applicable to electron excited auroral emissions in arbitrary conditions, not only to SAR-arcs. It has seemed worthwhile to do the calculation in that generalized way. It is in line with recent thinking that auroras excited by thermal electrons may be more prevalent than formerly believed. Since the calculation should be applicable to these electron excited auroras rather generally It may eventually serve as a diagnostic tool to distinguish them from other auroras or alternatively, the thermal electron excited auroras may provide data to check and refine the calculation. The main concern of the section is, however, the SAR-arcs and, after the general result is given, conditions are specialized to the case of a SAR-arc for comparison with observations.

According to *Cole* [1969] there is a class of auroral phenomena which may be called "thermal auroras". In such auroras the emitting species are excited primarily by thermal electrons. SAR-arcs seem to be members

of this class of auroras. Above 250 km one would expect the predominant radiation of a thermal aurora to be the emissions of atomic oxygen because of the abundance of that species. However, under conditions of direct excitation by thermal electrons one would also expect excitation of atomic nitrogen which has lower energy level structure and electron excitation cross-section similar to oxygen. The energy level diagram for oxygen and nitrogen are shown in Figure 5-1.

For observational purposes it is of practical value to know what ratio might be expected for the volume emission rates from the lowest excitation states of nitrogen and oxygen. A direct calculation of this ratio is precluded primarily by lack of information on the quenching of [NI] 5199A. By neglecting quenching of nitrogen one can calculate an upper limit of the emission ratio $F(5199)/F(6300)$. The upper limit is of some value in deciding whether it is practical to attempt to detect the 5199A emission and in comparing the observed ratio to the predicted result. It will be shown that the single observational datum available on the ratio yields as a result which corresponds approximately to the actual ratio being near the calculated upper limit.

The volume emission rate for [NI] 5199A is

$$F(5199) = \alpha_{4S_{3/2}^0}^{2D_{3/2,5/2}^0} n(N)n(e)A(5199) \left[\sum_{\lambda} A(\lambda) + \sum_x \beta_{2D^x} n(x) \right]^{-1} \quad (5-1)$$

where

$$\alpha_{4S_{3/2}^0}^{2D_{3/2,5/2}^0} = \int_0^{\infty} Q(4S_{3/2} \rightarrow 2D_{3/2,5/2}^0) v f(v) dv \quad (5-2)$$

Figure 5-1 Energy level diagrams of oxygen and nitrogen.

and where the notation is the same as Section 4 except instead of writing out the explicit but rather complicated subscripts of F, we have written the wavelength of the transition 5199A in parantheses. Henceforth we will also abbreviate $^4S_{3/2}^0$ and $^2D_{3/2,5/2}^0$ to 4S and 2D where the meaning is clear. In the denominator of the right hand side of equation (5-1), the first term sums the transition probabilities from the levels $J = 3/2$ and $J = 5/2$; i.e.,

$$\sum_{\lambda} A(\lambda) = A(5199) + A(5201)$$

but, in the second term, $\sum_x \beta_{2D^x} n(x)$, neither the quenching species (x)

nor rate coefficients (β_{2D^x}) are known for nitrogen.

For the volume emission rate of [OI] 6300A we have

$$F(6300) = \alpha_{3P^1D} n(O)n(e) A(6300) \left[A(6300) + A(6364) + \beta_{1DN_2} n(N_2) \right]^{-1} \quad (5-3)$$

where

$$a_{3P^1D} = \int_0^{\infty} Q(^3P \rightarrow ^1D) v f(v) dv \quad (5-4)$$

As discussed in Section 4, the quenching of [OI]6300A is found to be given approximately correctly by the term $\beta_{1DN_2} n(N_2)$ in equation (5-3). That is, one may either assume the nitrogen molecule is the sole quenching species for [OI]6300A or one may take the point of view that the actual quenching

process is more complicated but may be approximate empirically by

$$\beta_{1_D N_2} n(N_2). \quad [\text{Hunten and McElroy, 1966}] \quad [\text{Rees, Walker and Dalgarno, 1967}]$$

According to Hunten and McElroy the [OI]6300A quenching reaction may be

However, Rees, Walker and Dalgarno and others have mentioned the importance of O_2 as well, and certainly one would expect slight quenching by electrons. We will use $\beta_{1_D N_2} n(N_2)$ for the quenching of [OI]6300A with $\beta_{1_D N_2} \sim 7.5 \times 10^{-11}$ as suggested by *Petersen* and *Van Zandt* [1969] and discussed in Section 4. Although one can see some obvious analogs for quenching of [NI] 5199A, we refrain from guessing, being forewarned by Hunten and McElroy of the futility of attempting to predict the quenching of one species by analogy with another.

The volume emission rate ratio which we designate $\rho(h,T)$ is

$$\frac{F(5199)}{F(6300)} = \rho(h,T) = \frac{\alpha_{4_S 2_D}}{\alpha_{3_P 1_D}} \frac{n(N)}{n(O)} \frac{A(5199)}{A(6300)} \frac{A(6300)+A(6364)+\beta_{1_D N_2} n(N_2)}{A(5199)+A(5201)+\sum_x \beta_{2_D x} n(x)} \quad (5-5)$$

where $n(e)$ has cancelled except insofar as it may be in $\beta_{2_D x} n(x)$.

The theoretical cross-sections of Smith, Henry and *Burke* [1967] for the ($4_S \rightarrow 2_D$) nitrogen transition and the ($3_P \rightarrow 1_D$) oxygen transition are shown in Figure 5-2. The ratio of the α 's is given by

$$\frac{\alpha_{4_S 2_D}}{\alpha_{3_P 1_D}} = \frac{\int_0^\infty EQ(4_S \rightarrow 2_D) e^{-E/kT} dE}{\int_0^\infty EQ(3_P \rightarrow 1_D) e^{-E/kT} dE} \quad (5-6)$$

Figure 5-2 Cross sections for electron induced excitation of oxygen and nitrogen. From *Smith, Henry and Burke [1967]*.

as shown in Section 4. (Refer to equations (4-9, 10, and 11). Approximating the cross-sections by linear segments (as in equations (4-12 and 13), the a's are to be evaluated according to equation (4-15) for the coefficients given in Table 5-1.

The cross-sections are set equal to zero for $E > 13.6$ eV because the contribution from the corresponding range of the integration is insignificant.

The calculation of the ratio of the a's as a function of temperature was set up for automatic digital computation. The ratio $\frac{a_{4S^2D}}{a_{3P^1D}}$ is designated $g(T)$ and its computed values are plotted in Figure 5-3.

TABLE 5-1
Coefficients for evaluation of equation 5-6

E(ev)	α_{4S^2D}		α_{3P^1D}	
	a_{4S^2D}	b_{4S^2D}	a_{3P^1D}	b_{3P^1D}
0 - 1.96	0	0	0	0
1.96 - 2.37	0	0	.173	-.340
2.37 - 4.17	.415	-.984	1.73	-.340
2.37 - 5.15	.415	-.984	-.012	.443
5.15 - 13.6	-.0456	1.390	-.012	.443
13.6 -	0	0	0	0

It was found that the ratio could be approximated within 1% in the region $T = 2000^\circ$ to 9000° by the following quadratic function

$$g(T) = -1.555 T^2 \times 10^{-8} + 3.681 T \times 10^{-4} - 3.950 \times 10^{-1} \quad (5-7)$$

Figure 5-3 Plot of the ratio $g(T) = \frac{\alpha_4 S^2_D}{\alpha_3 P^1_D}$ as a function of temperature.

Using the transition probabilities for the oxygen ($^1D \rightarrow ^3P_{1,2}$) transitions given previously in equation (4-5) and for nitrogen the values

$$\left. \begin{aligned} A(5199) &= 1.6 \times 10^{-5} \\ A(5201) &= 7.0 \times 10^{-6} \end{aligned} \right\} \quad (5-8)$$

from *Chamberlain*, [1961], we may evaluate equation (5-5) except for the *in situ* species densities obtaining

$$\rho(h, T) = 2.3 \times 10^{-3} g(T) \frac{n(N)}{n(N_2)} \left(\frac{9.1 \times 10^{-3} + 7.5 \times 10^{-11} n(N_2)}{2.3 \times 10^{-5} + \sum_x \beta_{2D^x} n(x)} \right) \quad (5-9)$$

where $g(T)$ is given by equation (5-7). We note from 5-7 that $g(T)$ is roughly equal to unity in the temperature range of interest.

This intermediate **result** (equation 5-9) is presented because no atmospheric model has yet been invoked and because the numerical values of the species densities to be inserted next are known with less certainty than the numerical values which have been used so far. This result should have rather general applicability.

We will now assume the atmospheric environment to be approximately that of a SAR-arc since that phenomenon appears to be a good example of a thermal aurora. An approximate $n(N)$ value at 280 km is obtained using the data on $n(N)/n(N_2)$ given by *Ghosh, et al.* [1968] and the density of N_2 at 280 km from *CIRA* [1965]. Assuming diffusive equilibrium of the nitrogen at 1200° K gives a scale height of 71.5 km (the distance of one e-fold decrease) and the density $n(N)$ shown in Figure 5-4. Also shown in Figure 5-4 are the densities of oxygen and molecular nitrogen; both are appropriate

Figure 5-4 Density of the several species used in calculation of $\rho(h,T)$.

for the atmosphere under conditions of high solar activity [CIRA (1965), mod. 9]. The temperature of 1200° K which is used to estimate the scale height of nitrogen corresponds to the neutral temperature in a SAR-arc measured by Hays, et al. [1969].

The assumption of diffusive equilibrium at a constant temperature is, of course, a rough approximation; but in view of the wide variations that probably occur in the several densities and the uncertainty in their actual values (including the value of $n(N)$ at 280 km), a more sophisticated or refined nitrogen distribution would not improve overall accuracy significantly.

From the density distributions shown in Figure 5-4, we estimate

$$\left. \begin{aligned} \frac{n(N)}{n(0)} &\sim 1.6 \times 10^{-2} \\ n(N_2) &\sim 4.46 \times 10^{11} \times 10^{-h/100} \end{aligned} \right\} 250 < h < 600 \text{ (km)} \quad (5-10)$$

$$\rho(h, T) = 3.7 \times 10^{-5} g(T) \left(\frac{9.1 \times 10^{-3} + 3.34 \times 10^{12-h/100}}{2.3 \times 10^5 + \sum_x \beta_{2Dx} n(x)} \right) \quad (5-11)$$

To evaluate the upper limiting value of the ratio given by equation (5-11) the Nitrogen quenching term, $\sum_x \beta_{2Dx} n(x)$, is set equal to zero. The result for several electron temperatures is shown in Figure 5-5. From the result we can estimate immediately that the effective upper limit of the ratio is of order of magnitude 10^{-2} because the emission comes predominantly from altitudes around 400 km.

As mentioned previously, some quenching of radiation by electrons is

Figure 5-5 $\rho(h, T)$ as a function of altitude for several temperatures of the electrons (NO QUENCHING).

certainly to be expected. The quenching coefficients are temperature dependent according to Seaton whose values are summarized by Hunten and McElroy. In the 2000-5000° K range it is found that the quenching coefficients are given correctly within a few percent by the linear equations,

$$\begin{aligned}\beta_{1_D e} &= 10^{-9} (0.61 T \times 10^{-3} + 1.43) \\ \beta_{2_D e} &= 10^{-9} (0.44 T \times 10^{-3} + 0.42)\end{aligned}\tag{5-12}$$

It was determined by trial calculation that electron quenching of oxygen is relatively insignificant in the temperature range of interest. However, quenching of nitrogen by the electrons is quite significant as will now be shown.

A distribution of electrons in altitude must be assumed to calculate quenching and we have adopted the two distributions used for SAR-arc conditions by Roble and by Walker and Rees. These are marked R and WR in Figure 5-4.

Numerical evaluation of equation (5-11) with the second formula of equation (5-12) inserted for $\beta_{2_D e}$ and for the two $n(e)$ distributions mentioned yields the results shown in Figure 5-6. It is evident that electron quenching is strongly effective in the 400 km region, where, if the electrons are as dense as both R and W and R assume, the ratio is more than an order of magnitude below the upper limit (shown in dotted line for reference).

The assumed number density of electrons in the SAR-arc is therefore very important in so far as it affects the F(5199)/F(6300) ratio. The

Figure 5-6 The ratio $\rho(h, T)$ as a function of altitude in cases of quenching by electrons according to two electron distributions used by others and in the case of no quenching (upper limit).

number density of electrons has not been measured directly and there are some reasons to suspect that a lower density than others have assumed would prevail in a SAR-arc.

If, for example, electrons in the localized region of the arc were being heated, then if the number density of electrons also remained constant at the value it was before heating, the energy density would increase. The volume of the SAR-arc would thus define a region of relatively high partial pressure of the electron gas (energy density and pressure being identical quantities in this case) which would be unstable until the electrons dispersed sufficiently to balance the pressure. The observed long-term persistence of SAR-arcs suggests a steady state already prevails during the term of the arc and hence that the number density may already be relatively low. Furthermore, *Norton and Findlay* [1969] found that in Alouette satellite measurements made at an altitude of 1000 km the electron density dropped in the region above the arc to about 7% of the value that would have been expected by reference to an underdrawn baseline connecting the regions outside of the density depression. Other measurements which will be mentioned also suggest indirectly that the density might be lower than normal.

To show the effect of the electron density assumption, the $F(5199)/F(6300)$ ratio was evaluated for a range of electron densities at 400 km, and for several temperatures. The resulting values are shown in dotted lines in Figures 5-7. There is, however, the additional complication that if the electron density is reduced, the SAR-arc intensity will also be reduced since excitation of the oxygen is proportional to the electron

Figure 5-7 Variation of $\rho(h, T)$, ($h=400$ km), according to the electron density assumed at 400 km.

density. Thus, to consider a particular SAR-arc of a given intensity it is necessary to allow the assumed electron temperature to change in the calculation to compensate (according to Figure 4-9) for the change in electron density. When this is done the ratio $F(5199)/F(6300)$ for several different arc intensities varies with electron density as shown by the solid lines in Figure 5-7.

One measurement of the intensity of the [NI] 5199A and [NI] 5201A doublet in a SAR-arc has been reported [Carleton and Roach, 1965]. The value given is "approximately 100 R". The uncertainty in the measurement is estimated to be ± 50 R [F. E. Roach, 1969]. Figure 5-8 shows the time variation of [OI] 6300A during the exposure duration of the spectrogram [J. R. Roach, 1963]. The mean ratio of measured intensity of [NI] [5199 + 5201A] to [OI] 6300A is found to be 0.025 ± 0.012 .

To compare the measurement to the calculation we must take into account the fact that the doublet was observed rather than the 5199A line alone and that the measurement is an average value for a line of sight through the SAR-arc.

The first adjustment is easy to make because the doublet should be about 1.44 times as intense as the 5199A line since $(A(5199) + A(5201))/A(5199) = 1.44$.

The second adjustment requires computation of the line of sight average which we want in the form,

Figure 5-8 Time variation of [01] 6300A intensity during measurement of Carleton and Roach [1965].

$$\frac{\langle \rho \rangle}{\rho_{400}} = \frac{\int_0^{\infty} \rho(h) F(6300) dh}{\rho_{400} \int_0^{\infty} F(6300) dh} \quad (5-13)$$

For $F(6300)$, the intensity profile measured by *Tohmatsu and Roach* [1962] can be used. In principle $\rho(h)$ is not known at this stage but we note that the three solid line curves of Figure 5-6 would all give very similar results in equation (5-13) since they are relatively flat compared to $F(6300)$, and the fact that they differ from each other by a scale factor makes no difference in equation (5-13). Furthermore, in view of the large uncertainty in the measured ratio, some error in the line of sight average is tolerable. Equation (5-13) was evaluated numerically for the solid curve at 4000° K in Figure 5-6 with the result

$$\frac{\langle \rho \rangle}{\rho_{400}} = 1.20$$

The result is interpreted as meaning the line of sight integrated ratio is 20% higher than volume emission ratio at 400 km because of relatively strong weighting of high values of the ratio in regions below 400 km.

Thus for comparison, the measured ratio 0.025 ± 0.012 reduced to conditions for 5199A alone at 400 km is

$$\rho_{400 \text{ exp.}} = (0.025 \pm 0.012) \times \frac{1}{1.44} \times \frac{1}{1.20} = 0.014 \pm 0.007 \quad (5-14)$$

where "exp." means "experimental".

The intensity of the SAR-arc varied between 2 kR and 10 kR during the measurements of Carleton and Roach. The mean intensity was about 6 kR. According to Figure 4-9, this intensity range implies an electron temperature of $(2.6 \text{ to } 3.4) \times 10^3 \text{ }^\circ\text{K}$ during the event. We now pick points off the several working plots that have been developed. Tabulating cases for comparison we have

TABLE 5-2

Comparison of ρ for several cases

Case	Refer to	ρ (n(e), T, h)	Temperature $^\circ\text{K}$	Altitude	n(e)	Quenching
1	Fig. 5-5	1.3×10^{-2}	3.2×10^3	400 km	no assumption needed	none
2	Fig. 5-6	1.0×10^{-3}	3.2×10^3	400 km	Robles	by electrons
3	Fig. 5-6	3.5×10^{-4}	3.2×10^3	400 km	Walker & Rees	by electrons
4	Fig. 5-7	7.8×10^{-3}	4.2×10^3	400 km	$\frac{1}{10}$ of Robles	by electrons
5	Fig. 5-7	1.1×10^{-2}	4.5×10^3	400 km	0.07 of Robles	by electrons
6	to be discussed	$1.26 \times 10^{-2} \pm 0.16 \times 10^{-2}$	9000 $^\circ\text{K}$ Tail 4200 $^\circ$ for E<1.96	400 km	$\frac{1}{10}$ of Robles	by electrons
7	equation 5-14	$1.4 \times 10^{-2} \pm 0.7 \times 10^{-2}$	observed value adjusted to 400 km			

The basis for case number 6 in the table has not been discussed and remains to be explained in detail. For the other cases the following

comments are offered.

- Case 1. This is the upper limit of the ratio. Although close to the experimental value, the omission of electron quenching cannot really be justified.
- Case 2. More than a factor of 10 lower than the measured value but based on other's best estimates of conditions in a 6 kR arc.
- Case 3. Far lower than observed due to effectiveness of electron quenching and relatively high $n(e)$
- Case 4. Falls within error bars of the measured value. The temperature increase is that required to maintain 6 kR under reduced electron density.
- Case 5. Same as Case 4 except it is assumed the density depression measured by Norton and Findlay at 1000 km persists down to 400 km.

The conclusion to be drawn from these five cases is that the observed ratio can be explained on the basis of a rather lower electron density than others have assumed and a higher electron temperature. The higher temperature does not cause the arc to be brighter than observed as long as the density of electrons is appropriately reduced.

To explain Case 6, attention is now turned to the possibility that observed ratio is higher than several of the calculated values because there is a high energy tail on the Maxwellian distribution (as discussed in Section 4.) In effect, most of the analysis for this possibility has been done. Figure 5-3 illustrates the change in the calculated ratio due to a temperature change of the tail of the electron distribution between 1.96 and 2.37 eV. It is seen from Figure 5-3 that changing the

"tail-temperature" from 4000° to 9000° K gives less than a factor of 2 increase in $g(T)$ and hence in the ratio $F(5199)/F(6300)$. This small effect was to be anticipated because the excitation potentials for the two states are so much closer ($2.37 - 1.96 = 0.51$ eV) than they were for the $1D$ and $1S$ states of oxygen (2.21 eV). For the intensity ratio investigated in this section, the electron density effect is the most important on account of the strong influence of electron quenching on $N(^2D)$. But for the ratio of oxygen lines investigated in the last section the "tail temperature" has a major effect. The two different spectral line ratios investigated in the two sections thus afford some experimental separation of the "tail" and "density" effects of the electrons.

In the measurement of Carleton and Roach no enhancement of the 5577A line in the SAR-arc was reported. At a ratio $F(6300)/F(5577)$ of 26, a 5577A enhancement of more than 2×10^2 R would have occurred.

The lack of 5577A enhancement may be due to the fact that relatively strong 5577A emission in the arc occurs only sporadically. There appears to be less experimental justification for adding a high energy component to the electron distribution for the $F(5199)/F(6300)$ calculation but it would be consistent with the work of the last section to do so.

In joining a 9000° tail to the main (4200° K) distribution at 1.96 eV, the major effect is an increase of ρ by a factor of $1.83 = \frac{g(9000^{\circ}K)}{g(4200^{\circ}K)}$. In addition, quenching by electrons, which it is recalled is temperature dependent, may or may not be affected significantly by the small increase in electron population above 1.96 eV. If the bulk of quenching of the $N(^2D)$ state is done by electrons with energy > 1.96 eV, then the effect of

the tail will be important; otherwise it will not. The quantitative answer should lie between the two cases in which quenching is considered due to a 4200° K distribution and due to a 9000° K distribution. For $T = 9000^{\circ}$ K Hunten and McElroy give $\beta_{2De} = 3.2 \times 10^{-9}$. Thus the denominators of equation (5-11) for the two cases are

$$\begin{array}{ll} (2.3 \times 10^{-5} + 1.3 \times 10^4 \times 2.3 \times 10^{-9}) & \text{for } 4200^{\circ} \text{ K} \\ (2.3 \times 10^{-5} + 1.3 \times 10^4 \times 3.2 \times 10^{-9}) & \text{for } 9000^{\circ} \text{ K} \end{array}$$

where the electron density of Case 4 has been used. The first denominator is 78% of the second indicating that the temperature effect on quenching is small. The net effect of the high energy component is to increase ρ of Case 4 by a factor of 1.41 to 1.83; hence, the result $(7.8 \times 10^{-3} \left(\frac{1.41}{1.83} \right) = 1.26 \times 10^{-2} \pm 0.16 \times 10^{-2})$ presented for Case 6.

In summary of this section it must first be recognized that the rather large inherent uncertainties in the density estimates and the single observational datum certainly compromise any conclusions to be drawn. But, with such reservations in mind we may review what the results seem to suggest. From Table 5-2 we see that the single observational value available for the ratio ρ is very close to the calculated upper limit in the case of no quenching. But this same observational value is considerably higher than would be expected under conditions of electron quenching when two electron distributions in altitude that have been used by others are tried. Yet, quenching of [NI] (5199 + 5201A) by electrons is certainly to be expected. Therefore, the indication is that there are fewer electrons in a SAR-arc than either of the two distributions assumed. Measurements of

the scintillation of radiowaves passing through a SAR-arc also suggest an anomalously low electron density in the region of the arc [J. R. Roach, 1963]. If one assumes that a density depression in the region of the SAR-arc comparable to the one measured by Norton and Findlay at 1000 km (about a factor of 10) then agreement with the measured ratio is obtained.

The effect of adding a high energy tail to electron distribution as was done in Section 4 is relatively small. Such a tail may not have been present during the measurement of Carleton and Roach since no enhancement of 5577A was reported but we have seen that if it were present, the $F(5199)/F(6300)$ ratio would not have been changed significantly.

6. Identification of the Particles that Excite the SAR-Arcs

The purpose of this section is to specify the top-side source of energy that excites the SAR-arc. The fact that the SAR-arcs occur in unison with a decrease in the strength of the geomagnetic field at middle and low latitudes has been mentioned by others [*Rees and Akasofu*, 1963]. Such a temporal correlation alone infers no direct causal connection between the phenomena. But the overall physical processes that are believed to occur in the magnetosphere suggest that the field-decrease and SAR-arcs may be traced to a common cause. This idea was first advanced by *Cole* [1965]. In this section, information on the pertinent magnetospheric processes is presented first to illustrate why the field decrease and SAR-arcs should be related, then particular observations are described.

In Section 2 a brief description of the magnetosphere was given. The magnetospheric cavity in space is not only defined in extent by the static pressures of the solar plasma, but the cavity itself and the particles within it respond to the dynamic pressures of the solar plasma.

In a typical magnetic storm, the first geomagnetic event is a compression of the magnetosphere called the "sudden commencement". During the sudden commencement the magnetic field measured at equatorial latitudes rises quickly in the course of a few minutes. It remains increased for perhaps 4 hours and then begins to fall. The field will decay to its nominal value in perhaps an hour, but (perhaps) surprisingly, it passes directly through the nominal value and continues to drop for the next few hours. The field increase in the initial phase may be about $3 \times 10^{-4} B_0$

where B_0 is the normal value. But at the depths of the decrease (the "main phase" of the storm), the field may be subnormal by about $-10^{-3}B_0$. That is, the drop is typically greater than the initial increase. The field then increases slowly to its nominal value during a recovery phase that may last a day or two.

No geomagnetic storm is really so simple. The times and amplitudes may vary greatly from those given. Often as many as 10 sub-storms occur during the course of the whole event and the typical magnetogram thus tends to look rather "noisy" at first glance.

The magnetic field increase that occurs when the magnetosphere is compressed, is qualitatively what one would expect when the field lines are confined to a reduced volume. The subsequent decrease to subnormal values is more mysterious. It is not believed that the solar plasma flux decreases after a few hours but rather that it usually remains enhanced. Thus, it is not an expansion of the whole magnetosphere that causes the decrease. It is clear that a huge azimuthal current loop could cause the decrease and, though it's no longer believed that such a loop actually forms, the term "ring current" is still applied to the cause of the decrease.

More than a decade ago *Singer* [1957], [1962] proposed that charged particles with kilovolt energies were responsible for the main phase decrease in the geomagnetic field. *Dessler and Parker* [1959] extended and refined Singer's argument to conclude that the main contribution would arise from protons at geocentric distances of $3-5 R_e$. It was shown that if the region between a pair of dipole shells became heated, the effect would

be to distend the field in the heated region. Sometimes the process is described as the "inflation" of the heated region. When the heated region undergoes such a process, the part of the magnetosphere under the heated loops will have a weaker-than-normal magnetic field because the field lines move apart slightly to fill the enlarged volume. The process is illustrated in Figure 6-1. The field decrease occurs primarily in the horizontal component of B in equatorial regions. It is ordinarily a small change $\frac{\Delta B}{B_o} \approx -10^{-3}$ which permits simplifying approximations to be made in the quantitative treatment. It has been shown [Dessler and Parker, 1959] that the total energy E of charged particles is related to the decrease of the horizontal component B_h at the magnetic equator by

$$\frac{\Delta B_h}{B_{ho}} = -k \frac{E}{E_m} \quad (6-1)$$

where B_{ho} is the unperturbed (horizontal) field at the magnetic equator on earth, E_m is the total magnetic field energy above the earth's surface and k is of order unity.

Scopke [1966] has shown that $k = 2/3$ and, for the earth's dipole field equation (6-1) becomes

$$\Delta B_h = -2.6 \times 10^{-26} E \text{ (Gauss)} \quad (6-2)$$

In predicting that such particles might exist it was possible also to estimate the approximate position ($3-5 R_e$) and energy ($\sim 1 \text{ keV}$) of the particles. To begin with it was known that the field decrease occurred only at the low and middle latitudes. Thus, the bulk of particles had to be within those field line loops that intersected earth below about 60° geomagnetic latitude which was the limiting upper latitude of the decrease.

Figure 6-1 Illustrating the "normal" (upper half) and "heated" (lower half) configuration of the inner part of the geomagnetic field.

Furthermore, the total energy of the magnetic field beyond the $L = 5$ or 6 loops was considered not sufficient to contain the heated particles, and on those grounds they should also have been inside about $L = 5$ or 6. A sharp localization of the heated region was not expected because then, unless the particles were very dense, the individual particle energies would have to be high for a given total energy E in equation (6-1). This would have the effects of causing detectable dissipation of energy in the upper ionosphere or possibly causing a high-energy radiation belt which should have been detected in early satellite experiments.

Although there was considerable motivation to find the "ring current", whether or not the "ring current" itself had been located in some early satellite experiments remained a matter of controversy until the position was definitely established by *Cahill* [1966]. Cahill showed from magnetometer observations with Explorer 26 that a field decrease on 17 April 1967 was caused by a distention of the field in the region between 2.5 and $5 R_e$. Then it was reported that the particles themselves had been detected [Frank, 1967]. These results then helped clarify earlier measurements.

The particles that cause the decrease of the magnetic field are found to be localized in such a way that they approach earth closely in the mid-latitude region where the SAR-arcs occur. The implication is that these intermediate energy particles are the top-side energy source for the arcs. Attention is now directed to observations of the RC (Ring Current) particles.

Data pertaining to measurements made during the decline of the last solar maximum will be mentioned first. Figure 6-2 shows what is now

Figure 6-2 Detection of the "ring current" during the magnetic storm of early November 1961, from Frank [1966].

understood to be a detection of the RC particles during a magnetic storm in November 1961 [Frank, 1966]. These data were obtained with the Explorer 12 satellite and each datum shown is the CdS detector count rate on successive passes when the satellite intersected the $L = 3.5$ field lines. The expected linear correlation (required by equation (6-1)) between field decrease and total energy of the RC can be seen by comparing the Guam AB_h (top of Figure 6-2) to the detector count rate. It is, of course, of interest to know what the count rate was on other field line loops besides $L = 3.5$. These data were not reported having been "clouded by loss of telemetry" but the variation with L was probably much like that shown in Figure 6-3 which is from a similar measurement of the RC particles during a geomagnetic storm a few weeks later. It is now known that the L -variation shown in Figure 6-3 is quite typical. The main change from one geomagnetic storm to another is a tendency for the peak to sharpen toward lower L -values in stronger storms.

The reason for discussing this early November event rather than the one that occurred a few weeks later, where the distribution at different L 's was measured, is that ground based photometric data are available for this November event but not for the later one when the moon was up.

The ground based data taken on the night of 7/8 November 1961 at Fritz Peak, Colorado indicated a SAR-arc was occurring over the United States. Figure 6-4 is a map at 400 km altitude showing the maximum intensity region of the arc at 2155 MST. The photometric center lay approximately along the $L = 3$ intercept at 400 km.

Figure 6-3 L-dependence of peak count rate on 1 October 1961 from Explorer 12 measurements after *Frank* [1966].

Figure 6-4 Position of the brightest region of a SAR-arc recorded 7/8 November 1961 at Fritz Peak, Colorado, after Marovich [1966]

When the distribution of the RC particles with respect to L shown in Figure 6-3 is considered, the simultaneous observation of the RC particles at $L = 3.5$ and the SAR-arc at $L \sim 3$ supports the notion that the peak of the RC distribution would be at $L \sim 3$ and suggests that the SAR-arc marks the position of the near-earth approach of the RC particles. A much more detailed picture of the spatial distribution of the RC particles has become available since these Explorer 12 measurements were made. The distribution will be discussed in some detail later, but it is relevant to mention here that it shows a sharpening of the distribution of the RC particles toward the peak L of the distribution as earth is approached.

Even before the simultaneous observation of the RC particles and a SAR-arc just discussed, a definitive measurement of the spatial and temporal coincidence of a SAR-arc with a localized "belt" of hot particles was reported to have occurred on 28 November 1959 following a sudden commencement on 27 November [O'Brien et al., 1960]. At the time these 1959 measurements were reported the tendency was to think in terms of a pair of rather distinct inner and outer radiation (Van Allen) belts. The particles observed were thus described as "outer zone radiation zone" particles, though the data show them to have been localized around $L = 3$. It was noted that the energy spectrum of the particles was much softer than any ever seen before and that the width of the zone was much narrower than anything seen before. It seems clear now, to this writer at least, that the RC particles were what were detected over the SAR arc. The data were taken by the Explorer VII satellite at altitudes between 500 and 1100 km. The vehicle was just above, or even in, the top part of the SAR-arc. When

the outer boundaries of the detected radiation region were extended down field lines to 400 km, they defined the width of the observed SAR-arc with remarkable precision. Detector counting rate varied (decreased) on successive passes of the satellite, and the SAR-arc exhibited similar and simultaneous intensity variations. The brightest region of the SAR-arc and the maximum intensity region of particle radiation appear to have been just below $L \sim 3$ and both spanned some 5° of latitude.

Questions of what kind of particles (protons or electrons) were counted in these early measurements have been raised [*Hess, 1968*] and since the experimenters have not clarified the situation, we presume that sufficient information to do so is unavailable. However, the quantitative temporal, spatial and intensity correlations mentioned give apodictic evidence of particulate radiation at the topside of the SAR-arc.

Between late 1961 and mid-1966, no measurements of the RC particles were reported to have been made. This was generally a time of low solar activity.

The detailed shape of the RC particle distribution was well delineated by OGO-3 satellite measurements made in June and July of 1966 and reported by Frank [1967]. Measurements were made of the differential energy spectrum of electrons and protons separately in the energy range from 200 eV to 50 keV protons as shown in Figure 6-5. Note particularly the place where the tip of the distribution approaches earth. Frank estimates the maximum to intersect the 100 km altitude surface at about 55° geomagnetic latitude in the July 9 case shown. He notes also that in a smaller, late-June storm, the maximum was about 5° poleward. When the dipole field line

Figure 6-5 Contours of constant proton ($200 \text{ eV} < E < 50 \text{ keV}$) energy densities on 9 July 1966. From a report by *Frank* [1967] on the measurement of the extraterrestrial ring current during geomagnetic storms. The point of closest approach $\lambda_m \sim 55^\circ$ ($L \sim 3.04$) according to Frank.

configuration is combined with the July 9 distribution as we have done in Figure 6-5, we see that the inner-most tips of the iso-energy contours lie along the $L = 3.1$ field. lines.

In Figure 6-6 we have plotted the mean L - intercept at 400 km of several distinct SAR-arcs versus magnetic index A_p . The corresponding L -intercept of the RC particle region according to Frank's data are also shown. The statistical distribution of SAR-arcs during the last maximum is shown on the right hand side of the figure. Spatial and coincidence of the SAR-arcs and the tip of the RC distribution is strongly suggested.

Since the operation of the photometer at Richland was not started until September of 1967, photometric data from Richland taken simultaneously with Frank's data are not available. The Fritz Peak station made no photometric observation on the June and July occasions.

The OGO-3 satellite stopped functioning after a few months and no other detections of the RC were reported for the satellite. Information on the position of the RC particles during the span of photometric observing at Richland is probably available from the records of the Injun-5 satellite. These satellite data have not yet been reduced by the researchers responsible for them.

The total energy of the RC particles at the peak of the 9 July storm is calculated by Frank to be $\sim 2.6 \times 10^{22}$ ergs. Noting in equation (6-1) that the field decrease is proportional to the total energy we compute (as Frank does) a total decrease of about 6.9×10^{-4} gauss. The variation of the horizontal component of the field in the equatorial region is shown in Figure 6-7 and we note that there is good agreement with the calculated

Figure 6-6 Distribution of position of SAR-arcs during geomagnetic storms compared to position of the ring current tip reported by Frank [1967] for 23 June 1966 ($L \sim 4$) and 9 July 1966 ($L \sim 3$). The dashed line is only meant to suggest the trend toward higher L with weaker storms. A_p 's are averages during the SAR-arcs and the vertical bars indicate the drift of the SAR-arcs.

Figure 6-7 Variation of the horizontal component of the geomagnetic field. These are combined data presented by Frank [1967] from several low and mid-latitude stations.

decrease.

It is estimated from the smoothed line drawn on the magnetogram that the recovery required about 6 days or about 5×10^5 seconds. Thus, the RC particle energy was lost at a rate of about 5×10^{16} ergs/sec.

To see whether the loss rate represents an adequate source of energy to drive a SAR-arc, we refer to Figure 6-8 which gives SAR-arc intensity as a function of topside energy flux into the arc based on the calculations of *Roble* [1969]. Cole's original estimates agree with Roble's in the order of magnitude of flux required. Experience suggests the moderate storm of 9 July would produce at best a moderate arc of a few hundred Rayleighs, thus we estimate somewhat less than $0.1 \text{ erg/cm}^2 \text{ sec}$ would be required. Using the geometry shown in Figure 6-9 and assuming the SAR-arcs are about 200 km wide, it is found the surface area above the pairs of arcs at 1000 km is approximately 10^{17} cm^2 .

Thus, if the RC particle energy flowed through these topside surfaces, energy would be supplied at a rate of $\frac{5 \times 10^{16} \text{ ergs}}{10^{17} \text{ cm}^2 \text{ sec}} = 0.5 \frac{\text{ergs}}{\text{cm}^2 \text{ sec}}$.

This is some five times the energy flux required to drive a SAR-arc and we conclude that the total energy and loss rate of the RC energy source is adequate, even if only part of the energy flows into the SAR-arc region.

Without knowledge of the near-earth distribution of electrons in the RC region, the problem of working out the excitation of the SAR-arcs in terms of the incident charged particles involved must remain open. To our mind it is, however, such an important problem that some comments would seem to be in order.

Figure 6-8 Intensity of a SAR-arc as a function of top-side energy flux (at 1000 km) according to the calculations of *Roble* [1969].

Figure 6-9 Illustrating the top-side surface at 1000 km altitude used for calculation of incoming energy.

In the first place, we might ask whether the protons that are incident would not cause a "hydrogen arc" rather than a SAR-arc.

Such hydrogen arcs are observed to the north of our station. In some cases we are able to locate the hydrogen arcs by triangulation and they are found to be near $L = 4$ and higher. Several other relevant characteristics of observed hydrogen arcs are,

- a) Hydrogen arcs are much less stable than SAR-arcs, sometimes occurring strongly for only an hour or less and sometimes occurring, then disappearing and then reoccurring later the same night. This is based on the examination of meridian spectrograms.
- b) Relative to visible polar auroral arcs, the hydrogen arc is characteristically to the south of them before midnight, to the north after midnight [*Chapman, 1964*].
- c) Strong occurrence of a hydrogen arc is always associated with a polar auroral display.

Figures 6-10, 6-11, and 6-12, illustrate the measured location of a SAR-arc and a hydrogen aurora occurring contemporaneously.

The data do not seem to demonstrate conclusively that the RC distribution does not cause the hydrogen arc. But it does seem that the hydrogen arc is too far poleward since the tip of the RC distribution is probably below $L = 3$ in a strong $\left(\left|\frac{\Delta B_n}{B_{no}}\right| > 10^{-3}\right)$ main phase and the hydrogen arc is at $L \sim 4$. Furthermore, the hydrogen arc does not exhibit the consistent temporal correlation with the main phase that the SAR-arcs do. Rather, the hydrogen arcs seem to be the equatorward part of the more sporadic polar aurora.

Figure 6-10 Meridian spectrogram and densitometer tracing from north to south along the 6300 Å line, 23/24 March 1969, 2023 PST, Richland station. Note that the H_{α} emission is a few degrees above the north horizon and has only slight altitude extension. The 6300 Å emission in the SAR-arc peaks about 20° south of zenith.

Figure 6-11 Meridian spectrogram, 25 min. 23/24 March 1969 0307 (start) MST, Banff. Note that the H_{β} emission extends over most of the meridian. The H_{α} emission is obscured by bands of molecular nitrogen.

Figure 6-12 Position of the H_α and H_β emitting regions determined by triangulation. The extent of the emitting volume (at half-maximum) is indicated. The position of a SAR-arc recorded at Richland is shown at an (assumed) altitude of 400 km.

Perhaps more important than the apparent lack of correlation of the RC distribution with the observed hydrogen arcs is the fact that RC protons would probably not produce such an arc. *Prag et al.*, [1966] have shown that a flux of 5×10^7 protons/cm² sec with the protons at 4 keV initially would produce only the following radiations directly:

Emission λ	Intensity R
3914	0.8 - 1.8
7500	5.0 - 12.5
6300	5.0 - 7.3
5577	1.5 - 2.8
6563	1.5 - 2.3
4861	0.5 - 0.9

The 7500 λ emission is from the first positive system of N₂. The qualification "directly" means excited by H⁺ or H, not by secondary electrons. The flux assumed by *Prag et al.*, is roughly compatible with what we might expect from the RC distribution as can be seen by considering

$$\begin{aligned} \text{energy in} &= \left(5 \times 10^{-\left[\frac{2}{3}\right]} 5 \times 10^7\right) (4 \times 10^3 \text{ ev}) \left(1.6 \times 10^{-12} \frac{\text{ergs}}{\text{ev}}\right) \text{cm}^{-2} \text{sec}^{-1} \\ &= 0.2 \text{ erg cm}^{-2} \text{sec}^{-1} \end{aligned}$$

This is just in between the 0.1 erg/cm²-sec we estimated would be sufficient for the SAR-arc and the 0.5 erg/cm²-sec we estimated might be available from the RC energy loss rate. The factor $\left[\frac{2}{3}\right]$ accounts for the protons that *Prag et al.* found would be immediately expelled upward after one (relatively insignificant) reaction. The calculation on which these results are based was a Monte Carlo computation which considered the primary proton energy loss processes to be

where X is O, N₂, O₂ or He but predominantly O at high altitudes on account of the concentration. The energy loss for each proton charge exchange cycle was taken to be 170 eV in one case and 70 eV in another; these numbers bracket theoretical estimates. *Prag et al. estimate*, by means they do not describe and that we find hard to determine, that the energy of the secondary electrons will be around 20 eV. In the Monte Carlo computation the further reactions of these secondaries are ignored. It is of interest to consider some effects of these secondaries.

If we imagine one such electron at 20 eV (the same kind of argument will hold for a primary electron) it will be slowed by Coulomb collisions as well as by reactions with neutrals. Considering only Coulomb collisions with electrons first, we see that there are two extreme cases. The first is that the electron gives about half its energy to the other electron in the collision, in which case we would have the energy partitioned in the sense $20 \text{ eV} \rightarrow (10 \text{ eV} + 10 \text{ eV}) \rightarrow (5 \text{ eV} + 5 \text{ eV} + 5 \text{ eV} + 5 \text{ eV})$. That is, we would have 4 electrons around 5 eV after two slowing down stages. One more step and the electrons will be below the threshold of O(1S). In the other extreme, the electron may give very little energy up in each collision so none of the struck electrons will have as much as 4 eV and thus there is never more than the single original electron with sufficient energy to excite O(1S). Thus we conclude that the number of electrons

raised by each 20 eV secondary to energies that could excite $0(^1S)$ is between zero and three.

Since each proton goes through some 10^2 charge exchange cycles according to *Prag et al.*, we see that there will be

$$\frac{5}{3} \times 10^7 \times 10^2 \times \left(\frac{1}{1+3} \right) = \frac{1.7 \times 10^9 \text{ (electrons(E>5eV)/proton cm}^{-2}\text{sec}^{-1})}{6.7 \times 10^9 \text{ (electrons(E>5eV)/proton cm}^{-2}\text{sec}^{-1})}$$

electrons generated which could excite $0(^1S)$. In collision with neutral oxygen we note from Figure 4-3 that the transition ($^3P \rightarrow ^1D$) is 10 x as probable as ($^3P \rightarrow ^1S$). Thus in collisions with oxygen we will get at most

$$\left(\frac{1.7 \times 10^9}{6.7 \times 10^9} \right) \times \frac{1}{10} \text{ photons cm}^{-2}\text{sec}^{-1} \text{ at } 5577\text{\AA}$$

Dividing by $4\pi \times 10^6$ to get to Rayleigh units we have at most

$$\left(\frac{13}{53} \right) \text{ R at } 5577\text{\AA}$$

This would be roughly compatible with observations but it is probably a safe over estimate.

We suggest it is an over estimate because the Coulomb collision cross-section very much favors the second extreme process, that is giving up very little energy to the other electron in each collision. Furthermore, the cross-section for each small energy exchange collision is very large compared to that for oxygen excitation so that it was just a worst case to assume that all the secondary electrons and their off-spring would excite one or the other state of oxygen before further moderation. Since this is relevant to the treatment of primary electrons

(which we will not take up here) a brief look at the Coulomb cross-section may be warranted.

The standard result is

$$\frac{dQ}{d\theta} = \frac{e^4 2\pi \sin\theta \cos\theta}{E^2} \frac{1}{\sin^4\theta}$$

where E is in the incident energy and θ is the scattering angle. For a range of values of θ the target electron will have energy E_S given by

$$E_S = E \sin^2\theta$$

Integrating the cross-section

$$\begin{aligned} Q &= \frac{e^4 2\pi}{E^2} \int_{\sin\theta_1}^{\sin\theta_2} \frac{d(\sin\theta)}{\sin\theta} \\ &= \frac{e^4 2\pi}{-2E^2} \left(\frac{1}{\sin^2\theta} \right) \Big|_{\sin\theta_1}^{\sin\theta_2} \\ &= \frac{-e^4 \pi}{E^2} \left(\frac{E}{E_{S_2}} - \frac{E}{E_{S_1}} \right) \end{aligned}$$

the larger value of $\sin^2\theta \rightarrow$ the larger value of E_S hence,

$$Q = \frac{\pi e^4}{E} \left(\frac{1}{\underline{E}} - \frac{1}{\overline{E}} \right)$$

where $\overline{E}$ is the upper limit and $\underline{E}$ is the lower limit of the final energy of the struck electron. In units of eV we will have

$$Q = 6.5 \times 10^{-14} \frac{1}{E} \left(\frac{1}{\underline{E}} - \frac{1}{\overline{E}} \right) \text{ cm}^2$$

This result illustrates the characteristically powerful increase of the cross-section for low energy exchange scattering. For example for the struck particle to go into the $\left[\frac{1}{2}, 1\right]$ eV range the cross-section is

$$Q\left(\frac{1}{2}, 1\right) = \frac{1}{E} 2.6 \times 10^{-13} \text{ cm}^2$$

But to put the struck particle in the $[9\frac{1}{2}, 10]$ eV range, the cross-section is

$$Q(9\frac{1}{2}, 10) = \frac{1}{5} 3.2 \times 10^{-16} \text{ cm}^2$$

On the other hand, the oxygen excitation cross-section for $^3\text{P} \rightarrow ^1\text{S}$ is approximately $0.04 \pi a_o^2$ where $a_o = h^2/me^2 = 5.3 \times 10^{-9} \text{ cm}$

Thus

$$Q(^3\text{P} \rightarrow ^1\text{S}) = 3.5 \times 10^{-18} \text{ cm}^2$$

The oxygen concentration may indeed run a factor of 10^3 higher than the electrons in the region of interest but the low energy Coulomb scattering is still likely to dominate.

Although we have not mentioned it, the warm electrons are not able to transfer much energy to the heavy ions by Coulomb collisions because of the greater mass of the ions relative to the electrons.

The picture of SAR-arc excitation in terms of the incident charged particles is not complete but we have shown that the protons will not give rise to large optical effects which are not observed. Furthermore we have argued that electrons (secondary, but implicitly the primary ones too) can and likely do slow down without causing unobserved optical emissions. Our intuition suggests that observations of primary electrons from the RC distribution are going to be the key result in completing the data required to explain the SAR-arcs. The role of the protons, though discussed at length here, is likely to be the minor one. We are guided in this conjecture by the fact that relatively little neutral heating is observed nor is extensive ion production known to

occur. Too many protons would cause both of these effects.

A question that now arises is why the RC particles should be so characteristically peaked at $L \sim 3$. The answer, if known, would also explain why SAR-arcs are found in the same well defined geomagnetic position. To put it somewhat lightly, the RC particle distribution looks as if it were encountering a stone wall at $L \sim 3$. Frank's crescent shaped distribution is much more dispersed on the outer side than it is on the earthward side.

It is suggested that the answer is that the inner side of the RC particle distribution fits against the boundary of the plasmopause. It is known from whistler measurements that the relatively dense thermal plasma near earth is contained within the $L \sim 4$ shell in quiet times and within $L \sim 3$ or even less during the main phase. At the outer boundary, called the plasmopause, the thermal plasma density drops sharply by perhaps a factor of 50. The drop or so called "knee" is very sharp. The decrease occurs in a distance of half an L value or less during a geomagnetic storm.

The plasmopause or "knee" thus seems to define the innermost L-shell of the RC particles and hence the position of the SAR-arcs. The physical conditions which are believed to prevail are discussed in section 9.

7. Mapping of SAR-Arcs into the Magnetosphere

In the last section it was shown that the cusps of the iso-energy density contours of the RC distribution lay along a particular L shell. This L shell passed approximately through the energy density peak in the RC distribution. The narrow tip of the RC distribution near earth also lies along this same L shell and hence a SAR-arc occurring immediately below the tip may be used to define the location of the maximum of the RC distribution. It was suggested that the innerside of the RC distribution was proximate to the plasmopause. The plasmopause is known to have characteristic azimuthal asymmetry in the magnetosphere and if the RC distribution is closely coupled to the plasmopause then it might be expected that it would also have a similar asymmetry.

If the RC were asymmetrically distributed in the magnetosphere, the effect exhibited in the SAR-arcs would be a motion of the arc north or south as the earth rotates. As mentioned in section 3, such north-south drifts of the SAR-arcs are, in fact, observed. It would appear that optical data on the SAR-arc potentially provide detailed information on the RC distribution and perhaps the plasmopause.

The purpose of this section is to explore the ideas mentioned above by mapping the measured SAR-arc coordinates into the equatorial plane of the magnetosphere and by reviewing pertinent observations.

Glass, et al. [1970] have shown that the apparent equatorward drift of one SAR-arc observed 16 March 1969 near Australia, could be accounted for by the rotation of earth, by the fact that the SAR-arc was tilted with respect to L shells and by the fact that the arc was approximately stationary in a coordinate space of L-intercepts and hour-angles (local time). Following this idea, we have transformed the angular coordinates of the peak intensity region of the definite SAR-arcs listed in Table 3-1 to hour-angles and L-intercepts at 400 km. Figure 7-1 shows the geometrical significance of the transformation.

For periods of time as short as the few hours duration of a SAR-arc observation, the hour-angle planes can be considered fixed with respect to the earth-sun line and the stars. The hour angle planes define the local time coordinates. The SAR-arc is projected along field lines to the magnetic equatorial plane which is fixed with respect to the hour-angle planes though not exactly orthogonal to them because of the tilt of the magnetic dipole axis to the earth spin axis.

In Figure 7-1 the misalignment of the SAR arc with L intercepts is exaggerated in order to illustrate more clearly why the rotation of the earth causes an apparent equatorward drift of the SAR-arc with respect to a ground station. To visualize this motion, the points in the arc near earth may be imagined to "slide" along the near-earth L-intercept lines as the earth turns. Thus, as the ground station moves under the SAR-arc, an observer of the station

Figure 7-1 Mapping of the SAR-arc into the magnetosphere.

would record apparent equatorward drift of the arc.

A reason for the SAR-arc to occur at different L values for different hour-angles is that the RC distribution may vary in distance from earth as a function of local time.

In calculating the 400 km L-intercepts we have used the tabulated values of L at various altitudes given by Evans, et al., [1969]. These data are supposed to provide the most realistic and detailed model of the earth's field available. For interpolation between tabulated values, analytical expressions were developed which fit the tabulated L values to four significant figures in the geographic locale and in altitude range of the observation. The three main steps in the transformation of a datum are shown schematically in Figure 7-2.

Figure 7-2 The three steps in the transformation of coordinates illustrated schematically.

This transformation process was carried out for about 10 evenly spaced points in the brightest region of each definite SAR-arc for all photometric measurements of SAR arcs made from Richland. Since the arcs are scanned repeatedly, several thousand individual datum points required transformation.

The most significant potential sources of errors in determining the L , t_{loc} coordinates are, (i) angular resolution of the scanning equipment (± 3 degrees), (ii) variation of the altitude of the photometric center of the arc from the 400 km altitude assumed (± 25 km) and, (iii) inaccuracy of the tabulated L values.

We first assumed the tabulated L values provided a realistic representation of the field lines and adopted them as reference coordinates with no error ascribed. However, it was immediately apparent when the transformed data were displayed graphically that there were large systematic displacements in the datum points in the northwest sky. These displacements could not be attributed to any reasonable physical situation other than distortion of the actual magnetic field that was not given by the mathematical model.

The situation encountered when the raw data are transformed to (L, t_{loc}) coordinates is illustrated in the extreme by the examples shown in Figure 7-3. The sets of points connected by lines are points that were observed nearly simultaneously in a single arc. Approximately one quarter of an L -unit is expected experimental scatter (it varies with L) but the systematic displacement of the left end of the arcs is far beyond that.

In attempts to resolve the problem, the height assumption was first tested by trying different heights to try to "straighten" the arcs. The effect was minor compared to the systematic displacement. Next, an azimuthal rotation of the L -grid was artificially

Figure 7-3 Illustrating the distortion of the westward (l.h.) side of the SAR-arcs toward higher L's.

introduced because we had noted that our compass pointed about 20.45" east of north whereas the gradient across the computed L shells had a bearing of about 15° east of north (like a simple dipole model, where it would be 14.75° east of north).

The main effect for rotations of 5 to 10 degrees was, as anticipated, to raise the east (r.h.) systematically while lowering the west a little but not enough to cure the problem. Then rotation plus height variation was tried - still without success for reasonable changes.

Information was sought on Pacific Northwest magnetic anomalies and it was learned the magnetic field has major local distortions in the mountainous regions northwest of the station.

Thus, in the data, two effects are mixed. The L-values calculated from the angular coordinates of the arc have systematic displacement due to local distortion of the field and second, the L-values of the arc actually change as a function of local time presumably due to the asymmetry of the RC region in the magnetosphere.

To separate the two effects, the following procedure was tried. For a given arc, the points measured in the western sky at 10° elevation angle were converted to L values and at least squares fit of the points as a quadratic function of local time was computed. The same was done for the points measured at 15" elevation angle in the western sky, then for 20" W, 30 ° W and so forth across the arc to 10° elevation in the east.

The results for one SAR-arc are plotted in Figure 7-4. It is seen that the effect of the local distortion and the change in L with local time are now separated. The slope of the lines gives the desired dL/dt_{loc} . The separation in ordinates of the plots indicates the effect of the distortion. The vertical scale is considerably expanded in the figure and the "east" set of lines should be coincident within experimental scatter.

Figure 7-4 shows clearly that the distortion of the magnetic field is confined principally to the western side of the sky. Hence the data from the eastern side of the sky can be safely used to map the coordinates of the SAR-arc into the magnetosphere. The data from the northwestern half of the sky, in principle, provide information on the local field distortion and could therefore be useful in reformulating the mathematical model of the local field. But that task will not be assumed here.

When the L values of the SAR-arcs from the whole sky, except the northwestern quadrant above $L = 3$ (at 400 km), are plotted as functions of local time, the examples of maps of the equatorial plane shown in Figures 7-5a, b, c result. Maps for other SAR-arcs are presented in Appendix 2.

Figure 7-4 (11)

Figure 7-4 Plots of quadratic functions obtained by least squares analysis for separate regions of the SAR-arc.

Figure 7-5 a SAR-arc positions transformed to the magnetic equatorial plane.

Figure 7-5 b SAR-arc positions transformed to the magnetic equatorial plane.

Figure 7-5 c SAR-arc positions transformed to the magnetic equatorial plane.

130

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Figure 7-6 Azimuthal configuration of the plasmasphere exaggerated for clarity, from "Physics of the Earth in Space", page 84, National Academy of Sciences report (1969).

The location of the plasmapause as a function of magnetic activity in (L, t_{loc}) coordinates has been worked out on a statistical basis by *Rycroft and Thomas* [1970]. But, the statistical scatter of their input data is very great. For example, for a mean statistically expected position of the plasmapause center of $L = 4.2$ with $k_p = 3_+$ the measured position of the center of the plasmapause is in one case $L \sim 3.2$ and in another $L \sim 5.8$. Clearly it would be unsound to attempt to specify the position of the plasmapause on the occasions of the SAR-arcs from the statistically expected position. It appears to be better to look at specific cases.

In Figure 7-7 the RC particle energy density in the equatorial plane is shown according to *Frank* [1967] (this is the measurement which was discussed extensively in Section 6). Also, on the same figure is plotted the proton density of the plasmapause (at the sametime) according to *Taylor, et. al.*, [1968]. The measurements were made by the same satellite OGO-3.

Suppose one now assumes a "reasonable" energy density for the thermal protons of the plasmasphere. A first guess might be about 2 eV per particle. Then the very interesting result shown in Figure 7-8 is obtained. The total energy density of protons has a significant depression at the interface of the RC particles and the plasmapause. Assuming that the plasmapause protons have energies of 10 eV each, relieves the energy anomaly considerably but it is still there.

Figure 7-7 Plasmasphere density and RC energy density versus L according to Taylor, et al., [1968] and Frank [1967].

Figure 7-8 Illustrating the energy density anomaly at the interface of the plasmopause and the RC distribution.

To remove the anomaly entirely the energy of the individual protons in the plasmasphere would have to increase precipitously as shown in Figure 7-9.

Since the preceeding argument is based on points measured by hand from other's published data and is thus imprecise because of both experimental and mechanical scaling errors, the results can not be taken as absolute in any sense. However, the results, coarse as they are, seem to suggest that there may be an energy density depression at the interface of the ring current and the plasmasphere unless some special behavior of the electrons is invoked in that region.

Although it has not been stated explicitly, it is implicit in the foregoing argument that in a steady state situation such an energy density depression can not be maintained since it is equivalent to a low pressure zone that would cause bulk motions of the medium.

It is suggested that it would not be surprising to find the interface of the plasmasphere and the RC distribution to be a region of supra-thermal electrons.

Since the presence of such electrons is essentially a conjecture here, attempts at a more detailed description hardly appear warranted. It is of interest to note, however, that a "trough" of hot, low density electrons has been observed to be associated with the plasma pause but to our knowledge no physical basis for its presence has been given. *Rycroft and Thomas [1970]* conclude that on a statistical

Figure 7-9 Energies required of plasmasphere protons to remove the density anomaly.

basis the observed "trough" is on the same field lines as the middle of the plasmapause "knee" and that, if anything, it tends to be somewhat to the earthward side of the center of the plasmapause when the magnetosphere is disturbed.

Near earth, the electron trough is definitely known to be associated with the SAR-arc. Shown in Figures 17-10 and 17-11 are data from a report by *Norton and Findlay* [1969] on the subject of the coincidence of the electron trough and the SAR-arc. The ground based data on SAR-arc position were supplied by the Richland and Fritz Peak stations.

Rycroft and Thomas [1969] have deduced the empirical formula

$$L_t = 5.64 - (1.09 \pm 0.22) \sqrt{K_p}$$

for the trough. They find the gradient, dL_t/dt_{loc} , to be approximately 0.1 hour^{-1} which agrees approximately with the asymmetry of the distributions of 7-5 .

The observed motion of the SAR-arc is a measure of the asymmetry in the equatorial plane. The functional relation is straightforward to derive in the case of dipole L shells. For an arc at altitude h moving north with velocity v (km/hr)

$$R_e + h = L \cos^2 \lambda$$

Differentiating yields

$$\frac{dL}{d\lambda} = \frac{2L^2 \cos \lambda \sin \lambda}{R_e + h}$$

Figure 7-10 Electron density at approximately 2000 km on 28/29 September 1967, from *Norton and Findlay* [1969].

Figure 7-11 Electron temperature at approximately 2000 km on 28/29 September 1967, from Norton and Findlay [1969].

But v must be

$$v = (R_e + h) \frac{d\lambda}{dt} = (R_e + h)^2 \frac{dL}{dt} \frac{1}{2L^2 \cos \lambda \sin \lambda}$$

or

$$v = \frac{1}{2} \frac{dL}{dt} \frac{(R_e + h)}{L} \cot \lambda \quad (7-1)$$

Substituting $L = 2.9$, and $\lambda = 52.90$ for Rattlesnake the result is

$$v = 8.6 \times 10^2 \frac{dL}{dt}_{loc}$$

For $dL/dt_{loc} = -0.1 \text{ hr}^{-1}$ as suggested by *Rycroft and Thomas [1970]* for the plasmopause and electron trough asymmetry, the resulting drift of the SAR-arc would be $v = -86 \text{ km/hr}$. (south). This is a typical observed value.

If the plasmopause as a whole were moving toward or away from earth, this would also contribute to dL/dt_{loc} . The relatively stable character of the SAR-arc suggests that such 'breathing' of the plasmopause is generally fairly slow. The greatest velocity of a SAR-arc observed was about 400 km/hr for less than an hour. Substituting this into equation (7-1) yields $\frac{dL}{dt}_{loc} \sim 0.46 \text{ hr}^{-1}$. This could be a combination of **asymmetry** and gross motion of the plasmopause .

In Figure 7-12 position as a function of time for several different SAR-arcs in the meridian plane is shown. When measurements are restricted to one spatial intercept as in Figure 7-12 the

Figure 7-12 Position as function of ime for everal SAR-arcs in the meridian plane

detailed spatial variations in time are exhibited more clearly than on the polar plots where points from many places in the arcs are used. It can be seen in Figure 7-12 that in some instances the arc moved north. Whether this is the effect of a bulge or distortion in the source region or a quick expansion can't be resolved. In principle, similar data from points along the arc could help sort out the effects and, if the field line configuration were well known, multiple stations along an east-west line could resolve the shape, position and motion of the source region in the magnetosphere in detail. In fact, even if the field line configuration were not well known it could be determined by many measurements from an east-west line of stations.

It is of interest to put all the data together on one plot to see what general shape in the magnetosphere is defined. This is done in Figure 7-13. An inner and outer bounding line has been added by eye to suggest the range of shapes defined by the data.

The potential of these ground based optical observations for rather precise exploration of magnetospheric structure is apparent from preceding work.

Although it would be valuable and satisfying to use experimental data to describe the physical conditions in the magnetosphere with certainty from the SAR-arc region to the equatorial plane, uncertainties in the data (and in interpreting them properly) preclude this. At most it can be concluded that the SAR-arcs are physically near the field lines of the plasma pause and the electron density trough.

Figure 7-13 Distribution of SAR-arcs transformed to magnetic equatorial plane.

The asymmetry of the SAR coordinates mapped into the equatorial plane certainly supports a correspondence of the SAR-arc with the plasmapause. The motion of the SAR-arc and the asymmetry of the plasmapause are compatible. The RC distribution, when it is present, probably has similar asymmetry if we take it that the SAR-arc marks the tip of the RC distribution. The depression of electron density which is known to be associated with the SAR-arc may be an expected feature at the interface of the plasmapause and the RC distribution. From the plausibility argument given, for the electron density depression, it seems reasonable that the electron density trough would be quite near the tip of the RC distribution at low altitudes which would be compatible with observations. A more precise localization of the knee, trough, and RC distribution with respect to each other and the arc would be difficult to justify on the basis of the data reviewed here.

The physical processes that may be occurring in the magnetosphere when a SAR-arc occurs are treated in the next section.

8. The Heating Mechanism

The question of how the RC distribution arises in the first place is an open one. The informal suggestions are that it is "injected" into the magnetosphere by the solar wind or that it is a matter of energization or redistribution (or both) of the pre-existing plasma. To our knowledge, formal hypotheses have not been advanced on the first "injection" idea; it is a matter of discussion at the moment. In the latter, "redistribution" category, Cole has long advocated a process wherein energetic particles are "pumped" deeper into the magnetic field by fluctuating electric fields [Cole, 1964]. Frank [1967] discusses a similar inward movement. We do not wish to take up the entire matter of the creation of the RC distribution here because the problem is too large and difficult. But in exploring the problem we have noted that hydromagnetic waves such as the incoming pulse of the sudden commencement should exhibit a highly peculiar and rather suggestive behavior in the region of the plasma pause. We believe that this has not been noted before and should not be overlooked in detailed analysis of the problem.

The purpose of this section is to present the analytical basis on which peculiar behavior of the plasma pause is expected and to discuss its significance.

The character and behavior of hydromagnetic* waves are determined by the properties of the medium. The important physical properties of the

* "Hydromagnetic" or (hm) seems preferable to "magnetohydrodynamic" (mhd). We believe they are synonymous.

medium are the distribution of electrons and ions and the underlying B field. Given these quantities and the gravitational and psuedo forces, the problem of what happens when additional forces are applied may be formulated. To formulate and solve the problem, simplifying approximations are always made and in hm problems, they are characteristically severe simplifications. We wish to illustrate a first order effect and will therefore try to use the simplest model that will exhibit the result.

The magnetic field is taken to be a symmetrical dipole out to about 10 Re in the equatorial plane. Relatively little direct information from *in situ* measurements of the magnetospheric plasma is available. *Serbu and Maier* [1965, 1966] have used a retarding potential analyzer on IMP I and IMP II to measure the flux and temperature of magnetospheric electrons. They normally find the plasma to have a double peaked energy distribution. The cooler component has a characteristic energy of a few eV increasing going away from earth. The IMP data are believed to be somewhat inaccurate, particularly at large distances but the essential fact for our purposes is that the IMP II data showed that the second peak in the energy distribution, due to the high energy component, represented a particle flux of only about 1% of the thermal component. This is believed to be reliable information.

A first order model of the physical medium may thus consider only the thermal plasma in the magnetic field. On the basis of mass, the thermal plasma comprises by far the greatest portion of plasma in the magnetosphere.

The density distribution of the thermal plasma has been determined by

whistler measurements. These are measurements of the dispersion of circularly polarized electromagnetic waves guided along field lines. Apparently most whistlers are initiated by lightning strokes and the "time of flight" for a wave of a particular frequency is a function of the electron gyrofrequency and the plasma frequency $(n_e^2/2\pi m)^{1/2}$. Thus the fact that the arrival time is related to n means the electron density can be determined from the whistler records.

Carpenter [1963] discovered by such measurements that the radially decreasing density suffers an abrupt drop in a fraction of an earth radius, then it continues to decrease at a slower rate. The region of abrupt change, called the plasmopause or the "knee" or "Carpenter's knee", was discussed briefly in the last section.

According to *Dungey* [1967], the number density of electrons or protons in the equatorial plane is adequately represented by $8 \times 10^3/r^3$ between 1.5 and 3 R_e . Then there is the sharp drop somewhere in the 3 to 4.5 R_e region. Beyond the knee, the number density is approximately $10^3/r^3$. It is sufficiently accurate to assume the mass density to be given entirely by the proton mass density.

The mass density ρ is combined with the field strength in the important parameter* $B/\sqrt{4\pi\rho}$ which is equal to the Alfvén wave velocity V_A . This is the velocity of a transverse hm oscillation along a magnetic field line analogous to a transverse traveling wave on a stretched string.

* Gaussian - cgs, units are used throughout unless noted.

Dungey has given an approximate plot of the Alfven velocity in the equatorial plane (Figure 8-1). This plot is consistent with density estimates from whistler data.

For analysis we may approximate V_A by functions that are "linear in the logarithms", i.e.,

$$\log V_A = m \log L + b \quad (8)$$

$$\text{with } m = \begin{cases} -1.544 \\ +4.90 \\ -1.435 \end{cases} \quad b = \begin{cases} 8.864 \\ 5.675 \\ 9.275 \end{cases} \quad \text{for } L = \begin{cases} 1.45 \text{ to } 3.14 \\ 3.14 \text{ to } 3.68 \\ 3.68 \text{ to } 10.00 \end{cases}$$

and $L = r/R_e$.

This is equivalent to writing

$$V_A = V_o r^m \quad (8-2)$$

with 3 appropriate V_o 's and m's.

The Alfven (phase) velocity combines the effective plasma density and magnetic field. Thus we may solve for the effective density in a dipole representation obtaining.

$$\log p = n \log L + \text{const.} \quad (8-3)$$

or

$$\rho = \rho_o r^n \quad (8-4)$$

$$\text{where } n = -2(m + 3) \quad (8-5)$$

$$\text{and } \log p_o = 2 \log B_e - \log 4\pi - 2b \quad (8-6)$$

Figure 8-1 Alfvén velocity in equatorial plane.

for B_e the magnetic field at the equator on the earth surface.*

The density is shown in Figure 8-2.

In general, hydromagnetic waves that have longitudinal components (with respect to the magnetic field direction) will have phase velocities that are a combination of the Alfvén and acoustic phase velocities. The acoustic phase velocity is defined

$$v_s^2 = \frac{\partial P}{\partial \rho} \quad (8-7)$$

where P is the kinetic pressure. The kinetic pressure is the ordinary kind of gas pressure but in hm calculations a "magnetic pressure" is sometimes discussed - hence the distinction is made. The kinetic pressure gradient can be determined by requiring that the bulk plasma configuration be instantaneously at rest with respect to radial motion. For the plasma to be so at rest, the sum of all radial forces must vanish. The pressure gradient is one of these forces and if the rest are properly estimated we may evaluate it. We have found by such calculation that v_s

* (5 & 6) follow from:

$$v_A = \frac{B_e}{L^3} (4\pi\rho)^{-1/2} \Rightarrow \log v_A = \log B_e - 3 \log L - 4 \log 4\pi\rho$$

Substituting v_A from (8-1) $\Rightarrow \frac{1}{2} \log \rho = -\frac{1}{2} \log 4\pi - 3 \log L + \log B_e - m \log L - b$ or, $\log \rho = -\log 4\pi + 2 \log B_e - 2b - 2(m + 3) \cdot \log L$ which we rewrite

$$\log \rho = \log \rho_0 + n \log L$$

and identify n and $\log \rho_0$ as in equations (8-5) and (8-6).

Figure 8-2 Plasma density in equatorial plane.

is an order of magnitude smaller than V_A (in agreement with other's estimates [*Parker*, 1967]) and that V_s has a small jump discontinuity at the boundaries of the knee. Only the order of magnitude of V_s with respect to V_A is required in subsequent discussion and the rather lengthy analytical derivation of its value is therefore omitted. We now consider the propagation of hm waves.

For hm waves, attention is conventionally focused on the velocity of the wave displacement rather than the amplitude. A velocity field is thus defined throughout the medium and except for an unimportant phase factor this velocity field exhibits harmonic variation as the displacement would. In the velocity field the wave is assumed to have the form

$$\vec{V} = \vec{V}_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)} \quad (8-8)$$

where $\vec{k}$ and ω may be complex to account for wave attenuation. When derivatives are taken we have $\vec{W} \rightarrow i\vec{k} \cdot \vec{V}$ and $\frac{\partial \vec{V}}{\partial t} \rightarrow i\omega \vec{V}$ in the usual way. The wave equation with derivatives already taken in the manner above is well known (see for example *Jackson* [1962])

$$-\omega^2 \vec{V} + (V_s^2 + V_A^2)(\vec{k} \cdot \vec{V})\vec{k} + \vec{V}_A \cdot \vec{k}[(\vec{V}_A \cdot \vec{k})\vec{V} - (\vec{V}_A \vec{V})\vec{k} - (\vec{k} \cdot \vec{V})\vec{V}_A] = 0 \quad (8-9)$$

where $|\vec{k}| = V_{ph}$ (ph = phase) and $\vec{k}$ is in the direction of propagation.

$\vec{V}$ = velocity displacement

$\vec{V}_A = \frac{\mathbf{B}}{\sqrt{4\pi\rho}}$ the Alfvén wave phase velocity (note this is a vector equation)

$v_s = \left(\frac{\partial P}{\partial \rho}\right)^{1/2}$ the acoustic wave phase velocity

For a longitudinal wave we set $\vec{k}$ perpendicular to $\vec{B}$. Then since $\vec{v}_A$ is parallel to $\vec{B}$, $(\vec{v}_A \cdot \vec{k}) = 0$. In the longitudinal wave the velocity field vector $\vec{v}$ must be parallel to $\vec{k}$ hence $\vec{v} \cdot \vec{k} = vk$ and equation (8-9) becomes simply

$$-\omega^2 v = (v_s^2 + v_A^2)k^2 v \quad (8-10)$$

or, dividing out the velocity field

$$\omega^2 = (v_s^2 + v_A^2)k^2 \quad (8-11)$$

$$k^2 = \frac{\omega^2}{v_s^2 + v_A^2} = \frac{\omega^2}{v_{ph}^2} \quad (8-12)$$

We therefore have the plausible result that the longitudinal phase velocity in the B - field plus plasma is the square root of the sum of the squares of the separate phase velocities for the two media. It is reasonable that the combined phase velocity is higher than either separate phase velocity, because the compound medium is stiffer than either component. The nature of the wave is illustrated schematically in Figure 8-3.

The wave suffers no attenuation if there are no loss mechanisms in the medium; thus we must introduce a conductivity σ and/or viscosity to have the wave energy deposited in the plasma. It can be shown that viscous loss is expected to be much smaller than resistive loss, consequently we keep only σ and assume viscosity is negligible. The effect of a large but finite (non infinite) conductivity may be taken into account by adding

Figure 8-3 Nature of the longitudinal wave.

a small imaginary component to the frequency and acoustic velocity (see for example *Jackson*, [1962]). Thus, we make the modifications

$$\left. \begin{aligned} v_s^2 &\rightarrow v_s^2 (1 + i\varepsilon) \\ \omega^2 &\rightarrow \omega^2 (1 + i\varepsilon) \end{aligned} \right\} \quad (8-13)$$

where

$$\varepsilon = \frac{c^2 k^2}{4\pi\sigma\omega} \quad (c = 3 \times 10^{10} \text{ cm/sec})$$

We wish to solve equation (8-12) for the real and imaginary parts of k . But since the ε introduced is proportional to k^2 , the task has certainly become much more difficult than first appeared unless ε is very small compared to 1 (8-12 is now a quartic equation in complex variables). We thus must make an order of magnitude estimate of ε to assure that it is small before proceeding.

Inserting $c = 3 \times 10^{10}$ cm/sec, we have

$$\varepsilon = 9 \times 10^{20} \frac{\omega^2}{v_{ph}^2} \frac{1}{\sigma} \frac{1}{12.6}$$

For conductivity we take

$$a \sim 10^7 T^{3/2} \text{ sec}^{-1} \quad \text{Spitzer [1956]} \quad (8-14)$$

and then we have $a \gtrsim 10^{13}$ for $T > 10^4 \Rightarrow \sim 1 \text{ eV}$

(which is a low estimate of T).

From (8-12) we note v_{ph} is greater than the Alfvén velocity hence

$$v_{ph} > v_A \gtrsim 10^{7.5} \quad (\text{see Figure 8-1})$$

Thus,

$$\epsilon \lesssim \omega^2 \times 10^{-7}.$$

We see that as long as ω is less than 10^2 we have $\epsilon < 10^{-3}$.

So we are assured that $\epsilon \ll 1$ as long as ω is well below audio frequencies and we certainly expect it to be.

Inserting (8-13) into (8-12) we have

$$k = \pm \left(\frac{\omega^2 (1 + \epsilon)}{v_s^2 + v_A^2 + i\epsilon v_s^2} \right)^{1/2} \quad (8-15)$$

Letting $v_s^2 + v_A^2 = v_{ph}^2$ to save writing and multiplying numerator and denominator of the rhs of (8-15) by the complex conjugate of the r.h. denominator gives

$$k = \pm \left(\frac{\omega^2 v_{ph}^2 + i(v_{ph}^2 \omega \epsilon - v_s^2 \omega^2 \epsilon) + \omega^2 \epsilon^2 v_s^2}{v_{ph}^4 + v_A^2 \epsilon^2} \right)^{1/2}$$

Dropping terms of order ϵ^2 and extracting common factors gives

$$k = \pm \frac{\omega}{v_{ph}} \left(1 + i\epsilon \frac{v_A^2}{v_{ph}^2} \right)^{1/2} \quad (8-16)$$

which to first order in ϵ is

$$k = \pm \frac{\omega}{v_{ph}} \left(1 + i \frac{\epsilon}{2} \frac{v_A^2}{v_{ph}^2} \right) \quad (8-16')$$

For positive (outgoing wave) k we take $k = k_r + ik_i$

$$k_r = \frac{\omega}{v_{ph}} \quad (8-17)$$

$$k_i = \epsilon k_r \left(\frac{1}{2} \frac{v_A^2}{v_{ph}^2} \right) = \frac{k_r^3}{8\pi\sigma\omega} \frac{v_A^2}{v_{ph}^2} \quad (\text{to first order in } \epsilon) \quad (8-18)$$

These are the results sought and we are particularly interested in how these **functions** behave in the region of the density knee. Let us attempt to evaluate the two components of k as functions of radius in our simple model of the magnetosphere. Beginning with k_i we have,

$$k_i = \left(\frac{\omega}{v_{ph}} \right)^3 \frac{v_A^2}{v_{ph}^2} \frac{1}{\omega} \frac{c^2}{8\pi\sigma} = \frac{\omega^2 c^2}{8\pi\sigma} \left(v_A^2 / v_{ph}^5 \right)$$

Substituting for v_{ph}^2 the expression

$$v_{ph}^2 = v_A^2 \left(1 + \frac{v_s^2}{v_A^2} \right)$$

we find

$$k_i = \frac{\omega^2 c^2}{8\pi\sigma} (v_A)^{-3} \frac{1}{\left(1 + \frac{v_s^2}{v_A^2} \right)^{5/2}}$$

As mentioned previously $\frac{v_s^2}{v_A^2} \ll 1$ which implies the factor to the $5/2$ power is of minor importance. Converting to radial dependence,

$$v_A = \frac{B}{\sqrt{4\pi\rho}} \Rightarrow (v_A)^{-3} = \frac{(4\pi\rho)^{3/2} r^9}{B_e^3 R_e^9} \quad (\text{since } B \propto r^{-3})$$

and

$$p = \rho_o r^n \quad \begin{array}{l} \text{from equation (8-4)} \\ \text{(recall } \rho_o \text{ and } n \text{ are discontinuous functions} \\ \text{of } r) \end{array}$$

Thus,

$$(v_A)^{-3} = \frac{(4\pi)^{3/2}}{B_e^3 R_e^9} \left[\rho_o^{3/2} r^9 + 3n/2 \right]$$

and

$$k_i = \frac{\omega_c^2}{8\pi\sigma} \cdot \frac{(4\pi)^{3/2}}{B_e^3 R_e^9} \cdot \frac{1}{\left(1 + \frac{v_s^2}{v_A^2}\right)^{5/2}} \left[\rho_o^{3/2} r^9 + 3n/2 \right] \quad (8-19)$$

where the important radial dependence is in the square brackets.

Noting that equations (8-1) and (8-15) give

$n = -3$	$L = 1.4 \text{ to } 3.14$
-16	$3.14 \text{ to } 3.68$
-3	$3.68 \text{ to } 10$

We have k_i dependent upon the following powers of r .

$9 + n\frac{3}{2} = +4\frac{1}{2}$	$L = 1.4 \text{ to } 3.14$
-15	$3.14 \text{ to } 3.68$
$+4\frac{1}{2}$	$3.68 \text{ to } 10$

The radial dependence is plotted in Figure 8-4.

It is now of interest to examine the radial dependence of the volume heating rate but first let us evaluate the real part of k . (It is not essential to the remainder of the work but we give it for completeness). We have from equation (8-17)

$$\begin{aligned} k_r &= \frac{\omega}{v_A} \frac{1}{\left(1 + \frac{v_s^2}{v_A^2}\right)^{1/2}} \\ &= \frac{\omega}{B_e^2 R_e^3} r^3 \rho^{1/2} \left(\frac{4\pi}{1 + \frac{v_s^2}{v_A^2}} \right)^{1/2} \end{aligned}$$

Figure 8-4 Radial dependence of k_i and k_r .

$$k_r = \frac{\omega}{B_e^3 R_e^3} \left(\frac{4\pi}{1 + \frac{v_s^2}{v_A^2}} \right)^{1/2} \left[\rho_o^{1/2} r^{3 + n/2} \right] \quad (8-20)$$

where again the significant radial dependence is in the square brackets. The exponents of r are,

$3 + n/2 = 3/2$	$L = 1.4 \text{ to } 3.14$
-5	$3.14 \text{ to } 3.68$
$3/2$	$3.68 \text{ to } 10$

The radial dependence of k_r is shown in the dotted line in figure 8-4.

With the radial dependence of the whole wave vector now in hand we are in position to calculate the wave energy lost at a particular radius.

Equation (8-8) may be rewritten

$$\vec{V} = \vec{V}_o e^{-\vec{k}_i \cdot \vec{r}} e^{i(\vec{k}_r \cdot \vec{r} - \omega t)}$$

The time averaged kinetic energy is simply

$$E = \frac{1}{2} \rho_o \langle V^2 \rangle = E_o e^{-2\vec{k}_i \cdot \vec{r}} \quad (8-21)$$

For simplicity let us assume the wave to be propagating along a radius in the equatorial plane. Then the change in energy per unit path will be

$$\frac{dE}{dr} = E(r) (-2) \left\langle r \frac{dk_i}{dr} + k_i \right\rangle \quad (8-22)$$

The amount of energy deposited in the medium per path is dW/dr and is the same as dE/dr except for sign.

Taking the derivative^t of (8-19) (but only the term in square brackets) yields $\frac{dk_i}{dr} = (9 + 3n/2) \frac{k_i}{r}$ whereupon (8-22) implies

$$dW = 2E(r)k_i(10 + 3n/2)dr \quad (8-23)$$

Now a key fact has emerged. Equation (8-23) shows that if anywhere, n is less than $-6\frac{2}{3}$ (more negative than $-6\frac{2}{3}$) then the energy deposited in the medium is negative - that is, the wave is amplified. This is the signature of an instability. It is to be recalled that the plasma density has radial dependence r^n (equation 8-4) and n is estimated to be -16 in the knee. Thus, waves entering the knee region will be amplified.

Since we have considered only the outgoing wave it is perhaps worthwhile to re-examine (8-22) explicitly for an incoming wave.

From (8-22) we have first

$$\Delta E = E(r)(-2) \left(r \left(\frac{dk_i}{dr} \right) + k_i \right) \Delta r \text{ with } \Delta r \text{ positive.}$$

For an incoming wave

$$\Delta E = E(r)(-2) \left(r \left(\frac{-dk_i}{dr} \right) - k_i \right) (-\Delta r)$$

[†] It is the 'slope' that is needed, not the mathematician's derivative. We see that the ρ_o 's just keep k_i continuous while leaving the discontinuities in the slope.

where the sign of the radial increment Δr is now reversed as are the signs of the propagation vector k_i and its gradient dk_i/dr . The necessity to reverse signs of k_i and dk_i/dr for the incoming wave is apparent on physical grounds as well as from equation (8-16). The result is that AE in a radial increment $|\Delta r|$ has the same sign whether the wave travels from left to right or vice versa. Since this is commonly the case for waves passing through absorbers the result is intuitively satisfactory.

Schematically, the effect of passing through an instability is illustrated in figure 8-5.

In the attempt to proceed expediently to point where the instability could be illustrated, the effect of the factor $1 + \left(\frac{v_s^2}{v_A^2} \right)$ in (8-19) and (8-20) was ignored. For example in calculating the gradient of k_i just before equation (8-23), only the explicit radial dependence shown in (8-19) was used. Although the factor $1 + \left(\frac{v_s^2}{v_A^2} \right)$ is close to unity, it has a small discontinuous jump at the boundaries of the knee. The jump is caused by corners at the intersection of the line segments used to model the density distribution. Thus, in reality it is likely to be just a fast change in value not a jump. The reason that this is of concern here is that it is the abrupt change in k at the interface of two media that will cause reflection of the wave.

Figure 8-5 Change in wave energy in the region of the instability ignoring reflections.

If such reflections occur it might seem possible that the wave could build up in the knee, being amplified on each reflection until some extreme situation was reached.

In appendix 3 the criterion for a wave build up in multiple reflections is established and it is found that there is no possibility of such an occurrence.

One can show using (8-21) that for a wave originating at r_o in the knee and going to r_i , that energy is increased by a factor of approximately

$$e^{2|k_i(r_i)r_i - k_i(r_o)r_o|}$$

which, using (8-17), (8-18), (8-12) and $V_{ph} \sim V_A$ is

$$\sim e^{\epsilon\omega \left| \frac{r_i}{V_A(r_i)} - \frac{r_o}{V_A(r_o)} \right|}$$

or from the work just ahead of equation (8-14) it is

$$\sim e^{\omega^2 \times 10^{-7}} \sim 1$$

Thus, the knee is not so much a region of amplification as it is a place where a longitudinal wave started there or entering it will propagate freely to a boundary where it will lose its energy quickly to the adjacent medium.

If a rather simple analog be permitted, the function of the knee appears to be rather like that of the shelf shown in Figure 8-6.

Figure 8-6 Simple analog illustrating the function of the knee.

When a sudden commencement occurs there will be an incoming longitudinal pulse and many subsequent disturbances. This analysis suggests that the knee will tend to concentrate the deposition of incoming longitudinal wave energy at its inner boundary and concentrate outgoing longitudinal wave energy at the outer boundary. Localized heating at the inner boundary might be consistent with the development of the ring current.

To our knowledge no one has previously considered the plasma-pause to be an unstable region with respect to the propagation of longitudinal hm waves - unstable in the sense that such waves may propagate through it with no loss and even with some energy gain, until they encounter a boundary. Although we have handled only a one dimensional case, longitudinal means only that $\vec{k}$ is perpendicular to $\vec{B}$ not that $\vec{k}$ is parallel to a radius. For example, some non-radial paths with $\vec{k}$ perpendicular to $\vec{B}$ are shown in Figure 8-7. During a geomagnetic storm a magnetogram typically shows a nearly continuous spectrum of fluctuations superposed on the main phase depression and many of these fluctuations have amplitudes comparable to the depression itself. The recovery phase is generally much smoother. Out in the magnetosphere the variations would be, if anything, stronger. During the sudden commencement the longitudinal wave propagates inward from the outer boundary in about 2 minutes [Hess, 1968], the arrival on the dark side lags the arrival on the sunward side by about 10 seconds indicating that the dark side wave originated on the exterior (sides) of the

rearward magnetosphere where the solar wind shock front took a little longer (traveled farther) before it made contact. When the magnetosphere is first squeezed by the enhanced solar wind, the pressure must be first applied to the front and sides of the magnetosphere. The back side of the inner magnetosphere may then be left bulging out behind initially but it can not remain that way. The inner magnetosphere must rotate with earth, otherwise the thermal plasma would be driven by enormous $\vec{v} \times \vec{B}$ forces that do not appear to be present. The forced rotation of the rear-side plasma into the constricted region may produce longitudinal waves of the kind illustrated in figure 8-7.

We have seen that the main phase depression will require a RC distribution with a total energy of about 10^{22} ergs. The question is, where does that energy come from?

The sudden commencement field-increase requires a compression of the inner magnetosphere. Figure 8-8 shows the amount of compression required to obtain a certain increase AB. The estimate is on the basis of mathematical models of the magnetosphere balanced against a certain relative solar wind pressure p/p_0 where p_0 is the normal quiescent pressure [Hess, 1968].

The energy of the magnetic field between L shells is proportional to r^{-4} because $dV/dr \propto r^2$ where V is the volume within an L shell and $E_B \propto B^2 \propto r^{-6}$. Thus, the energy of the whole field (external to earth is)

Figure 8-7 Wave in which $\vec{k} \perp \vec{B}$ but $\vec{k}$ not $\parallel$ to $\vec{r}$

Figure 8-8 Compression of the magnetosphere versus field increase at sudden commencement, after Hess [1968].

$$\int_{1R_e}^{10R_e} \frac{dE_B}{dr} dr = E_o (1 - 10^{-3}) \sim 10^{25} \text{ ergs}$$

and that energy between say $R_e = 7$ and $R_e = 10$ is

$$\int_{7R_e}^{10R_e} \frac{dE_B}{dr} dr = E_o (3 \times 10^{-3} - 10^{-3}) \sim 2E_o \times 10^{-3} \sim 2 \times 10^{22} \text{ ergs}$$

Thus, if the field were suddenly compressed to $7 R_e$, the field energy brought inside $7 R_e$ (previously outside) would be $2 \times 10^{-3} \times 10^{25} = 2 \times 10^{22}$ ergs.

That amount of energy would cause a main phase decrease of -5×10^{-4} Gauss according to equation 6-2. According to figure 8-8 the field increase in the sudden commencement would also be about 5×10^{-4} Gauss. These numbers are not too far from the typical increase and decrease one sees, though usually the decrease is greater in magnitude than the increase. The answer to the question of where the energy of the RC distribution comes from might be that it comes, perhaps in large part, from the potential energy compressed into the magnetosphere in the sudden commencement. The compression of the internal field is relieved by the development of a higher energy RC distribution since the increased random transverse motion of charged particles in the B field essentially makes individual current loops that reduce the field. The generation of kinetic energy might be by means of the dissipation of longitudinal waves in the knee region against the boundaries of the knee.

Field fluctuations occurring during the course of the storm can also contribute kinetic energy in the same way. This would give rise to a RC distribution in the observed place at the appropriate time and there appears to be about the right amount of energy available to do it. Given a ring current, near the knee, it can lose its energy to the upper atmosphere at mid-latitudes giving rise to the SAR-arcs.

9. Summary and Conclusions

Those items of this investigation that are new, in the sense that to the author's knowledge they are significant and not done elsewhere, include the following:

1. SAR-arc data described in Section 3 are unique. Dates and locations given may be valuable to others for correlations.
2. The fact that a simple Maxwellian distribution of electrons cannot give the red-green ratio that sometimes occurs is new.
3. The sporadic occurrence of a small high energy tail of electrons corresponds to the sporadic occurrence of 55778 observed and implies electron heating is in progress.
4. Ratio of 5199A/6300A is calculated for general conditions.
5. For SAR-arc conditions the 5199A/6300A ratio infers lower electron density than others have assumed and higher temperature.
6. The 5199A/6300A ratio and 6300A/5577A ratio allow electron density and tail effects to be separated experimentally and both require results compatible with electron heating in progress.
7. Observations agree with lower than normally assumed electron density.
8. 1961 observation of RC distribution and observation of a SAR-arc from Fritz Peak simultaneously.

9. Suggestion that 1959 low altitude satellite measurement reported by O'Brien, et al., was early detection of RC coincident with SAR-arc.
10. Correlation of measured near-earth distribution of RC with SAR-arc positions.
11. Demonstration that measured energy and energy loss rate of RC distribution fit SAR-arc requirements.
12. Presentation of simultaneous spectrographic triangulation of SAR-arc and hydrogen arc.
13. Showing the asymmetric maps of the SAR-arcs in the magnetosphere have similar form to plasmopause.
14. Suggestion that the RC distribution shares plasmopause asymmetry.
15. Drift of many arcs interpreted and formula for drift speed as function of asymmetry given.
16. Effect of field distortion northwest of station noted.
17. Plausibility of the electron "trough" observed over the SAR-arcs noted at interface of RC and plasmasphere.
18. Derivation of k_r and k_i for longitudinal hm waves in simple magnetosphere model with a knee.
19. Noting instability of knee region to propagation of longitudinal hm waves and possibility of localized heating at knee boundary.

It is now possible to sketch an overall picture of how the SAR-arcs occur. In reviewing the mechanism we will discuss what ~~seem~~ to be the weak links in the chain of understanding and suggest research that might provide clarification.

Considering matters from the earth outward, we can now be quite sure that the OI(6300-6364A) emission of the SAR-arc is due to excitation of atomic oxygen by electrons. The relative intensities of the spectral lines of oxygen and nitrogen correspond to excitation by ambient electrons which are being heated. Because of the typically sharp cutoffs of residual energies in chemical reactions, one would not expect the observed range of values of the [OI] 5577A intensity if a chemical reaction were in progress. Information on the [OI] 5577A and [NI] 5199A emissions in the SAR-arcs can add to the understanding of the electron energy spectrum but data are very sparse. The situation could be improved simply by using larger aperture photometers which would have greater sensitivity to weak emissions. This would also improve the sensitivity to [OI] 6300A and the frequency of occurrence of SAR-arcs fainter than 50R could be determined.

The source of energy for the SAR-arcs appears to be the ring current distribution. We have seen that the RC distribution is spatially and temporally correlated with SAR-arcs and that the measured rate of energy dissipation of the RC is adequate to drive the arcs.

The detailed excitation process in terms of the precipitated charged particles and their offspring needs clarification. A first step would be a thorough comparison of the existing Injun-5 satellite data with existing photometric data on SAR-arcs. Several simultaneous observations should be available in these data. A proper analytical model of the precipitating RC particles interacting with the atmosphere in the SAR-arc region also ought to be formulated.

The location of the RC distribution and its asymmetric shape suggest

that it is intimately associated with the knee or plasmopause. In fact, to put it somewhat lightly, the observations of the SAR-arc, the electron density trough, the knee, and the RC distribution all on the same field lines seem to suggest the situation may be like that of the several blind men describing different aspects of an elephant. It would be well to understand how these several features of the plasmopause region are interrelated. For example, the intermediate energy particles that comprise the RC distribution may be boiled off the plasmasphere through the dissipation of hm waves at the boundary of the knee, or alternatively, the RC particles may originate elsewhere and "pile up" at the plasmopause. In either case the position of the RC appears to be defined by the plasmopause which is the main structural feature of the thermal plasma of the inner magnetosphere. The converse statement, that the plasmopause position is determined by the RC distribution seems less likely to be true because the plasmopause is essentially always present, though not always well defined, while the RC is associated with magnetic storms.

The transport of particles from the plasmasphere to the RC distribution would be consistent with the shrinking and sharpening of the plasmopause during a magnetic storm. A subsequent outward expansion and smearing of the knee region would be consistent with the weakening of the RC.

It would be very useful to establish what part of the knee is associated with the field lines leading to the SAR-arc because it is possible to locate these field lines continuously and precisely by optical techniques. Once the relationship between these field lines and the plasma-

pause is known, a powerful tool to monitor the plasmapause is available. An experiment or series of experiments which could give a definitive answer might be performed with an airplane instrumented for optical observations and with ground based whistler (proton and electron) stations shown in Figure 9-1.

The airplane flies with the rotation of the earth in the general locale of the L=3 field line (a zig-zag path along the L line may be best). With a net rate of 330 km/hr along L=3 and a 3000 km circle of view, the field lines around the entire dark side of the magnetosphere will be scanned in a 6-hour flight. The ground based whistler stations at A and B (at least) can monitor the knee location simultaneously.

Ground based observations of electron and proton whistlers made in conjunction with ground based optical observations of SAR-arcs can also accumulate data which could establish the relation between the SAR-arc field lines and the plasmapause. New aeronomy facilities within line of sight range of the intersection of plasmapause field lines at altitudes of a few hundred kilometers are being planned. We believe that optical techniques can have an important role in plasmapause studies at these new facilities and therefore the site selection considerations should include acceptably clear weather conditions and a low stray light level.

The mechanism by which the energy of the solar plasma gives rise to the RC distribution is not well-defined. We have suggested that the mechanism is internal to the magnetosphere.

A satisfactory theory of the magnetosphere which describes how it will respond to perturbations such as a typical shock front in the solar

Figure 9-1 Suggested experiment

plasma is lacking. Thus one cannot say whether the development of the ring current is an expected internal process or whether the RC particles must be "injected". The formulation of the model appears to be a large and long range task to be based on the results of many measurements. Additional measurements of the temperature and density of the thermal plasma ($\lesssim 10$ eV) in the 2-10 R_e range appear to be needed for this work.

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APPENDIX 0

Record of observations, visibility
and geomagnetic activity for the
period September 27, 1967, through
March 31, 1970, at Richland, Wash-
ington.

Statistics of Photometric Observing
September 27, 1967, through March 31, 1970

Total nights	918	100%
Scheduled for observations	486	52.9
Nights when data obtained and acceptable visibility	259	28
Acceptable visibility but equipment break-down	10	0.01
Scheduled but poor visibility	217	23.6

A definite or probably SAR-arc was observed on 23 of the 259 nights when data were taken (8.9%). This provides a first estimate of frequency of occurrence of SAR-arcs brighter than 50 R and **equatorward** of L₄.

WINTER 1968

SPRING 1968

AUTUMN 1968

WINTER 1969

SPRING 1969

AUTUMN 1969

APPENDIX 1

Estimate of the concentration ratio $n(O^1D)/n(O^3P)$

Appendix 1

An estimate of the $1D$ density can be made by considering the number of 6300A photons emitted in transitions from that state. For a flux of 6300A photons measured in Rayleighs

$$\frac{R_{6300} \times 10^6}{D} = \langle F_{1D^3P_2} \rangle \quad (A-1)$$

where $\langle F_{1D^3P_2} \rangle$ is the average volume emission rate and where D is the effective SAR-arc thickness given by

$$D = \frac{\int_0^\infty F_{1D^3P_2}(h) dh}{F_{1D^3P_2}(\text{peak})} \quad (A-2)$$

Figure A-1 shows an experimentally determined plot of $F_{1D^3P_2}(h)$. [Tohmatsu and Roach, 1962]. By numerical integration D is found to be 1.77×10^7 cm. The relative volume emission profile in Figure A-1 is an average derived from several SAR-arcs and we assume it to be approximately correct for the case at hand.

From the observed fact that 5577A radiation in the SAR-arc is much weaker than the 6300A radiation one concludes that nearly all oxygen atoms in the $1D$ state decay or are quenched; for those excited to $1S$ would be evidenced by 5577A emission.

For a unit volume, the fraction of reactions occurring to atoms in the $1D$ state which give rise to 6300A photons is

Figure A-1 Relative volume emission rate and oxygen concentration

$$\frac{A_{1D^3P_2}}{A_{1D^3P_2} + A_{1D^3P_1} + \beta_{1DN_2} n(N_2)}$$

Thus, the net rate for all reactions in the unit volume is

$$F_{\text{net}} = F_{1D^3P_2} \frac{A_{1D^3P_2} + A_{1D^3P_1} + \beta_{1DN_2} n(N_2)}{A_{1D^3P_2}}$$

The lifetime of an O^1D atom is on the average

$$t_{1D} = \frac{1}{A_{1D^3P_2} + A_{1D^3P_1} + \beta_{1DN_2} n(N_2)}$$

The number of atoms in the unit volume must be

$$\langle n(O^1D) \rangle = F_{\text{net}} t_{1D} = \frac{F_{1D^3P_2}}{A_{1D^3P_2}} \quad (\text{A-3})$$

Using (A-1) to estimate $F_{1D^3P_2}$ with $D = 1.77 \times 10^7$ cm we find

$$\langle n(O^1D) \rangle \sim 8.2 R_{6300} \quad (\text{A-4})$$

Now the density of the O^3P atoms must also be estimated in a consistent way. Let

$$\langle n(0^3P) \rangle = \frac{\int_0^\infty n(0^3P) F_{1D^3P_2}(h) dh}{DF_{1D^3P_2}(\text{peak})} \quad (\text{A-5})$$

Before proceeding, it is noted that for $R_{6300} \sim 10^3$ equation (A-4) yields $\langle n(0^1D) \rangle \sim 10^4$. However, the total density of $n(0)$ is $\sim 10^7$. Consequently, $n(0^3P)$ is equal to $n(0)$ to a good approximation. Equation (A-5) is evaluated numerically using the values of $n(0)$ shown in Figure A-1. The result is $\langle n(0^3P) \rangle = 2.12 \times 10^8$.

Thus,

$$\frac{n(0^1D)}{n(0^3P)} \sim \frac{\langle n(0^1D) \rangle}{\langle n(0^3P) \rangle} \sim 3.9 R_{6300} \times 10^{-8} \quad (\text{A-6})$$

APPENDIX 2

SAR-arc positions transformed to
the magnetic equatorial plane.

Figure A-2a Sept. 28/29, 1967

Figure A-2d Feb. 28/29, 1968

Figure A-2e Oct. 30/31, 1968

Figure A-2f Oct. 31/Nov. 1, 1968

Figure A-2g Mar. 19/20, 1969

Figure A-2h Mar. 24/25, 1969

Figure A-2i May 14/15, 1969

Figure A-2j Sept. 14/15, 1969

APPENDIX 3

Criterion for energy gain under internal reflection
of hm wave in the plasmopause knee.

Appendix 3

The wave equations of concern for two media (a) and (b) with interface at x and incident (I), reflected (R), and transmitted (T), occurring are in scalar form,

$$V_I e^{ik_a x} + V_R e^{-ik_a x} = V_a$$

$$V_T e^{ik_b x} = V_b$$

Conservation of momentum and continuity leads to

$$V_R = \frac{k_a - k_b}{k_a + k_b} V_I$$

$$V_T = \frac{2k_a}{k_a + k_b} V_I$$

Squaring to obtain energies yields

$$\frac{E_R}{E_I} = \frac{(k_a - k_b)^2}{(k_a + k_b)^2} \quad \text{reflected energy fraction}$$

$$\frac{E_T}{E_I} = \frac{4k_a k_b}{(k_a + k_b)^2} \quad \text{transmitted energy fraction}$$

and we note that

$$E_R + E_T = E_I$$

so we have checked that energy is conserved.

Assuming the jump in k is small compared to k let $k_b = k_a(1 + \Delta)$

Then $\frac{E_R}{E_T} \sim \frac{\Delta^2}{4}$. If Δ is small then reflection

is small, also, $\frac{E_T}{E_I} \sim 1 - \frac{1}{4} \Delta^2$. (A-1)

Transmission is near unity for $\Delta \ll 1$.

Let the gain in energy of the wave crossing the knee of width $(x_2 - x_1)$

be G where

$$G_{12} = \frac{1}{E(x_1)} \left\{ E(x_1) + \int_{x_1}^{x_2} dE \right\} = \frac{E(x_2)}{E(x_1)} \quad 1 \rightarrow 2$$

going from boundary 1 to 2 and

$$G_{21} = \frac{1}{E(x_2)} \left\{ E(x_2) + \int_{x_2}^{x_1} dE \right\} = \frac{E(x_1)}{E(x_2)} \quad 2 \rightarrow 1$$

going from 2 to 1. From equation (8-21) we have

$$G_{12} = e^{-2k_i(x_1) x_1 + 2k_i(x_2) x_2}$$

$$G_{21} = e^{2k_i(x_1) x_2 - 2k_i(x_1) x_1}$$

implying $G_{12} = G_{21} = e^{2 | k_i(x_1) x_1 - k_i(x_2) x_2 |}$

as expected.

Let Δ_1 be the jump in k at the inner boundary and Δ_2 be the jump at the outer boundary of the knee.

Then for a wave coming in, we will have energy

$$E(x_2) = (1 - \frac{1}{4} \Delta_2^2) G$$

after one pass through the knee. Then with reflection at x_1 we will have

$$E(x_2) = (1 - \frac{1}{4} \Delta_2^2) G^2 \frac{1}{4} \Delta_1^2$$

Then in the next step the fraction reflected for a second inward pass is $\frac{1}{4} \Delta_1^2$. Consequently at the outset of the second inward pass the wave has energy

$$E(x_2) = (1 - \frac{1}{4} \Delta_2^2) G^2 \frac{1}{4} \Delta_1^2 \frac{1}{4} \Delta_2^2$$

We are back at the starting point now and if this energy is larger than the initial energy $E(x_2)$ there will be a resonant power excursion. That is, if

$$(1 - \frac{1}{4} \Delta_2^2) \frac{1}{16} \Delta_1^2 \Delta_2^2 G^2 > 1$$

This requires that

$$e^{4 |k_i(x_1)x_1 - k_i(x_2)x_2|} > \left\{ (1 - \frac{1}{4} \Delta_2^2) (\frac{1}{16} \Delta_1^2 \Delta_2^2) \right\}^{-1} \quad (A-2)$$

for an excursion.

It is now shown that there can be no such excursion. Since $k \sim \frac{\omega}{v_{ph}}$, the jump in k is due to a jump in v_{ph} . But $v_p = (v_A^2 + v_s^2)^{\frac{1}{2}}$. We have taken v_A^2 to be continuous at the boundary so the jump is in v_s^2 . It was noted that $v_s^2 = \frac{\alpha P}{\alpha \rho}$. Thus $v_s^2 = \frac{\alpha P}{\alpha r} \left(\frac{\alpha \rho}{\alpha r}\right)^{-1}$. As mentioned earlier it is possible to calculate $\alpha P / \alpha r$ by the requirement of net radial force balance and $\alpha \rho / \alpha r$ is assumed to be known (e.g., Figure 8-2). The task is quite lengthy and will not be reproduced here for the result is that $v_s \leq \frac{1}{10} v_A$ everywhere and the jump in v_s at the knee is less than $\frac{1}{10} v_s$. The fact that v_s is small compared to v_A is in itself sufficient to negate possibility of the excursion and others [Parker, 1967] agree with that estimate of v_s . From the several relations mentioned in the paragraph above, one estimates that $A \sim \frac{1}{v_{ph}} \times (\text{jump in } v_{ph}) < 10^{-4}$. Thus equation (A-2) becomes

$$e^{4 | k_i(x_1)x_1 - k_i(x_2)x_2 |} \geq 16 \times 10^{16}$$

$$\text{or } e^{\frac{\epsilon 2\omega}{v_{ph}} | x_1 - x_2 |} \geq 16 \times 10^{16} \text{ approximately}$$

$$\text{or } e^{2\epsilon\omega} > 16 \times 10^{16}, \text{ for a reasonable } |x_1 - x_2| \text{ and } v_{ph}.$$

Since $\epsilon < 10^{-3}$ for all reasonable frequencies, the LHS is many orders of magnitude less than the RHS and the excursion cannot occur.

Furthermore, for $A < 10^{-4}$, reflections at the boundaries of the knee are very small as may be seen from (A-1).

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