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DETECTION OF ALPHA PARTICLES
IN AURORAL PHENOMENA

by

David Lukens Reasoner

A THESIS SUBMITTED
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Thesis Director's signature:

A handwritten signature in dark ink, appearing to read "Brian J. Davis", is written over a horizontal line.

Houston, Texas

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TABLE OF CONTENTS

	Page
1. <u>INTRODUCTION</u>	
A. Objective of the Proton-Alpha Experiment	1
B. Auroral Theories	2
C. Effect of Magnetospheric Storage on the Alpha-Proton Ratio	13
D. Prediction of Auroral Alpha-Proton Ratio from Auroral Theories	17
E. Related Solar-Wind Alpha-Proton Measurements	20
F. Related Experimental Investigations	21
G. Summary	21
2. <u>ION-ATMOSPHERE INTERACTIONS</u>	
A. Charge Exchange in Ionic Beams	23
B. Spectral Line Emission	26
3. <u>SCIENTIFIC DETECTORS AND PAYLOAD INSTRUMENTATION</u>	
A. Choice of Launch Vehicle	33
B. Scientific Detectors	34
1. Proton-Alpha Detectors	34
2. Ion Spectrometer	43
3. SPECS	44
4. G.M. 8001	45
5. Magnetometer	46
C. Payload Data Handling and Control Systems	47
1. Data Encoder	47
2. Pulse Height Analyzer System	51
3. Telemetry-Transmission and Antenna System	52
4. Power Control and Housekeeping	53

D.	Payload Design Criteria and Testing	54
E.	Data Translation and Reduction	55
4.	<u>PRE-LAUNCH AND POST-LAUNCH AURORAL CONDITIONS AND GROUND PHOTOMETRIC MEASUREMENTS ASSOCIATED WITH THE PROTON-ALPHA EXPERIMENT</u>	
A.	Choice of Suitable Aurora	59
B.	Launch Conditions	61
C.	Payload Performance	63
5.	<u>EXPERIMENTAL RESULTS</u>	
A.	Energetic Protons and Alpha Particles	65
B.	Possible Contamination of the Data	69
C.	Photometric Search for Helium Emissions	72
D.	Comparison of Auroral Alpha-Proton Data with Solar-Wind Alpha-Proton Densities	75
E.	Comparison of Measured and Predicted H β Intensities	77
F.	Morphology of Proton and Electron Precipitation	80
G.	Summary of Experimental Results	82
6.	<u>GENERAL DISCUSSION AND CONCLUSIONS</u>	84
	<u>Acknowledgements</u>	90
	<u>Bibliography</u>	91
	<u>Figure Captions</u>	97

CHAPTER 1

INTRODUCTION

A. Objective of the Proton-Alpha Experiment

Studies of the aurora by various experimental techniques are primarily directed to solution of the fundamental problems of determining the source location of auroral particles and understanding the processes responsible for acceleration of these particles. The various experimental methods, e.g. ground-based studies, balloon measurements, rocket and satellite studies, by their very nature concentrate on differing aspects of the aurora, but all techniques have contributed data leading toward an understanding of the physical processes responsible for the appearance of auroral particles and their deposition into the atmosphere. The ultimate aim of auroral research should be the development of a theory which allows one to predict the exact configuration of auroral activity over some future time period. This, however, is probably not unlike asking a meteorologist to predict the exact worldwide cloud pattern 24 hours in advance, and just as impossible.

The primary objective of the proton-alpha experiment was to measure the ratio of the fluxes of energetic alpha particles and protons in an aurora, and then to compare the auroral zone value with values measured at other places in the magnetosphere and the solar wind, and from this comparison attempt to deduce the location of the immediate source of auroral particles. For example, if the auroral alpha-proton ratio were found to be equal to the solar wind ratio, e.g. .01-.2:1, then one might deduce that auroral particles result from direct energization of solar

wind particles. If the auroral alpha-proton ratio were found to be 10^{-3} - 10^{-4} :1, then one might deduce that either auroral particles were originally in the terrestrial ionosphere, or that there was a process which discriminated drastically against alpha particles relative to protons as they made the transition from solar-wind particles to auroral particles. The proton-alpha experiment therefore can be thought of as using the alpha-particle component of the auroral particle flux as a "tracer" to determine possible source locations of this flux, and thus provide a test of some of the various theories concerning the origin of the aurora. The following sections will discuss various auroral theories and the predictions they make, either expressed or implied, about the expected auroral alpha-proton ratio.

B. Auroral Theories

This section will discuss several of the theories which attempt to explain the presence of energetic particles which produce auroras. Many of the current theories are based on the fact that the solar wind interacts with the earth's magnetic field to produce an extended "tail" on the night-side (Ness, 1965). Other theories, in the main prior to 1962, are based on a closed configuration of the geomagnetic cavity. Features such as neutral points (Chapman and Ferraro, 1931) and magnetospheric convection (Axford and Hines, 1961) were invoked to explain auroral particle fluxes. Insofar as possible, this discussion of auroral theories will follow chronological order.

The idea that streams of charged particles ejected sporadically from the sun during solar flare activity were responsible for auroras and magnetic storms was suggested in the early 1900's by Birkeland (1908, 1913), Chapman (1918, 1919), and Lodge (1900). Lodge supported his idea that charged particles emanated from the sun at sporadic intervals by noting that solar radiation pressure alone could not account for the extension of comet tails. He postulated that the average velocity of the solar corpuscular streams was 480 kilometers per second, a value remarkably in agreement with the most recent measurements of the solar wind velocity of 300 to 500 kilometers per second (Hundhausen, et al., 1967).

Chapman and Ferraro (1931) later showed that a stream of ionized plasma impinging upon the earth's magnetic field would confine the field to a closed cavity. The boundary conditions of such a configuration required currents on the surface of this cavity in order to terminate the earth's B field, and it was postulated that these currents were responsible for the depression of the magnetic field on the surface of the earth measured during magnetic storms. The authors also tried to show that the effect of the solar plasma stream upon the configuration of the earth's magnetic field could be represented by summing the fields of the earth's dipole and that of an image dipole located at some point along the earth-sun line. Figure 1, from Chapman and Ferraro (1931) shows an idealized model of the distortion of the earth's magnetic field by a solar plasma stream, along with the equivalent image dipole. The points labeled "Q" are the points where the magnetic field strength is

zero. The authors postulated that solar plasma would enter the geomagnetic cavity at these neutral points and ultimately flow into the polar regions, thus causing auroras. Chapman and Ferraro (1932) realized that this auroral theory was incomplete, since lack of information concerning the exact field line configuration in the geomagnetic cavity made it impossible to trace particle trajectories from the neutral points into the auroral zones.

Earlier in this section it was pointed out that observation of comet tails by Lodge (1900) led him to speculate that the sun ejected streams of plasma. Biermann (1951) showed that solar radiation pressure alone could not account for the elongation of comet tails, and that it was necessary to invoke an additional continuously acting source of pressure. He postulated that the sun continuously emitted a stream of high velocity plasma, with a density of 10^3 - 10^5 particles/cm³, a velocity of 10^3 kilometers per second, and a temperature of 10^4 °K. Biermann went on to speculate that the outward-flowing solar plasma carried along a magnetic field, and that this plasma was directly responsible for the aurora. This conjecture was supported by the observation of Meinel (1951) of the Balmer lines of hydrogen in the auroral spectrum which were Doppler-shifted toward shorter wavelengths. This Doppler-shift indicated that protons with maximum velocities of at least 3000 kilometers/sec were incident on the upper atmosphere.

Parker (1959) showed that the solar plasma flow postulated by Biermann could be explained by considering the plasma flow as a continuous expansion of the hot ($2-4 \times 10^6$ °K) solar corona. Solution of the hydrodynamic equations gave a

velocity of 500 km/sec and a density of a few hundred particles/cm³, in rough agreement with Biermann's numbers. Parker suggested that this solar plasma stream be called the "solar wind", a term which is now generally used. It should be noted that the solar-wind velocity calculated by Parker is both supersonic and super-Alfvenic, that is the flow velocity exceeds both the velocity of sound, given by

$$V_s = (\gamma P / \rho)^{\frac{1}{2}} \quad (\text{c.g.s. units}) \quad (1-1)$$

and the Alfven velocity, given by

$$V_a = B_o / (4\pi\mu\rho)^{\frac{1}{2}} \quad (\text{c.g.s. units}) \quad (1-2)$$

where P is the plasma pressure, ρ is the plasma density, B_o is the strength of the magnetic field, and μ is the relative permeability of the plasma.

Dessler (1967) showed that solar-wind acceleration to supersonic velocities has an analog to the creation of supersonic gas flow with a converging-diverging orifice, or de LaValle nozzle. The analog to the constriction of the nozzle in the gas-dynamical situation is supplied, in the case of the solar wind, by solar gravity. Parker and Dessler both showed that if the corona were too cool, there would be no expansion at all and hence no solar wind. Likewise, if the corona were too hot ($T > 4 \times 10^6$ °K) only subsonic flow would result. The surprising result is that supersonic solar wind can occur only for a limited range of solar coronal temperatures, from about 10^6 degrees to 4×10^6 degrees Kelvin.

Definitive experimental establishment of a continuous solar wind was provided by detectors on board Mariner 2

(Neugebauer and Snyder, 1962) and the Soviet space probes Lunik II and III (Gringauz, 1961). Gringauz reported solar wind fluxes of $\approx 2 \times 10^8$ ions/cm² sec and Neugebauer and Snyder reported solar wind velocities ranging from 320 to 770 kilometers/sec and temperatures ranging from 3×10^4 °K to 6×10^4 °K. Thus the existence of a continuous solar wind first postulated in 1951 was established by direct measurements. It therefore followed that distortion of the geomagnetic field was a permanent feature rather than a transient occurrence and that a continuous source of energy was available which might account for various geophysical phenomena.

Axford and Hines (1961) proposed a model to explain geomagnetic phenomena based on convective flow of plasma in a closed, distorted magnetosphere. The magnetospheric cavity was assumed to be filled with plasma, and momentum transfer through a viscous interaction at the magnetospheric boundary from the solar wind to the internal plasma set the latter in motion in a gross convection pattern. Plasma was postulated to flow away from the earth on the boundary and to complete a return path in the internal regions of the magnetosphere. The effect of the rotation of the earth on the general flow pattern was also included, resulting in an overall flow pattern as shown in Figure 2, from Axford and Hines (1961).

The conductivity of the magnetospheric plasma was presumed to be infinite, so that the magnetic field lines were "frozen into" the plasma, or there was no plasma flow perpendicular to magnetic field lines. With this situation, the convective motion could be transferred to all parts of the

magnetosphere, including the ionosphere. Turbulent motions superimposed upon the gross convection pattern were also proposed, which could result in acceleration of the plasma to auroral energies and could produce high latitude magnetic disturbances.

Piddington (1960) proposed that the geomagnetic cavity would be elongated and opened on the night side of the earth during the transition period between the sudden commencement and main phase of a magnetic storm. Although the process was not explained in detail, he proposed that a cloud of solar plasma ejected during solar flare activity would become attached to the geomagnetic field lines and drag them out to form a tail. Other features of this model included a twisting of the extended field lines due to the earth's rotation, and a neutral sheet on the night side near the magnetic equator where the magnetic field strength was zero.

Space charge fields and various instabilities were invoked to explain direct injection of solar plasma into the magnetosphere and the subsequent acceleration of particles to energies typical of auroral and Van Allen fluxes. During the recovery phase of a magnetic storm, the tail would recover to the original closed, stable configuration, and in the process energetic particles to supply the Van Allen Belts and auroral fluxes would be confined within the magnetosphere.

While adhering to a closed magnetospheric configuration Johnson (1960) suggested that the magnetospheric tail may be kept open by hydromagnetic waves generated by turbulence at the magnetospheric boundary. Dessler (1964) proposed that this was indeed the case, that the radiation pressure of hydromagnetic waves in the tail was sufficient to keep

the tail open for a distance comparable to the radius of the solar wind cavity in the interplanetary medium, or some 20-50 A.U. As hydromagnetic waves with amplitude b_0 propagated down the tail away from the earth, the magnitude B_0 of the ambient magnetic field would decrease with distance from the earth until eventually the ratio b_0/B_0 became on the order of unity. At this juncture, the background plasma would be controlled in part by the HM wave and carried along with it, thus exerting a pressure which would force the tail to remain open. Dessler further concluded that magnetic merging as a mechanism to close the tail would not operate, since the conductivity of the plasma in the tail is essentially infinite in the limiting case of D.C. fields. In order for magnetic merging to proceed quasi-statically in a magnetized plasma, Joule dissipation mechanisms must operate to dissipate the energy which appears from the annihilation of magnetic fields. Dessler felt that since the tail plasma conductivity was infinite, no dissipation and consequently no magnetic merging could occur. This point of whether or not merging takes place is the basis of considerable controversy, as will be discussed later.

The open tail magnetosphere concept was used by Dessler and Juday (1964) as a basis for a model of auroral particle acceleration and an explanation of the gross features of the auroral zones. Field lines from the auroral and polar regions, it was theorized, were distorted by solar wind pressure to form an extended, open tail. The rotation of the earth and the co-rotation of the ionosphere combined to twist the field lines into two helixes bounding two tubes of flux, with the wavelength of a helix being on the order of

100 earth radii. Only field lines terminating in the auroral zones reached the external surface of the flux tubes, while field lines originating from the regions poleward of the auroral zones were buried inside the flux tubes and hence had no contact with the solar wind. It was postulated that auroral particles were energized along the boundary of the flux tubes by some sort of interaction with the solar wind, and these freshly energized particles would then follow the field line trajectories into the auroral zones. This model predicts only the gross features of the aurora, but provides no explanation of features such as arc formation, auroral substorms, or low latitude auroras. Also, this model predicts only statistical correlation between northern hemisphere and southern hemisphere auroral activity, but no detailed correlation of specific occurrences since the field lines from dipolar conjugate points would not be closed near the earth.

The discovery of a neutral sheet in the magnetospheric tail by Ness (1965) provided valuable new information concerning the topology of the magnetospheric cavity. The tail was found to be open to a distance of at least 31 earth radii, and the existence of a neutral surface separating regions of oppositely-directed magnetic fields was established. Satellite measurements by Anderson, et al., (1965) with IMP A and Frank (1965a) with Explorer 14 showed the existence of energetic electrons with $E > 40$ kev in the vicinity of the neutral sheet. These particle observations led Ness to speculate that particle-field interactions in the neutral sheet may result in energization of auroral particles. This idea was developed into models for auroral particle acceleration by Speiser (1965) and Axford (1967).

These two neutral-sheet acceleration mechanism models will now be discussed.

Speiser (1965) considered a model of the neutral sheet with the following features. First, the magnetic field varied continuously and linearly from a maximum value north of the sheet, decreasing to zero and reversing direction in the sheet, and increasing again south of the sheet. He postulated a continuous process of magnetic merging, resulting in both a perpendicular magnetic field component and an electric field lying in the sheet directed perpendicular to the earth-sun line. The trajectories of protons and electrons injected into the neutral sheet were calculated. The calculations showed that the injected particles would be accelerated by the electric field, and simultaneously undergo an oscillatory motion whose amplitude grew with time. This unstable oscillation would then result in the particles being ejected from the neutral sheet, whereupon they would follow field lines into the auroral zones. Figure 3 from Speiser (1965) shows the neutral sheet configuration and particle trajectories. An interesting feature of this model is that in order for an electron to gain the same energy as a proton, the electron must be ejected at a point farther from the earth, i.e. on a field line intersecting the auroral zone at a higher latitude than the corresponding field line at the point of ejection of the proton.

Axford (1964, 1967) flatly rejects the idea that there are no possible dissipative effects in the magnetospheric plasma. He states that although the plasma is certainly collisionless in the mechanical sense, particle-wave and wave-wave interactions provide an effective finite

conductivity so that the plasma behaves as a fluid allowing magnetic diffusion and field line merging. Solar-wind plasma is presumed to be injected and accelerated in the neutral sheet, due to processes resulting from sporadic merging of field lines and the subsequent conversion of magnetic energy into particle energy. This process is thought to be responsible for both auroral fluxes and radiation belt population. The acceleration of particles takes place adiabatically, that is the particle energy is increased as the magnetic field strength increases during the merging process which occurs slowly enough to conserve the first adiabatic invariant. An alternate viewpoint is to consider particle acceleration by the electric field E produced according to the equation

$$\frac{1}{c} \frac{\partial B}{\partial t} = \text{curl } E. \quad (1-3)$$

The sudden, sporadic character of the merging process was said (Axford, 1967) to be responsible for the auroral substorm described by Akasofu (1964). The author postulates that some particles freshly accelerated by the annihilation of magnetic field energy would travel directly to the auroral zone atmosphere. Other energized particles could drift into closed magnetospheric regions and populate ring currents and the Van Allen belts. In this model, the night side auroral zone is defined by the field lines which lie between the boundary of stable trapping of the Van Allen Belts and the boundary between open and closed field lines.

Axford's idea that auroral particles are freshly energized is supported by considering the energies involved in producing aurora. O'Brien (1967) points out that the energy required

to sustain the world-wide aurora is $\sim 10^{18}$ ergs/sec, while the energy content of the trapped radiation zones and neutral sheet are $\sim 10^{22}$ and 10^{20} ergs respectively. O'Brien concludes that if the immediate source of auroral particles is either of these two regions, or both, then a nearly continuous supply of freshly accelerated particles is necessary, since the energy content of these regions could sustain the aurora for less than 1 hour. Like Axford, O'Brien identifies the night side auroral zone as the field lines between the boundary of stable trapping and the magnetospheric boundary, and also points out that there is as yet insufficient evidence to determine the exact relationship between the boundary of stable trapping and the auroral zone. Stated in another way, the problem is that during periods of large magnetic activity, the auroral zone is observed to move equatorward, and there is no way to determine if these auroras are due to precipitated Van Allen particles or to freshly energized particles.

One of the main points of O'Brien's discussion is that the auroral zone is not delineated by the boundary between open and closed field lines but rather is delineated by the field lines which, although they may be closed, nevertheless are so distorted from a dipole configuration that the particles cannot drift stably in longitude and thus complete one complete orbit around the earth.

One possible location of the source of auroral particles is the upper ionosphere, in the region extending from a few hundred kilometers to some thousands of kilometers. In a series of papers, Mozer and Bruston (1966a, 1966b, 1966c) postulate the existence of magnetic-field-aligned electric fields in the upper ionosphere with intensities of a few

millivolts/meter to several hundred millivolts/meter. This conclusion resulted from examining proton and electron data from detectors flown into an auroral substorm or "breakup". The data showed anticorrelations between the intensities of proton and electron fluxes and an anomalously large flux of upward-moving protons. This indicated to the authors the presence of local electric fields of sufficient magnitude to accelerate particles in the high ionosphere to auroral energies.

C. Effect of Magnetospheric Storage on the Alpha-Proton Ratio

The dynamic behavior of alpha particles and protons in electric and magnetic fields is controlled by their energy, charge and mass. The equations for cyclotron radius, cyclotron period, and energy gain or loss by electromagnetic fields show that these quantities vary by no more than a factor of 2 for alpha particles and protons of the same energy. Thus it would appear that alpha particles and protons have nearly identical scale sizes in their dynamic behavior in electric and magnetic fields, and that acceleration processes consisting of particle-field interactions should not discriminate between these two ions to a large extent.

Another possibility for discrimination between protons and alpha particles in magnetospheric regions above 300 kilometers is collisional-radiative recombination. This process, for protons and alpha particles is represented by the equations below:

The recombination process on a macroscopic scale can be represented by an equation of the form:

$$\frac{dn^+}{dt} = -\alpha n^+ e. \quad (1-7)$$

n^+ and e are the ion and electron number densities, and α is the recombination coefficient. α is generally a function of the ion species, and the density and temperature of the plasma (McDaniel, 1964).

Using the recombination equation, a system of non-linear differential equations can be written to describe the changes in the ionic species of a plasma containing initially protons and alpha particles. This system of equations is shown below:

$$\frac{dH^+}{dt} = -\alpha_1 H^+ e \quad (1-8)$$

$$\frac{dHe^{++}}{dt} = -\alpha_3 He^{++} e \quad (1-9)$$

$$\frac{dHe^+}{dt} = -\alpha_2 He^+ e + \alpha_3 He^{++} e \quad (1-10)$$

$$H_o^+ = C_1 \quad (1-11)$$

$$He_o^{++} = C_2 \quad (1-12)$$

$$He_o^+ = C_3 \quad (1-13)$$

Solution of this system of equations will allow determination of the time behavior of the densities of the various ionic species. The ultimate goal is to answer the question, "If solar-wind plasma composed of protons and alpha particles is injected into the magnetosphere, how much storage time is required to change the ratio of alpha particles to protons to any great extent?"

Before attempting to solve the equations, values of the various physical parameters required in the solution will be determined. The initial solar-wind alpha-proton ratio will be taken as .05:1, a typical value (Hundhausen, et al., 1967). The plasma density and temperature at $L = 7$ will be used, since this is approximately the minimum L value at which plasma could be temporarily stored without becoming stably trapped Van Allen radiation. Values of electron density and temperature at this L value are typically $n_e = 10/\text{cm}^3$ and $T = 2000^\circ\text{K}$ (Carpenter and Smith, 1964). At other locations in the outer magnetosphere, the plasma density is less and the temperature is higher, and both of these effects decrease the recombination rate. Thus the recombination rate at approximately $L = 7$ is an upper limit to the speed of the process in magnetospheric regions where stable trapping does not occur.

Calculations of the recombination coefficient as a function of plasma density and temperature have been done by Bates, et al., (1962) for an optically thin proton-electron plasma. The recombination coefficients for He^{++} and He^+ have been determined by Mosburg (1966) by normalizing theoretically calculated values to measured experimental values. Data from these various sources are plotted in Figure 4. Curves of the proton recombination coefficient

as a function of temperature for $N_e = 10^8$ electrons/cm³ and $N_e \rightarrow 0$ electrons/cm³ from the data of Bates, et al., (1962) are shown, along with the data of Mosburg (1966) for the He^{++} recombination coefficient. Based on the proton data, the curve of the He^{++} recombination coefficient was extrapolated to obtain a value for the conditions $T = 2000^\circ\text{K}$ and $N_e \rightarrow 0$. A similar process was used to obtain a value of the He^+ recombination coefficient. For the purposes of the calculation, the following values of the recombination coefficients will be adopted:

$$\alpha_{\text{H}^+} = 1.3 \times 10^{-12}$$

$$\alpha_{\text{He}^+} = 2.5 \times 10^{-12}$$

$$\alpha_{\text{He}^{++}} = 3.1 \times 10^{-10}$$

The He^{++} recombination coefficient is seen to be approximately 200 times larger than the corresponding coefficient for H^+ . Thus, the ratio of H^+ to He^{++} in a plasma will increase with time due to differential recombination. In order to obtain quantitative information, the system of recombination equations must be solved.

The system of recombination equations will now be re-written for the sake of clarity, along with the initial conditions. These are shown below:

$$\frac{d\text{H}^+}{dt} + -\alpha_1 \text{H}^+ e \quad (1-14)$$

$$\frac{d\text{He}^{++}}{dt} = -\alpha_3 \text{He}^{++} e \quad (1-15)$$

$$\frac{d\text{He}^+}{dt} = -\alpha_2 \text{He}^+ e + \alpha_3 \text{He}^{++} e \quad (1-16)$$

$$\alpha_1 = \alpha_{H^+} = 1.3 \times 10^{-12} \text{ cm/sec}$$

$$\alpha_2 = \alpha_{He^+} = 2.5 \times 10^{-12} \text{ cm}^3/\text{sec}$$

$$\alpha_3 = \alpha_{He^{++}} = 3.1 \times 10^{-10} \text{ cm}^3/\text{sec}$$

$$H_o^+ = 10 \text{ ions/cm}^3$$

$$He_o^+ = 0$$

$$He_o^{++} = .5 \text{ ion/cm}^3$$

$$e_o = 11 \text{ electrons/cm}^3$$

This system of equations was solved numerically to obtain characteristic times for changes in the He^{++}/H^+ ratio. The solution showed that the time required for this ratio to change by a factor of only 2 from an initial value of .05:1 to .025:1 was 2.1×10^8 seconds, or about 7 years. Thus it is highly unlikely that even if magnetospheric plasma storage does occur, the time scale would be sufficiently long for any significant change in the auroral alpha-proton ratio relative to the solar-wind alpha-proton ratio to occur.

D. Prediction of Auroral Alpha-Proton Ratio from Auroral Theories

The various open tail or long tail theories (Dessler, 1964; Axford, 1967; Speiser, 1965) all involve direct injection of solar wind plasma into the magnetosphere and subsequent acceleration of some of the solar wind particles to auroral energies. In these theories auroral zone field lines are either open for great distances, some hundreds of

earth radii, or these field lines are so distorted from a dipolar configuration that the particles cannot execute stable trapped orbits. These theories predict that auroral particle fluxes are freshly energized solar wind particles, and there is no intermediate storage of the auroral particles, either before or after energization. Thus the expected auroral alpha-proton ratio would be equal to the solar-wind alpha-proton ratio, if the acceleration process does not discriminate between these ions.

The model of Axford and Hines (1961) involving a closed magnetosphere and plasma convection offers the possibility of depletion of the alpha particle component relative to the proton component. If the storage time were sufficiently long, or if the magnetosphere were a closed system with no particle input from the solar wind, then differential recombination would result in a decreased auroral alpha-proton ratio relative to the solar-wind value. A value of the expected auroral alpha-proton ratio is however impossible to predict from this theory, since an estimate of the time delay between injection of solar wind plasma and the appearance of some of this plasma as auroral particle fluxes is not given.

Mozer and Bruston (1966a, 1966b, 1966c) postulated that auroral particle fluxes were accelerated from constituents of the terrestrial ionosphere by local electric fields. In order to predict the resulting auroral alpha-proton ratio, the proportions of H^+ and He^{++} in the upper ionosphere must be known. An upper limit to the He^{++} to H^+ ratio will now be determined.

Based on drag data from the Echo Satellite, Nicolet (1961) predicted that helium and helium ions were important

constituents of the ionospheric region above 500 kilometers. It was previously believed (Hanson and Ortenburger, 1961) that protons and oxygen ions were the principle constituents of this region. A measurement of total positive ion concentration by Hale (1961) was interpreted by Hanson (1962) as indicating that He^+ ions were present in approximately the abundances predicted by Nicolet.

The concentration of H^+ and He^+ ions in the mid-day ionosphere was measured by Taylor, et al., (1963), using a Bennett-type ion mass spectrometer. The altitude distribution curve of the concentrations of H^+ and He^+ are shown in Figure 5. No trace of the He^{++} ion was detected, but the minimum detectable concentration based on instrumental sensitivity was 10 ions/cc. This places an upper limit on the He^{++} to H^+ ratio between 500 and 1000 kilometers in the daytime ionosphere of .01:1.

A more relevant measurement was made by Taylor, et al., (1965) with an ion spectrometer on the OGO-A satellite. Concentrations of He^+ and H^+ were measured at nighttime at altitudes ranging from 1000 to 28,000 kilometers. The ion concentration data are shown in Figure 6. Again, no evidence of He^{++} ions was found, and from the sensitivity of the instrument and the data one can deduce an upper limit of 2×10^{-4} :1 for the He^{++} to H^+ ratio in the nighttime ionosphere between 1000 and 20,000 kilometers.

The conclusion is that if auroral fluxes result from local acceleration in the ionosphere by electric fields, the ratio of alpha particles to protons at the same energy per unit charge will be less than 2×10^{-4} :1.

E. Related Solar-Wind Alpha-Proton Measurements

A comparison of the auroral-zone alpha-proton ratio with the solar-wind alpha-proton ratio could lead to determining the immediate history of auroral particles. If this were known, then the information could be compared with predictions from the various auroral theories and a process of acceptance and/or rejection could occur. Unfortunately for the experimental objective, the solar wind alpha-proton ratio is not constant. Neugebauer and Snyder (1962) reported that the solar wind proton-alpha ratio varied from 0.3:1 to 0.1:1 while Hundhausen, et al., (1967) report variations of 0.2:1 to conditions when the alpha particle flux was below the sensitivity of the instrument. The mechanism producing these variations is unknown, although Jokipii (1966) showed that radial diffusion in the solar corona could lead to depletion of the solar-wind alpha particle flux relative to the alpha particle concentration in the solar photosphere.

It is obvious that simultaneous measurements of the auroral-zone and solar-wind alpha-proton ratios are highly desirable. Fortunately, data from the satellites Vela 3a and b (Bame, private communication) and Pioneer 7 (Wolfe, private communication) on the solar wind alpha-proton ratio at the time of the auroral zone experiment have been made available. This data greatly increased the value of the experiment, changing it from an isolated measurement to part of an experimental system making coordinated measurements of alpha particle "tracers" in interplanetary space and in the auroral zone.

F. Related Experimental Investigations

The primary objective of this experimental investigation was to measure the auroral alpha-proton ratio. As will be seen in Chapter 3, the instrumental package was capable of particle measurements of both protons and electrons over a very wide range of energies (500 ev - 600 ev), and therefore was capable of a number of other experiments.

Simultaneous data on incident auroral protons and ground-based photometric measurement of hydrogen emission intensity were used to test the accuracy of photon production curves derived by Eather (1967), calculated from experimental and theoretical cross sections for proton impact on atmospheric gases from various investigators.

The experimental package sampled proton and electron fluxes over approximately 3° of latitude, and this report discusses an experimental measurement of the characteristics of proton and electron precipitation during the flight of the package and in particular compares the observed characteristics over this latitude range with morphological data for comparable latitude ranges and for auroral conditions which characteristically precede in time by a few hours the type of auroral activity directly investigated.

G. Summary

This dissertation reports on three separate, though related, experimental investigations. The alpha-proton experiment attempts to provide an answer to the perplexing problem of the source of auroral particles. The second experiment essentially uses the aurora as an upper-atmospheric laboratory to check the accuracy of existing data

relating hydrogen emission intensity to incident fluxes of protons on atmospheric gases. The final experiment is a morphological study of proton and electron precipitation.

In the following chapter some characteristics of ion-atmosphere interaction processes which relate to these experiments will be discussed. Chapter 3 is a detailed report of the detectors and other components of the experimental package. Chapter 4 discusses the morphology of the auroral display investigated and also coordinated ground-based photometric measurements. Experimental results are presented in Chapter 5, and finally the concluding chapter discusses the implications of the experimental results and proposes further investigations which would extend the scope of the present experiments.

CHAPTER 2

ION-ATMOSPHERE INTERACTIONS

The experimental study of auroral ions required knowledge of specific ion-atmosphere interactions. In particular, quantitative knowledge of processes responsible for hydrogen and helium spectral emissions, and of changes in the charge state of ionic beams by the process of charge-exchange was necessary. As will be seen in the discussion to follow, the two problems are related, for knowledge of charge-exchange processes is useful for calculation of spectral emissions. The process of charge-exchange in ionic beams penetrating the atmosphere will be discussed first.

A. Charge-Exchange in Ionic Beams

Rocket-borne electrostatic-deflection experiments measuring positive ion fluxes potentially can be jeopardized because of changes in the charge state of the ions due to charge-exchange with constituents of the upper atmosphere. In particular, an alpha particle penetrating the atmosphere will undergo many charge-exchange collisions before finally becoming thermalized. The alpha particle will spend significant fractions of its energetic lifetime as a He^+ ion and as a neutral helium atom. An alpha-particle detector which requires a helium beam to be fully ionized for detection will therefore see only a portion of the incident alpha particle beam, if the detector is at an altitude where charge exchange is important. The system of equations describing the change in charge-state composition of a helium beam is given by Allison (1958) as:

$$\frac{dF_0}{d\pi} = -F_0(\sigma_{01} + \sigma_{02}) + F_1\sigma_{10} + F_2\sigma_{20} \quad (2-1)$$

$$\frac{dF_1}{d\pi} = F_0\sigma_{01} - F_1(\sigma_{10} + \sigma_{12}) + F_2\sigma_{21} \quad (2-2)$$

$$F_2 = 1 - (F_0 + F_1) \quad (2-3)$$

where F_0 , F_1 , and F_2 are the beam fractions of He, He^+ and He^{++} respectively, π is the number of target atoms per cm^2 traversed by the beam, and the σ_{if}^s are cross sections for collisions resulting in charge changing from an initial state i to a final state f . A final equation

$$\frac{dE}{d\pi} = -\sigma_E \quad (2-4)$$

describes the energy loss of the beam. In practice, however, energy loss for alpha particles with $E > 10$ kev or so is negligible at altitudes greater than 150 kilometers, and the beam energy may be assumed constant. On the other hand, the σ_{if}^s are functions of target gas composition, which is in turn a function of altitude. Therefore, the equations are more easily solved by numerical methods.

If constant beam energy and target gas composition are assumed, then the charge-exchange cross sections are constant. This assumption immediately leads to a limiting case in the solution, that of equilibrium. The beam component fractions eventually reach a state where there is no further change in these quantities. The equilibrium values of quantities F_0 , F_1 and F_2 designated as $F_{0\infty}$, etc. can be readily evaluated

by setting the left hand side of equation (2-1) and (2-2) to zero, and solving the resulting system algebraically. This procedure is useful for checking the validity of a numerical solution of the equations.

An IBM numerical integration subroutine was used to solve the system of equations. This subroutine uses Hamming's Predictor-Modifier-Corrector Method along with a Runge-Kutta routine to supply the starting values. The atmospheric model was for night-time conditions at sunspot minimum, from the Satellite Environment Handbook, second edition. Charge-exchange cross-section values were taken from the review article by Allison (1958), and interpolative techniques were used to compute the values for various atmospheric compositions (Vogel, private communication). The calculations were done for various beam energies ranging from 50 kev to 500 kev, starting with a pure alpha particle beam at an initial altitude of 1000 km. In each case, the calculations were performed until there was no change in the beam component fractions with decreasing altitude, or until the equilibrium values of the beam component fractions were reached.

Results of the calculations for initial beam energies of 50 and 200 kev are shown in Figures 7 and 8 respectively. The curves at differing energies appear qualitatively the same, although the relative composition at altitudes between 200 and 400 kilometers is seen to be a strong function of beam energy. Of particular interest are the drastic changes in the beam charge-state composition at altitudes between 200 and 400 kilometers, and the attainment of equilibrium below approximately 200 kilometers. Based on these data, the atmosphere can be divided roughly into three regions.

These are:

- (1) $H > 400$ kilometers - Helium⁺⁺ beam unaffected by atmospheric charge exchange.
- (2) $200 \text{ km} < H < 400 \text{ km}$ - Helium beam charge state composition changing rapidly.
- (3) $150 \text{ km} < H < 200 \text{ km}$ - Helium beam charge state composition is in equilibrium.

Thus, measurements of alpha particles must be made at altitudes greater than 400 kilometers in order that the measurements are a true indication of the incident auroral flux. Measurements at lower altitudes will be affected by atmospheric effects, and hence are potentially subject to large errors, corrections and uncertainties due to atmospheric model uncertainties and to unknown variations in the atmosphere due to the aurora itself.

B. Spectral Line Emission

This section will discuss methods of calculation and experimental measurements leading to determination of the intensities of spectral line emissions produced by ion beams bombarding the atmosphere. In particular, production of H α and H β emission by proton beams and production of the He I 5876Å emission by alpha particle beams will be considered. The mathematics involved for the cases of proton and alpha particle beams are nearly identical, since at altitudes where light emission is important ($H < 300 \text{ km}$) the alpha particle component of the resulting helium beam can be neglected. Both hydrogen and helium beams can be treated as two component systems, consisting of H and H⁺,

and He and He^+ respectively (Eather, 1966).

Before discussing the mathematics of spectral-line emission, the quantities used in the treatment will be defined. These quantities are listed below.

N_a	= density of atmospheric atoms
N_0	= density of H or He in beam
N_1	= density of H^+ or He^+ in beam
v	= velocity of beam
n	= quantum state of H or He atom
σ_{01}	= cross section for ionization of neutral H or He atom
σ_{10}	= total cross section for electron capture by H^+ or He^+
$\sigma_{10}(n)$	= cross section for electron capture resulting in population of n^{th} quantum state
$\sigma_{00}(n)$	= cross section for excitation of neutral atom to the n^{th} quantum state.
$A_{nn'}$	= probability for electron transition from quantum state n to n'
N_n	= number density of H or He with electron in state n
F	= flux of particles in units of particles/cm ² -sec
$I_{nn'}$	= volume emission rate of photons resulting from electron transitions from the n^{th} to the n'^{th} state.

The volume emission rate of photons from a particular atomic transition is given by:

$$I_{nn'} = N_n A_{nn'} \text{ photons/cm}^3\text{-sec} \quad (2-5)$$

The problem then is to determine the quantity N_n . This is done by use of the equation for statistical equilibrium of the population of the n^{th} quantum state. This equation, from Chamberlain (1954) equates the source and loss rates for atoms in the n^{th} state, and is shown below.

$$N_1 N_a \sigma_{10}(n) v + \sum_{n''=n+1}^{\infty} N_{n''} A_{n''n} + N_0 N_a \sigma_{00}(n) v = N_n \sum_{n'=1}^{n-1} A_{nn'} \quad (2-6)$$

The terms on the left represent the contributions to population of the n^{th} state from electron capture, cascading from higher states and neutral excitation respectively, while the right-hand side is a depopulation rate by transitions to all lower states. A second equation expresses the condition of ionization equilibrium and is written

$$N_1 N_a \sigma_{10} v = N_0 N_a \sigma_{01} v \quad (2-7)$$

Manipulation of these two equations, and recalling that $F = (N_0 + N_1) v$ gives the result

$$I_{nn'} = N_n A_{nn'} = \frac{F N_a A_{nn'}}{\sum_{n'=1}^{n-1} A_{nn'}} \left(\frac{\sigma_{01} \sigma_{10}(n) + \sigma_{00}(n) \sigma_{10}}{\sigma_{01} + \sigma_{10}} \right) \quad (2-8)$$

The cascading term in equation (2-6) has been neglected in

obtaining this result. The cascade contribution was calculated by Chamberlain (1954) by an iteration process and the solution appears in this work.

The result expressed in equation (2-8) can be given an elegant and simple physical interpretation with some manipulation. Recalling that the ion beam was assumed to be in charge-state equilibrium, the equilibrium fractions are given by the equations from Allison (1958) as:

$$F_{0\infty} = \sigma_{10}/(\sigma_{01} + \sigma_{10}) \quad (2-9)$$

$$F_{1\infty} = \sigma_{01}/(\sigma_{01} + \sigma_{10}) \quad (2-10)$$

Substitution of these equations into equation (2-8) gives the result

$$I_{nn'} = FN_a \frac{A_{nn'}}{n-1} \left(F_{1\infty} \sigma_{10}(n) + F_{0\infty} \sigma_{00}(n) \right) \quad (2-11)$$

$$\sum_{n'=1} A_{nn'}$$

The term $F_{1\infty} \sigma_{10}(n)$ represents the contribution to the total intensity from electron capture, while the term $F_{0\infty} \sigma_{00}(n)$ represents the contribution from neutral collisional excitation. This form of the equation is convenient for calculations, since the capture cross sections $\sigma_{10}(n)$ and the neutral collisional cross sections $\sigma_{00}(n)$ are generally tabulated separately. The total ionization and capture cross sections σ_{01} and σ_{10} do not appear in the equation, while the equilibrium functions $F_{0\infty}$ and $F_{1\infty}$ for hydrogen and helium are available from Allison (1958).

Chamberlain (1961) calculated emission of $H\alpha$, $H\beta$ and $Ly\alpha$ photons using theoretically calculated cross section

data of Bates and Dalgarno (1953) and Bates and Griffing (1953, 1955). The result of these calculations are shown in Figure 9, from Chamberlain (1961). The photon production curves are plotted as a function of the proton range in the atmosphere at standard conditions (STP) for the following reason. In order to calculate the total photon emission resulting from a proton with initial energy E (or range r_0) the integral

$$\text{Total photons} = \int_0^{r_0} \text{photons/proton-atm-cm} \cdot dr$$

must be evaluated. This is done quite simply by measuring the area under the curve from $r = 0$ to $r = r_0$. Using this method, a curve of photon production per proton versus proton energy can be produced. This latter curve is convenient for calculation of the light produced by an incident proton flux.

Measurements of the cross section $\sigma_{10}(n)$ for hydrogen beams by Philpot and Hughes (1964) and for helium beams by Head and Hughes (1965) were used by Eather (1966, 1967) to recalculate $H\alpha$ and $H\beta$ production rates, and to calculate corresponding production rates of HeI 5876Å emission. Figures 10 and 11 from Eather (1967) show production rates for $H\beta$ and HeI 5876 respectively. In each case the contribution due to electron capture only and the total contribution are plotted separately. As pointed out by Eather (private communication) the cross sections for neutral excitation of both hydrogen and helium atoms are based on theoretical calculations and may be in error by a factor of 2. Nonetheless, the curves should be reliable upper and

lower limits for the true photon production. Figure 12 shows total photon production of H β versus initial proton energy, from Eather (1967). This last curve will be used in a later chapter to calculate the expected H β intensity resulting from an experimentally measured proton flux.

A final aspect of line emission from incident ions is the phenomenon of Doppler broadening and shifting of the spectral lines. Emitting atoms are in general moving with respect to a ground based observer with a distribution of velocities, and this velocity distribution is reflected as a Doppler broadening and/or shifting of the spectral line, so that the total photon emission is spread over a range of wavelengths. Line profiles measured looking at the magnetic zenith show broadening and shifting, while magnetic horizon profiles show broadening only. In the former case, the velocity distribution is predominantly toward the observer, while in the latter case the observer is viewing perpendicular to the magnetic field line and there is no preferred motion in his direction.

Line profiles for H α and H β in the magnetic zenith and horizon from various experimenters are shown in Figure 13, from Eather (1967). Although discrepancies exist, in general the peaks of the zenith profiles are shifted approximately 6Å, and the half intensity widths are approximately 20Å.

The line profiles of hydrogen and helium emissions should not be taken as indicative of the incident ion velocity spectrum. The profiles are strongly influenced by the shape of the electron capture and excitation cross sections versus energy curves. The line profiles can only set a lower limit to the maximum incident ion velocity. For example, Figure 10 shows that no appreciable H β emission occurs for protons

unless the proton energy is below 300 kev. Thus, a beam of 300 kev protons and a beam of 500 kev protons will produce exactly the same magnetic zenith line profile.

This chapter has outlined briefly some of the ion-atmosphere processes of which quantitative knowledge is necessary in this experimental investigation. The charge-exchange problem was discussed and in following chapters it will be seen that this problem was overcome by using a Javelin sounding rocket to launch the experiment package. The photon production data will be used to compare calculated and measured $H\beta$ intensities, and supplement the experiment's rocket-borne alpha particle search with ground-based photometric measurements.

CHAPTER 3

SCIENTIFIC DETECTORS AND PAYLOAD INSTRUMENTATION

A. Choice of Launch Vehicle

The proton alpha experiment required an in situ measurement of particle fluxes in an active aurora. An essential requirement was for the instruments to attain an altitude of greater than 400 kilometers, in order that the particle fluxes were pure, that is to say unaffected by atmospheric and ionospheric effects such as coulomb scattering, current systems, and serious depletion of any alpha particle flux by charge exchange. A secondary, though no less important requirement was the capability of launching instrument package on very short notice of a few minutes when favorable auroral activity occurred.

The sounding rocket as a vehicle to carry the instruments into the aurora fitted the above requirements very well, due in no small way to the presence of an excellent launching facility at Fort Churchill, Manitoba, Canada in the middle of the auroral zone. Two of the most popular sounding rockets for auroral research are the Nike-Apache and the Nike-Tomahawk. These vehicles were considered, but ultimately rejected because they did not have the altitude capability required. Maximum altitude of the Nike-Apache is only about 200 kilometers and of the Nike-Tomahawk 300 kilometers. The final choice was the Argo D-4 Javelin Rocket.

The Javelin is a four stage solid propellant vehicle capable of lifting a 140 pound payload to a maximum altitude of 800 kilometers with a flight time of approximately 15 minutes. In addition, the Javelin can be held in a ready-to-

launch condition for as long as desired, with only 90 seconds required between the final decision to launch and the actual time of launching. An additional 120 seconds is required for the payload instruments to be exposed by ejecting a nose cone. Thus, only 3.5 minutes elapse between the time that the launch decision is made and the time that the instruments actually begin functioning.

The scientific payload was instrumented with a group of detectors designed to measure the fluxes of protons, electrons, and alpha particles in various energy ranges extending from 50 ev to 600 kev. A summary list of the detectors, their energy ranges, particle types, and orientation with respect to the central payload axis (spin axis) is given in Table 1. Figure 14 shows the energy ranges and particle types measured by the various detectors.

The following sections of this chapter will discuss the payload system in detail.

B. Scientific Detectors

1. Proton-Alpha Detectors

In order to identify uniquely protons and alpha particles and their energies it is necessary to employ two methods of particle separation. For example, any method involving static electric fields acts equally upon all ions with the same energy to charge ratio. Consider an ion with energy E , charge q , and mass m moving in the x direction initially. Let the ion encounter an electric field ϵ in the y direction for a distance dx . The particle trajectory in the region of the electric field will be parabolic, and will emerge from the region of the field with its velocity vector deflected

TABLE 1

Proton-Alpha Payload Detectors

<u>Detector</u>	<u>Particle Type</u>	<u>Energy Range</u>	<u>Orientation</u>
Proton-Alpha 1	Protons Alpha Particles	100 kev 200 kev	0°
Proton-Alpha 2	Protons Alpha Particles	100 kev 200 kev	45°
Ion Spectrometer	Ions	90-650 kev	45°
SPECS	Protons Electrons	500 ev - 100 kev 50 ev - 100 kev	45°
G.M. 8001	Protons Electrons	E > 600 kev E > 60 kev	45°
Magnetometer	N.A.	N.A.	45°

through an angle θ . The equations for the angle θ are:

$$\theta = \tan^{-1} v_y / v_x \quad (3-1)$$

$$v_y = at = \frac{eq}{m} \cdot \frac{dx}{v_x} \quad (3-2)$$

$$\tan\theta = \frac{eq}{m} \cdot dx \cdot \frac{1}{v_x^2} = \frac{eq dx}{2} \cdot \frac{1}{E} \quad (3-3)$$

Thus, $\tan\theta = K \cdot (q/E)$, and it is seen that the variable determining the ion trajectory is the ratio of the charge of the ion to the energy of the ion. The trajectory of an ion in a static magnetic field can be calculated by knowing the radius of curvature of the ion at each point. The radius of curvature is given by the equation:

$$r = \frac{mv}{qB} \quad (3-4)$$

Thus magnetic field selection will act equally upon all ions with the same momentum to charge ratio.

With the above information at hand, it is seen that it is possible with a combination of electric and magnetic fields to design a system to select nearly monoenergetic, separated beams of protons and alpha particles out of an incident flux consisting of protons and alpha particles of all energies. A schematic sketch of a possible detector design is shown in Figure 15. As a starting point, assume it is desired to detect 10 kev protons and 20 kev alpha particles. Let us now proceed to calculate the electric and magnetic field intensities required. Using the previous notation:

$$\tan\theta = .177 = \frac{\epsilon dx}{2} \cdot q/E \quad (3-5)$$

$$.177 = \epsilon \cdot \frac{5}{2} \cdot \frac{4.8 \times 10^{-10}}{1.6 \times 10^{-8}} \quad (3-6)$$

$$\epsilon = 236 \text{ volts/cm} \quad (3-7)$$

The required magnetic field strength may be calculated in the following manner. The path length of the ion in the magnetic field is approximately the diameter of the field region, or 2 cm. Thus

$$\tan\theta \approx \frac{2 \text{ cm}}{r_c}, \text{ giving } r_c = \frac{2}{\tan 10^\circ} = 11 \text{ cm.} \quad (3-8)$$

Using the equation for the radius of curvature of a 20 kev alpha particle

$$r_c = \frac{m_\alpha v}{qB} = \frac{m_\alpha \sqrt{\frac{2E}{m_\alpha}}}{qB} = \frac{m_\alpha^{\frac{1}{2}} \sqrt{2E}}{qB} \quad (3-9)$$

solving for B gives $|B| = 1950$ gauss. Now the difficulty appears. A field strength of 2000 gauss over a length of 2 centimeters would require a rather large and heavy magnet, something on the order of 100 cm^3 in volume and 2 kilograms in weight. A detector of these dimensions would be rather impractical for rocket-borne instrumentation. Accordingly, a method involving electrostatic separation and particle energy measurement was chosen.

From the foregoing discussion, it is clear that if a particle detector were available which could measure the energy of an incident ion, this could be used in conjunction with an electrostatic deflection system to measure the fluxes

of protons with energy E and α particles with energy $2E$. The solid-state detector is such a device. This detector is essentially a back-biased silicon or germanium diode, which operates as a solid state equivalent of a gas ion chamber. The reverse bias forms a depletion region on both sides on the p-n junction in which there are no mobile charge carriers. All of the electrons in the depletion region are in the valence band, which is separated from the conduction band by approximately 1 ev. A charged particle traversing the depletion region imparts energy to the valence band electrons which excites them into the conduction band. These now-free electrons are swept out of the depletion region by the electric field and appear as free charge at the terminals of the device. A charged particle produces on the average one free electron for each 3.5 ev of energy loss. Thus, the detector produces an amount of charge proportional to the energy lost by the particle in the depletion region. If all of the particle's energy is lost in the depletion region, then the detector produces a charge pulse in magnitude proportional to the incident energy of the particle. So in order to produce linear operation the depletion region must be thicker than the range of the highest energy particle that is desired to be measured. The amount of material the particle must traverse before entering the depletion region, known as the dead layer, also must be made as small as possible, since energy loss in this layer does not produce any charge output. The solid state detectors used in this experiment were of the type known as gold-silicon surface barrier. In this type, a p-n junction is formed on the surface of a silicon wafer,

and the junction coated with a thin layer of gold 75Å to 150Å in thickness to provide an electrical contact. The only dead layer is the gold coating, and represents a negligible particle energy loss for the requirements of the proton-alpha detector. The loss in the dead layer was calculated to be 2 kev for a 100 kev proton.

The charge output of the detector is converted to a voltage pulse by a charge sensitive preamplifier. This preamplifier is basically a high gain inverting amplifier with a feedback capacitor connected from output to input. A schematic of a solid-state detector and preamplifier is shown in Figure 16. C_f is the feedback capacitor and C_s is the stray capacitance of the detector, wiring, and preamplifier input, and A is the amplifier gain. Applying standard linear circuit theory, the transfer function of the circuit may be written as

$$V_{out} = \frac{+A}{C_s + (A-1)C_f} \cdot q \quad (3-10)$$

For $A \gg 1$; $AC_f \gg C_s$, the equation reduces to:

$$V_{out} = q/C_f \quad (3-11)$$

Thus the output voltage pulse is proportional to the charge pulse q , which is in turn proportional to the energy of the particle.

The proton-alpha detectors were designed to measure the fluxes of protons and alpha particles in the energy range 100-300 kev. The detectors consisted of a pair of concentric cylinders acting as an electrostatic lens, a series of baffles to minimize particle scattering, and a solid state detector at the focus point of the lens. The

outer cylinder was at ground potential, and a fixed negative voltage was applied to the inner cylinder. Positive ions entering the annulus between the two cylinders were deflected toward the central axis of the detector. All positive ions with a given range of energy to charge ratio were focused onto the surface of the solid state detector. For example, with -5000 volts applied to the inner cylinder of the electrostatic lens, protons with energies of $100 \text{ kev} \pm 15 \text{ kev}$ and alpha particles with energies $200 \text{ kev} \pm 30 \text{ kev}$ were focused onto the solid state detector. The remainder of the proton-alpha detector system consisted of a series of pulse amplifiers and a 64-channel pulse height analyzer. A more complete description of the pulse height analyzer system will be given in a following section. Thus, in theory, an incident particle flux containing a mixture of protons and alpha particles will result in a pulse height spectrum with two peaks at V_0 and $2V_0$, corresponding to protons and alpha particles respectively. Figure 17 shows an idealized output spectrum for an incident flux of protons and alpha particles in a 10:1 ratio. A dimensional sketch of the proton-alpha detector is shown in Figure 18, and Figures 19 and 20 are photographs of the detector.

The calibration of the proton-alpha detector system naturally divided itself into two parts. The first part was the calibration of the subsystem consisting of the solid state detector, the amplifiers, and the pulse height analyzer. The end result of this calibration was determination of the curve of incident particle energy versus pulse height analyzer channel number. The second part of the calibration was the determination of the properties of the electrostatic lens.

These properties were the energy passband, the angular response, and the geometric factor.

The instruments used in the first part of the calibration were a vacuum system, a Texas Nuclear Neutron Generator, a Nuclear Data Pulse Height Analyser, and a Berkeley Nucleonics Precision Pulse Generator. The Texas Nuclear Generator was used as a source of protons with energies up to 120 kev. This accelerator produced protons by radio-frequency excitation of hydrogen gas, and accelerated them to the desired energy by an electrostatic field. Unfortunately, the resulting particle beam was neither pure nor monoenergetic. Ions of atmospheric gases were present in the beam and particles with energies less than the desired energy were present. The presence of this low energy component was probably due to charge exchange, with some of the ions becoming neutralized in the electric field region and hence not gaining maximum energy. Before reaching the solid state detector, the beam was purified by a system consisting of an electromagnet, electrostatic deflection plates, and collimators. With this system, it was assured that only monoenergetic protons reached the detector. The output spectrum of the detector and preamplifier was measured by the Nuclear Data Analyzer. A curve of particle energy versus channel number was plotted for particle energies of 70 to 110 kev. With the beam off, the output of the precision pulse generator was introduced into the preamplifier input in a manner to simulate the charge pulse of the detector. In this way, a calibration relating particle energy to pulse amplitude from the pulse generator was obtained. Finally, the rocket-borne 64-channel analyzer was calibrated by

exciting the solid state detector preamplifier with the precision pulse generator, resulting in the desired system calibration. The calibration curve of particle energy versus pulse height analyzer channel number for detector p/α 2 is shown in Figure 21. The calibration also resulted in determining the energy and noise resolution of each solid state detector-preamplifier combination so that selection was made on the basis of overall resolution.

The second part of the calibration involved extensive measurements to determine the energy passbands and geometric factors. An electron gun system capable of producing a uniform, monoenergetic beam over the entire entrance annulus of the detector was available in the laboratory. The validity of using electrons instead of protons for the calibration may have been questionable, but a rough calibration with a proton beam from the Texas Nuclear Generator showed that the particle type made no difference to the calibration. The solid state detector was not used as the actual particle detector in the calibration. Electron beam energies of 1 to 10 kev were used, and the solid state detector could not detect reliably particles with energies less than 50 kev due to the inherent noise level of the device. Instead, a funnel channeltron operating in the counting mode was used, along with a circular aperture 0.25 cm^2 in area which duplicated the active area of the solid state detector. The electrostatic lens-funnel channeltron system was mounted on a rotating plate in the path of the beam. With a potentiometric readout of the angle of the mounting plate, the angle of incidence of the beam to the detector was measured to an accuracy of ± 0.25 degrees. The calibration procedure is detailed in step-by-step fashion

below:

- (1) Fix a deflection voltage of +200 volts on the inner cylinder of the electrostatic lens.
- (2) Fix a beam energy.
- (3) With the aid of an X-Y recorder and data processing system, plot count rate versus angle of beam incidence.
- (4) Repeat the measurement (Step 3) for all beam energies which show a measurable response.

A typical response curve for a beam energy of 3500 electron volts is shown in Figure 22. In order to convert the data to an energy response function the integral

$$R(E) = 2\pi \int_{-\theta}^{\theta} R(E, \theta) \sin\theta \, d\theta \quad (3-12)$$

had to be evaluated for each beam energy. The integral was approximated by the sum:

$$R(E) = 2\pi \sum_i R_i(E, \theta) \sin\theta_i \Delta\theta \quad (3-13)$$

The intervals of $\Delta\theta$ were 0.25 degrees.

The resulting energy passband curve is shown in Figure 23, translated for a deflection voltage of 5300 volts, corresponding to the voltage used for p/α 2. The passband for the 5300 volt deflection voltage was calculated by multiplying the particle energy scale for a deflection voltage of 200 volts by the factor 5300/200. The geometric factor was calculated to be $1.4 \times 10^{-2} \text{ cm}^2 \text{ ster}$ at the peak of the energy passband, or 100 kev.

2. Ion Spectrometer

The ion spectrometer was designed to measure the flux and energy spectrum of ions in the energy range 90 to 650 kev. Apart from the scientific usefulness of this data, results from this detector were used as a cross-check of the data from the proton-alpha detectors.

This detector used a solid state detector-pulse height analyzer system identical to that of the proton-alpha detectors. A series of circular apertures to define the acceptance angle and a broom magnet to exclude electrons were placed in front of the solid state detector. The electron rejection capability of the magnet was measured with a Sr^{90} beta source. The rejection ratio was greater than $10^4:1$ for electrons with energies less than 600 kev. Additional protection against possible electron and cosmic ray contamination was obtained by using a detector with a depletion region depth of only 60 microns. A relativistic particle penetrating the detector normal to the surface deposits only 30 kev in the depletion region, resulting in a pulse well below the threshold of 90 kev set in the pulse-height analyzer circuitry.

Calibration of the ion spectrometer, like the p/ α detectors, fell into two parts. Determination of particle energy versus pulse height analyzer channel number was done by the same method used for the p/ α detectors. The effective area of the spectrometer was the active area of the solid state detector, which was 0.25 cm^2 . The acceptance angle was measured by rotating the detector in the proton beam of the Texas Nuclear Accelerator to determine the response curve. Figure 24 shows the measured response curve. Since

the detector was cylindrically symmetric, the solid angle was calculated according to the formula:

$$\Omega = 2\pi(1 - \cos \frac{\theta}{2}) \quad (3-14)$$

where θ was the full included angle at the half-height of the response function, measured to be 9.2 degrees. This gave $\Omega = 1.98 \times 10^{-2}$ steradian and the geometric factor was therefore $4.95 \times 10^{-3} \text{ cm}^2 \text{ ster}$. Photographs of the ion spectrometer are shown in Figures 25 and 26.

3. SPECS

The Switching Proton-Electron Channeltron Spectrometer was designed to measure the fluxes and energy spectra of protons and electrons in the energy range of $\sim 100 \text{ ev}$ to 100 kev . SPECS employed a pair of electrostatic deflection plates, a switching high voltage supply for the deflection voltage, and six channel electron multipliers, or channeltrons. Five of the channeltrons were special 270° circular types, with an elliptical entrance aperture $1\text{mm} \times 3\text{mm}$. The channeltrons were mounted with their entrance apertures to one side of the central axis of the collimator and deflection plate system, as shown in Figure 27 from O'Brien, et al., (1967). Particles passing through the deflection plates were separated in trajectory according to energy and therefore each of the five channeltrons received particles in different energy passbands. The sixth channeltron had a funnel-shaped entrance aperture 8mm in diameter, and was mounted on the opposite side of the deflection plate axis from the five channeltrons. The stepping high voltage supply provided voltages of $\pm 35 \text{ volts}$, $\pm 350 \text{ volts}$ and

± 3500 volts to the deflection plates in a six step sequence, thus providing the capability of detecting protons and electrons over 3 decades in energy. A complete cycle of the six high voltage levels occurred every six seconds. The five channeltrons were used for detailed 15 point measurements of proton and electron energy spectra, while the funnel channeltron, with its wide energy passband and large geometric factor, was used for studies of fast time variations of particle fluxes. The energy passbands of SPECS are shown in Figure 28. In the figure, each passband is indexed with a two-digit number. The first digit is the number of the channeltron and the second digit is the indicator for the value of the deflection voltage. For example, E_{22} is the passband of channeltron number 2 with a deflection voltage of 350 volts. The five 270° channeltrons are numbered 1 through 5, and the funnel channeltron is number 6. A complete report on SPECS may be found in O'Brien, et al., (1967).

Calibration of SPECS was accomplished with the electron beam system used for the proton-alpha detector calibration. In a similar manner, the angular response function at various energies for each of the six channeltrons was measured, and from this data the energy passbands were calculated (J. Burch, private communication).

4. G.M. 8001

The G.M. 8001 detector was based on an Eon type 8001 Geiger-Muller tube having an active area of approximately 9 cm^2 . The window was mica with a mass per unit area of 2.7 mg/cm^2 . A honeycomb collimator in front of the window

defined the acceptance angle. This detector was sensitive to electrons with $E > 600$ kev.

Calibration involved determining the window thickness, measuring the acceptance angle, and determining the r versus R function, which was the curve relating true counting rate to apparent counting rate (L. Westerlund, private communication). The window thickness was determined by measuring the counting rate as a function of distance between the window and a Po^{210} alpha particle source in air. The alpha particle energy required to produce counts in the geiger tube was calculated from the dE/dx function of alphas in air, and the window thickness determined by range-energy curves for alphas in mica. Angular acceptance was measured by rotating the detector in front of a Pm^{147} beta ray source. The r versus R calibration was accomplished by using a series of Pm^{147} beta ray sources. The r versus R calibration was accomplished by using a series of Pm^{147} sources of known intensities. The geometric factor of the detector was calculated to be $0.3 \text{ cm}^2\text{-steradian}$.

5. Magnetometer

The magnetometer was a Schonsted flux-gate Type RAM-5B. This instrument measured the vector component of the magnetic field along the axis of the probe. The angle of the probe axis with respect to the local magnetic field vector can be calculated with the equation:

$$\theta = \cos^{-1} \frac{B_m}{B_o} \quad (3-15)$$

where B_o is the absolute value of the local magnetic field

and B_m is the field component measured by the magnetometer probe. The axis of the probe was aligned with p/α 2, the proton spectrometer, SPECS, and the GM 8001. With the magnetometer data, the instantaneous aspect of these four detectors with respect to the magnetic field was determined.

A summary of the characteristics of the payload detectors is given in Table 1. Figure 29 is a photograph of the payload, showing the locations of the various detectors.

C. Payload Data Handling and Control Systems

Encoding and transmission of data from the various scientific detectors were accomplished by a rather elaborate set of subsystems, including a pulse height analyzer, a digital data encoder, RF transmitter, and other devices. While these devices are not strictly classed as scientific detectors, nonetheless the success of the experiment depended upon their functioning properly. Indeed, the scientific worth of the experiment was to some extent controlled by the data subsystems, in that such parameters as data sampling rates, resolution of analog signals and overall data quality were controlled directly by these devices. The components of the payload system will now be discussed in turn. For the sake of clarity, a block diagram of the payload is shown in Figure 30.

1. Data Encoder

The nucleus of the data system was the digital data encoder, built to Rice University specifications by Space Craft, Inc. The primary function of the encoder was to receive the random pulse inputs from the various detectors

and encode the data into a serial train of binary digits in a specified format. The basic format was a frame containing 14 twelve-bit words, with each 12-bit word representing a piece of scientific or engineering information. Some of the 12-bit words actually contained two separate pieces of data encoded as six-bit words. The data transmission rate was 20,000 bits per second, resulting in a frame rate, which was also the detector sampling rate, of 131 per second. The data format is shown in Figure 31. The function of each of the words will now be discussed.

(a) Frame Sync - Word 1

The frame sync word was a fixed bit pattern, viz. 111000100101, which served to identify the beginning of a data frame. Although spurious sync words could appear at other places in the frame, this problem was minimized in the data reduction process by requiring the occurrence of two consecutive sync words spaced the proper interval apart to identify a proper data frame.

(b) Frame Counter - Words 2 and 3a

The frame counter was an 18 bit non-resetting register which was incremented by one each time a frame was transmitted. Thus, a unique number was assigned to each data frame for use in subsequent data reduction. The capacity of the register was 262,144, and so 2000 seconds of data transmission were possible before the frame counter started over. The flight time was only 900 seconds.

(c) Magnetometer - Word 3b

The analog voltage (0-5 volts) from the magnetometer was digitized by an analog-to-digital converter in the encoder and transmitted as a six bit word.

(d) Ion spectrometer, p/α 1 and p/α 2, Words 4, 5 and 6

These words were the pulse amplitudes and rates for the ion spectrometer, p/α 1 and p/α 2. Signals to these registers originated in the pulse height analyzer system, which will be discussed in detail later.

(e) SPECS Status - Word 7b

This word was the output of a six-bit parallel entry register controlled by the status lines from SPECS. The three high-order bits transmitted the state of the switching high voltage supply, while the three low-order bits transmitted the number of the channeltron from which data was being received.

(f) p/α 1 and p/α 2, Lower and Upper Windows - Words 8 and 9

These words transmitted the pulse rates from two channel analyzers of the pulse amplitudes of p/α 1 and p/α 2. These analyzers will be discussed in a later section on the pulse height analyzer system.

(g) Corona Register - Word 10a

This register contains six bistable elements for the purpose of recording and transmitting the occurrence of corona pulses detected by the corona detector operating with the p/α 1 and p/α 2 high voltage deflection plate supplies.

(h) Analog Multiplex - Word 10b

An analog multiplexer and ADC sequentially samples up to 19 analog signals and transmits each digitized value once per 20 frames. The first frame in the sequence of 20 contains a sync word, viz. 111111, which, like the main frame sync word, allows determination of the beginning of the subcommutation sequence.

(i) GM 8001, SPECS Continuous, SPECS Switching, SID - Words 11, 12, 13 and 14

These words are the outputs of 12 bit resetting binary accumulators to transmit the average pulse rate over a frame interval of the geiger tube and SPECS. Word 12 is the output of the funnel channeltron in SPECS and Word 13 is the subcommutated output of the five channeltrons. A pulse occurring at the time the accumulator of Word 13 is reset is transmitted from the encoder to SPECS in order to provide a signal to synchronize the channeltron selection and high voltage switching circuits with the frame rate of the encoder.

The various timing functions in the encoder were controlled internally by a master oscillator, or clock, and a programmer. The programmer served to select the various accumulators in sequence, transfer the data to a shift register, inhibit data input during transfer, and reset the accumulators when appropriate. Data were shifted out of the shift register to form the serial data train with no gaps between the words. An additional output circuit converted the bilevel binary code, known as non-return-to-zero (NRZ)

to a format known as Manchester, or bi-phase. See Figure 32 for a sketch of these two code types. Manchester code is preferred to transmission because there is always at least one transition between two levels per bit interval. With Manchester code, the transmission system does not have to have response to very low frequencies, as it does for NRZ code.

2. Pulse Height Analyzer System

The pulse height analyzer system, hereafter referred to as the PHA, served to convert the pulse amplitudes from the proton spectrometer, p/α 1, and p/α 2 to a train of digital pulses whose number was proportional to the original analog pulse amplitude. Three separate 64-channel analyzers were included in the system, along with post amplifiers, threshold discriminators, and various logic circuits to interface the PHA system with the data encoder. In order for analysis to occur, the input pulse amplitude was required to fall between two discriminator levels. The lower threshold setting was determined by the noise level of a particular solid state detector and associated amplifiers, while the upper threshold was set so that the maximum number of pulses in the output pulse train was 63. This limit of 63 pulses maximum was required since the output pulse train was counted by a 6-bit accumulator in the data encoder, and accumulator overflow had to be prevented to insure against ambiguous data. The maximum average analysis rate was 131 conversions per second, corresponding to the data encoder frame rate. All detector pulses which had amplitudes between the threshold limits were counted by separate six-bit

accumulators in the data encoder, so that the true count rates of the three detectors could be determined. If this had not been done, the absolute counting rate, and hence the particle flux, could not have been determined at all if the average particle arrival rate was greater than 131 counts/second. The theory of statistics shows that if counting the number of frames in which pulse height analysis had occurred were the only way to determine the true average counting rate, then for an average particle arrival rate of 131 per second, 50% of the particles would not have been recorded. In fact, for the number of particles per second not recorded to be 2% or less of the average arrival rate, the average rate would have to be 50 particles per second or less. In addition to the 64-channel analyzers, two window analyzers were incorporated into the systems for p/α 1 and p/α 2. One window, the upper window, was set so that it straddled the position of an expected alpha particle peak. The other, the lower window, was set for the same energy width adjacent to and on the low side of the upper window. The reason for this was to provide a cross-check of the data.

3. Telemetry - Transmitter and Antenna System

The payload transmitter was a solid state, nominally 2 watt, frequency modulation unit operating at 244.3 megacycles supplied by Vector Manufacturing Co. The Manchester Code from the encoder was applied directly to the transmitter modulation input without any signal conditioning, other than a network to adjust the amplitude of the signal to obtain the proper modulation index. The antenna was a four-element turnstile array with the plane of the turnstile

perpendicular to the spin axis of the payload. The antenna was connected to radiate right-hand circularly polarized radiation toward the ground, in order to be compatible with the receiving antennas at the telemetry station at Fort Churchill.

Selection of the transmitter power and modulation index was based on a series of laboratory tests to determine bit error probability as a function of receiver terminal signal strength and average carrier deviation. The test apparatus is shown in Figure 33. Data from the PCM simulator were compared bit-by-bit with the same data transmitted over a simulated R-F link. The bit error probability was determined by the ratio of the error rate from the comparator to the PCM bit rate. The results are shown in Figures 34 and 35. Figure 34 is a plot of BEP versus average carrier deviation for a signal strength of 1 μ V. There is a distinct minimum at 90 kilocycles average deviation. Figure 35 is a plot of BEP versus signal strength at 90 kilocycles deviation. As can be seen, 2.0 microvolts of signal at the receiver terminals is sufficient to insure a BEP of 10^{-6} . Final selection of transmitter power was based on recommendations by personnel at the Sounding Rocket Division of Goddard Space Flight Center. The BEP during the flight was less than 10^{-7} .

4. Power Control and Housekeeping

Two separate battery packs were used, one for the low-voltage payload components and one for the various detector high voltage supplies. This was done to minimize introduction of spurious noise into the payload data systems

resulting from any arcing or corona in the high voltage supplies. Various umbilical lines were provided so that the payload could be powered from an external source for purposes of general testing and for final checkout immediately prior to launch. A Raymond Engineering Labs, Inc. Model 1850 Program Timer was employed to turn on the high voltage supplies and to fire the line cutters which deployed the antennas. This timer was started at the instant of nose-cone ejection. In addition, the timer turned off the high voltage deflection plate supplies to $p/\alpha 1$ and $p/\alpha 2$ for one minute each during the latter portion of the flight so that the contamination of the data due to system noise and high energy penetrating radiation could be determined.

Analog housekeeping signals, which were engineering measurements such as battery voltages, payload temperatures, and high voltage supply on-off indicators were processed and transmitted by the analog multiplexer and ADC section of the data encoder (see discussion of Word 10b in the section on the data encoder). Although the housekeeping information turned out to be only of passing interest, it would have been valuable in diagnosing any malfunction.

D. Payload Design Criteria and Testing

Design of the payload to perform particular scientific measurements was naturally the primary requirement. An important secondary requirement was qualifying the various payload components to operate as a well integrated system in a rather severe environment of temperature, vacuum, and vibration. Exact duplication of flight conditions simultaneously was impossible with available facilities. The

testing had to be accomplished in separate phases, such as thermal tests, vacuum tests, and vibration tests. This sort of piecewise testing is based on the theory that the total is never greater than the sum of the parts, which may or may not be valid. The payload had to operate over a temperature range of -20° to $+50^{\circ}$ Centigrade, operate at ambient pressures ranging from atmospheric to vacuum (less than 10^{-6} millimeters of mercury) and survive linear accelerations of 40 g^{S} and vibration levels up to 35 g^{S} . Temperature and vacuum tests were performed at Rice University, and vibration tests at Goddard Space Flight Center in Greenbelt, Maryland.

E. Data Translation and Reduction

Approximately 800 seconds of useful scientific data were obtained from the proton-alpha experiment. At a bit rate of 20,000 bits per second, this is 16 million binary bits of information. Put into other terms, a telemetry frame contained 16 separate scientific measurements, excluding sync words, frame counter, and engineering measurements. Thus, 800 seconds represents about 1.7 million separate scientific measurements. If the data were printed out with one line per telemetry frame on an IBM line printer, some 3200 feet of paper would be required. The obvious fact emerging from this discussion is that sophisticated computer data reduction techniques were required to extract useful scientific information simply because of the overwhelming amount of telemetered data available. In the discussion to follow, the entire data reduction process from reception of telemetry to computer processing for scientific information will be described.

The serial binary data train was received and recorded during the payload's flight by the telemetry facilities at Churchill Research Range. Timing codes and other data of an engineering nature were also recorded. Before any meaningful data reduction could occur, the original data had to be translated into a form compatible with the Rice University IBM 7040 Computer. This translation was accomplished by a facility built around an SDS-92 digital computer. The original data tape was played back on a video tape recorder. The serial binary data were first processed by a signal conditioner to produce data compatible with the system hardware. This reconstituted serial data were then processed by a device which separated the data into the original twelve-bit telemetry words. The twelve-bit words were then processed and recorded by the SDS-92 onto a tape whose format was compatible with the IBM 7040 system. Simultaneously, timing information from the original tape was decoded by a time code translator and this information was interspersed with the telemetry data on the 7040 tape. Time information was recorded once every tape record, or once every .98 seconds in real time.

• Programs to implement data reduction on the IBM 7040 were created by the Service Bureau Corporation. These programs allowed communication between the translated data and the FORTRAN language. The original telemetry frame of 14 12-bit words was converted to an array of 21 variables representing the original scientific information. The routines also allowed addressing the data at any chosen tape record or frame counter number. The circuit was now complete, in that the original scientific data in the form of random detector pulses in the payload were converted to

FORTTRAN variables. The versatility of this language could now be used for sophisticated data reduction.

The various data reduction programs contained safeguards against processing unreliable data. For example, a telemetry frame had to be bracketed by frame sync words and have a valid frame counter number as a condition for processing. All frames in which the corona detector indicated corona or arcing in the p/α detector high voltage supplies were deleted. Occasional bursts of bad data which were detected by checking the frame counter for proper incrementing and the SPECS status indicators for the proper stepping sequence were not processed. Fortunately, the number of such occurrences was small, less than 100 frames in 800 seconds, or about 100,000 frames.

The statistical accuracy of any given measurement depends on three factors. There are the incident particle flux magnitude, the geometric factor of the detector, and the sampling rate, or frame rate of the data encoder. The last factor is an excellent example of how an engineering system influences scientific results in a tightly integrated payload. The average number of counts in a telemetry frame interval is given by the equation:

$$N = \text{Counts/Frame} = \text{Particle Flux} \times \text{Geometric Factor} \times \text{Seconds/Frame} \quad (3-16)$$

The standard deviation S of N is given by:

$$S = \sqrt{N} \quad (\text{Beers, 1957}) \quad (3-17)$$

Thus, as N becomes larger, the statistical percentage error becomes smaller. There is therefore a tradeoff between time

resolution and statistical accuracy. Averaging data over greater and greater numbers of frames decreases the uncertainty in the value of the average flux over the interval, but at the expense of time resolution. As an example, consider that it is desired to calculate the uncertainty in single-frame measurements of particle flux with a detector having a geometric factor of 10^{-3} , which is a value representative of detectors used in the experiment. The percentage uncertainty in a measurement is:

$$\% \text{ Uncertainty} = \frac{\sqrt{N}}{N} \times 100 = 3 \times 10^4 / (\text{flux})^{\frac{1}{2}} \quad (3-18)$$

Thus, for example, a particle flux of 10^9 particles/cm²-sec-steradian can be measured each frame, or every 7.9 milliseconds, with a statistical accuracy of 1%.

CHAPTER 4

PRE-LAUNCH AND POST-LAUNCH AURORAL CONDITIONS AND GROUND PHOTOMETRIC MEASUREMENTS ASSOCIATED WITH THE PROTON-ALPHA EXPERIMENT

A. Choice of Suitable Aurora

The primary launch requirement was the presence of $H\beta$ emission at locations in the sky beneath the trajectory of the payload, indicating the presence of precipitating protons on field lines in the vicinity of the payload trajectory. A ground-based photometric system, located approximately 10 kilometers from the launch site, was used for detection of $H\beta$ emission.

This photometric instrument, known as a "tilting filter photometer", used a $2.0\text{\AA}$ full width-half maximum interference filter centered at $4865\text{\AA}$ to scan the line profile of the Doppler-shifted $H\beta$ emission resulting from the incident protons. The angle between the filter normal and the optical axis of the photometer was varied cyclicly from 0° to 10° with a cam and motor assembly, thus scanning the wavelength range $4865\text{\AA}$ to $4840\text{\AA}$ every 15 seconds.

The remainder of the photometer consisted of a lens behind the filter, a field stop to limit the field of view to 5° full included angle and an E.M.I. type 6094B photomultiplier tube.

Photon pulses from the anode of the tube were amplified, discriminated in amplitude, and the average pulse rate was converted to an analog voltage with a ratemeter circuit. The ratemeter voltage, linearly proportional to the light intensity in the $\text{photons/cm}^2\text{-sec}$ reaching the photomultiplier tube, was recorded on a strip chart recorder along with

timing information, filter position indicator, and data from three other similar photometers. Two of these instruments monitored $\lambda 3914\text{\AA}$ and $\lambda 5577\text{\AA}$ with fixed interference filters, and the remaining instrument was a tilting filter type to monitor $\lambda 5876$ HeI emission. A complete description of the tilting filter type of photometer and method of intensity determination may be found in Eather and Jacka (1966).

In addition to serving as an indicator of satisfactory launch conditions, the ground photometric system was used to measure auroral emissions produced by particles at the payload location throughout the flight. This required determining the location in azimuth and elevation of the point at the 100 km level intersected by the magnetic field line extending up to the location of the payload. The location of the payload as a function of time was taken from a pre-launch nominal trajectory supplied by Goddard Space Flight Center. Tracing of the field line from the payload position to the 100 km level was done with the values of field line inclination and declination of 6.5° and 3° west of north, respectively (Technical Support Section, Churchill Research Range, private communication). Table 2 lists the photometer look angles as a function of time from liftoff.

The values in the foregoing table show the difficulty of performing good ground-based photometric measurements in conjunction with the Javelin sounding rocket down range. The elevation angles quickly become so small that large, uncertain corrections for the Van Rhijn effect and atmospheric extinction are required. In addition, effects of ground albedo and ice crystals in the atmosphere undoubtedly introduce errors at low photometer elevation angles. Eather (private communication) estimated the error in reported

TABLE 2

Photometric Look Angles for Javelin Payload

Fort Churchill, Canada

Flight Azimuth = 70°

<u>Time after Liftoff (sec)</u>	<u>Payload Altitude (km)</u>	<u>Payload Range (km)</u>	<u>Photometric Look Angles</u>	
			<u>Azimuth</u>	<u>Elevation</u>
120	175	60	63	59
150	250	75	59	52
175	325	83	55	50
200	400	100	54	44
250	525	125	52	38
300	625	150	53	33
400	750	200	53	25
500	800	250	55	20
600	750	300	58	15
700	650	350	61	13
800	450	400	65	10
900	200	450	69	9

zenith intensities to be $\pm 10\%$, and an error of at least $\pm 30\%$ for intensities at photometer elevation angles less than 45° .

B. Launch Conditions

The proton-alpha payload was launched on February 9, 1967 at 0016 hours local time (0616 UT) into a post-breakup auroral display extending over the entire northeastern quadrant of the sky. 40 Rayleighs of $H\beta$ emission in the zenith were recorded at the time of launch.

The following section will discuss the auroral activity observed both visually and photometrically on the night of February 8-9, 1967 at Fort Churchill. All times will be given in Central Standard Time (C.S.T. + 6 hrs = UT). Auroral intensities will be reported in Rayleighs if recorded photometrically, or in terms of the International Brightness Coefficient if estimated visually. The IBC scale is logarithmic, with IBC I corresponding to 1 kilorayleigh (Chamberlain, 1961), IBC II corresponding to 10 kilorayleighs and so on. The minimum intensity at $5577\text{\AA}$ detectable by the unaided human eye is 500 to 1000 Rayleighs. Thus, an IBC I aurora is just barely visible to a dark-adapted human observer, if it occurs in structural forms.

Auroral activity of the night of February 8-9, 1967 began rather early in the evening, following a 24 hour period of magnetic disturbances of amplitudes of 50γ - 100γ peak-to-peak (where $1\gamma = 10^{-5}$ gauss) of the north-south and east-west magnetic field components. These magnetic disturbances were recorded by a 3-axis flux-gate magnetometer at Fort Churchill.

Visual aurora was first noted at 1900 hours, appearing as a stable IBC I arc overhead extending from the eastern to western horizon. Over the next two hours, the overhead arc gradually changed into featureless, patchy glows, diminishing in intensity. By 2100 hours, no visual trace remained of the forms overhead. At 2100 hours, an IBC I diffuse arc appeared on the southern horizon at a zenith angle of 60° - 70° . This arc began to move slowly northward at 2130, reached the zenith at 2200, and slowly faded until at 2230 there was no visual aurora to be seen in the entire sky. This uncomfortable state of affairs lasted until 2300 hours, at which time a thin arc of IBC I to II developed in the south approximately 45° in zenith angle. The appearance of this arc signaled the beginning of the auroral sequence known as "breakup".

Motion and intensity of the $H\beta$ emission was monitored with the photometric instrument described in the preceding section. The geographic north-south distribution and intensity of $H\beta$ emission as a function of time is shown in Figure 36. In the period from 1900 to 2100 the zone of $H\beta$ emission gradually moved from north to south. By 2300 hours, the $H\beta$ emission zone was confined to a region in the sky extending from 50° to 70° zenith angle. This region was southward of the thin bright electron-excited arc which appeared at 2300. The $5577\text{\AA}$ emission excited by the incident protons, together with Van Rhijn enhancement made the proton arc faintly visible as a diffuse arc separated from and lying southward of the thin, bright (electron-excited) arc. This situation remained stable for a period of over one hour, extending to 0005 hours. At this time the display in the south suddenly brightened, and began a rapid advance

northward. By 0013 it was clear that auroral breakup was occurring with intense, fast-moving rayed structures in the zenith and auroral spreading to the northern horizon. The countdown was resumed at T-3 minutes at this time, with a 20 second hold at T-90 seconds for a final verification of the presence of H β emission in the expected payload trajectory. Liftoff occurred at 0016.18. At the time of firing, the intense auroral activity had begun to disappear, leaving a stable glow over the entire northeastern sky of intensity IBC I to II. This condition remained until the end of the payload flight at approximately 0032 hours.

C. Payload Performance

The payload performed well in almost every respect. The flight azimuth, planned at 70° was actually 65°. This slight error was compensated for in the photometric look angles by simply subtracting 5° from the precomputed azimuth values (see Table 2). Payload altitude at apogee was 755 kilometers. Nose cone ejection, antenna deployment, and the internal payload timer all functioned as planned. The received signal strength was 10 microvolts or greater throughout the flight, and telemetry data of excellent quality was received.

The high voltage deflection plate supply for the detector p/ α 1 failed sometime between launch and nose cone ejection, and at any rate the supply never came on with the remaining high voltage supplies. All proton-alpha data reported will refer to the detector p/ α 2.

The central axis (spin axis) of the payload was at an angle of 15° with respect to the magnetic field direction.

All detectors from which data was obtained in this report were mounted at 45° to the spin axis, and thus all data is from particles with pitch angles between 25° and 65° .

CHAPTER 5

EXPERIMENTAL RESULTS

A. Energetic Protons and Alpha Particles

This section will discuss the results from the ion spectrometer and the proton-alpha detector. The differential spectrum of ions with $90 \text{ kev} < E_i < 650 \text{ kev}$ and the ratio of the fluxes per unit energy interval of alpha particles with $E_\alpha \approx 200 \text{ kev}$ and protons with $E_p \approx 100 \text{ kev}$ were measured with these two detectors respectively.

Data from the ion spectrometer were initially divided into 50-second segments in order to investigate possible changes in the shape of the ion spectrum during the course of the flight. No statistically significant changes in the spectrum shape of ions with energies between 90 and 650 kev could be detected. The stability of this energetic ion flux is further emphasized by a plot of the integral flux of ions with $E_i > 90 \text{ kev}$ versus time, from the absolute counting rate of the ion spectrometer. Figure 37 is a plot of 6-second averages of this energetic ion flux throughout the flight. As can be seen, during the period from $T + 150$ to $T + 800$ seconds the ion flux in the aforementioned energy range varied by less than a factor of ≈ 25 from the minimum to maximum value. Examination of the data on a shorter time scale of approximately 0.5 seconds did not change this conclusion.

The spectrum of ions with $90 \text{ kev} < E_i < 650 \text{ kev}$ is shown in Figure 38, representing data accumulated over a 10 minute interval from $T + 150$ to $T + 740$ seconds. The data appears reliable, as can be seen from the fact that

deviations from a smooth curve are with the Poisson statistical error limits shown. The ion spectrum from 90 kev to 400 kev can be represented by a power law spectrum of the form:

$$j(E) = j_0 \left(\frac{E}{E_0} \right)^{-n} \text{ ions/cm}^2\text{-sec-ster-ev} \quad (5-1)$$

where $E_0 = 100 \text{ kev}$, $j_0 = 0.8$ and $n = 5.25 \pm .25$.

The departure of the measured ion spectrum from a power law dependence in the energy range 400 to 650 kev was possibly due to contamination by high energy electrons which were able to penetrate the field of the broom magnet or the magnesium detector housing and undergo large-scale scattering in the solid state detector. This conclusion is borne out by examining the pulse height spectrum from the proton-alpha detector during the interval when the high voltage to the deflection plates was turned off. This point will be discussed in detail later. It may well be that the measured spectrum in the 400 kev - 650 kev range is the true ion spectrum, and illustrates the difficulty in trying to force an auroral particle spectrum to fit simple mathematical functions. Whatever the case, the measured spectrum from 400 to 650 kev certainly represents a reliable upper limit to the true ion flux in this energy range.

The proton-alpha detector data, like the ion spectrometer data, were initially divided into 50 second segments to look for temporal changes in the alpha-proton ratio. Again, no significant changes were discovered, and data analysis proceeded on the assumption that the alpha-proton ratio was essentially constant throughout the data

accumulation interval.

Proton-alpha detector data was accumulated over two intervals, $T + 150$ to $T + 663$ seconds and $T + 665$ to $T + 720$ seconds. During the first interval the detector was active, and during the second interval the high voltage to the electrostatic focusing system was turned off by a timer in the payload. Data accumulated during this off interval allowed evaluation of contamination of the primary data from sources such as cosmic radiation and high energy penetrating electrons.

The measured ion spectrum (see Figure 38) was used to construct calculated output pulse height spectra for the proton-alpha detector. The measured ion spectrum represented by the equation

$$j(E) = j_0 (E/E_0)^{-n} \text{ ions/cm}^2\text{-sec-ster-ev} \quad (5-2)$$

was convolved with the energy passband of the electrostatic deflection system and the energy resolution of the solid state detector in order to produce these spectra. Two cases were calculated, the first assuming a pure proton flux and the second assuming a pure alpha particle flux. The spectrum of both particle types was assumed to be the same.

The calculated proton-alpha detector spectra are shown in Figure 39. Also shown is the pulse height spectrum received during the interval in which the high voltage to the electrostatic focusing system was turned off. These data represent the contribution to the primary data due to all external contamination effects. The "protons-only" spectrum is the actual proton contribution to the primary proton-alpha detector spectrum, while the "alpha-particles-

only" spectrum is plotted to an arbitrary scale. The procedure used in actually determining the alpha-proton ratio was to assign an arbitrary scale to the "alpha-particles only" spectrum, and then sum together all three spectra. This procedure was repeated for various values of the alpha particle spectrum scale until the best fit to the experimental data was achieved.

The result of this analysis procedure is shown in Figure 40. The observed proton-alpha detector pulse height spectrum is shown in histogram form, along with calculated spectra representing the cases of alpha-proton ratios of 0.1%, 1.6% and 10% respectively. An alpha-proton ratio of 1.6% was found to be the best fit to the experimental data. The 0.1% and 10% curves demonstrate the "sensitivity" of the detector to various alpha-proton ratios, and also show that a 0.1% alpha-proton ratio was about the minimum detectable, this limit being set by the background contamination. The statistical limits of the alpha-proton ratio were 0.9%-2.3%. Thus, the experiment detected fluxes of alpha particles in an aurora, and measured the ratio of the directional flux of alpha particles per unit energy interval to the directional flux of protons per unit energy interval to be

$$j_{\alpha}/j_p = (1.6 \pm 0.7)\% \quad (5-3)$$

for $E_p \approx 100$ kev and $E_{\alpha} \approx 200$ kev.

The method of data analysis used to derive the alpha-proton ratio increased confidence in the measurement since it was possible to reproduce the experimental data from the measured ion spectrum and the proton-alpha detector energy passbands. However, determination of the alpha-proton ratio did not depend absolutely upon this particular method of analysis. The ratio could have been determined simply by

calculating the ratio of the counting rate at $E = 200$ kev to the counting rate at $E = 100$ kev, or the ratio of the counts in channel 32 to channel 16 of the pulse height spectrum (see Figure 40). This procedure results in a ratio of 1.5 %. The response of the detector to 200 kev protons is only 0.1% of the response to 100 kev protons. This is reflected in the "protons only" curve of Figure 39, showing that the contribution to the data from protons at $E = 200$ kev (channel 32) is two orders of magnitude less than the actual data, so that the counts at $E = 200$ kev must have been due almost entirely to alpha particles. Thus this data analysis method of simply calculating the ratio of the counts accumulated in channels 32 and 16, corresponding to ion energies of 200 kev and 100 kev respectively, results in an alpha-proton ratio nearly equal to the ratio determined by the more involved method reported earlier.

B. Possible Contamination of the Data

Possible sources of proton-alpha 2 data contamination will now be discussed and evaluated. The possible sources were:

- (1) Internal payload noise
- (2) Electrons entering the detector entrance aperture and scattering to the solid state detector
- (3) High energy penetrating radiation
- (4) Proton pulse pile-up
- (5) A large nearly monoenergetic flux of 200 kev protons which would have been interpreted as alpha particles.

The effects of payload noise were checked prior to flight and found to be non-existent. The electron rejection efficiency of the electrostatic focusing system was measured in the laboratory by placing the detector in an electron beam with the electron energy set at the peak of the pass-band. The rejection ratio was computed by measuring the fluxes of electrons reaching the position of the solid state detector for both positive and negative values of the deflection voltage. This rejection ratio was measured to be 10^{-4} :1.

Although laboratory measurements are certainly useful in establishing confidence in a detector, it is rather difficult to simulate all possible flight conditions. An in-flight check of data contamination was provided by turning off the deflection plate voltage of the proton-alpha detector for approximately one minute from T + 665 to T + 720 seconds. In this manner, a direct in-flight evaluation of all contamination effects except proton pulse pile-up was accomplished. Figure 39 shows the data received during this off period. Comparison of the pulse height spectra of Figures 39 and 40 show that the contamination in the energy passbands of protons and alpha particles is less than 1%.

Proton pulse pile-up is an effect whereby false pulses which are interpreted as alpha-particle pulses at 200 kev are caused by the arrival at the solid state detector of two 100 kev protons with a time difference shorter than the resolving time of the electronics. The rate of n-fold coincidences may be calculated according to the formula below from Fillius (1963):

$$R_n = \nu \left[1 - e^{-\nu\tau} \left(1 + \nu\tau + \frac{(\nu\tau)^2}{2!} + \dots + \frac{(\nu\tau)^{n-2}}{(n-2)!} \right) \right] \quad (5-4)$$

where R_n is the rate of n -fold coincidences, ν is the average rate of arrival of particles, and τ is the resolving time of the instruments. For double coincidences the formula reduces to:

$$R_n = \nu(1 - e^{-\nu\tau}) \approx \tau\nu^2 \quad (5-5)$$

The average count rate due to protons in proton-alpha 2 was ≈ 100 counts/second, and was never greater than 300 counts/sec. The resolving time of the electronics was 1.0 micro-second. Thus the accidental coincidence rate was:

$$R_n = 10^{-6} \times (10^2)^2 = 10^{-2} \quad (5-6)$$

Thus the ratio of the accidental coincidence rate to the proton pulse rate was 10^{-4} , which of course sets a theoretical lower limit to the detectable alpha particle pulse level. Since the alpha particle flux was measured to be 2% of the proton flux, it is seen that proton pulse pile-up made no significant contribution to contamination of the alpha particle data.

There remains the possibility that the counts in the alpha particle channels of proton-alpha 2 ($\sim$ channel 32) were actually due to a large flux of 200 kev protons which were not detected in the spectrum of ions (see Figure 38). The following analysis will show to a high degree of certainty that this was indeed not the case.

Suppose for the sake of argument that the counts in channel 32 were due entirely to 200 kev protons. The

response of the detector to 200 kev protons was about .001 times the response to 100 kev protons (see Figure 23), and thus it would have been necessary for the flux of 200 kev protons to be 16 times the flux of 100 kev protons in order to produce a counting rate at 200 kev of 1.6% of the counting rate at 100 kev. This condition would have had to exist during the entire 10 minute data accumulation interval. The flux of 200 kev ions (Figure 38) was $345 \text{ ions/cm}^2\text{-ster-sec-10 kev}$ corresponding to 333 actual counts in channel 20 of the ion spectrometer. The standard deviation of this number is $\sqrt{333}$ or 18 counts. On the other hand, the presence of a sufficient flux of 200 kev protons to account for the counts in the alpha particle channels of proton-alpha 2 would have resulted in about 2×10^5 counts in channel 20 of the ion spectrometer, compared with 333 counts actually observed. Speaking in statistical terms, this would require that the number of counts in channel 20 be about 10^4 standard deviations higher than the observed value, and thus the probability of this having occurred, and hence the probability of the alpha particle flux being in fact due to a proton flux is indeed vanishingly small.

C. Photometric Search for Helium Emissions

The rocket-borne search for alpha particles in the auroral flux was supplemented by a photometric search for the $5876\text{\AA}$ line of HeI. R. H. Eather used the ground photometric system described earlier to make a systematic search for the presence of this emission, both during the flight of the payload and at other times during November 1966 and February and March 1967 (Eather, 1968). An emission line

profile located a few Å to the blue side of 5876Å was detected. This emission feature showed no correlation with auroral activity, and always exhibited a strong Van Rhijn effect. This suggested that the emission was an airglow feature. A final definitive test was made by comparing the line profiles for the two cases when the photometer was pointed at the zenith and the horizon. Figure 41 shows the zenith and horizon profiles of the emission near 5876Å. The lack of any systematic difference in the profiles indicates that the emission was not due to light emitted by auroral alpha particles incident on the top of the atmosphere. It was concluded that the emission feature was part of the 8-2 hydroxyl system, and the emission was also seen as a regular feature of the mid-latitude airglow having been detected at Houston, Texas in May 1967.

Eather (1968) estimated the upper limit of 5876Å emission from auroral alpha particles to be 1 Rayleigh, giving an upper limit to the $I_{5876}/I_{H\beta}$ ratio of approximately 0.02.

Upper limits to the j_{α}/j_p ratio were calculated assuming an average proton energy of 15 kev and for the following three cases:

- (a) Alpha particles and protons having the same average energy
- (b) Alpha particles having twice the average energy as the protons
- (c) Alpha particles and protons having the same average velocity.

For case (a), $j_{\alpha}/j_p < .06$, case (b), $j_{\alpha}/j_p < .02$, and for case (c), $j_{\alpha}/j_p < .007$.

The measured alpha-proton ratio of 1.6% for alpha particles and protons of 100 kev per unit charge, when combined with the analysis assumption that both ions have the same form of energy spectrum for $E > 100$ kev, leads to the implication that the ratio of differential fluxes of alpha particles and protons at the same energy (e.g. 100 kev) was $(1.6 \times 2^{5.2}) \sim 50\%$. There is no objection to this suggestion per se, but if such a ratio also applied at lower energies, then the theoretical $\lambda 5876$ HeI intensity according to Eather's (1966) calculations would be ~ 30 R. This intensity would have been readily detectable. However, as was emphasized earlier, the analysis leading to the ratio of 1.6% is not at all sensitive to the assumed alpha energy spectrum of E^{-5} ; this was just a convenient analysis assumption based only on the high-energy (≥ 100 kev) data. The fact that no He optical emission was detected in fact gives the additional valuable information that the ratio of alpha flux to proton flux at the same energy must decrease at lower energies and that this E^{-5} law does not persist at lower energies, as indeed is seen in the spectrum of protons from 500 ev to 650 kev, as shown in Figure 43 and discussed in section E following.

If forced to make a "best-estimate guess" at the low-energy alpha spectrum, it is preferable to postulate that the alpha particle flux at $E_{\alpha} = 2E$ remains at about 1.6% of the proton flux at $E_p = E$. Pursuing this postulate and using the proton spectrum of Figure 43, a theoretical "guess" at the total alpha spectrum was constructed, and convolved with the $\lambda 5876$ HeI production data (Eather, 1966) to calculate the expected helium intensity. This resulted in a value of 1.9 ± 0.5 R, which should be compared with the

experimental upper limit of 1 R. In view of the gross assumptions involved in the calculation, it is not felt any inconsistency exists.

D. Comparison of Auroral Alpha-Proton Data with Solar-Wind Alpha-Proton Densities

The alpha-proton ratio of 2% reported here may seem small compared to the solar-wind value which is most often assumed to be 10%. As pointed out in Chapter 1, the solar-wind alpha-proton ratio is not constant at a value of 10%. This point is illustrated vividly by Figure 42, a plot of the frequency of occurrence of solar-wind alpha-proton density ratios from Hundhausen, et al., (1967). This Figure shows that a solar-wind alpha-proton density ratio of 10% is the exception rather than the rule, and in fact the most probable value is 2-3%.

Conjecture as to the solar-wind ratio at the time of the auroral experimental measurement is unnecessary, since data were available from Vela 3a and 3b (Bame, private communication) and Pioneer 7 (Wolfe, private communication).

The Vela data reported a solar-wind alpha-proton density ratio of 5% - 10%, while the Pioneer 7 data showed 1.8%. Recalling the auroral zone value measured in this experiment of $(1.6 \pm .7)\%$, it is seen that this value is within a factor of 3 of solar-wind ratios measured simultaneously by other experimenters.

This comparison between solar-wind and auroral alpha-proton ratios has been made between the density ratio in the solar wind and the flux ratio at the same energy per unit charge in the auroral flux (i.e. 100 kev protons and

200 kev alpha particles). Comparison in this manner tacitly assumes that the acceleration mechanism responsible for accelerating ions to auroral energies is quasi-electrostatic in nature, so that if the mechanism has a certain probability of accelerating a proton to an energy E , it has the same probability of accelerating an alpha particle to an energy $2E$. In fact, an additional correction factor to the auroral flux ratio enters because of the velocity ratio of an alpha particle with $E_{\alpha} = 2E$ to a proton with $E_p = E$, which is $v_{\alpha}/v_p = .707$, so that auroral alpha-proton flux ratios should be multiplied by 1.4 for comparison with solar-wind densities, under the assumptions stated above. However, this factor of 1.4 was less than the other experimental uncertainties, and so was neglected in this analysis.

The foregoing comparison suggests that auroral fluxes in the energy range considered (~ 100 kev) are of solar origin, and in particular they were originally a component of the solar wind in the vicinity of the magnetosphere. The upper limit of 2×10^{-4} for the $\text{He}^{++}/\text{H}^+$ ratio in the night time magnetosphere between 1000 and 20,000 kilometers deduced from the data of Taylor, et al., (1965) shows that the energetic particle fluxes could not have originated in this region. The conclusion is that the acceleration process responsible for the appearance in auroral fluxes of ions with energies on the order of 100 kev is located at an altitude of greater than 20,000 kilometers, and that these ions are of solar origin. Further implications of this auroral alpha particle experimental measurement will be discussed in the concluding chapter.

E. Comparison of Measured and Predicted H β Intensities

In Chapter 2 the mathematical procedure for calculating production rates of spectral emissions resulting from ion-atmosphere interactions was outlined, and results for proton and alpha particle impact from calculations of Chamberlain (1961) and Eather (1967) were shown. In this section the measured proton spectrum and the photon production curve of Eather (1967) (see Figure 12) will be used to predict an H β intensity, and this predicted intensity will be compared with the actual intensity measured by the ground-based photometric apparatus.

The predicted H β intensity is calculated from a proton spectrum and the photon production curve in the following manner. Let $j(E, \alpha)$ be the incident differential proton energy spectrum in units of protons/cm²-sec-ster-ev. Let $P(E)$ be the photon production/proton. Then:

$$H\beta(\text{Rayleighs}) = \frac{1}{10^6} \int_{E=0}^{\infty} \int_{\alpha=0}^{\pi/2} j(E, \alpha) P(E) 2\pi \sin\alpha dE d\alpha \quad (5-7)$$

If pitch angle isotropy is assumed, then:

$$H\beta(\text{Rayleighs}) = \frac{2\pi}{10^6} \int_{E=0}^{\infty} j(E) P(E) dE \quad (5-8)$$

In practice, the integral can be replaced by a numerical summation, and evaluation can proceed in a straightforward manner.

Data on low-energy (500 ev - 50 kev) protons were obtained from SPECS, and combined with the high energy proton data from the ion spectrometer to produce the proton spectrum for $500 \text{ ev} < E_p < 650 \text{ kev}$ as shown in Figure 43.

The alpha particle contribution as measured by the proton-alpha detector was subtracted from the ion spectrum in order to produce the high energy portion of the total proton spectrum. The time interval of this data was $T + 260$ to $T + 280$ seconds, a time chosen such that the field lines through the rocket trajectory were within the photometer's field of view at the 100 kilometer level.

The decreased efficiency of the Channeltrons in SPECS to low energy protons made it necessary to make considerable corrections in order to obtain flux values below ~ 1 kev. These corrections were made using data from Frank (1965b). The dominant error in the low energy proton spectrum arises from errors in this correction process and this is the error bar shown. The Poissonian error was negligible.

The upper and lower limits of the $H\beta$ intensity, corresponding to the upper and lower limits of the photon production curve as discussed in Chapter 2 were calculated to be

$$H\beta(\text{max}) = 105 \pm 30 \text{ Rayleighs}$$

$$H\beta(\text{min}) = 35 \pm 10 \text{ Rayleighs.}$$

The $H\beta$ intensity measured by the ground photometer was 46 ± 5 Rayleighs. Thus the measured $H\beta$ intensity lies between the upper and lower limits of the calculated intensity. The present data indicate that the contribution to the total photon production rate from neutral collisional excitation is too high by a factor of approximately 4, or that the total photon production function is too high by a factor of 2. Nonetheless, the data show that the photon production

rates calculated by Eather (1967) are reliable upper and lower limits to the actual values.

The agreement between the calculated and measured H β intensities is much better than in previously conducted proton flux-hydrogen emission coordinated experiments. For example, McIlwain (1960) measured protons in the energy range 80 - 300 kev with a rocket-borne detector and reported that the proton flux was represented by an integral spectrum of the form:

$$J(>E) = 2.5 \times 10^6 \exp\left(-\frac{E(\text{kev})}{30}\right) \text{ protons/cm}^2\text{-sec-ster} \quad (5-9)$$

The measured H β intensity was 60 Rayleighs. Converting this spectrum to a differential spectrum and calculating the expected H β intensity results in a maximum value of 35 Rayleighs. However, as pointed out by McIlwain (1960) since he measured only high-energy protons while most of the light results from low-energy protons, even this agreement is surprisingly good.

Romick and Sharp (1967) reported simultaneous measurements of protons with $E > 21$ kev and ground-based measurements of H α . The measured H α intensity was 280 Rayleighs, while the theoretical intensity calculated by the above authors from the extrapolated proton spectrum and the photon production curve of Eather (1967) was only 64 Rayleighs.

The discrepancies between calculated and measured hydrogen emission intensities were probably due to a combination of errors in measured hydrogen emission and errors in the proton fluxes used in the calculations. With proton energy spectra characterized by e-folding energies of 15 to

30 kev as reported by these investigators, over 75% of the hydrogen emission is due to protons in the energy range 1 to 10 kev. This spectral region was not measured directly in either case, but rather flux values were obtained by extrapolation of measurements at higher energies, which extrapolation could be justified in no way whatever. In this study the complete proton spectral range was measured, and very sensitive and accurate photometric techniques were used directly under the zone of the actual proton precipitation.

F. Morphology of Proton and Electron Precipitation

The morphology of the auroral activity on the night of February 8-9, 1967 has been discussed in Chapter 4. The important feature to recall is that from early evening on up to just prior to breakup, the zones of electron and proton precipitation were separated in latitude. The maximum of the proton precipitation zone was always equatorward of the maximum of the electron precipitation zone. In particular, stable proton and electron arcs existed on the southern, or equatorward horizon for approximately 1 hour prior to breakup, and these two arcs were clearly distinguishable visually. This behavior of proton and electron precipitation prior to breakup is very typical, agreeing in general character with morphology reported by Eather and Jacka (1966). This separation of proton and electron precipitation zones observed photometrically and visually has been confirmed by satellite observations. Figure 44 from Evans (1965) shows proton and electron precipitation data from detectors on board a polar-orbiting satellite for a

northbound pass over the northern night-side auroral zone. The detector responses are proportional to the total energy deposited by particles above the indicated thresholds. These data show that for this event the maximum in the proton and electron precipitation zones are separated by approximately 1° in latitude, a value typical of separations observed photometrically (Eather, private communication). It is obvious that a plot of the ratio of proton to electron energy deposition versus latitude would show a clearly defined variation of approximately a factor of 10 over a latitude range of approximately 3 degrees.

On the night of the experiment reported here, the zones of proton and electron precipitation appeared by photometric observation to merge at the onset of breakup and then to spread uniformly and homogeneously over the entire northeastern sky. As pointed out in Chapter 4, however, there were large uncertainties in the photometric measurements at large zenith angles due to uncertain corrections for Van Rhijn enhancement and atmospheric extinction. The Javelin payload, however, by virtue of its downrange velocity of about 0.6 kilometers/second, its long flight time (900 seconds), and its flight azimuth of 65 degrees crossed L-shells from $L = 9.0$ to $L = 11.1$, corresponding to a range of invariant latitude Λ of 70.5° to 72.5° (invariant latitude is defined by the relation $\cos^2 \Lambda = 1/L$). Thus regions not accessible to accurate photometric observations were readily accessible to the particle detectors on board the payload, and hence a survey of the ratio of proton energy deposition versus electron energy deposition as a function of latitude was made.

The ratios of proton to electron energy deposition for particles with $0.5 < E < 30$ kev is shown in Figure 45. The data are plotted as a function of L value and invariant latitude Λ . There is a possible tendency for the ratio to increase slightly at higher L values, but this may be due to temporal changes. There is however, no systematic change of the proton-electron energy deposition ratio over this latitude range of 2 degrees, and this is to be compared with the character of proton and electron precipitation prior to breakup.

This study therefore confirms the photometric observation that prior to breakup the zones of electron and proton precipitation are typically distinctly separated, and that typical post-breakup conditions find that these zones merge into a zone of nearly homogeneous proton and electron precipitation.

G. Summary of Experimental Results

The alpha-proton ratio experiment showed that the ratio of the flux of alpha particles with $E \approx 200$ kev to the flux of protons with $E \approx 100$ kev was approximately 2%, and that this ratio agrees within a factor of 3 with the alpha-proton ratio measured simultaneously in the solar wind. Comparison of the theoretical intensity of $H\beta$ emission calculated from the measured proton flux and the photon production rates of Eather (1967) to the $H\beta$ intensity measured by a ground-based photometric instrument have shown the validity of the photon production rates. Finally, the morphological study of proton and electron precipitation has indicated the swift and total merging of zones of

proton and electron precipitation at the occurrence of auroral breakup. The implications of these various experimental results will be discussed in the following, and concluding chapter.

CHAPTER 6

GENERAL DISCUSSION AND CONCLUSIONS

The proton-alpha experiment measured fluxes of auroral alpha particles and showed that the ratio of alpha particle flux to proton flux was $\approx 2\%$ for ions with energies of a few hundred kev. This ratio was shown to be nearly equal to the solar-wind alpha-proton density ratio, and at least two orders of magnitude greater than the alpha-proton ratio in the night magnetosphere between 100 and 20,000 kilometers altitude. Thus the experimental data is consistent with the proposition that auroral ions of $E > 100$ kev were originally components of the solar wind, and that they were accelerated to auroral energies at altitudes greater than 20,000 kilometers.

The possibility remains open that lower energy auroral particles result from acceleration processes in the upper ionosphere. If this were the case, detectable fluxes of He^+ ions would be present. The proton-alpha detector was unable to distinguish between protons and He^+ ions, and so this question remains unresolved.

The measurements of Taylor, et al., (1965) show the He^+/He ratio in the night ionosphere to be approximately 1%, while the He^+/H^+ ratio in the solar wind is presumed to be negligibly small. Thus, no matter what the source of energetic auroral ions was, any possible contribution to the proton-sensitive channels of the proton-alpha detector from He^+ ions would have been insignificant and the basic experimental result remains unaffected.

Recalling the comparison of measured and calculated $\text{H}\beta$ intensities, it was shown in that comparison that the

photon production data of Eather (1967) were reliable upper and lower limits to the true photon production rate. This conclusion naturally assumes that the rocket at an altitude of approximately 500 kilometers was indeed seeing all of the protons which ultimately precipitated into the atmosphere, or in other words that there was no additional source of 1-10 kev protons between 100 and 500 kilometers. If, on the other hand, the photon production rates are accepted a priori as valid, then the chain of logic can be inverted to argue against the existence of a dominating low-altitude acceleration mechanism. The measured H β intensity was 46 Rayleighs. Therefore, at least 75% of the measured H β emission is accounted for by the protons measured at 500 kilometers.

From the foregoing discussion it is obvious that an experimental search to measure fluxes of protons, He⁺ ions and alpha particles with energies from 1 to 100 kev and flux ratios ranging from 10⁻⁴:1 to 1:1 would be valuable for resolving the question of ionospheric acceleration mechanisms. If it were established that auroral particle fluxes of all energies were of solar origin exclusively, and if photometric instruments could be developed which were capable of quantitative measurement of weak HeI 5876Å emissions in the presence of the hydroxyl airglow contamination, then the solar-wind alpha-proton ratio could be monitored by routine ground-based auroral zone photometric measurements. To go a step further, continuous monitoring of the solar-wind alpha-proton ratio by in situ satellite measurements and of auroral helium emissions could determine the time lag between changes in the solar-wind and auroral-

zone alpha-proton ratios, and thus offer valuable information about transport of particles from the solar wind to the auroral zones. This possibility is within the state of the art, requiring a fortuitous combination of weak hydroxyl airglow and a large alpha-proton ratio in the solar wind.

The alpha-proton ratio experiment and the hydrogen emission comparison experiment have demonstrated two features of importance to theories of auroral acceleration processes.

First, the results are consistent with the source of energetic auroral ions being the solar wind and further, that these ions were accelerated by some processes at altitudes above approximately 20,000 kilometers. Second, the photometric and proton data have argued against the existence of low-altitude acceleration mechanisms, hence implying that the above statements pertaining to energetic ions also are true for the lower energy ions as well.

These observations are therefore consistent with the various open-tail or long-tail magnetospheric theories (Dessler, 1964; Axford, 1967; Speiser, 1965) which all involve direct injection of solar-wind plasma into the magnetosphere and subsequent acceleration of some of the solar-wind particles to auroral energies. These theories predict an auroral alpha-proton ratio equal to the solar-wind alpha-proton ratio, and this experiment has found this to be the case.

Although the experiment has indicated the solar origin of energetic auroral ions, it has not ruled out the possibility of storage and convection of auroral particles in the magnetosphere prior to precipitation, such as postulated by

Axford and Hines (1967). In Chapter 1 it was shown that a storage time on the order of years would be required to significantly decrease the alpha-proton ratio in such a stored plasma. In this context, as mentioned earlier, ground-based monitoring of auroral helium emissions coupled with satellite monitoring of the solar-wind alpha-proton ratio will make it possible to measure any storage or transport times.

The proton-alpha payload data were used to demonstrate the spatial merging of zones of electron and proton precipitation at the onset of auroral breakup. This was shown to be in stark contrast to the precipitation pattern prior to breakup, when the zones of electron and proton precipitation were separated by approximately 1 degree in latitude, or about 100 kilometers along a line running roughly north-south.

Taylor and Hones (1965) calculated the adiabatic motions of magnetospheric particles, using a model magnetosphere including an extended tail, a neutral sheet, and an electric field system derived from interaction of the solar wind with the outer magnetosphere, the rotation of the earth, and ionospheric current systems. The electric field system was mapped throughout the magnetosphere by assuming that the magnetic field lines were equipotentials, i.e. by assuming "frozen-in" flux.

Particle trajectories in this model of electric and magnetic fields were calculated assuming conservation of total particle energy,

$$K = W + qV$$

(6-1)

and of the first two adiabatic invariants

$$\mu = W_{\perp}/B \quad (6-2)$$

and

$$J = \oint p_{\parallel} ds \quad (6-3)$$

The calculations were used to predict the gross features of auroral particle precipitation. In particular, the calculations predict that the zones of proton and electron precipitation will be separated in the evening prior to midnight, with the proton zone equatorward of the electron zone with a separation of 100 to 500 kilometers, in very good agreement with observations. Although the adiabatic theory of Taylor and Hones (1965) is remarkably successful in predicting features of quiescent aurora, it does not predict either the occurrence of auroral breakup or the merging of the zones of proton and electron precipitation. It is interesting to speculate whether by removing the restriction of frozen-in-flux the adiabatic theory can account for breakup and zone merging, or if indeed breakup is the result of the sudden and sporadic appearance of a completely different non-adiabatic acceleration process such as field line merging in the neutral sheet as proposed by Axford (1964, 1967) and Speiser (1965).

A measurement of the spectrum of precipitating protons along with a measurement of the height profile of hydrogen emission in the evening proton precipitation zone would offer valuable information in two separate contexts. First, it would be useful to compare the proton spectrum during the stable evening proton arc with the proton spectrum observed just after breakup, as was done in this experiment.

This would help answer the question posed in the preceding paragraph concerning the acceleration mechanisms responsible for auroral particle precipitation at these two times. Second, the hydrogen emission height profile could be compared with theoretical profiles calculated from the measured proton spectrum and model atmospheres for various ionospheric temperatures, and thus allow determination of the atmospheric heating caused by auroral protons.

The conclusions presented in this chapter have indicated the solar origin of auroral particles. The experiments proposed in this chapter would hopefully add more information toward solution of the problem of the history of particles between the solar wind and the auroral zones.

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FIGURE CAPTIONS

- Figure 1: Effect on a dipole magnetic field configuration by a perfectly conducting thin plane sheet. The equivalent image dipole is denoted by the arrow. This is an approximation to the distortion of the earth's magnetic field by an oncoming stream of solar particles (Chapman and Ferraro, 1931).
- Figure 2: The magnetospheric convection diagram of Axford and Hines (1961). The diagram shows the postulated flow pattern resulting from a superposition of a gross convection pattern and the rotation of the earth.
- Figure 3: Neutral-sheet configuration and particle trajectories according to the model of Speiser (1965). Magnetic merging in the neutral sheet produces a transverse electric field which is responsible for particle acceleration.
- Figure 4: Radiative-recombination coefficient data as a function of electron density and temperature for H^+ and He^{++} ions.
- Figure 5: He^+ and H^+ concentrations measured in the daytime ionosphere to an altitude of 940 kilometers (from Taylor, et al., 1963).
- Figure 6: He^+ and H^+ concentrations in the nighttime magnetosphere at altitudes between 1000 and 26,000 kilometers (from Taylor, et al., 1965). The ion number densities are proportional to the currents shown.

Figure 7: Change in the charge-state composition of a He^{++} beam as it penetrates down into the atmosphere. The beam was initially pure He^{++} with $E = 50$ kev at an altitude of 1000 kilometers. Of particular interest are the drastic changes in the beam component fractions He , He^+ and He^{++} at altitudes between 400 and 200 kilometers, and the attainment of equilibrium below 200 km.

Figure 8: Same as Figure 7, except the initial beam energy is 200 kev, which was the energy of the alpha particles detected in the experiment. Figures 7 and 8 clearly show the necessity of alpha particle measurements at altitudes greater than 400 kilometers.

Figure 9: Photon production for $\text{H}\alpha$, $\text{H}\beta$ and $\text{Ly}\alpha$ per proton-atmosphere-cm. as a function of proton range in atmosphere-cm., calculated by Chamberlain (1961).

Figure 10: Photon production of $\text{H}\beta$ per proton atmosphere-cm. versus proton energy, calculated by Eather (1967). The two curves represent the contribution due respectively to electron capture (charge exchange) only and due to electron capture plus neutral collisional excitation.

Figure 11: Photon production of $\text{HeI } 5876\text{\AA}$ per He-atmosphere-cm. versus He energy, calculated by Eather (1967).

Figure 12: Total $\text{H}\beta$ photon production per incident proton versus initial proton energy (from Eather, 1967).

Figure 13: Horizon and zenith line profiles of auroral hydrogen emission from various experimenters indicated on the figure. The ordinate is the velocity of the emitting hydrogen atom relative to the observer's line of sight direction. The Doppler broadening of the horizon profiles and the Doppler shifting and broadening of the zenith profiles is clearly seen (from Eather, (1967)).

Figure 14: Sketch showing the particle types and energy ranges detected by the various detectors on the Proton-Alpha Javelin Payload.

Figure 15: Dimensional sketch of a possible detector using electrostatic and magnetic fields to separate protons and alpha particles into respective ionic beams.

Figure 16: Schematic diagram of a solid state detector with associated charge-sensitive amplifier. The charge-sensitive amplifier is represented by an operational amplifier along with a feedback capacitor C_f . Typical circuit values are shown.

Figure 17: Theoretical output pulse-height spectrum of the proton-alpha detector, assuming proton and alpha particle spectra such that $dj/dE = \text{Constant}$, and a ratio of alpha particle flux to proton flux per unit energy interval of 0.1:1.

Figure 18: Dimensional sketch of the proton-alpha detector. The sketch shows the electrostatic focusing system and the solid-state detector.

Figure 19: Photograph of the unassembled components of the proton-alpha detector, showing the deflection and focusing assembly, the solid state detector and amplifier section, and the amplifier section housing.

Figure 20: Photograph of the assembled proton-alpha detector.

Figure 21: Pulse-height analyzer channel number versus particle energy calibration for the solid state detector-PHA system of the proton-alpha detector.

Figure 22: Relative response versus angle of particle beam to central axis for the electrostatic focusing system of the proton alpha detector. The curve is for fixed deflection voltage and beam energy. From this curve, a relative energy response function $R(E)$ was calculated using the equation:

$$R(E) = \int_0^{\pi/2} R(E, \theta) 2\pi \sin\theta d\theta$$

Figure 23: Energy response function $R(E)$ versus E for the proton-alpha detector. This curve was plotted by using points calculated from curves similar to Figure 22 for various particle beam energies.

Figure 24: Angular response function for the ion spectrometer. The angular acceptance in steradians was calculated from this curve using the formula

$$\Omega = 2\pi(1 - \cos\theta/2)$$

where θ is the full width in degrees at half height of the angular response curve.

- Figure 25: Photograph of the unassembled components of the ion spectrometer.
- Figure 26: Photograph of the assembled ion spectrometer.
- Figure 27: Diagram of the detector section of SPECS, showing the deflection plates, the five 270° channeltrons, and the funnel channeltron, from O'Brien, et al., (1967).
- Figure 28: Sketch of the energy passbands of SPECS, for all six channeltrons at the three decade values of the deflection plate voltage, from O'Brien, et al., (1967).
- Figure 29: Photograph of the assembled Proton-Alpha Javelin Payload.
- Figure 30: Block diagram of the electronic circuitry of the payload, showing the interrelations between the scientific detectors, the pulse-height-analysis system, and the digital data encoder.
- Figure 31: PCM digital data format of the Proton-Alpha Javelin Payload.
- Figure 32: Illustration of non-return-to-zero (NRZ) and Biphasic, or Manchester binary code types.
- Figure 33: Experimental test apparatus for measuring bit error probability of the data transmission link as a function of transmitter carrier average deviation and signal strength at the receiver terminals.

- Figure 34: Plot of bit error probability (BEP) versus average carrier deviation for a receiver signal strength of 1 microvolt.
- Figure 35: Plot of bit error probability versus signal strength at the receiver for an average carrier deviation of 90 kilocycles.
- Figure 36: North-South meridian plots of the $H\beta$ intensity during the night of February 8-9, 1967 at Fort Churchill. Note the north-to-south movement of the $H\beta$ emission during the early evening and the spreading of the zone from the south to the entire sky at breakup at 0040 hours.
- Figure 37: Flux of ions with $E_i > 90$ kev versus time after launch.
- Figure 38: Differential spectrum of ions with $90 \text{ kev} < E_i < 650 \text{ kev}$ measured by the ion spectrometer.
- Figure 39: Theoretical spectra of the proton-alpha detector, obtained by using the ion spectrum shown in Figure 38 and the proton and alpha particle energy passbands of the proton-alpha detector. Details of the derivation of these spectra are found in the text. Also shown is the background spectrum measured during the interval when the electrostatic deflection voltage of the proton-alpha detector was turned off.
- Figure 40: Data from the proton-alpha detector, shown in histogram form. The dashed curves result from summing the three curves of Figure 39 for the various indicated assumed alpha-proton ratios.

Figure 41: Integrated spectral sums over 60 scans of an emission feature near $5876\text{\AA}$, compared with the scan of a He spectral lamp. The magnetic horizon scan has been normalized to the same peak intensity as the magnetic zenith profile (from Eather, (1968)).

Figure 42: Vela 3 measurements of the relative frequency of occurrence of solar-wind alpha-proton ratios (from Hundhausen, et al., 1967).

Figure 43: Differential spectrum of protons with $500\text{ ev} < E_p < 650\text{ kev}$ for the period $T + 260$ to $T + 280$ seconds. This spectrum combines data from SPECS and the ion spectrometer.

Figure 44: Satellite observation of separated zones of electron and proton precipitation in the north night auroral zones (from Evans, 1965).

Figure 45: Proton-Alpha Javelin Payload observations of the ratio of proton to electron energy deposition as a function of L value and invariant latitude Λ . The data show no significant systematic shift in the ratio with L value or Λ , in comparison with the data shown in Figure 44.

FIGURE 1

FIGURE 2

$B = b \ln \hat{x} - \frac{x}{d} \hat{y}$ in the sheet
 B is uniform outside the sheet
 $E = -\alpha \hat{z}$

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

201350-A

FIGURE 7

201350

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

FIGURE 13

PARTICLE TYPES & ENERGIES MEASURED BY PROTON-ALPHA PAYLOAD DETECTORS

201347

FIGURE 14

MODEL DETECTOR FOR DETECTION OF
PROTONS & ALPHA PARTICLES

FIGURE 15

SCHEMATIC SOLID STATE DETECTOR
AND PREAMPLIFIER

FIGURE 16

FIGURE 17

FIGURE 18

FIGURE 19

PROTON-ALPHA 1

FIGURE 20

FIGURE 21

201360-D

FIGURE 22

ENERGY PASSBAND OF P/α 2

201360-B

FIGURE 23

201360-8

FIGURE 24

PROTON SPECT.

FIGURE 25

FIGURE 26

FIGURE 27

ENERGY PASSBANDS OF "SPECS"

PARTICLE ENERGY (kev)

P54117

FIGURE 28

FIGURE 29

PROTON-ALPHA JAVELIN PAYLOAD
BLOCK DIAGRAM

201061

FIGURE 30

P/α JAVELIN TELEMETRY FORMAT

1 2 3 4 5 6 7

FRAME SYNC	FRAME COUNT	MAGNETOMETER	PROTON SPEC. COUNTS	PROTON SPEC. P.H.A.	P/α 1 COUNTS	P/α 1 P.H.A.	P/α 2 COUNTS	P/α 2 P.H.A.	SID STATUS	SPEC. STATUS
------------	-------------	--------------	---------------------	---------------------	--------------	--------------	--------------	--------------	------------	--------------

8 9 10 11 12 13 14

P/α 1 LOWER WINDOW	P/α 1 UPPER WINDOW	P/α 2 LOWER WINDOW	P/α 2 UPPER WINDOW	CORONA	ANALOG MPX	G. M. 8001	SPEC. CONTINUOUS CHANNEL	SPEC. SWITCHING CHANNEL	S. I. D.
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21.6 Kc. BIT RATE
12 BITS/WORD
14 WORDS/FRAME
128.5 FRAMES/SEC.

P 54263

FIGURE 31

**ILLUSTRATION OF NRZ AND
MANCHESTER BINARY DATA CODES**

201360-6

FIGURE 32

**APPARATUS FOR PREDICTING BIT ERROR
PROBABILITY OF DATA CHANNEL**

201360-F

FIGURE 33

201348 - 8

FIGURE 34

BIT ERROR PROBABILITY
VERSUS SIGNAL LEVEL

201348-C

FIGURE 35

FIG.
H β INTENSITIES FOR FEB 8-9, 1967
FORT CHURCHILL, MAN., CANADA

201066

FIGURE 36

201351

FIGURE 37

FIGURE 38

FIGURE 39

FIGURE 40

FIGURE 41

FIGURE 42

28359

FIGURE 43

FIGURE 44

201387

FIGURE 45