An in situ measurement of charged mesospheric dust during a sporadic atom layer event

Lynette Jean Gelinas
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An in situ measurement of charged mesospheric dust during a sporadic atom layer event

Abstract
In this thesis we discuss the results of the Sudden Atom Layers (SAL) sounding rocket, launched from Puerto Rico the evening of February 19, 1998, as part of the Coqui II sounding rocket campaign. A charged dust detector was constructed and flown on the Sudden Atom Layers (SAL) sounding rocket. The existence of charged dust population has implications for many upper atmospheric processes, including the formation of sporadic atom layers (Na's), thin layers of neutral atomic metal which form in the Earth's mesosphere. In particular we focus on the interesting results from the charged dust experiment and the electric field measurement.

The dust detector, a sensitive Faraday cup, used a synchronous detection method to measure a limited mass range of charged dust. Other instruments on the SAL payload measured the in-situ electric fields, plasma density and neutral sodium density. Ground measurements taken at Arecibo confirmed the presence of a double sporadic sodium layer and a sporadic E layer at the time of the rocket launch. These layers were also observed in-situ. The dust detector measured a broad layer of positively charged dust (≈ 20 cm⁻³) in the vicinity of both the sporadic sodium and sporadic E layers. This charged dust experiment has provided the first observation of charged meteoric dust in the tropical mesosphere.

While the rocket data is not conclusive evidence of a correlation between mesospheric dust and sporadic sodium layer formation, it is an in-situ observation of the existence of mesospheric dust near a sporadic atom layer, as predicted by some Nas models. We discuss the characteristics of the observed charged dust layer, including the unexpected positive charge and inferred physical structure, and the observed correspondence between this layer and other mesospheric layering observed at the same time. We also report on a measurement of the gradient drift plasma instability observed on the top side of the accompanying sporadic E layer. The local nonlinear growth rate for the instability was calculated, and wavelength inner and outer scales determined.

Keywords
Physics, Fluid and Plasma, Physics, Astronomy and Astrophysics

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An In-Situ Measurement of Charged Mesospheric Dust
During a Sporadic Atom Layer Event

BY

Lynette J. Gelinas
B.S. University of New Hampshire (1990)
M.S., University of New Hampshire (1992)

DISSERTATION

Submitted to the University of New Hampshire
in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy
in
Physics

May 1999
This dissertation has been examined and approved.

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Research Professor of Physics

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Professor of Physics

Martin Lee
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Robert Talbot
Research Professor of Earth Sciences

Michael Kelley
Professor of Electrical Engineering
Cornell University

April 13, 1999
Date
Dedication

For my parents
Acknowledgments

First of all, I would like to thank my advisor, Dr. Kristina Lynch, for her direction and advice throughout the dust detector project. She has been a great pleasure to work with. Kristina has a knack for asking just the right kind of questions; I thank her especially for making me try to explain synchronous detection, the gradient drift instability and electric field mapping factors. Next, I need to thank my committee member and SAL P.I. Mike Kelley. I have learned a great deal from the many email discussions about electric field and dust data analysis over the past year. And I especially thank him for his 1989 text, “The Earth's Ionosphere”; without it I would not have understood any “Mike-mail!” I also thank my committee members, Roger Arnoldy, Marty Lee, and Bob Talbot for their input during thesis discussions and for their comments during the final review process.

The dust detector would never had made it off the ground without the help of many people at UNH: Eugene Sartori for the electronics prototype design, Dave Rau for his help with the mechanical design and fabrication, John Googins for his tireless (almost) soldering and re-wiring, and the machinists for a job well done. I particularly need to thank Steve Longworth for all his help with the electronics in the last few months before integration: fixing timing errors, removing the preamp DC offsets, all the tweaking to reduce noise levels, and the idea for using a battery pack to power the preamp. Thanks to all of you for making the d**n thing work! I also thank Steve Baker at Cornell for his dedication to SAL, for his patient tutoring in the ways of rocket science, and for explaining what can and cannot be flown on a rocket.

I also acknowledge financial support from the NASA Graduate Student Researchers Program through this fellowship.
I am grateful to all my friends and family for their support, though I'm not sure if reading my thesis will help them understand what it is that I do all day. I appreciate all the offers of dust that I've received over the years, but I'd like to remind everyone that I'm only in the market for real “space dust”, not the stuff that is all over the living room. Thanks to Reuben for believing I could do it. And last, but definitely not least, I thank my monsters Duncan, Charlotte, and Wilbur, for being silly, sitting on my lap, and not asking me any hard questions!
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ABSTRACT

An In-Situ Measurement of Charged Mesospheric Dust During a
Sporadic Atom Layer Event

by

Lynette J. Gelinas
University of New Hampshire, May, 1999

In this thesis we discuss the results of the Sudden Atom Layers (SAL) sounding rocket,
launched from Puerto Rico the evening of February 19, 1998, as part of the Coqui II
sounding rocket campaign. A charged dust detector was constructed and flown on the
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In particular we focus on the interesting results from the charged dust experiment and the
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The dust detector, a sensitive Faraday cup, used a synchronous detection method to
measure a limited mass range of charged dust. Other instruments on the SAL payload
measured the in-situ electric fields, plasma density and neutral sodium density. Ground
measurements taken at Arecibo confirmed the presence of a double sporadic sodium layer
and a sporadic E layer at the time of the rocket launch. These layers were also observed in-
situ. The dust detector measured a broad layer of positively charged dust (≈20 cm⁻³) in the
vicinity of both the sporadic sodium and sporadic E layers. This charged dust experiment
has provided the first observation of charged meteoric dust in the tropical mesosphere.

While the rocket data is not conclusive evidence of a correlation between mesospheric
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Chapter 1

Introduction

1.1 Sporadic Atom Layers

1.1.1 Introduction

Study of phenomena of Earth's mesosphere region, in the altitude range between 80 and 120 km, has been overlooked until recently. Too low for satellite measurements and too high for balloons and airplanes, sounding rockets have been the only means of in-situ measurements of this region. Recently, more powerful radars and the development of lidars has expanded study of this region with ground-based measurements, spurring new interest in mesospheric phenomena.

The mesosphere is a transition region between the atmosphere, where neutral winds and chemistry are the dominant processes, and the ionosphere, where magnetic and electric fields and ion chemistry take over. All of these processes play a role in the physics of the mesosphere: the neutral air density ($10^{12}$/cc) supports neutral wind motion, and photoionization creates a significant plasma density ($10^3$/cc). Ions in this region are collisional, but not electrons, which are constrained by the magnetic field. Neutral winds and electric fields mapping from higher altitudes affect motion of both the plasma and neutral constituents via neutral-ion collisional coupling. In addition, the neutral density in this region is high enough to cause ablation of incident meteor material, adding atomic metals and dust to the mesospheric constituent mix.
1.1.2 Observations and Morphology

The meteor ablation results in a broad background layer of atomic sodium, stretching from about 80 km to 100 km. Models of differential meteor ablation are able to describe adequately some characteristics of the background sodium layer [McNeil, 1997, Plane et al., 1998]. Deposition of sodium from ablating meteors occurs over a ten to twenty kilometer altitude range, centered around 90 km altitude, creating the background neutral sodium layer. Within this broad background layer, thin (≈ 1 km) sporadic sodium layers have been observed. These Sudden or Sporadic Atom Layers (generally designated N₅, or Na₅ for sodium layers), have been recognized for almost 20 years, but the mechanism of their formation is still unknown.

Their morphology has been catalogued by Clemenha (1995). The layers develop within a few minutes, last up to a few hours, and then fade quickly. The typical altitudinal FWHM of the neutral metal layer is on the order of 1 km, with a horizontal extent of several hundred to several thousand kilometers [Kane et al., 1991].

The layers are observed using resonance lidars; sodium layers have been studied extensively, as sodium is the easiest mesospheric metal to observe. Sporadic sodium (Na₅) layers occur most frequently at high and low latitudes, and are relatively rare at mid-latitudes. Calcium and iron layers have also been observed; iron layers may occur more frequently than sodium layers, and are fairly common at mid-latitudes [Kane et al., 1993b, Alpers, 1990, Bills et al., 1990, Granier et al., 1989]. The metal concentration in the layer can be up to 40 times higher than the total column density of background metal, implying that layer formation isn’t simply a reorganization of background material, and raising a difficult source
question.

In addition to the general statistical features of Na$_s$ layers described above, there are many more phenomenological observations and problems which must fit into a complete Na$_s$ model. Until recently, almost all Na$_s$ measurements have been made by ground or airborne instruments. Without horizontally sweeping lidars which can track individual structures in the Na$_s$ layers, the assumptions about spatial extent and formation time can be interpreted in different ways: the observed short formation time could be the result of the horizontal movement of a limited layer across the viewing area. Spatial advection of a Na$_s$ layer across the observation site could account for the short apparent formation time of the Na$_s$ layer, eliminating the necessity of a fast sodium source. However, the layers appear to form more quickly than they dissipate, which is inconsistent with an advecting Na$_s$ layer. Airborne lidar and airglow measurements have also measured temporal changes in an Na$_s$ layer, indicating that Na$_s$ can form quickly over large geographic areas [Gardner et al., 1991]. Sodium airglow enhancements are also observed in connection with Na$_s$ layers, along with small enhancements in OH airglow [Beatty et al., 1989]. Airglow enhancements are typically related to wave perturbations in the atmosphere, which may point to a gravity wave mechanism for Na$_s$ [Clemesha et al., 1995]. Clemesha (1995) also notes that thin, concentrated sodium layers are very common at low latitudes, possibly indicating that these “layer enhancements” may differ from true sporadic sodium layer formation.

The primary questions with respect to Na$_s$ formation are (a) the source of the excess sodium and (b) the striation mechanism which results in a thin, concentrated layer. In the mesosphere, plasma layers are fairly common and can be explained by a windshear perpen- dicular to a magnetic field at mid-latitudes, discussed in detail later in this chapter. These
sporadic E (designated \( E_s \)) layers appear to be correlated with the appearance of \( N_{as} \) layers, but the windshear mechanism should not be able to organize neutral particles into a narrow layer [von Zahn et al., 1987, Kwon et al., 1988, Batista et al., 1989, Kane et al., 1993a, Nagasawa and Abo, 1995]. \( N_{as} \) layers are almost always accompanied by \( E_s \) layers, although the reverse is not necessarily true. Competing models of \( N_{as} \) formation include recombination of metal ions in the \( E_s \) layer, and sodium adsorbed onto mesospheric dust released by some unknown mechanism.

1.1.3 Overview of Mesospheric \( N_{as} \) Processes

Plasma Layering Mechanisms

Since \( N_{as} \) layers are known to be correlated with sporadic E layers, it is instructive to review the basic theory of \( E_s \) formation. At mid and low latitudes, a windshear mechanism serves to gather ions in nodes of the neutral wind [Whitehead, 1970]. At altitudes below 125 km, the ions are collision dominated and are therefore subject to the zonal (east-west) winds. Charged particles dragged by the zonal winds across a magnetic field are subject to the Lorentz force; at latitudes where there is a northward component of the magnetic field \( B \), ions subject to the zonal wind will feel a vertical Lorentz force. Westward winds will push (positive) ions downward, eastward winds will push ions upward. Ions will tend to accumulate in nodes with a westward wind above and an eastward (or smaller westward) wind below [Mathews, 1998].

To maintain the layer, the ion lifetime against recombination must be long. The most abundant ions at altitudes between 80 and 125 km are \( \text{NO}^+ \), \( \text{O}^+ \), and \( \text{O}_2^+ \), all which have relatively short recombination times [Kelley, 1989]. The recombination times of metal ions,
Figure 1-1: Illustration of windshear mechanism of sporadic E layer formation. Collisional ions are subject to downward $\mathbf{U} \times \mathbf{B}$ force from westward wind above, upward $\mathbf{U} \times \mathbf{B}$ force from eastward wind below. Electrons are dragged along with the ions by Coulomb forces.

such as Fe$^+$, Mg$^+$, and Ca$^+$ are long enough to account for the observed plasma densities observed in the $E_s$ layers (up to $10^6$/cc). Compare this to the background sodium ion concentration modeled by McNeil (1997) which predicts a peak density of $\approx 200$/cc sodium ions at altitudes near 100 km. In-situ measurements of sporadic E composition have confirmed that metal ions are the dominant ion component of low latitude layers [Herrmann et al., 1978]. Note that the only source of metal ions in the mesosphere is meteor ablation; the predicted relative number density of sodium ions relative to the other metallic ions (Fe$^+$, Mg$^+$, Ca$^+$) in $E_s$ layers is 3-4% [Hansen et al., 1990, Kopp, 1997].

Background Neutral Sodium Layer Formation

Just as meteoric material is the sole source of metallic ions in the mesosphere, so is it the only source of neutral metals. The background neutral sodium layer stretches from about 90 km to 110 km altitude, roughly the region where sodium is ablated from incident meteors.
The composition of the incident meteor material is just a few percent sodium by weight. The modeled background profiles predict a peak neutral metal density of 1000-2000/cc at altitudes near 90 km, with a FWHM of ≈15 km [McNeil, 1997].

1.1.4 Theories of Na$_2$ Formation

As stated earlier, no complete theories yet exist to explain the accumulated measurements of Na$_2$ layers [Clemesha et al., 1995, Gardner et al., 1993]. The two competing theories which address the problem of excess sodium in the Na$_2$ layers are recombination of Na$^+$ in E$_s$ layers [Cox et al., 1998, Heinselman et al., 1998] and sodium ions or atoms adsorbed onto meteoric dust particles which are somehow released [von Zahn et al., 1987].

Sporadic E Sodium Ion Recombination

The basic premise of the recombination model is that there are enough sodium ions in the accompanying E$_s$ plasma layer to account for the observed increased neutral sodium density in the neutral Na$_2$ layer. Chemical models indicate that under some conditions, recombination of Na$^+$ in an E$_s$ layer is sufficient to account for neutral Na$_2$ formation. The density of Na$^+$ ions in a typical E$_s$ layer is 3-4%, so for a fairly strong layer (10$^6$/cc) there can be a substantial reservoir of Na$^+$ ions available for recombination. This mechanism seems to explain adequately high altitude (≥100 km) Na$_2$ layer formation, where Na$^+$ lifetime is long enough to build up a substantial Na$^+$ population in an E$_s$ layer. Recent results by Heinselman (1998) and Cox (1998) suggest that this recombination mechanism may also be valid for altitudes less than 100 km at polar latitudes. Other models indicate that below 100 km, sodium released from the surface of meteoric dust is a likely Na source.
[Hansen et al., 1990].

A lingering problem with the recombination model is the rate of sodium ion-electron recombination, which in the absence of a catalyst is much too slow to explain the quick neutral Na\textsubscript{a} layer formation.

Recent chemical models of gas-phase charge exchange reactions postulate that fast pathways from Na\textsuperscript{+} to Na exist, fast enough to account for the short layer formation time [Cox et al., 1998, Cox et al., 1993]. Recent lidar measurements of an Na\textsubscript{a} event at Sondrestrom indicated that a descending E\textsubscript{a} layer triggered the formation of an Na\textsubscript{a} layer, evidence that recombination could be the appropriate formation mechanism in this case [Heinselman et al., 1998]. However, other observations seem to refute this model, asserting that there is no apparent correlation between wind structure (supposedly responsible for E\textsubscript{a}) and Na\textsubscript{a} layers [Qian et al., 1998].

**Sodium From Dust Particles**

Sodium adsorbed onto meteoric dust particles may also be a source of sodium for Na\textsubscript{a} formation, in addition to or in place of ions in an E\textsubscript{a} layer [von Zahn et al., 1987, Beatty et al., 1989]. As will be described in Chapter 2, meteoric material ablates and recondenses into nanometer-sized dust particles in the mesosphere. Atomic sodium adsorbed onto these particles may be released by some (unknown) mechanism, forming Na\textsubscript{a} layers. Given predicted concentrations of meteoric dust in the mesosphere (≈10\textsuperscript{3}/cc), 6-7 sodium atoms must be released from each dust particle to account for the increase in sodium concentration inside the Na\textsubscript{a} layer [von Zahn and Hansen, 1988].

Again, the layering and release mechanisms remain a problem. Atmospheric processes
may be able to create the thin, concentrated dust layers required for formation of a thin, concentrated neutral metal layer. Windshears are able to organize aerosol layers in the stratosphere; other mesospheric processes such as variations in the rate of infalling meteoric material or gravity wave breaking may be able to organize thin dust layers at higher altitudes. If the dust population carries a charge (as it would tend to do when immersed in a plasma), it could also be organized by electric fields [Clemesha et al., 1995].

Release mechanisms are similarly sketchy. At polar latitudes bombardment by auroral electrons could release sodium atoms through a sputtering process [von Zahn et al., 1987]. At low latitudes, $E_s$ ion-dust collisions or cluster ion chemistry could result in the release of sodium atoms [Beatty et al., 1989]. This mechanism removes the requirement that the dust layer itself be narrow, as the thickness of the $E_s$ layer would determine the Na$_s$ thickness. In the case of charged dust, electrostatic forces may result in the disintegration of dust particles and the release of atomic sodium [Kirkwood and von Zahn, 1991].

In summary, no coherent model yet exists which can adequately explain Na$_s$ formation at all latitudes. Since the possible sodium sources (dust or Na$^+$ ions) are present at all latitudes, it is desirable to find a source and release mechanism viable at all latitudes to explain the common features of the layers; neither of the models described above is able to do so. Given their reliance on $E_s$ ions and layering mechanisms, these models have similar characteristics. Recent work has focused on the recombination model, since this is easier to study from ground-based measurements. If an in-situ meteoric dust population is observed in the appropriate altitude range, the focus may shift toward the dust-sodium source model.
1.2 Mesospheric Dust Observations

Until recently, there was little experimental evidence but strong theoretical expectations for the existence of a meteoric dust layer in the mesosphere. As is the case with Na\textsubscript{2} layer observations, the altitude range of the deposited dust layer is inaccessible to both satellite observations and airplane or balloon measurements. Ground-based measurements are also impractical, as the scattering cross-section from nanometer-sized dust particles is small compared to the return from neutral gas. The low density of the material also presents a problem for in-situ rocket experiments.

Early In-Situ Experiments

The mesospheric dust population usually has been inferred from lower altitude aerosol measurements [Chesworth and Hale, 1974, Hunten et al., 1980]. As the initial small meteoric dust particles descend through the atmosphere, they coagulate into larger particles; particle sizes at altitudes between 20 and 30 km are on the order of microns, and are more easily collected by balloon and airplane experiments. Ground-based scattering measurements are also able to characterize the stratospheric distribution of these aerosols. Using models and observations of meteor ablation in the mesosphere to determine initial dust particle size and density, and atmospheric processes (diffusion, condensation) to describe the particle size and density as it descends through the atmosphere, a model of dust particle size and density vs. altitude can be calculated [Hunten et al., 1980, Rosinski and Snow, 1961]. Low altitude observations can then serve as a check for the model.
Ground Observations

While ground-based measurements are unable directly to detect nanometer-sized dust particles, the existence of a dust population can be inferred from other scattering measurements. Measurements of the electron and negative ion densities in the 1960s showed that the electron recombination vs. solar zenith angle proceeded much faster than expected. The presence of particulates at altitudes between 80 and 100 km was inferred from these observations to account for the high recombination rate. It was postulated that some sort of dust particulate surface chemistry was involved in the electron-negative ion conversion [Chesworth and Hale, 1974]. Other fast recombination processes involved three-body interactions, which are unlikely at high altitudes because of the low atmospheric density.

More recent studies of Polar Mesospheric Summer Echoes (PMSE) have also postulated the existence of a mesospheric dust population serving as condensation nuclei for ice particles in the cold summer mesopause region near 85 km altitude [Haines et al., 1990b, Cho and Kelley, 1993]. Anomalous radar backscatter (echoes) from this region may be due to a population of charged ice particles. Radar scattering is only possible from charged particles; lidar measurements may be able to detect larger uncharged dust particles, on the order of 50 nanometers or greater [Kelley et al., 1998]. Indeed, there is strong evidence for the existence of a sub-micron-sized ice particle population at the polar summer mesopause; Noctilucent Clouds (NLCs) have been observed in this region for over 100 years [Thomas, 1991]. Conditions in the polar summer mesosphere may allow formation of ice particles, as the extremely low temperatures in summertime may allow condensation at even the lowest water vapor pressures. Measurements of ice particle populations may then be
related to the meteoric dust population serving as ice nuclei. But, these extremely cold conditions are not thought to be common at other latitudes and seasons, and scattering from ice particles is not a definitive measurement of a meteoric dust population: homogeneous nucleation (in which no dust nucleus is necessary) may also be possible at these temperatures.

**Recent Charged Dust Observations**

Attempts at characterizing the mesospheric dust population recently have become more successful measuring the charged component of the dust population. In the lower ionosphere, at altitudes near 90 km, the plasma density is sufficient to cause charging of the mesospheric dust particles. These singly-charged dust particles are still resistant to ground observation, as the radar scattering cross-section is still very small, but in-situ measurements have had better success. Mass spectrometer measurements have indicated the existence of negatively charged heavy ions (≥400 amu) at altitudes over 80 km [Arnold et al., 1982, Schulte and Arnold, 1992].

Recent experiments designed to measure in-situ charged ice populations have also had some success. Detectors flown on sounding rockets through NLC and PMSE indicate the presence of charged ice particles with sizes as small as 20 to 30 nanometers (10⁷ to 10⁸ amu) [Havness et al., 1996a, Havness et al., 1996b]. These detectors use RPA (retarding potential analyzer) screens to reject thermal plasma particles, and then measure the plasma cloud generated by large ice particle impacts. There is some ambiguity about the charge of the ice particle in these measurements, as the detector RPA screens do not distinguish between positive, negative and neutral ice particles, all of which contribute to the impact plasma.
current. All charged dust particles are able to pass through the RPA screens, so the current collected from the impact plasma is the proportional to the total dust flux to the detector. The collected current is the sum of the incident dust charge and the plasma produced by impact with the anode, making identification of the charge if the incident particle difficult.

Using measurements of charged dust particles to characterize the total (charged and uncharged) mesospheric dust population is not without its own model dependence. The dynamics of dust charging in the mesosphere is complicated, and must take into account many processes, including direct plasma collection, photoelectron emission, photodetachment of electrons, and secondary electron emission, to name a few. Laboratory measurements of dust charging processes can be used to verify and fine-tune dusty plasma theory under controlled conditions, but it is still difficult to simulate complex mesospheric conditions in the laboratory [Walch et al., 1994].

1.3 Sudden Atom Layers Sounding Rocket

The Sporadic Atom Layers (SAL) sounding rocket, launched from Puerto Rico on 19 Feb 1998 at 2009 LT, was instrumented to characterize the electrodynamics and chemistry of Na\textsubscript{2} layers. Instruments included a fast temperature probe measuring the electron temperature, plasma frequency and DC probes measuring the absolute electron density, a positive ion mass spectrometer, sodium and potassium lamps and photometers measuring neutral atom abundance near the payload, electric field booms, and the charged dust detector. A TMA (trimethyl aluminum release) rocket launched 20 minutes later profiled the neutral mesospheric and lower thermospheric winds.

Ground observations from the Arecibo lidar and radar facilities confirmed the presence
of a double Na\textsubscript{s} layer and accompanying E\textsubscript{s} layer at the time of the rocket launch. The on-board plasma instruments also observed the E\textsubscript{s} layer in-situ, and the on-board sodium airglow experiment confirmed the ground Na\textsubscript{s} measurement. Also detected was an \approx 5 km thick layer of positively charged dust, which will be discussed extensively in the following chapters.

1.4 Summary

In the following chapters we report on a new charged dust measurement in the mesosphere over Puerto Rico on February 19, 1998. In Chapter 2 we discuss the dust production and charging processes in more detail, setting the parameters for the design of the charged dust detector described in Chapter 3. Analysis of the data from the dust detector, and several other instruments on the sounding rocket, is detailed in Chapter 4. Finally, in Chapter 5, we discuss the charged dust measurement in the context of the observed mesospheric conditions on the night of the rocket launch. This charged dust experiment has provided the first observation of charged meteoric dust in the tropical mesosphere. We also discuss the dust data in relation to ground and in-situ observations of Na\textsubscript{s} and E\textsubscript{s}, and report on an interesting gradient drift wave measurement related to the E\textsubscript{s} layer.
Chapter 2

Mesospheric Dust Model

2.1 Dust Production

Every day, between 40 and 100 metric tons of meteoric material enter the Earth’s atmosphere [Hunten et al., 1980, Kane et al., 1993c]. At altitudes between 90 and 100 km, the viscous air drag is high enough to cause heating of the incident meteors, which then begin to burn up. The mesospheric dust layer accumulates from the deposition of this ablated material. The altitude at which ablation begins depends on the incident meteor velocity, entrance angle through the atmosphere, size, and composition [Opik, 1958]. The altitude distribution of the mesospheric dust population depends heavily on these factors, most of which can only be estimated. For instance, the mass median weight of incident meteors is approximately 10 μg (corresponding to a radius of 100 μm for a density of 2 g/cc), but the mass flux as a function of size is still only sketchily known. The meteor velocity is an important factor in the ablation model, as it determines the height at which ablation begins, but this also is not well known. The mean velocity is between 14.5 and 17 km/s, but may vary greatly depending on the meteor source; for instance, the annual Leonid meteor showers (originating from comet Temple-Tuttle) enter the Earth’s atmosphere at velocities up to 70 km/s [Hunten et al., 1980, Jenniskens, 1996]. The most recent, and thorough, modeling investigation of the mesospheric dust population was made by Hunten (1980), which we outline here.
2.1.1 Model of Mesospheric Dust Density

The model developed by Hunten (1980) calculates the meteoric dust profile by breaking down the dust production process into three parts: meteor ablation, dust or smoke formation, and atmospheric diffusion and sedimentation processes. The first part, ablation, depends on the meteor velocity, size, and physical structure. The ablation products include micrometeorites (particles which have not been vaporized), residual particles (particles not completely vaporized, though melted), and dust particles. The second part, dust formation, is the result of recondensation of vapors in the meteor trail. The size of the initial smoke particle depends on the coagulation rate and rate of diffusion of vapors in the meteor trail. The dust model outlined here assumes a uniform initial smoke particle size of 1.3 nm. Here, "smoke" refers to the initial particle produced in the meteor trail, and "dust" refers to the resultant particle after coagulation, diffusion, etc. The complete model described by Hunten (1980) gives the altitude and size distribution of dust particles starting from several initial particle sizes, ranging from 0.2 to 10 nm. Atmospheric processes, including the rate of coagulation, sedimentation and eddy diffusion, affect the final altitude and size distribution of the dust population. These effects are difficult to model, as most vary with altitude; an analytic solution to the dust production equations can be found if we neglect the effects of eddy diffusion and coagulation, which we will do below. In this model, the population of 1.3 nm dust particles vs. altitude is calculated, assuming the initial particle size is 1.3 nm and the only variation of dust particle density with altitude depends only on its fall speed through the atmosphere. Complete numerical calculations of the dust density profile taking into consideration eddy diffusion and coagulation were performed by Hunten.
(1980). The calculation outlined below serves as an order-of-magnitude calculation of the
dust density profile, for illustration purposes.

The dust continuity equation is:

$$\frac{d\phi}{dz} = q - kn^2, \quad (2.1.1)$$

where $\phi$ is the dust particle flux through the atmosphere, $q$ is the dust creation rate from
meteor ablation, $n$ (cm$^{-3}$) is the dust density as a function of altitude $z$, $k$ is the coagulation
kernel (which we neglect for this calculation).

The dust flux $\phi$ is given by:

$$\phi = nw - Kn_a \frac{dn}{dz} \left( \frac{n}{n_a} \right), \quad (2.1.2)$$

where $w$ is the fall speed of the particle in cm/s, $K$ is the eddy diffusion coefficient (to be
neglected in this calculation), and $n_a$ is the atmospheric density.

The terminal velocity (fall speed) for particles with a density of 2 g cm$^{-3}$ in air of
number density $n_a$ is:

$$w = 7.8 \times 10^{15} \times \frac{r}{n_a} \text{ cm/s} \quad (2.1.3)$$

Solving equations 2.1.1, 2.1.2, 2.1.3, neglecting eddy diffusion and coagulation gives:

$$n = \frac{\phi}{w} = \frac{n_a}{7.8 \times 10^{15} \times r} \int_{z}^{\infty} q(h)dh \quad (2.1.4)$$

This equation illustrates how the dust density profile varies with smoke particle produc-
tion rate. Depending on the incident meteor velocity, the peak smoke production rate can
vary significantly with altitude. Given an initial smoke particle production rate vs. altitude
of $5 \times 10^{-3}$, 1.3 nm radius particles per cm$^{-3}$ s$^{-1}$, peaking at 85 km, the mesospheric dust
Figure 2-1: Dust density for $r = 1.3$ nm.

distribution is given in Fig. 2-1. The production profile used in this figure is the same described by Hunten, with a peak production rate of approximately $5 \times 10^7$ cm$^{-3}$s$^{-1}$ at an altitude of 85 km. Eddy diffusion and coagulation can be incorporated into the above model through numerical integration, following Hunten (1980). We will use these complete dust density profiles in the following model of the charged dust population, though we do not reproduce those results here.

2.1.2 Structure and Composition of Recondensed Particles

The dust production and coagulation model described above does not take into account the physical structure or composition of the resultant dust particle. The recondensed smoke particles consist mostly of oxides of silicon and iron (magnetite, Fe$_3$O$_4$, and silicates, SiO$_2$), and a trace amount of metals (sodium constitutes about 2%) [Biermann et al., 1996, McNeil, 1997]. If it is assumed that recondensation in the meteor trail proceeds similarly
to formation of water droplets, the recondensed smoke particles can be approximated by smooth, solid spheres. Huten suggests the initial particle size is 0.2 nm, roughly the size of a single silicate molecule. After the initial recondensation, these initial smoke particles can then form aggregate dust particles, with an average dust surface area proportional to the packing efficiency of the conglomerate spheres. Rosinski and Snow (1961) calculated particle agglomeration rates in meteor trails after the initial recondensation of the meteor vapor, and found that particles 0.5 to 10 nm can be produced by agglomeration, depending on the temperature and density of the meteor trail. The resulting aggregates formed from the silicon and metal vapors should be spongelike in structure. The structure of the dust particle may affect the way it collects charge; this effect will be discussed later in the chapter, after a review of steady state dust charging.

2.2 Dust Charging

2.2.1 Steady State Nighttime Dust Charge

Dust immersed in a plasma will tend to acquire a charge from collection of plasma particles. A steady state charging model gives a first order approximation to the charge state and charge density of the dust population immersed in a plasma [Havnes et al., 1987, Havnes et al., 1990a, Goertz 1989]. Assuming nighttime conditions, where photoelectron emission is not significant, the primary currents to the dust grain are from thermal electrons and ions. The equilibrium condition for current collection by the dust particle is:

\[ I_e + I_i = 0 \]  

(2.2.1)
Following Havnes (1987), for a dust cloud immersed in a plasma, the distribution function of the plasma electrons and ions (species designated by the subscript \( j \)) is Maxwellian:

\[
f_j(w) = n_0 \left( \frac{m_j}{2 \pi kT} \right)^{3/2} \exp \left( - \frac{m_j w^2}{2 kT} - \frac{Z_j e V}{kT} \right)
\]

(2.2.2)

where \( V \) is the (reference) potential of the plasma, and \( w \) is the magnitude of the plasma particle's thermal velocity. This distribution function can then be used to calculate the plasma density, assuming spherical symmetry:

\[
n_j = 4\pi \int_0^\infty f_j(w) w^2 \, dw
\]

(2.2.3)

and the current to the dust particle:

\[
I_j = 4\pi Z_j e \int_{w_0}^\infty \sigma_j(w) f_j(w) w^3 \, dw
\]

(2.2.4)

Where the effective cross section for a collision with a dust particle is:

\[
\sigma_j(w) = \pi a^2 \left( 1 - \frac{2 Z_j e U}{m_j w^2} \right)
\]

(2.2.5)

\( U \) is the dust particle surface potential \( \psi_s \) minus the plasma potential \( V_p \), and \( a \) is the radius of a dust grain.

In the absence of photoelectrons, dust immersed in a plasma will tend to charge negatively due to the higher flux of lighter, faster electrons to the grain. In this case \( U < 0 \), and the lower integration limit (Eqn. 2.2.4) for electrons is \( w_0 = \sqrt{\frac{2 Z_j e U}{m_j}} \), since only particles with kinetic energy greater than \( Z_j e U \) can hit the charged dust particle. For ions, the lower limit is zero \( (w_0 = 0) \), since ions of all energies are able to enter the cloud. The resulting equations describing the electron and ion currents to a dust particle are:

\[
I_e(Z_e U \geq 0) = \pi a^2 e Z_e \left( \frac{8 kT}{\pi m_e} \right)^{1/2} n_e e^{-\frac{Z_e e U}{kT}}
\]

(2.2.6)
\begin{equation}
I_i(Z_iU \leq 0) = \pi a^2 e Z_i \left( \frac{8kT}{\pi m_i} \right)^{\frac{1}{2}} n_i \left( 1 - Z_i \frac{eU}{kT} \right) \tag{2.2.7}
\end{equation}

The density of each plasma species is:

\begin{equation}
n_j = n_0 e^{-Z_j \frac{eV}{kT}}. \tag{2.2.8}
\end{equation}

Substituting 2.2.6, 2.2.7, and 2.2.8 into 2.2.1 gives:

\begin{equation}
0 = \sqrt{\frac{m_e}{m_i}} e^{-\frac{eV}{kT}} \left( 1 - \frac{eU}{kT} \right) - e^{\frac{eV}{kT} + \frac{eU}{kT}} \tag{2.2.9}
\end{equation}

The charge on a dust particle (in cgs units) can be related to its surface potential by:

\begin{equation}
q_{dust} = C U = a \frac{U}{300} \tag{2.2.10}
\end{equation}

where \( U \) is the dust grain surface potential in volts and the capacitance of a small dust grain is approximately equal to its radius (in cgs units). The factor of 300 in Eqn. 2.2.10 is from the conversion of the grain surface potential \( U \) from mks to cgs units.

Therefore, in a dusty plasma the equation for conservation of charge is:

\begin{equation}
(n_e - n_i)e - \frac{N_d a U}{300} = 0 \tag{2.2.11}
\end{equation}

Substituting 2.2.8 into 2.2.11:

\begin{equation}
(e^{\frac{eV}{kT}} - e^{-\frac{eV}{kT}}) - \frac{N_d a T_e V}{n_0 300e} \left( \frac{eU}{kT} \right) = 0 \tag{2.2.12}
\end{equation}

where \( T_e V = \frac{kT}{e} \).

Defining a parameter \( P \) proportional to the dust density, dust size, electron temperature and plasma density (\( P = \frac{N_d a T_e V}{n_0 300e} \)),

\begin{equation}
2 \sinh \left( \frac{eV}{kT} \right) - P \left( \frac{eU}{kT} \right) = 0 \tag{2.2.13}
\end{equation}
The solution of this equation is plotted in Figs. 2-3 and 2-2, showing $\frac{eV}{kT}$ and $\frac{eU}{kT}$ as functions of $P$. The calculation was done assuming an NO\(^+\) plasma, with a density of 10,000/cc and a temperature of 200 K. The dust density vs. dust size was taken from the complete dust production model described in Hunten (1980), for dust particles in the size range of 0.2 to 1.4 nm. Fig. 2-3, $\frac{eV}{kT}$ vs. $P$, shows the bulk plasma potential inside the dusty plasma; this is the reference potential from which the dust surface potential ($\psi_s$) is defined. The dust cloud potential $U$ is shown in Fig. 2-2, as $\frac{eU}{kT}$ vs. $P$, the potential difference between the dust surface and the surrounding plasma. For a given value of $P$, the charge of the dust can be calculated from Eqn. 2.2.10:

$$q_{dust} = \frac{T_eV_0}{300} \left( \frac{eU}{kT} \right)$$

(2.2.14)

where $T_eV$ is the plasma temperature measured in eV.

For the dusty plasma parameters given above, and choosing the parameter $P$ to cover the range of dust particle sizes 0.2 to 1.4 nm, the result of these calculations gives the charged
dust fraction ($Z_d = q_{dust}/e$) as a function of dust size is plotted in Fig. 2-4, using the results for $\frac{q}{kT}$ shown in Fig. 2-2. Note that the charged fraction is equivalent to a charge of less than one electron; this implies that only a fraction of these small dust particles, on average, carry a single electron. The number of grains carrying more than one charge is very small compared to the singly-charged dust population, and is neglected in these calculations.

The total charged dust density in the dust cloud is shown in Fig. 2-5, for a range of dust radii. The dust density vs. dust particle size is calculated from the complete dust production model described in Hunten (1980). Although smaller particles carry a smaller fractional charge than larger ones, judging from Fig. 2-4, the predicted density of smaller particles at 90 km altitude is high, so that they contribute disproportionately to the charge per unit volume.

The important result of these calculations is the charged dust density distribution shown in Fig. 2-5. This model serves as the basis for the design of the dust detector to be described
in Chapter 3. These results were used to choose the particle size acceptance of the dust detector. Charged dust particles in a size range from \( \approx 0.7 \) to \( 2.0 \) nm have kinetic energies (in the moving frame of the rocket) of 10 to 30 eV, sufficient to distinguish them from the thermal plasma (0.017 eV), and exist at a measurable charge density. As will be described in Chapter 3, smaller particles are difficult to detect since, in the moving frame of the rocket, their kinetic energy is only about 1 eV.

**Charging of Spongelike Dust Grains**

The steady state theory described above does not address the physical process of electron and ion absorption by the dust particle, nor does it assume any charging effects due to a possibly irregular dust surface. The potential (and therefore charge) of the dust surface depends on the charge collection model described above, as well as the dust particle's structure. The simplest dust particle model is that of a smooth, conducting sphere on which
Figure 2-5: Charge per unit volume vs. dust radius at 90 km.

The charge is evenly distributed over the surface. Incident ions are neutralized on this surface and leave as neutral particles (removing an electron from the dust surface), while incident electrons are absorbed by the surface [Whipple et al., 1985]. However, if the dust particle is a loosely-bound structure composed of a dielectric material (such as meteoric silicates or metal oxides), the charging process may be altered, resulting in an irregularly charged grain. Plasma particles hitting the grain may stick to the grain surface, or neutralize locally, rather than neutralizing the grain as a whole; coagulation of oppositely charged particles may also result in an irregularly charged dust grain. The result would be that the particle becomes a collection of loosely-bound charged pieces, with an overall single net charge, in which charged pieces may be easily broken off by mechanical impact with a surface. Irregularly shaped particles may also be more prone to electrostatic disruption or field emission, leading to a charged dust population with an average size smaller than predicted [Mendis and Rosenberg, 1994]. How these effects relate to the dust detector results will be
discussed in Chapter 5.

2.2.2 Other Mesospheric Charging Processes

Modifications to the steady state charging process described above must also be made if there are significant photon fluxes to the dust particle. This may be the case for twilight (rather than nighttime) conditions, where the Lyman α photon flux is significant, or where refracted solar UV photons can remove electrons via photoionization or photodetachment. These processes may cause the dust particle to charge positively, rather than negatively as expected from the nighttime steady state model.

Daytime Equilibrium Conditions

Photoelectron emission in daytime conditions will tend to cause the grain to charge positively [Goertz 1989]. The primary photoionization source in the daytime mesosphere is solar Lyman α photons, which transmit almost unattenuated through the atmosphere down to altitudes below 80 km [Rees, 1989].

For negative dust surface potentials, the photoelectron current from the dust particle is:

\[ J_\nu = \pi a^2 K \]  

(2.2.15)

For positive dust surface potentials, in which case low energy photoelectrons may be re-absorbed, the photoelectron current is:

\[ J_\nu = \pi a^2 Ke^{\frac{\nu_\nu x}{\nu_\nu}} \]  

(2.2.16)

where \( K = \eta(5.0 \times 10^{11}) \) photoelectrons cm\(^{-2}\) s\(^{-1}\) at the top of the atmosphere (Lyman α only [Banks and Kockarts, 1973]), \( \eta \) is the photoemission efficiency of the material (≈1
for metals and \( \approx 0.1 \) for dielectrics), \( \psi_s \) is the surface potential of the dust particle, and \( T_p \) is the temperature of the Maxwellian photoelectron spectrum, taken to be 1 eV. Under daytime conditions, the photoelectron flux is on the order of or greater than the electron flux to the dust particle, resulting in a positively charged dust population.

To estimate the relative influences of the various charging processes, consider the time constants for electron and ion attachment to the dust particle and photoemission from the dust particle. The charging time of a neutral dust particle due to plasma particle collection can be estimated by:

\[
\tau = \left( n_e v_{\text{the}, \text{thi}} A_{\text{dust}} \right)^{-1}
\]  

(2.2.17)

for fluxes of thermal electrons \( (v_{\text{the}}) \) and ions \( (v_{\text{thi}}) \). The electron thermal velocity for a plasma temperature of 0.017 eV (200 K) is \( 5.5 \times 10^5 \) cm/s, the ion thermal speed is \( 2.3 \times 10^4 \) cm/s. For a plasma density of \( \approx 1000/\text{cc} \) and a dust surface area corresponding to a 1 nm sphere, the time constant for the neutral dust particle to pick up a negative charge is 24 minutes. The time constant for a neutral dust particle to pick up a positive ion is 96 hours. The equivalent time constant for photoelectron emission is

\[
\tau = (K A_{\text{dust}})^{-1}.
\]  

(2.2.18)

which, under daytime conditions \( (K = \eta(5.0 \times 10^{11}) \approx 10^{10} \) photoelectrons cm\(^{-2}\) s\(^{-1}\)), corresponds to a positive (dielectric) dust particle time constant of 13 minutes.

After the neutral dust particle acquires a charge via one of these processes, it may be neutralized by recombination with ions (for negative dust particles) or electrons (positive dust particles). Neutralization of the positive dust particles proceeds rather quickly; a
positively charged dust particle will attract electrons, so the electron current to the dust is:

$$I_e = I_{e0}(1 + \frac{e\psi_s}{kT})$$  \hspace{1cm} (2.2.19)

where $\psi_s$ is the surface potential of the positive dust particle. Using $q = C\psi_s$, where $C = 4\pi\varepsilon_0 r_{dust}$ for a sphere, assuming one (positive) charge then $\psi_s = 1.5V$, with $kT/e = 0.02$ eV. The Coulomb attraction increases the electron flux to the positive dust particle by a factor of $\approx 50$, so the electron-positive dust recombination time is short ($\approx 1$ minute), but the electron collection by neutral particles is long ($\approx$ hours). So, under daytime conditions or when there is a significant photon flux to the dust particle, the equilibrium condition is that approximately 7% of the dust particles will carry a positive charge (given the ratio of the photoelectron time constant to the recombination time constant).

Neutralization of negative particles by recombination with positive ions (or other positive dust particles) proceeds at a much slower rate, since the thermal velocity of ions and (positive) dust particles is several orders of magnitude less than the electron thermal velocity. Photodetachment is the dominant process for removal of an electron from a negatively charged dust particle, as will be discussed in the following section [Whipple, 1965].

**Twilight Lyman Alpha Photons**

If the Lyman $\alpha$ photon flux disappeared, the dust population would quickly be neutralized and begin to collect electrons, acquiring a negative charge. However, a significant scattered Lyman $\alpha$ photon flux exists even long after sunset (up to $10^{10}$ cm$^{-2}$s$^{-1}$ [Stroebel et al., 1974]), increasing the relaxation time from daytime (positive dust) to nighttime (negative dust) steady state conditions. The primary source of Lyman $\alpha$ photons in the nighttime ionosphere is geocoronal and extra-terrestrial hydrogen Lyman alpha radiation
(H 1216 A), resulting from multiple scattering of solar Lyman alpha photons by hydrogen atoms in the outer atmosphere [Young et al., 1971]. Additional nightglow sources (Lyman β, etc.) are also present, but less intense (up to $10^7$ cm$^{-2}$s$^{-1}$). Near the day-night terminator, refracted solar photons may also be available for photoionization of dust particles, but the refracted solar photon flux is difficult to calculate for solar zenith angles greater than 70 degrees [Banks and Kockarts, 1973]. Neglecting refracted photons gives a lower limit for the number density of positively charged dust particles.

The photoemission time constant for nighttime (twilight) conditions is approximately 2 hours, but may be significant enough to compete with electron attachment, or at least may effectively increase the relaxation time from daytime to nighttime conditions, depending on the efficiencies of the two processes. Photodetachment, in which an incident photon detaches an electron from a negatively charged particle, may efficiently neutralize negatively charged dust particles, but still proceeds at a rate proportional to the photon flux, without the η factor as in Eqn. 2.2.18 [Whipple, 1965, Chesworth and Hale, 1974]. In this case, the time constant for photodetachment is approximately 16 minutes, of the same order as electron attachment time constant. The Lyman α flux is over $10^9$ cm$^{-2}$s$^{-1}$ for solar zenith angles less than 150 degrees, and so remains a significant contributor to dust charging, even at night.
<table>
<thead>
<tr>
<th>Process</th>
<th>time constant $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron attachment</td>
<td>24 minutes</td>
</tr>
<tr>
<td>ion attachment</td>
<td>96 hours</td>
</tr>
<tr>
<td>photoelectron emission</td>
<td>$\approx$ 2 hours (twilight)</td>
</tr>
<tr>
<td>photoelectron emission</td>
<td>13 minutes (daytime)</td>
</tr>
<tr>
<td>electron photodetachment</td>
<td>$\approx$ 16 minutes</td>
</tr>
</tbody>
</table>

Table 2.1: Time constants for various dust charging processes in twilight conditions.

Summary of Charging Processes

To summarize the charging processes contributing to the production of singly-charged positive and negative dust particles [Whitten and Poppoff, 1971]:

$$\frac{dN_d^-}{dt} = -\alpha_d N_d^- N_d^+ + \beta n_e N_d - \rho N_d^-$$  \hspace{1cm} (2.2.20)

$$\frac{dN_d^+}{dt} = q - \alpha_e n_e N_d^+ - \alpha_d N_d^- N_d^+$$  \hspace{1cm} (2.2.21)

where $N_d^-$ is the number density of negative dust particles and $N_d^+$ is the number density of positive dust particles. The processes for production of negative particles are, by term in Eqn. 2.2.20: negative dust-positive dust recombination, with rate coefficient $\alpha_d$, electron attachment, with efficiency $\beta$, and photodetachment, with rate $\rho$. Eqn. 2.2.21 describes the processes contributing to the production of positive dust, which are: photoionization (photoemission) with production rate $q$, electron-positive dust recombination, with rate coefficient $\alpha_e$, and negative dust-positive dust recombination, with rate coefficient $\alpha_d$.

The relative magnitudes of the rate coefficients can be considered by comparing the time constants of the various charging processes, as calculated above. Estimates of time constants for twilight charging processes are given in Table 2.1. The time constants for photoelectron emission and electron photodetachment were calculated using Eqn. 2.2.18,
and using the twilight value of K (10⁹ photoelectrons cm⁻² s⁻¹ for solar zenith angles less than 150 degrees). The electron photodetachment process is not affected by the factor of η in Eqn. 2.2.18, accounting for the factor of 10 rate increase in the photodetachment process, as compared to photoemission.
Figure 2-6: Model of meteor ablation and charging in the Earth's mesosphere.

2.3 Summary

Fig. 2-6 summarizes the processes involved in the production of the charged dust layer in the Earth's mesosphere. The model of the mesospheric charged dust density outlined in this chapter is an important element in the design of the dust detector, to be described in Chapter 3. Using this estimate of the charged dust density, the charged dust flux to the detector can be predicted, and the detector performance modeled. We discuss the performance simulations, based on this charged dust model in the following chapter. This dust model will also be important in our interpretation of the dust data from the SAL flight, described in Chapter 5. In particular, the discussion of charged dust structure and positive charging mechanisms will be relevant in the explanation of several unusual effects observed in the SAL dust detector data.
Chapter 3

Dust Detector.

In this chapter we describe the modeling and design of the charged dust detector flown on the Sudden Atom Layers sounding rocket, using the dust charge density model developed in the previous chapter. The dust detector mass and angular acceptance are calculated, and results from the flight calibration of the detector are shown. The mechanical and electric design of the dust detector are also discussed, including noise reduction modifications of the flight detector.

3.1 Charged Dust Detection Method

In Chapter 2 we discussed a model of the mesospheric dust population, which predicted a total (neutral and charged) 1 nm sized dust density of approximately 1000/cc at an altitude of 90 km. The dust charging model showed that only about 5% of this population should carry a single charge, resulting in a charged dust density of $\approx 50$/cc. Both the plasma and neutral air density are many orders of magnitude greater than the charged dust density; the plasma density at this altitude is on the order of 1000-10000/cc, and the neutral air density is on the order of $10^{12}$/cc. The kinetic energy of the incident dust particles in the moving rocket frame is used to distinguish the charged dust particles from the background thermal plasma particle current. The plasma particles having masses less than $\approx 30$ amu enter the detector with little more than their thermal energy, about 0.017 eV for a 200 K plasma. Heavier dust particles (1000 to 10000 amu) enter the detector with a kinetic
energy proportional to the rocket ram velocity: a velocity of \( \approx 770 \text{ m/s} \) corresponds to a dust kinetic energy range of about 10 to 30 eV for dust masses of 1000 to 10000 amu (0.7 to 1.3 nm).

A rough estimate of the charged dust current to the detector on the moving rocket payload is given by

\[
I = n_{\text{dust}} v_{\text{rocket}} A_{\text{acceptance}} q_{\text{dust}}
\]  

which for a dust density of 1000 cm\(^{-3}\), rocket velocity of 770 m/s, detector acceptance area of 40 cm\(^2\), and 5% of the dust carrying a single charge gives a charged dust current of 25 pA. To pick out this small dust current from the larger plasma background current, a synchronous detection scheme is used.

**Overview of Detector Operation**

The basic operation of the detector is described in Fig. 3-1. A pair of electrodes halfway between the detector entrance and the anode uses an oscillating voltage (1 kHz, 20 V peak-to-peak) to entrain the charged dust as it passes through the detector. The rocket ram velocity of 800 m/s pushes the dust through the detector to one of two anodes, depending on the phase of oscillation of the charged dust. The dust charge is collected by the split anode; when the signal from the anode halves is differenced (anode A minus anode B), the resulting charged dust signal is a 1 kHz sine wave almost in phase with the forcing oscillation. The time of flight of the dust through the detector results in a slight phase shift between the forcing oscillation and the dust signal; this phase shift can be calculated and corrected for in the detector electronics. A synchronous detection method is used to amplify only the 1 kHz component of the resulting phase-corrected dust signal, preventing
amplification of ambient noise. This amplified, synchronously detected signal is rectified and then integrated over 125 ms to give an output voltage proportional to the collected dust current.

**Dust Charge Collection**

Using this method, the detector collects the dust charge, acting as a Faraday cup, and the output is a signal proportional to the magnitude of the collected charge. This signal should be insensitive to the sign of the incident dust particle. Looking at Fig. 3-2, for a
Figure 3-2: Trajectories of positive (blue) and negative (red) particles through dust detector.

given electric field between the electrodes, the red lines represent negative dust particles which hit the left anode, and positive dust particles (blue) hit the right anode. This results in a 180 degree phase difference between the signal collected from positive and negative particles. If the anode directly collects the dust charge, this phase difference is negated because the sign of the charge collected from positive dust is opposite that of negative dust. So the dust signal should be insensitive to the charge of the collected dust particle: though the positive dust oscillates 180 degrees out of phase with respect to the negative dust, the charge sign of the dust is also opposite, and these two “opposites” cancel.
Detector Particle Acceptance

The synchronous detection scheme allows only a specific mass (rammed kinetic energy) range of dust particles to reach the anode. Charged dust particles smaller than \( \approx 1000 \text{ amu} \), light ions, and electrons, are over-deflected by the oscillating field, and do not reach the anode. Larger charged dust particles \( (\geq \approx 10,000 \text{ amu}) \) are only minimally deflected by the oscillating field, and do not contribute to the total charged dust signal after the anode differencing, especially considering the predicted small population of these larger particles at 90 km. Neutral dust and neutral atmospheric particles are not affected by the oscillating field, and do not contribute to the charged dust signal.

Other secondary dust and non-dust related processes which could also contribute to the collected dust current are reduced by the detector geometry and electrostatics. Secondary electron emission is the most obvious possible contaminant, but this noise source can be eliminated through the detector geometry. The possible secondary electron processes inside the detector are: high energy \( (> 10 \text{ eV}) \) secondary electron emission from dust impacts at the entrance screens, which may be properly deflected in the oscillating field, and impacts near the anode by charged dust particles which were properly deflected in the field. In the first case, the combination of a low dust-screen collision cross section (screen transmission is \( \approx 94 \% \)), a secondary electron emission energy threshold of \( \approx 14 \text{ eV} \), and the small population of heavy dust particles (heavy enough to cause the ejection of a \( \approx 10 \text{ eV} \) electron) makes secondary electron collection at the anode energetically unlikely.

The second case, electron emission from direct dust collisions with the anode, is also inhibited by the detector electrostatics. Low energy \( \text{up to } \approx 5 \text{ eV} \) secondary electrons
emitted from the anode are recollected by the positively biased anode. A series of positively biased screens in front of the positively biased anode sets up an electric field forcing emitted electrons back toward the anode. Secondary electrons emitted from charged particle impacts with these "accelerating" screens could be a problem, but once again the low collisions cross section should minimize this source of contamination. These positively biased accelerating screens near the anode, and the anode itself, also repel light positive thermal plasma particles, if any should make it past the oscillating field. A negatively biased screen sandwiched between two grounded screens at the entrance to the detector repels thermal electrons (Fig. 3-1).

3.2 Detector Simulations

The design of the dust detector components was determined by several computer models, starting with electrostatic particle detector software (ELECTRO and the similar Simion 6.0), and continuing with models of integrated detector current using IDL.

3.2.1 Electrostatic Design: Energy/Mass Acceptance

The energy (mass) acceptance of the dust detector was determined by 2-D detector models. Appendix B contains dust particle trajectories for the range of masses given in Table 3.1 for two different amplitudes of the oscillating electric field. The actual current collected by the detector is a summation over these individual trajectories, weighted by the relative charged dust density as a function of mass. Results from the simulation of the actual detector current will be discussed later in this section.
Low Mass Dust Particle Acceptance Cutoff

From the particle trajectories shown in Appendix B, there is an obvious range of accepted mass (energy) dust particles. The low mass cutoff is close to 10 eV. Figs. B-1 and B-6 show the trajectory of a 10 eV dust particle (carrying a single charge) through the detector. The low mass cutoff is determined by the lowest mass (kinetic energy) dust particle that is not overswept by the oscillating electric field. Particles that are overswept hit the sides of the detector; the charge is conducted away via the bias supply to spacecraft ground. At the maximum oscillation voltage ($\pm$ 10 V), a 10 eV dust particle is overswept and never reaches the anode. However, at half the maximum voltage ($\pm$ 5V) most of the incident particles reach the anode. Because the detector integrates over several sweeps of the oscillation voltage, this lower energy particle is able to contribute to the total dust current if the 10 eV (mass equivalent $\approx$3000 amu) charged dust population is significant (several thousand/cc). Incident dust particles with a kinetic energy lower than about 10 eV will not contribute significantly to the total current, because the segment of the oscillation cycle which results in anode hits is even more restricted. This is confirmed by laboratory calibrations, which will be discussed later in this chapter.

High Mass Dust Particle Acceptance Cutoff

The high mass cutoff of the dust detector can be similarly determined. As the incident dust energy (mass) increases, the particles are deflected less in the oscillating field. Since the resulting dust signal is the difference between the current collected on each of the two anodes, when the particles deflect less, this difference also decreases. At an incident energy of 40 eV (mass equivalent $\approx$12,900 amu), the dust particles are deflected significantly only
at the higher oscillation voltage (see Figs. B-4 and B-9, comparing deflection of 40 eV particles at 10 V and 5 V, respectively). Since the total dust current is a summation over many oscillation voltages, these heavier particles will not contribute significantly to the dust current. And, according to the dust production/population model discussed in Chapter 2, the population density of these heavier particles is expected to be small, approximately a few tens to a few hundred/cc, further reducing the expected contribution to the total dust current.

**Plasma Particle Rejection**

At this latitude, the number of energetic (> 10 eV) plasma particles is not expected to be significant. The thermal electron temperature is only ≈0.017 eV, so the retarding potential screen (biased at -1.5 V) at the detector entrance is sufficient to reject thermal electrons (Fig. B-11). The ram energy of heavier ions is much greater than their thermal energy, but is still insufficient for contribution to the detector signal. The trajectory of a 1eV (equivalent to ≈320 amu) ion is shown in Fig. B-12. The particle does not have enough energy to pass through the positively biased (+2V and +3V) screens, even when incident at an angle of 10 or 20 degrees with respect to the detector symmetry axis (see Fig. B-13 and B-14). However, even when the oscillation voltage is zero no ions with energies less than 5 eV can reach the anode (which is biased at +5V). Zero oscillating field ion trajectories are shown in Fig. B-15.

The negative ion population at altitudes above 85 km is not expected to be significant [Kelley, 1989], so only positive ions are considered. Light negative ions (up to about 500 amu) would be stopped by the retarding potential screen (biased at -1.5 V). The high-
<table>
<thead>
<tr>
<th>Dust Kinetic Energy (eV)</th>
<th>Dust Mass (amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3200</td>
</tr>
<tr>
<td>20</td>
<td>6500</td>
</tr>
<tr>
<td>30</td>
<td>9700</td>
</tr>
<tr>
<td>40</td>
<td>12,900</td>
</tr>
<tr>
<td>50</td>
<td>16,200</td>
</tr>
</tbody>
</table>

Table 3.1: Dust mass in amu vs. incident kinetic energy for detector simulations, assuming the rocket velocity is 770 m/s.

...est density ion populations are O⁺, O₂⁺ and NO⁺, some heavier water cluster ions, and HCO₃⁻, all of which have masses less than 100 amu (less than 1 eV rammed energy) [von Zahn and Murad, 1990]. Ions with rammed energies greater than 5 eV (1600 amu) may contribute to the dust current, but the definition of an “ion” in this mass range is confusing; at masses greater than 1000 amu the difference between a charged “dust” particle and an “ion” is unclear.

3.2.2 Electrostatic Design: Angular Acceptance

The 2-D electrostatic simulation used to determine the accepted mass range can also be used to determine the angular acceptance of the detector. A 3-D simulation was used to calculate the actual acceptance area vs. angle, and will be discussed below. Appendix B contains dust particle trajectories for particles incident in the plane of the oscillating field, shown in Figs. B-16 to B-21. The angular acceptance in the plane perpendicular to the oscillating field (into the paper, looking at the figures in Appendix C) is proportional to the cosine of the incident angle. The angular acceptance in the plane of the oscillating field varies more than the cosine of the incident angle: the particles take a slightly different path...
in the dipole field of the electrodes, and particles with a large incident angle will either hit the sides of the detector or fall on the "wrong" anode.

Figs. B-16 and B-19 show particle trajectories for an incident angle of plus and minus 5 degrees, respectively. The operation of the detector at this incident angle is not significantly different from zero degree incidence, shown in Fig. B-2; the particles are effectively swept onto the appropriate anode halves. At plus or minus 10 degree incident angle (Figs. B-17 and B-20) the acceptance area of the detector starts to decrease. Some particles which would have hit the anode if incident at zero degrees are now overswept and hit the side of the detector, or fall on the "wrong" anode half. By plus or minus 15 degree incident angle (Figs. B-18 and B-18) this effect is more severe. From these trajectory plots, we determine that for optimum detector operation, the angle-of-attack (angle between the rocket velocity vector and the detector axis) should be less than 10 degrees. Useful data can still be obtained at an angle-of-attack of up to 15 degrees, but corrections due to oversweeping, etc. become significant error factors in the data analysis.

A 3-D dust particle trajectory model was used to determine the actual acceptance area for various angles-of-attack, the results of which are listed in Table 3.2. The detector model used in this simulation is simplified from the 2-D electrostatic model described above. The 3-D electrostatic model of the detector is basically three stacked potential "boxes" with sides at different potentials to simulate the anode and electrodes. The electric field at all points inside the detector is computed from the analytical solution of the potential inside a box with five sides at 0 V and one side at a potential V [Jackson, 1975]. Particles are started in a grid pattern at the top of the detector, and the acceptance area is determined by the number of particles which make it to the anode. A plot of particle hits for an incident
Figure 3-3: Dust particle anode hit pattern for grid of 64 equally spaced 20 eV particles incident at zero degrees at top of detector.

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>Acceptance area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3.2: Calculated (simulated) detector acceptance area vs. angle of attack.

angle of zero degrees is given in Fig. 3-3. Figs. 3-4 and 3-5 show dust particle anode hits for incident angles of 5 and 10 degrees, respectively.

Detector Current Model

The 3-D model of the detector output signal (the difference between the dust current collected by the two anodes) was used to simulate the sensitivity of the detector to angle-of-
Figure 3-4: Dust particle anode hit pattern for grid of 64 equally spaced 20 eV particles incident at 5 degrees at top of detector.

Figure 3-5: Dust particle anode hit pattern for grid of 64 equally spaced 20 eV particles incident at 10 degrees at top of detector.
attack and dust particle flight time through the detector. A random particle distribution, weighted to the predicted dust mass/density population derived in Chapter 2, was used to determine the particle flux to the detector. Sample plots of the dust output signal vs. time over one oscillation cycle are given in Figs. 3-6, 3-7, and 3-8. The strange shape of the current signal is due to the multiple dust particle masses: some particles are overswept (effectively clipping the dust output sine wave), some underswept. The output current is the sum of all these particle types.

The phase of the detector output current with respect to the oscillation phase can be affected by the dust particle’s flight time through the detector. The particle flight time is 0.13 ms, determined by the distance between the beginning of the oscillating field and the anode ($\approx 10$ cm) divided by the rocket velocity ($\approx 770$ m/s). The electric field oscillation frequency of 1 kHz corresponds to a period of 1 ms. The flight time of the particle through the detector therefore results in a phase shift between the oscillation cycle and the output signal, as can be seen in Fig. 3-6. If the phase shift is not removed, a portion of the signal is lost with the rectification and integration, as the integrators will add a “negative” part of the signal. This phase shift was nulled in the detector electronics.

This 3-D collected current model was also useful in determining the actual response of the electronics integration to angle-of-attack effects in the detector current. As can be seen in Figs. 3-7 and 3-8, the result of a non-zero angle-of-attack is that the differenced anode signal becomes lopsided. Because of the rectification scheme, this effect is averaged out: the first half of the cycle may contribute less to the total signal, but the second half contributes more, resulting in a signal approximately the same magnitude as a zero angle-of-attack signal. This is true for angles-of-attack less than about 10 to 15 degrees, as discussed in the
Figure 3-6: Detector current, anode A minus anode B, for one sweep of the electrode potential. Relative phase of the sinusoidal oscillation with respect to the detector output is shown (dashed line).

3.3 Detector Design

This section describes the mechanical and electrical design of the dust detector flown on the SAL rocket. The detector was mounted on the fore deck, uncovered by the nosecone ejection. The electronics for the detector were mounted on the aft side of the fore deck, with signal lines passing through the deck. The detector itself was electrically insulated from the deck plate and biased at a reference potential, defined as the average potential of the four electric field experiment floating spheres. The rationale for this biasing scheme will be discussed in Chapter 4. The dust detector is a ram-based instrument, so the payload was flipped at apogee using the ACS system for operation of the detector on the downleg trajectory. The detector was designed to sample the charged dust population at a spatial
Figure 3-7: Detector current (anode A minus anode B) for one sweep of the electrode potential for particles with an incident angle of 5 degrees. Relative phase of the sinusoidal oscillation with respect to the detector output is shown (dashed line).

Figure 3-8: Detector current (anode A minus anode B) for one sweep of the electrode potential for particles with an incident angle of 10 degrees. Relative phase of the sinusoidal oscillation with respect to the detector output is shown (dashed line).
resolution of \( \approx 6 \) m, corresponding to a sampling rate of 125 Hz (8 ms sample period). At apogee, a mode change allowed the detector to step through a range of (negatively charged) dust masses, determined by the voltage of the rejection screen at the entrance to the detector. Besides the apogee mode change, the payload Attitude Control System (ACS) system was designed to align the payload to within a few degrees of the velocity vector at an altitude of 87 km, minimizing the angle-of-attack through the predicted dust layer. The following sections describe the detector components in detail.

### 3.3.1 Mechanical Design

Mechanical drawings of the dust detector are given in Appendix A. For the SAL flight, the dust detector footprint was a 10 cm x 10 cm area on deck 1 of the payload. Nosecone clearance requirements restricted the detector height to 20 cm. The dust detector body, electrodes and ground screen frames were constructed from aluminum; since there were no weight restrictions for the SAL flight the detector box was made from solid aluminum pieces. All detector parts, except the flight electronics circuit boards, were fabricated in-house.

**Detector Components**

The grounded screen holders used a tongue-in-groove design to secure the screens to the holders (see Figs. A-3, A-4, A-5, A-6, A-7). The design for the bias screen holder used a third aluminum frame piece to ensure good electrical connection to the screen. The screens themselves were 30 line/inch 0.001" nickel wire mesh. The electrode design was based on electrostatic modeling of the detector potentials, using the ELECTRO software. The dogbone-shape of the electrodes was chosen to both to avoid sharp edges (and associated
fringing fields) and to keep the electric field between the electrodes as uniform as possible (Fig. A-1). The overall effect of the bone-shaped electrodes (vs. flat electrodes) on dust trajectories is fairly small, however, and should not influence the design of future detector with restricted space or weight requirements. The detector anode was etched from a tinned circuit board, fabricated in-house. The separation between the two halves of the anode was 1 mm. Wires soldered onto the anode surface, near the edge of the detector, carried the collected current to the preamplifier, which was located directly below the anode. These wires also carried the +5V bias voltage to the anode.

Battery Box Design

After construction of the flight detector it was determined that noise from the detector electronics DC/DC converter was contaminating the preamplifier bias voltages, adding noise to the preamplifier output. A set of lithium batteries was attached to the side of the detector box to bias the anode, detector, and accelerating screens. Electrode voltages and stepped rejection (veto) voltages were generated by the original detector electronics. The battery box consisted of a hollowed-out aluminum slab containing six 3V lithium batteries, connected in series, and voltage dividers to generate the appropriate detector voltages. The box was filled with RTV potting compound to prevent mechanical failure of the wire connections.

Voltages from the battery pack were used to bias the accelerating screens, anode, and detector box (at the plasma reference potential). The voltages of the accelerating screens were modified from the original design to accommodate the limited number of signal wires from the battery pack: voltages were changed to zero volts (reference potential) and +2.5V. The change in biasing potentials did not affect detector performance, as confirmed by sim-
ulations and vacuum chamber testing.

3.3.2 Electrical Design

Space on the bottom side of deck 1 was reserved for most of the dust detector electronics; the preamp was contained inside the detector box. An umbilical cord connecting the detector to its electronics box below deck carried bias voltages for the veto screen, the detector reference potential for the battery pack, oscillating voltages for the electrodes, and the detector output from the preamp. The output from the preamp was carried on shielded coaxial cables, to protect the signal from pickup of payload and 1 kHz noise. The 1 kHz driving frequency is also carried by coaxial cable to prevent 1 kHz contamination of bias voltages and grounds.

Preamplifier and Electronics Description

A schematic of the preamplifier circuit and a flow chart describing the detector electronics are given in Appendix A. The preamplifier was designed for high gain, low noise operation, using TLC 2202 and TLE 2062 operational amplifiers in the three gain stages. The inputs to the preamp from the anode are AC coupled to remove the +5V bias potential from the dust signal. The first stage of the preamplifier is an integrator operating as a current-to-voltage converter, with a gain such that 1 pA input current results in 1 µV output voltage. The second and third stage amplifiers each have a gain of 100. The third stage amplifiers operate as differential amplifiers, the output of which is the difference between anode A and anode B; the two outputs of the preamplifier correspond to the differences A-B and B-A (see Fig. A-8).
This signal is carried by the umbilical cord connecting the detector to its electronics box to the synchronous detection circuit, shown in the block diagram in Appendix A. A sine wave at the same frequency and phase as the driving signal (1 kHz) of the detector electrodes is used to generate a square wave in phase with the driving frequency. This square wave serves as the trigger for a digital switch, which chooses which of the preamp outputs to feed to the final integrator, either A-B or B-A. The result is that the differential signal from the anodes is rectified and integrated in phase with the driving oscillation frequency. The phase of the square wave trigger pulse with respect to the driving frequency can be adjusted to account for the dust time-of-flight through the detector. The synchronous detection scheme is described in detail in Horowitz & Hill (1989).

The final output of the detector is this rectified, synchronously detected signal integrated over 8 sweep cycles (8 ms). There were four different integrators, each with a different gain, corresponding to an output of 10 pA/V, 30 pA/V, 70 pA/V, and 200 pA/V. Each integrator is reset every 8 sweeps by a trigger pulse synchronized to the oscillation frequency. The output from each integrator (negative) is inverted and clipped to a 0-5 V output signal, sent to telemetry.

Reference Potential

The detector is electrically isolated from the rocket payload and floats at a reference potential, defined as the DC average of the 4 electric field probe spheres. Since the electric field preamplifiers are high impedance, each sphere assumes the floating potential which is on the order of \(-5kT_e/e\), or \(-88\text{mV}\) at 200 K. Because the kinetic energy of the rammed dust is on the order of 10 to 20 eV, changes in the payload potential of several volts could affect the
dust collection. Floating the detector at the reference potential removes this dependence. The screen, anode and electrode voltages are all biased with reference to this potential, rather than the payload ground. A voltage proportional to the detector reference potential was sent to telemetry for use in data analysis.

Noise Reduction

The synchronous detection method eliminates noise sources different from the driving frequency, and is only marginally sensitive to 1 kHz noise out of phase with the driving frequency. The major noise contribution to the output signal is pickup from the driving 1 kHz signal, which tends to contaminate the bias potentials and grounds despite the coaxial cable shielding. Since the preamp gain is very high, any contamination of the bias voltages carried by the umbilical cord can translate into significant output signals. This effect resulted in a 0.5 V DC offset (corresponding to a 5 pA dust signal on the high gain channel) over the 0-5 V detector output. A portion of the dust signal did fall below this 0.5 V "zero" current offset; explanations for this result will be considered in Chapters 4 and 5.

Veto Screen

After the apogee maneuver, a timer-commanded mode change allowed the dust detector to attempt a crude dust mass analysis on the downleg trajectory. The (rejection) veto screen, sandwiched between the two grounded screens at the entrance to the detector, was biased at four different negative voltage steps to screen out specific mass ranges of negatively charged dust particles. The successive veto screen steps of -1.5 V, -3 V, -6 V and -9 V occurred at the sample rate of 125 Hz, meaning that the spatial resolution of each mass range of
dust particles would be \( \approx 24 \text{ m} \) (instead of 6 m) on the downleg. The veto screen stepping voltages also introduce a small amount of noise to the detector output signal. The range of available detector voltages limited the maximum voltage step to only -9 V, much less than the rammed kinetic energy of the assumed nominal dust particle (20 eV). In case of a large population of low mass, negatively charged dust particles, changes in the detector output over the veto screen steps would distinguish this population. This mass stepping was designed to screen out only negatively charged particles; positively charged dust particles would not be affected.

3.4 Laboratory Calibration

The prototype and flight dust detectors were calibrated in-house using a low energy electron gun (10 to 100 eV), positioning table and vacuum chamber. Charged dust particles were simulated with electrons of comparable kinetic energy to an incident dust particle (see Table 3.1). The goal of calibration was to verify the angular and energy acceptance simulations described earlier. Since electrons have a very short time-of-flight in the detector, being much less massive than a dust particle, the time-of-flight phase correction for dust particles was set to zero for these tests. Data were acquired from the dust detector electronics using an A/D converter board, so that signals mimicking those to be sent to telemetry would be monitored.

The goal of the laboratory calibration was proof-of-concept, not a direct calibration of the detector parameters, since fast, heavy charged particles were not available in the lab. However, a cursory examination of the detector angular and energy acceptance was done in the vacuum chamber; the results are outlined below.
Angular Acceptance Calibration

One shortcoming of the laboratory calibration was the operation of the electron gun at low energies. At low energies (10-20 eV) the gun output was fairly weak, so it had to be positioned within a few centimeters of the detector entrance. Since in this configuration the gun was basically a point source, the laboratory measurements did not adequately simulate the uniform dust distribution expected during the rocket flight. The results of the detector performance vs. pitch angle with respect to the detector axis are given in Fig. 3-9. There is a distinct drop-off in detector performance at angles-of-attack greater than 10 degrees, but because of the position of the gun, the severe decrease in detector performance predicted by the simulations (given in Table 3.2) was not observed.

Energy Acceptance Calibration

A plot of the energy acceptance of the detector is given in Fig. 3-10. The gun current output at low energies (below about 50 eV) varied significantly with energy; high energies had a significantly higher electron flux than low energies. The angular spread of the electron beam was smaller at higher energies, tending to increase the flux of high energy electrons entering the detector at the correct angle. In Fig. 3-10 these effects have been corrected for (as much as possible), and the calibration confirms the simulated detector energy acceptance discussed in the previous section. The peak acceptance energy of the detector is \( \approx 14-20 \) eV, with a significant reduction in the measured current for higher and lower energies.
Figure 3-9: Laboratory calibration of detector angular acceptance. Detector output given as a fraction of total output at an incident angle of 0 degrees.

Figure 3-10: Laboratory calibration of dust detector energy acceptance. Detector output given as a fraction of the total output at an incident electron energy of 14 eV.
3.5 Summary

In this chapter we have described the design and simulation of the charged dust detector, and verified its performance via laboratory testing. The dust detector described here was designed to measure a small population of negatively charged, nanometer-sized dust particles, the population predicted by the steady state model of Chapter 2. In the following chapters we discuss the results from the flight of the SAL dust detector which indicate the presence of a dust population different from the one predicted.
Chapter 4

Observations and Analysis

4.1 The Sudden Atom Layers Sounding Rocket

The Sudden Atom Layers sounding rocket was launched from Puerto Rico on the evening of February 19, 1998, at 8:09:02 LT. In this chapter we discuss the mesospheric conditions at the time of the rocket launch, as determined by radar and lidar measurements at the Arecibo Observatory, and present in-situ data from the SAL experiments. Several SAL instruments did not perform as expected; data from successful instruments is presented below.

4.1.1 Mission Description and Instrumentation

The main scientific goal of the Sudden Atom Layers (SAL) sounding rocket was an in-situ measurement of ionospheric and atmospheric conditions during a sporadic sodium layer (Na\textsubscript{s}) event. The payload instruments included a charged dust detector to measure mesospheric dust over a mass range of 1000 - 10,000 amu, a Langmuir probe operating as a Fast Temperature Probe to measure plasma density and electron temperature, a plasma frequency and DC probe to measure absolute electron density, electric field booms to measure fields from DC to 5 kHz, telescopes to measure sodium airglow, photometers and lamps to measure neutral sodium and potassium densities, and a positive ion mass spectrometer. A TMA (tri-methyl-aluminum) rocket was launched 20 minutes later to measure the neutral
Figure 4-1: Sporadic Atom Layers payload schematic.
wind profile.

4.1.2 Launch Conditions

The SAL rocket (21.117) was launched from a temporary rocket range at Tortugauro Beach, Puerto Rico on the evening of February 19, 1998 at 20:09:02 LT. The SAL rocket flew through a neutral background sodium layer stretching from 80 km to over 105 km altitude containing thin Na\textsubscript{s} layers at 94 km and 97 km. The peak sodium densities in the layers were 6000/cc and 4000/cc, respectively, as determined by the Arecibo sodium resonance density lidar. Fig. 4-2 shows the all-night lidar measurement taken at Arecibo for the evening of Feb. 19. The Arecibo radar measurement of the electron density for the evening of Feb. 19 is shown in Fig. 4-3. At the time of the rocket launch two ionization layers were present, one intermediate layer at \(\approx\)115 km and one sporadic E (E\textsubscript{s}) layer at \(\approx\)92.5 km. The rocket apogee was 115.5 km, so no reliable data is available for this upper layer. The lower E\textsubscript{s} layer had a peak density of 25,000/cc, and occurred near the bottom edge of the lower Na\textsubscript{s} layer. The upper Na\textsubscript{s} layer disappeared shortly after the conclusion of the rocket’s flight, as did the 92.5 km E\textsubscript{s} layer. The lower Na\textsubscript{s} layer remained visible to the lidar through the night, slowly descending to 92 km. In Fig. 4-4 we plot ground observations of the plasma density and sodium atom density integrated over the rocket flight. The TMA rocket launched approximately 20 minutes after the SAL rocket flight characterized the mesospheric neutral winds. The TMA trails released by the rocket on its upleg and downleg trajectory were monitored on the ground at several sites on the island. Triangulation of the TMA trail diffusion determined the altitude profile of the neutral winds. The resulting wind profiles had a broad maximum toward the east between 104 and 108 km, a large shear below 104 km,
Figure 4-2: All night lidar return February 19, 1998.
Figure 4-3: All night radar return February 19, 1998.
Figure 4-4: Arecibo ground observations of plasma and neutral sodium density integrated over the rocket flight.
and a wind reversal with a maximum westward wind between 94 and 96 km. The eastward maximum was approximately 100 m/s, the westward maximum near 90 m/s (M.F. Larsen, pers. comm., 1998). Fig. 4.1.2 shows a schematic of the east-west wind profile.

4.2 Data Presentation

4.2.1 Dust Detector

In this section we present the data from the SAL dust detector, which was described in Chapter 3. The raw data from the dust detector on the rocket upleg and downleg is shown in Fig. 4-6; data is shown in the altitude range from 85 to 100 km. Note that all plots of dust data are in units of collected current, rather than charge density. Positive current corresponds to negative dust, as explained in Chapter 3. The altitude range of optimum detector operation was from 85 to 100 km; ACS noise on the rocket upleg, and re-entry noise on the downleg contaminate the dust data below 85 km, and the rocket’s angle of attack (the angle between its velocity vector and symmetry axis) was too large for proper detector operation above 100 km altitude. The sample rate was 125 Hz, and given an average rocket velocity of 770 m/s, the altitude resolution of the dust data is approximately 6 meters.

The raw data show an ≈5 pA DC offset, which is caused by synchronous noise integration, as discussed in the previous chapter. The circuit which generates the sinusoidal voltage oscillation for the detector electrodes contaminates the ground and signal wires with a small in-phase sine wave, which the integration electronics amplifies. This 5 pA DC offset proved advantageous, as the interesting portion of our dust signal was below this “zero” level. This indicates that there was a sign change in the charge collected by the detector,
Figure 4-5: Schematic of neutral wind profile 20 minutes after SAL flight. Solid line is east-west wind, dashed line meridional winds. (Courtesy M.F. Larsen, Clemson University.)
Figure 4-6: Raw dust detector data (collected current in pA) measured on the rocket upleg and downleg trajectory.

Figure 4-7: Frequency analysis of dust detector signal over the altitude range from 88 to 95 km on rocket upleg and downleg trajectory.
occurring at an altitude of 90 km. As discussed in Chapter 3, the detector should have been insensitive to the actual sign of the incident charged dust particle, and the output signal should always have been positive with respect to the DC offset “zero”. We attribute the sign change in the measured dust current to dust-anode impact phenomena, probably due to fracturing of the dust particle. Using this interpretation of the dust detector operation, we conclude that there is a large positive dust layer, from 90 to 94 km, with a small negative dust layer from 89 to 90 km. We will discuss this interpretation in detail in Chapter 5.

Missing Data Reconstruction

A significant positively charged dust current was measured in the altitude range between 90 and 94 km. A portion of this raw dust data is cut off at the hard zero (0V) level, as seen in Fig. 4-6. A frequency analysis of the dust data, shown in Fig. 4-7, shows a flat Gaussian noise spectrum for the upleg trajectory, and a flat Gaussian spectrum with a superimposed 4 Hz source on the downleg trajectory. The 4 Hz noise is an artifact introduced by the veto screen stepping electronics, and is not physical. The standard deviation calculated for segments where there is no missing (cut off) data is constant, at about 2.9 pA. We can “reconstruct” this data, for the purposes of taking running averages without averaging in too many false zeros, by replacing the zeroes with a Gaussian noise distribution matching the rest of the data. The Gaussian reconstructed dust data is plotted in Fig. 4-8.

Spatial Resolution vs. Noise Reduction

Although the data was taken at 6 meter intervals, the low signal to noise levels at this scale prevents drawing any conclusions about the dust structure at small spatial scales.
Figure 4-8: Gaussian reconstruction of dust detector data (collected current in pA) measured on the rocket upleg and downleg trajectory, DC offset removed.
Figure 4-9: Upleg and downleg dust data averaged over 10 samples (60 meter resolution).

The overall shape of the raw data suggests some possible larger-scale structures, as the amplitude of the reconstructed dust signal varies from -5 pA to 5 pA over a 5 km altitude range. If we integrate over several data points, the noise is reduced by a factor proportional to the square root of N, the number of samples averaged. We chose to reduce the data spatial resolution to approximately 60 meters, which improves the signal to noise by a factor of 4. By using the Gaussian reconstruction of the dust data, we can accurately represent the dust current when taking this average. At a spatial resolution of 60 meters, the noise level is reduced to a standard deviation of approximately 0.7 pA. Plots of the averaged (60 meter resolution) dust data are shown in Fig. 4-9.

Downleg Mass Analysis

The raw downleg data is noticeably noisier than the upleg data, a feature which can be traced to the stepping of the veto screen, which introduced a 4 Hz component to the
detector noise spectrum (see Fig. 4-7). The 4 Hz component is constant through the downleg trajectory, and starts when the apogee mode change is activated, so although we were not able to pinpoint the source in the detector electronics, we are able to attribute it the the screen stepping. We remove this component of the dust signal using a reconstructed FFT.

The purpose of the veto screen was to reject ranges of low-mass dust particles, an attempt at a mass analysis of the charged dust population. If there exists a significant distribution of low mass negatively charged dust, the detector output should change between the different veto screen steps. The dust data subdivided into veto step segments is plotted in Fig. 4-10. The altitude resolution of the raw downleg data in this case is 24 meters, since each veto voltage step occurs every 4th data point. Averaging over 10 cycles to reduce the Gaussian noise by a factor of 4 gives 240 meter resolution. There does not appear to be any variation in the detector output from step to step consistent with the rejection of any specific mass range of negative dust. The veto screen does not give any mass information if the incident dust particle is positively charged. Since, judging from the plots in Fig. 4-10, it is not useful to separate the downleg data into its individual veto components at the expense of spatial resolution, we prefer to look at the downleg data as a whole and keep the spatial resolution comparable to the upleg data.

Rocket Angle-of-Attack Correction

The averaged dust data presented in Fig. 4-9 shows a difference in amplitude between the upleg and the downleg data, which can be attributed to the rocket angle-of-attack. The calculated detector acceptance area vs. angle-of-attack was listed in Table 3.2. The rocket angle of attack varied throughout the flight: the ACS goal was to point the payload to within
Figure 4-10: Dust data for each veto step on downleg trajectory. 4 Hz noise component has been filtered out, data averaged over 10 samples (240 meter resolution).
a few degrees of the velocity vector at an altitude of 87 km. Simulations and laboratory measurements of the dust detector showed that the detector operation is acceptable at an angle-of-attack of less than about 15 degrees, with optimum performance when the angle-of-attack is less than 10 degrees. The actual angle-of-attack of the SAL rocket is shown in Fig. 4-11, verifying that the dust detector response should be reliable for altitudes less than 100 km. The angle-of-attack differed significantly between the upleg and downleg trajectories, at about 2 degrees at 92 km on the upleg and 8 degrees at 92 km on the downleg. The acceptance area of the detector begins to drop off noticeably below 5 degrees; the difference in acceptance area between the upleg and downleg trajectory is about 15 cm².

The dust data corrected for angle-of-attack is plotted in Fig. 4-12, where now the dust data is given in units of charge density rather than collected current. The charge density is calculated from:

\[ \rho = \frac{I_{dust}}{A_{detector} v_{rocket} \epsilon} \]  

(4.2.1)

where \( I_{dust} \) is the collected current, \( A_{detector} \) is the acceptance area of the detector (which varies with angle-of-attack, as described in Chapter 3), and \( v_{rocket} \) is the rocket velocity. In this calculation, we have assumed that each dust particle contributes a single charge to the collected dust current, an approximation we will discuss further in Chapter 5. The upleg and downleg charged dust profiles shown in Fig. 4-12 are quantitatively similar, implying that the charged dust layer was stable over the course of a few minutes. The horizontal separation between the measurement of the upleg and downleg dust profile, assuming a horizontal rocket velocity of 350 m/s, was approximately 50 km.
Figure 4-11: Rocket's angle-of-attack for upleg (solid) line and downleg (dashed line).

Payload Potential Gradient

Some of the remaining large-scale structure in the dust data shown in Fig. 4-12 can be attributed to changes in the payload potential gradient, the derivative of the payload potential. The detector was biased with respect to the plasma reference potential, instead of the payload ground, as was mentioned in Chapter 3. This was done to prevent the detector from responding to changes in the payload potential as it passed through the $E_s$ layer. Figs. 4-13 and 4-14 show that this biasing scheme worked as expected: the payload potential changed by over 1 volt in passing through the $E_s$ layer, yet the dust detector showed no response. There is a small secondary detector response to this biasing scheme, which can be removed in data processing. The AC coupling between the detector preamplifier and the detector reference ground, used to avoid detector response to the DC payload potential, does not prevent a detector response from fast changes in the payload potential. There are
Figure 4-12: Upleg and downleg dust data, corrected for angle-of-attack, averaged over 10 samples (60 meter resolution). Dust data is now presented in units of charge density, calculated using rocket velocity and acceptance area. 4 Hz noise component has been removed from downleg data.
several examples of this effect throughout the flight, one of which occurs inside the dust layer, and must be corrected for: as the rocket passed through the \( E_a \) layer, the payload potential changed quickly from \(-1 \) V to \(-2 \) V, causing a small, non-physical variation in the detector signal.

To calibrate this payload potential gradient effect, we looked at the payload potential gradient and dust detector data in an area where the rocket angle-of-attack was such as to prevent the dust detector from measuring any particles. The payload gradient effect is illustrated during a few seconds at the beginning of the flight, where the electric field booms had been deployed but the ACS system was still operating, causing the reference potential to oscillate quickly. Fig. 4-15 shows the dust detector current compared to the payload potential and the gradient of the payload potential during this upleg ACS maneuver. The dust detector response is clearly correlated with the derivative of the payload potential (bottom Fig. 4-15), rather than the payload potential itself (top Fig. 4-15). The magnitude
Figure 4-14: Downleg dust data (4 Hz noise component removed) and payload potential.

Figure 4-15: Dust detector current and (top) payload potential (blue line, units of 5*Volts), (bottom) payload potential gradient (blue line, units Volts/sec.) during upleg ACS maneuver.
Figure 4-16: Final processed dust detector data in units of charge density, corrected for all effects mentioned in Section 4.2.1.
of the dust detector response due to payload potential changes was derived from this data segment. Using the calibration from this period in the rocket flight, we can subtract the derivative of the payload potential from the dust current in the region of the $E_z$ layer, where payload charging caused a steep gradient in the payload potential. The final processed dust detector data is given in Fig. 4-16, corrected for angle-of-attack, with the data reconstructed and averaged over 10 samples to give 60 meter resolution, the 4 Hz noise component removed from downleg spectrum, and the payload potential gradient removed.

Summary of Dust Data

The dust data presented in Fig. 4-16 show that there is a thin layer of negatively charged dust below 90 km, and a broad layer of positively charged dust stretching from 90 to 94 km. The upleg and downleg charged dust profiles are remarkably similar, to within the resolution of the instrument, indicating that the charged dust layer is stable over a time scale of at least a few minutes. Some differences in the dust layer structure between the upleg and the downleg data are still apparent; whether they are significant with respect to the noise level is unclear. We will neglect this smaller scale structure in favor of discussion of the characteristics of the overall dust layer, which we will continue in Chapter 5.

4.2.2 Electric Field Experiment

Instrument Description

In this section we present electric field data from the SAL flight, which used the standard Cornell electric field detectors (see payload schematic, Fig. 4-1). A set of four 1.5 meter Minnesota-type booms were used in the aft experiment section to deploy the system, which
<table>
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<th>Channel</th>
<th>Gain</th>
<th>Low Cutoff (Hz)</th>
<th>Hi Cutoff (Hz)</th>
<th>Offset (Volts)</th>
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<td>19.9</td>
<td>5.1k</td>
<td>2.52</td>
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<tr>
<td>HF34</td>
<td>91.6</td>
<td>19.7</td>
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<td>2.53</td>
</tr>
<tr>
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<td>5.0k</td>
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</tr>
<tr>
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<td>20.0</td>
<td>5.1k</td>
<td>2.49</td>
</tr>
<tr>
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<td>0</td>
<td>1.0k</td>
<td>2.54</td>
</tr>
<tr>
<td>V34M</td>
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<td>0</td>
<td>1.06</td>
<td>2.53</td>
</tr>
<tr>
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<td>1.01</td>
<td>2.60</td>
</tr>
<tr>
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<td>851</td>
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</tr>
<tr>
<td>V34H</td>
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<td>0</td>
<td>871</td>
<td>2.52</td>
</tr>
<tr>
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<td>0</td>
<td>756</td>
<td>0.719</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of Cornell University SAL experiment.

used high impedance electronics and carbon-coated spheres to measure fields from DC to 5 kHz. A summary of the experiment’s telemetry channels and their characteristics is given in Table 4.1.

Low Gain Channels

Raw data from the low gain electric field channels, V12M, V14M, and V34M on the upleg and downleg trajectory are shown in Figs. 4-17, 4-18, and 4-19. The raw data has a 1 Hz sinusoidal modulation corresponding to the spin frequency of the payload. The upleg ACS maneuver ended at approximately 86 seconds after launch, at an altitude of 88 km, so electric field information below that altitude is poor. The apogee ACS maneuver occurred between 160 and 170 s, and is not shown here. Re-entry effects begin to contaminate the downleg data at approximately 255 seconds after launch, at an altitude of 85 km.
Figure 4-17: V12 low gain DC channel.

Figure 4-18: V14 low gain DC channel.
Waveforms and Noise Sources

A strong feature of the data shown in Figs. 4-17, 4-18, and 4-19 are high frequency (≈100 Hz) spikes superimposed on the data occurring every half spin. The waveforms of the two crossed-boom DC channels, V12 and V34, for a period during the rocket upleg trajectory are plotted in Fig. 4-20. The ≈100 Hz spikes are probably related to the operation of the Langmuir probe, discussed in the following section.

Comparing the waveforms of V12 and V34 shown in Fig. 4-20, it is apparent that the V34 channel is much cleaner than V12. This is attributed to a noisy sphere #2, as evidenced by comparing V14 data to V12 and V34. Data from V14, which confirms that it is the sphere #2 which is noisy, are shown in Fig. 4-21. Data from this channel are not useful for the remainder of the analysis, however, since the waveform is not sinusoidal.
V12 and V34 also exhibit this non-sinusoidal waveform shape, but to a lesser extent. This "double-exponential" waveform is probably due to low-density wake effects (M.C. Kelley, pers. comm., 1999).

Frequency analysis of the V12 and V34 channels showing these noise sources is presented in Fig. 4-22, taken over the time interval from 110-112 seconds after launch, where no geophysical wave activity is present. Note that the V34 channel noise spectrum is much smoother over the entire frequency range. The Langmuir probe pickup noise is strongest at 97 Hz and its harmonics. Since this 97 Hz noise and harmonics contaminate the electric field data at higher frequencies, we low pass filter the data at 97 Hz and focus on lower frequency wave activity. Low pass filtered upleg and downleg data for V12 and V34 with a 97 Hz cutoff are shown in Figs. 4-23 and 4-24.

DC Fields

Fig. 4-25 shows the orientation of the payload with respect to the Earth's magnetic field through the upleg and downleg trajectories. The major contribution to the measured DC field (the magnitude of the spin modulated electric field in Figs. 4-23 and 4-24) is from the $V \times B$ component of the electric field. The magnitude of the $V \times B$ component is given in Fig. 4-26. When this $V \times B$ field is spun up and removed from the measured electric field, the resulting DC electric field is on the order of 5 mV/m, as shown in Figs. 4-27 and 4-28. The upleg data is much less reliable measuring these small fields because the noise associated with the bad sphere (sphere #2) is proportional to the measured electric field. On the upleg the field is dominated by the $V \times B$ component, which is large, so the corresponding noise is also large. The downleg data is much more reliable because the $V \times
Figure 4-20: Waveforms of crossed-boom pairs V12 and V34 low gain DC channels.
Figure 4-21: Waveform of V14 low gain DC channel.

Figure 4-22: Frequency analysis of V12 and V34 over time interval 110-112 seconds after launch.
Figure 4-23: V12 low gain DC channel, low pass filtered at 97 Hz.

Figure 4-24: V34 low gain DC channel, low pass filtered at 97 Hz.
Figure 4-25: Orientation of payload with respect to the Earth’s magnetic field on upleg and downleg trajectory.

B field is smaller, meaning that the sphere #2 noise is smaller. Although the upleg data is less pleasing to display, it is in complete agreement with the downleg data in terms of where wave activity is present, where the DC fields change direction, and the overall magnitude of the fields.

The electric field data plotted in an orthogonal coordinate system with components parallel to B and perpendicular to B is shown in Figs. 4-29 and 4-30. The rotation of the electric field into a coordinate system perpendicular to B was done using the on-board magnetometers. The component of the electric field parallel to B is taken to be zero. The non-zero components of this coordinate system are defined to be in (a) the westward direction, and (b) the component of the right-handed coordinate system perpendicular to both B and west, in this case in the northward-upward direction. There are some overall trends in the DC electric field data: the eastward field is fairly constant at 2-3 mV/m through the altitude range of 92 to 115 km, and falls rapidly just below the E layer. There are some changes in the eastward field correlated with the neutral wind profiles.
Figure 4-26: VxB electric field.

Figure 4-27: Low gain DC channels with VxB electric field removed, upleg.
Figure 4-28: Low gain DC channels with VxB electric field removed, downleg.

Figure 4-29: Despun electric field in perp-B coordinates, upleg.
Figure 4-30: Despun electric field in perp-B coordinates, downleg.

discussed earlier in this chapter, most noticeably, the inflection points in the electric field at \( \approx 104 \) km, corresponding to an eastward maximum in the neutral wind speed, and \( \approx 94 \) km, corresponding to a westward maximum in the neutral wind. The other component of the perp-B field is in the southward-downward direction throughout the altitude range from \( \approx 90 \) km to 115 km, which is typical of the nighttime ionosphere [Kelley, 1989].

**High Gain Channels**

The electric field data in Figs. 4-29 and 4-30 show strong wave activity localized in the region of the \( E_s \) layer, in the 92 km to 93 km altitude range, present in both the upleg and downleg data. Data from the HF channels, plotted at an expanded scale, are shown in Fig. 4-31. The high frequency data is useful in locating the wave activity with respect
to the E, layer; the spin frequency on the low frequency channels makes the edges of the wave layer difficult to pick out easily. Unfortunately, no information above 100 Hz was gained from the high frequency channels because of the 100 Hz contamination attributed to the Langmuir probe operation. The high frequency channels were high-pass filtered with a cutoff frequency of 20 Hz, so information below this frequency was also lost. The peak wave power of the wave burst (discussed in the next section) was at a frequency of < 20 Hz (as measured in the moving frame of the rocket), so much of this information is missing from the high-frequency channels. No information was gained from the high gain channels (V12H and V34H), which had a DC offset which pushed them off scale through interesting parts of the flight.

Wave Fields

In Fig. 4-32 we plot the two downleg low frequency data channels, V12 and V34, as well as the magnitude of the wave electric field. The 1 Hz spin component has been removed from V12 and V34 data by over-smoothing and subtracting out the DC electric field spin component. The wave activity is confined to a finite wavelength range, from about 10 meters to about 50 meters, corresponding to wavenumbers between 0.6 rad/m and 0.1 rad/m. A spectral analysis of the electric field data is shown in Fig. 4-33. The wavelength and wavenumber were calculated by assuming:

(a) the wave is propagating perpendicular to B,

(b) the rocket velocity perpendicular to B (≈ 160 m/s eastward) is much greater than the phase velocity of the wave in this direction. The observed wave frequency in the rocket
Figure 4-31: High gain channels (downleg) vs. altitude near the E_s layer. Electron density taken by the Arecibo radar shows the location of the E_s layer with respect to the wave activity.
frame is \[Pfaff \textit{et al}., 1987\]:

\[
\omega_{\text{obs}} = k \cdot \mathbf{V}_R - k \cdot \mathbf{V}_\phi - k \cdot \mathbf{U}_N
\]  

(4.2.2)

where \( \mathbf{V}_R \) is the rocket velocity, \( \mathbf{V}_\phi \) is the wave phase velocity, and \( \mathbf{U}_N \) is the neutral wind velocity. Using assumption (b), the second term can be neglected. Gradient drift waves propagate parallel to the electron drift velocity \((\mathbf{E} \times \mathbf{B})\), which in this case is in the east-west direction, so only the zonal components of the rocket and neutral wind velocity contribute. Therefore,

\[
\lambda = \frac{V_{\text{zonal}}}{f} = \frac{V_R + U_n}{f}
\]

(4.2.3)

where \( f \) is the frequency of the wave observed in the moving frame of the rocket. The rocket velocity in Eqn. 4.2.3 is measured in the moving frame of the neutral wind, assuming a zonal wind speed of \( \approx 90 \text{ m/s} \) (westward), giving the motion of the rocket in the eastward direction at \( \approx 250 \text{ m/s} \) with respect to the neutral wind.

Also plotted in Fig. 4-33 is the frequency spectrum of a region just outside (below) the wave activity. The peak wave power occurs at a frequency of about 12 Hz in the moving rocket frame, corresponding to a wavenumber of 0.3 rad/m. Most of the 1 Hz spin component has been fitted and removed; the remaining spin frequency components can also be seen in the non-wave region plot (red line).

Figs. 4-34 and 4-35 show the wavelength and wavenumber spectra of the two downleg channels, V12 and V34, and the power law behavior beyond the spectral peak. For \( k > 0.7 \text{ rad/m} \) there is a power law with a slope close to \( k^{-3} \). This is typical of plasma gradient drift instability observations made on other rockets in the E-region \[Pfaff \textit{et al}., 1987\].
Figure 4-32: Low gain DC channels (downleg only), with the spin component of electric field removed, vs. altitude near the $E_s$ layer. Square root of the sum-of-the-squares electric field magnitude is also plotted in the right-hand panel.

*Kelley et al., 1995*. We will discuss the wave data in the context of gradient drift wave theory in Chapter 5.

**Wavelet Analysis**

The localized nature of the wave burst suggests that wavelet transforms may yield additional useful information. The rationale for using the wavelet technique is that the wave components can be localized in both frequency and time. This means that the spin frequency contamination seen in the FFT spectra can be separated spatially from the wave burst. The IDL code used to generate the wavelet spectra was written by Torrence and Compo (1995-96). Wavelet power vs. altitude and wavelength perpendicular to $B$ are shown
Figure 4-33: Spectral analysis of low gain DC channels on downleg trajectory, inside (upper, black line) and outside (lower, red line) the the E₄ layer.

Figure 4-34: Spectral analysis of V12 channel on downleg trajectory, showing $k^{-n}$ power law.
Figure 4-35: Spectral analysis of V34 channel on downleg trajectory, showing $k^{-n}$ power law.

Figure 4-36: Wavelet analysis of V12 channel on upleg trajectory. Wavelet power is plotted vs. wavelength (perpendicular to B) and altitude.
Figure 4-37: Wavelet analysis of V34 channel on upleg trajectory. Wavelet power is plotted vs. wavelength (perpendicular to B) and altitude.
Figure 4-38: Wavelet analysis of V12 channel on downleg trajectory. Wavelet power is plotted vs. wavelength (perpendicular to B) and altitude.
Figure 4-39: Wavelet analysis of V34 channel on downleg trajectory. Wavelet power is plotted vs. wavelength (perpendicular to $\mathbf{B}$) and altitude.
in Figs. 4-36, 4-37, 4-38, and 4-39. The broad red band at \(\approx 2\) m is from the spin component of the DC field. The \(\approx 150\) m noise (and its harmonics) every half spin due to contamination from the Langmuir probe, as was mentioned previously. The wavelet analysis shows the spatial scale of the wave burst on both the upleg and downleg. The noise from sphere #2 contaminates the upleg V12 data somewhat, but both the V12 and V34 data show that the wave burst occurs at the same altitude on the upleg and downleg trajectories. The wavelet analysis also confirms that the wave power peaks at a wavelength (determined by Eqn. 4.2.3) of \(\approx 20\) m. Examination of the individual wavelet components of the wave burst will be continued during the discussion of gradient drift waves in Chapter 5.

Payload Skin Potential

The payload skin potential, monitored on the V1S telemetry channel, is shown in Fig. 4-40. The payload potential changed dramatically as the rocket passed through the 92.5 km \(E_s\) layer, at 103 seconds on the upleg, and 243 seconds on the downleg trajectory. The change in skin potential seems to be related to electron collection by the Langmuir probe; this instrument will be discussed in the following section. It is possible that the presence of massive, charged dust near the \(E_s\) layer influenced charge collection by the payload or the Langmuir probe, resulting in the sharp increase in payload skin potential evident from Fig. 4-40. Other explanations for this payload charging effect including metallic ions are being investigated, but will not be presented here.
Figure 4-40: Payload skin potential on upleg and downleg. Measurement is potential of sphere #1 (plasma potential) minus payload skin potential, so the positive V1S reading corresponds to a negative payload potential.
4.2.3 Langmuir Probe

Instrument Description

In this section we present in-situ electron density data from the Langmuir probe on the SAL flight. A detailed description of this instrument, which was originally included on the payload as a Fast Electron Temperature Probe, is given in Sierfring (1998). The Langmuir probe consisted of a 1.5 cm carbon-coated sphere at the end of a 30 cm long fiberglass boom. The sphere was biased at 1V with respect to the plasma potential, as determined by the average of the four electric field spheres, similar to the biasing scheme of the dust detector described earlier. A 115 Hz, 280 mV (peak-to-peak) AC voltage modulation was applied to the sphere, and the collected current sampled at 8000 samples/s. Rather than sweeping a bias voltage to determine the current-voltage (IV) characteristic for the local plasma, as is typical of Langmuir probe operation, the probe was DC biased to put it in the electron retardation region of the IV curve. The ratio of the fundamental and second harmonics of the AC oscillation frequency determines the electron temperature, since this ratio depends only on the electron temperature and the amplitude of the voltage modulation. The amplitude of the first harmonic (amplitude of the RMS current) is proportional to the electron density.

Measured RMS current

The measured RMS current from the Langmuir probe is plotted in Figs. 4-41 and 4-42 for the upleg and downleg trajectories. The instrument switched to low gain mode inside the $E_s$ layer (note data spikes just above and below the observed $E_s$ layer), where the plasma
density is highest. Instrument saturation was a problem in some regions both inside and outside the $E_s$ layer; data from these regions is not useful. There is also a strong 2 Hz (twice spin) modulation in the data, which has not been explained.

Fig. 4-43 shows the Langmuir probe waveform in a non-saturated region, and Fig. 4-44 shows a frequency analysis in a non-saturated region of data on the upleg trajectory. Looking at these two plots, it is obvious that the ratio of the first to the second harmonic is much higher than expected; in fact the second harmonic (at 230 Hz) is several orders of magnitude smaller than the first. This corresponds to an impossibly large electron temperature if the analysis of the probe operation by Siefring (1998) is followed. Two (related) explanations for the failure to measure a reasonable electron temperature are that the instrument was not operating as expected at the low plasma temperatures, in this case around 200 K (/citeKelley89), or that the 1V DC bias put the probe operation in the electron saturation region of the current-voltage (IV) curve. In this latter case, the response of the probe to the voltage modulation would be almost linear and would produce no second harmonic.

Electron Density Measurement

If the probe was operating in the electron saturation region, it should be possible to extract some plasma density information from the data. Following Whipple (1981), the expression for the orbit-limited electron current collected by a positively biased probe in a plasma is given by:
Figure 4-41: Langmuir probe RMS collected current, upleg. Instrument switched to low-gain mode as it entered the $E_s$ layer at $\approx 102$ seconds.

Figure 4-42: Langmuir probe RMS collected current, downleg.
Figure 4-43: Segment of Langmuir probe RMS collected current showing waveform in a non-saturated region.
Figure 4-44: Frequency analysis of Langmuir probe RMS current in the time segment from 105 to 107 seconds after launch, where the instrument is not saturated.
\[ I_e = 4\pi R^2 n q \left( \frac{kT}{2\pi m_e} \right)^{\frac{1}{2}} \left( 1 - \frac{qV}{kT} \right) \]  \hspace{1cm} (4.2.4)

where \( R \) is the probe radius and \( V \) is the probe potential. For a sphere positively biased at 1 V immersed in a plasma with a density of 1000/cc and temperature of 200 K, the expected electron saturation current is \( \approx 0.16 \mu A \). This predicted current is several orders of magnitude higher than that observed, so some other effect must be limiting the collected electron current.

**Payload Effects**

Comparing Fig. 4-40, the payload skin potential measurement, with the Langmuir probe RMS current in Fig. 4-45, it appears that the electron collection by the Langmuir probe drives the payload skin potential negative. Judging by the shape of the \( E_s \) layer recorded by the Langmuir probe and the payload skin potential (Fig. 4-46), the payload appears to have a characteristic RC time constant of approximately 500 ms. This could be caused by a delay in the ion collection as the rocket traverses the \( E_s \) layer.

**In-situ Sporadic-E Layer Height**

Although the Langmuir probe did not supply any electron temperature information, and the collected current magnitude is problematic, it does provide an important in-situ measurement of the altitude and width of the \( E_s \) layer. The Arecibo radar measurement of the sporadic E layer is subject to systematic altitude errors due to signal delay times, radar look angles, etc., and the altitude resolution of the measurement is 150 meters. In addition, the altitude of the \( E_s \) layer may vary between the rocket position and the radar location.
Figure 4-45: Magnitude of Langmuir probe RMS current vs. seconds after launch on upleg and downleg, smoothed over 100 samples to reduce noise.
Figure 4-46: Shape of skin potential (upper line) and FTP RMS current magnitude (lower line) vs. time through the $E_s$ layer on the upleg trajectory.
Figure 4-47: Langmuir probe RMS current and Arecibo radar data vs. altitude on upleg trajectory. Langmuir probe data smoothed over 100 samples.

All these factors make it difficult to identify the absolute altitude of the layer at the location of the payload. Locating the layer in the rocket frame becomes especially important when considering possible meter-scale gradient drift wave activity on the topside of the Eₙ layer, as will be discussed in Chapter 5. The layer altitude was determined using the Langmuir probe RMS current; the Arecibo radar measurement was normalized to this altitude. Figs. 4-47 and 4-48 show the Langmuir probe RMS current vs. altitude on the upleg and downleg, and the Arecibo radar measurement, which has been adjusted in altitude by about 0.5 km to match the Eₙ peak recorded by the probe.
Figure 4-48: Langmuir probe RMS current and Arecibo radar data vs. altitude on downleg trajectory. Langmuir probe data smoothed over 100 samples.
Figure 4-49: Upleg sodium density profile taken by Arecibo lidar (solid line) and by in-situ sodium airglow (dashed line).
4.2.4 In-situ Sodium

The in-situ relative neutral sodium density was measured by telescopes on the rocket upleg and downleg trajectory. Sodium nightglow emission is produced by the Chapman mechanism [Chapman, 1939]:

\[
Na + O_3 \rightarrow NaO + O_2 \tag{4.2.5}
\]

\[
NaO + O \rightarrow Na^{(2}P_{\frac{1}{2}S}) + O_2 \tag{4.2.6}
\]

\[
Na^{(2}P_{\frac{3}{2}S_{\frac{1}{2}}}) \rightarrow Na^{(2}S_{\frac{1}{2}}) + h\nu \ (586.9 \ nm, 589.0 \ nm) \tag{4.2.7}
\]

Airglow brightness as a function of altitude was measured using a PMT with a filter centered around 5890 Angstroms (sodium airglow line). Differentiating (over about 1 km altitude thickness) gives the volume emission rate in photons/cm²s. This volume emission rate is proportional to the product of the Na and O₃ densities. The O₃ density is derived from the MSIS model of the O₂ density and the measured O density from the Larsen payload (21.119), flown 20 minutes after SAL. Neutral atmosphere and odd oxygen models are then used to get the sodium density. Since ozone (O₃) is in photochemical equilibrium at night the O₃ density can be calculated if the production and loss terms are known. O₃ is produced from O + O₂ and lost from the reaction of O₃ + H. The results from the upleg in-situ airglow measurement are shown in Fig. 4-49, normalized to and superimposed on the neutral sodium measurement taken by the Arecibo lidar. The slight rise in the airglow measurement near 85 km is probably due to some OH airglow that passes through the Na filter and has not been subtracted from the data. The 1 km altitude differentiation of the airglow data reduces the resolution of the in-situ measurement compared to the lidar measurement; the lidar observed a narrow sodium layer at 97 km which is not well distinguished in the in-situ
measurement due to this averaging (J. Hecht, pers. comm., 1999).

Other differences between the lidar and in-situ sodium density profiles are due to the different types of measurement. The lidar measurement depends on a resonant emission process which is able to measure only atomic sodium. Sodium airglow is a photochemical process, and can also be sensitive to molecular sodium or sodium attached to dust particle surfaces. The third sodium layer, measured by the in-situ sodium airglow, could therefore be an indication of either an Na$_2$ layer which does not exist at the location the lidar measurement is made, or a sodium-related chemical process, possibly a dust surface-sodium interaction.
Chapter 5

Discussion

In this chapter we discuss the SAL rocket data presented in Chapter 4, and relate the charged dust and electric field data to the ionospheric conditions at the time of launch.

5.1 Mesospheric Dust Measurement

In this section we study the results from the charged dust detector experiment, building on the theory developed in Chapter 2, and discuss the possible correlation between dust and sporadic atom layer (Na, a) formation.

5.1.1 Dust Fragmentation and Detector Charge Collection

In Chapter 2 we presented a model of the mesospheric dust population, and stated that the dust particles are likely to be charged, loosely-bound aggregates. This affects the operation of the dust detector, as discussed in Chapters 3 and 4; the collection of dust charge by the detector becomes much more complicated if the grains fragment upon impact with the anode. In this section we discuss the fragmentation probability and its influence on the collection of the dust charge.

Dust Fragmentation

The conditions for grain fragmentation in grain-grain collisions has been treated by Borkowski and Dwek (1995). If the collision energy exceeds a certain threshold, approximately equal to
$Am_pT/\rho$, where $A$ is the mean atomic mass in amu, $T$ is the tensile strength of the material, and $\rho$ is the material density, the particle will fragment on impact. The tensile strength of the material is proportional to the number of contact points between the individual initial smoke particles. Borkowski and Dwek (1995) calculate an approximate tensile strength by:

$$T = K_{IC}(\pi l)^{-\frac{1}{2}} = 2 \times 10^{11} \text{ dyn cm}^{-2}$$  \hspace{1cm} (5.1.1)

where $K_{IC}$ for a typical brittle material is $10^8$ dyne cm$^{-2}$ cm$^{1/2}$, and $l$ is the length of a “crack” in the material, in this case equal to the radius of the grain, $10^{-7}$ cm.

For silicates (the assumed dust composition, $A = 20$) with a density of 1 g cm$^{-3}$, the critical fragmentation energy for a small, brittle grain is $E_c = 4$ eV per atom. The binding energy of a silicate atom is 6.7 eV, so fragmentation can occur when collision energies are less than the binding energy of the dust grain. But this critical energy is still very large, considering that the dust particle contains several hundred atoms: on the order of 1-10 keV. This treatment of dust fragmentation is based on a “cracked crystal” model of the fragmenting grain, rather than considering the grain as an loosely-bound aggregate. Since the dust particle is unlikely to have a crystalline structure, the treatment outlined above overestimates the critical fragmentation energy of the dust particle.

Calculation of the tensile strength of such a porous dust grain has been attempted for interstellar aggregate dust particles [Greenberg et al., 1995, Mukai et al., 1992], and is considerably smaller than that calculated by Borkowski and Dwek (1995). In Greenberg (1995), the bonds of interstellar dust grains were approximated by a dipole-dipole bond, typical of ice. The tensile strength of solid ice is on the order of $10^7$ dyne cm$^{-2}$, and a loosely-
bound aggregate is several orders of magnitude smaller ($\approx 10^4$ dyne cm$^{-2}$). Using this estimate of the tensile strength of the dust grain, the critical energy for dust fragmentation is on the order of a few eV, depending on the mass and density of the dust particle.

**Mechanical Fragmentation**

Fragmentation of porous dust particles has implications for the operation of the dust detector, as discussed in Chapter 3. If the dust particle is a loosely-bound conglomerate of charged pieces, with a single net positive charge, mechanical or electrical disruption may affect charge collection by the detector anode. The field near the anode is such that low energy negatively charged particles are attracted to the anode; the potential difference between the screen and the anode corresponds to an electric field of $\approx 100$ V/m. If a charged dust particle hits the anode and fragments into multiple singly-charged pieces, the negative pieces will be collected by the anode, and the positive pieces will be pushed away, as illustrated in Fig. 5-1. This mechanism leads us to interpret the sign change in the collected current described in Chapter 4 as indicative of positively charged dust fragmenting at the anode.

**Dust Charge Collection**

If we assume a fragmentation model of charge collection by the dust detector, the dust charge density given in Fig. 4-16 must be taken as an estimate, rather than an absolute measurement of the in-situ dust charge density. Rather than a one-to-one correspondence between the number of charges collected and the number of dust particles collected, the measurement must take into account factors in the fragmentation process that are not known.
Figure 5-1: Illustration of charge collection from a multiply charged aggregate particle fragmenting on impact with the anode. The initial particle has a net positive charge.

These include the fragmentation probability, which itself depends on the particle composition and impact energy, and the number of charged pieces that make up the composite dust particle with its (presumed) single net charge.

Secondary Plasma Production

A common dust measurement technique used in space probes is the collection of secondary plasma produced by the impact of the dust particle with a metal surface. This is a useful method for heavy (micron-sized and larger) particles collected by fast-moving satellites (few km/s), but is less effective for rocket measurements of nanometer-sized particles. Secondary plasma production from particle impacts has been observed at low impact speeds, using cluster ions on clean gold targets at 10 km/s [Baragiola, 1994, Dalmann et al., 1977, Tegelhofer et al., 1993]. Using these data, secondary plasma production from high mass cosmic dust can be fitted over limited velocity ranges to \( Q/m = k \cdot v^B \), where \( B \approx 3.0 \). Plasma
production at lower velocities by higher mass particles has been extrapolated from these data, but the physics of secondary plasma production brings this assumption into question.

In addition to providing energy for ionization of the target material, the impact energy must also be available for heating of the target surface, excitation of vibrational modes, and compression of the dust particle, making ionization from low-energy surface impacts unlikely [Smith and Adams, 1973]. Smith and Adams (1973) describe the physical processes involved in plasma production from surface impacts, and note that while secondary production from projectiles with velocities of 1 km/s has been measured, the mass of the projectiles is on the order of $10^{-16}$ kg, much heavier than typical nanometer-sized mesospheric dust particles ($10^{-24}$ kg). The incident energy of these (for example, iron dust at 1 km/s) particles is $\approx 10^8$ eV, and only a fraction of this energy is available for ion-electron pair production. Smith and Adams give an ionization energy of $\approx 12$ eV for these target materials, though on average it takes $\approx 30$ eV to create an ion-electron pair in most materials [Encyclopedia of Physics, 1990]. Given the low energies involved in the SAL charged dust particle impacts, plasma production is not possible. Fragmentation of the charged aggregate particles into charged (and uncharged) pieces is energetically more likely than plasma production.

5.1.2 Photoelectrons, Photodetachment, and Positive Dust

Fig. 5-2 shows night terminator for the SAL rocket launch. The rocket was launched at $\approx 15$-20 minutes after sunset at 80 km. In Chapter 2, we discussed charging time constants for twilight ionospheric conditions, and found that the Lyman $\alpha$ flux just after sunset ($10^9$ cm$^2$s$^{-1}$) was sufficient to slow down the transition between daytime positive dust
to nighttime negatively charged dust. The daytime positively charged dust fraction was (roughly) estimated to be 7%; the nighttime negatively charged fraction was predicted to be on the order of 3-5%, depending on the dust particle size. At an altitude of 90 km, the photon flux is on the order of the electron flux to the dust particle for solar zenith angles less than \(\approx 120\) degrees. If the photoelectron (or photodetachment) efficiency is high, the dust will remain positively charged (on average). The fraction of dust particles carrying a charge will be proportional to the photoefficiency of the dust material; electron emission from metals is more efficient than from dielectrics.

5.1.3 Neutral and Charged Dust Density

In Chapter 2, we stated that the mesospheric dust charge density depends on the structure and charging history of the incident dust particle. Here we also include the condition that the percent of mesospheric dust particles carrying a charge depends on their composition and the Lyman \(\alpha\) flux to the dust particle. Although the dust particles themselves are thought to be composed mainly of silicates and metal oxides (dielectrics), sodium and other atomic metals may also be adsorbed onto the dust surface, increasing the photoefficiency over the pure dielectric case, as discussed in Chapter 2. Given all of these contributing factors, it is difficult to describe accurately the overall mesospheric dust density, both neutral and charged, as modeled by Hunten (1980). If we assume that because of the twilight charging conditions described above that about 2% of the dust particles carry a single (positive) charge, and that the estimate of charged dust density (\(\approx 20\) /cc) arrived at in the previous section is accurate to within a factor of two or three, the total charged and uncharged mesospheric dust density is on the order of 1000/cc, as predicted by Hunten's (1980) model.
Figure 5-2: Model of solar terminator at time of SAL rocket launch (launch point at center of circle, over Puerto Rico). Dark blue area denotes sunlit area at 120 km, light blue at 80 km, green at 0 km. Longitudinal division is 45 degrees (3 hrs) (Courtesy M. Kendra).
Figure 5-3: (a) Electron density. Apparent dust density and sodium density (smooth line) on upleg(b) and downleg(c). Apparent dust density assumes one charge collected by the anode per dust particle impact.

5.1.4 Charged Dust, Neutral Sodium and Sporadic E

In this section we compare the charged dust measurement to in-situ and ground measurements of plasma and sodium density, and consider the relationship of the charged dust to the plasma and neutral metal layers. The dust detector data is presented in the center (upleg) and right hand (downleg) panels of Fig 5-3. The sodium atom density is superimposed on the dust profile in the center panel, and the plasma density as determined by the Arecibo radar is also plotted in the left panel of Fig. 5-3.

Plasma Layer

As shown in Fig. 5-3, the $E_s$ layer peaks at the same altitude as the dust layer maximum, approximately 92.5 km. The electron density in the $E_s$ layer is on the order of 30,000/cc,
Figure 5-4: In-situ sodium airglow (black line), sodium density measured by Arecibo lidar (blue line), and charged dust density (red line). Horizontal axis is in arbitrary units.
compared to $\approx 1000/\text{cc}$ outside the layer. It is surprising that an increase in the electron density of over an order of magnitude does not seem to have any effect on the charged dust layer; the electron-positive dust recombination time constant should decrease by a factor of 10. The high electron density should correspond to an electron attachment time constant of about 3 minutes (outside the layer the attachment rate is $\approx 30$ min). If solar photons and plasma particles are the only charging sources, as described in Chapter 2, this may imply that the photoefficiency is high, characteristic of a metallic dust surface. Free sodium atoms or ions may be adsorbed onto the dust surface, raising the photoefficiency. The insensitivity of the measured dust charge to the increase in the plasma density inside the $E_s$ layer may indicate that the dominant charging process at the time of launch was indeed photoemission, rather than electron attachment.

**Sodium Layer**

The Arecibo lidar measurement of the sporadic sodium ($\text{Na}_s$) layers is plotted in relation to the dust data in Fig. 5-3. The charged dust layer is located directly below the $\text{Na}_s$ layers. The in-situ measurement of the sodium airglow, discussed in Chapter 4, is plotted alongside the lidar sodium measurement and the charged dust layer in Fig. 5-4. The altitude difference in the lidar sodium measurement and the airglow measurement is probably due to variations in altitude of the layer over the horizontal separation between the rocket position and the lidar beam location (about 15 kilometers). Comparing the dust measurement to the in-situ sodium measurement, and assuming that the altitude of the in-situ sodium measurement reflects the actual $\text{Na}_s$ layer altitude at the location of payload, two features stand out: (a) the topside of the dust layer occurs just at the bottomside of the strong $\text{Na}_s$ layer, and (b)
the lower in-situ sodium peak is co-located with the dust layer. The apparent relationship between the sodium airglow and dust measurements could be related to dust-sodium surface chemistry or the existence of a third Na₅ layer at the rocket location.

If the dust layer is acting as a source or sink of sodium for the strong Na₅ layer, the 93 km peak in the sodium airglow may be an indicator of some dust-sodium surface chemistry related to the Na₅ layer. Since the sodium airglow measurement is sensitive to NaO (see Chapter 4), the airglow measurement may be able to distinguish a sodium population not available for measurement by lidar, sodium attached to the dust particles. The fact that the charged dust layer coincides with the bottom of the strong Na₅ layer may indicate a sodium removal (or production) process related to the charged dust layer. The measured charged dust density is consistent with the mesospheric dust production model described in Chapter 2, which predicted a 1000/cc nanometer-sized dust particles. A model for a continuous distribution of dust particle sizes puts the total number of (neutral) dust particles even higher [Hunten et al., 1980]. Comparing this to the sodium density of the lower Na₅ layer, ≈6000/cc, each 1 nm dust particle would have to adsorb or release ≈6-7 sodium atoms to provide a sink or source for the atomic sodium. This agrees with some models of sporadic sodium layers, citing dust as a possible sodium source, which require each dust particle to carry 6-7 sodium atoms or ions each, as mentioned in Chapter 1 [von Zahn et al., 1987].

The in-situ sodium measurement may also be an indicator of a third Na₅ layer near the payload which was not present at the lidar site. In this case, the in-situ sodium peak which is co-located with the charged dust layer may indicate a more direct correlation between Na₅ formation and mesospheric dust.
5.1.5 Dust Measurement Summary

The dust measurement described here is the first observation of charged dust in the tropical mesosphere. The dust layer consisted of a broad positively charged layer stretching from 90 to 94 km altitude, with a thin negatively charged layer below, from 89 to 90 km altitude. The sign of the measured dust charge was unexpected; steady-state nighttime charging conditions should have resulted in a negatively charged dust population. The observed positive charge of the dust particle in near-nighttime conditions can be explained by the existence of a significant refracted Lyman α photon flux near the solar terminator. Other anomalies in the observed dust charge are more difficult to explain, namely, the absence of a change in the charge density of the dust in the region of the $E_s$ layer, where the plasma density increases by an order of magnitude. This points to the Lyman α photons as the primary dust charge source at this location; if simple plasma particle charge collection was dominant source, the dust should have charged more negatively inside the $E_s$ layer. The measured charge density of the dust population is further complicated by the operation of the dust detector, which was interpreted as fragmentation of the dust on the anode, affecting the collected charged dust current. The fragmentation model was chosen as the simplest explanation for the observed detector operation, although other dust-anode surface processes cannot be ruled out. Future experiments should attempt to characterize the both the dust charging surface chemistry and detector charge collection effects to accurately measure the charge dust population.

In addition to being the first measurement of charged dust in the tropical mesosphere, this experiment is also the first to observe dust near sporadic sodium and sporadic E layers.
This has implications for the theories of Na\textsubscript{a} formation discussed in Chapter 1; many theories have been proposed which include dust as a source of excess sodium in the layers, but until now dust near a layer has not been observed. The measurement of dust near an Na\textsubscript{a} layer may spur more serious investigation of possible sodium-from-dust release mechanisms.

5.2 Gradient Drift Waves

In this section we discuss the electric field wave data presented in Chapter 4 in the context of gradient drift theory. We describe the gradient drift instability and calculate growth rates, and show that the wave data fit the criteria for pure gradient drift instability.

5.2.1 Theory Overview

Ionospheric plasmas containing density gradients are subject to a gradient drift instability under the influence of an externally applied electric field or neutral wind [Kagan and Kelley, 1998, Reid, 1968]. Fig. 5-5 illustrates the operation of the gradient drift instability in an externally applied electric field \( \mathbf{E} \). The horizontal line represents a plasma density gradient, from more dense below to less dense above. Given an initial sinusoidal variation in the plasma density, the external field \( \mathbf{E} \) will cause both the ions and electrons to \( \mathbf{E} \times \mathbf{B} \) drift to the left. However, in the lower ionosphere the ion mobility is limited, so the electrons will drift farther than the ions, causing a space charge to build up. This gives rise to small scale electric fields \( \mathbf{E}' \), alternately directed left and right. The resulting \( \mathbf{E}' \times \mathbf{B} \) drift will then push the low density perturbation towards higher density regions, and the high density perturbation toward lower density region, causing the original thermal perturbation variation to grow. If either the density gradient or the external electric field direction were reversed, growth
of the sinusoidal perturbation would be inhibited. For gradient drift instability growth, the electric field must have a component parallel to the density gradient:

$$\mathbf{E} \cdot \nabla n > 0$$  \hspace{1cm} (5.2.1)

An externally applied westward neutral wind also has a destabilizing influence on the sinusoidal density perturbation, as $\mathbf{U} \times \mathbf{B}$ has the same effect as a downward electric field.

**Linear Theory and Growth Rate Calculation**

The growth rate for the gradient drift instability can be calculated using a linear approximation of the plasma fluid equations [Sudan et al., 1973, Kelley, 1989]. The assumptions of the linear theory are:

1. unmagnetized ions, since $\Omega_i \ll \nu_{in}$

2. electron gyroradius small compared to wavelengths of interest

3. electrostatic waves
4. near charge neutrality

5. ions and electrons are isothermal

6. waves propagate perpendicular to the magnetic field

7. electron inertia is neglected

Using these assumptions, the fluid equations for the electrons and ions are

\[
\frac{\partial}{\partial t} N_{e,i} + \nabla \cdot (N_{e,i} \mathbf{V}_{e,i}) = 0
\]

\[
\frac{e}{m_e} (\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) + \nu_e^2 \frac{\nabla N_e}{N_e} - \nu_e \mathbf{V}_e = 0
\]

\[
(\frac{\partial}{\partial t} + \mathbf{V}_i \cdot \nabla) \mathbf{V}_i = -u_i^2 \frac{\nabla N_i}{N_i} + \frac{e}{m_i} \mathbf{E} - \nu_i \mathbf{V}_i
\]

\[
N_e = N_i = N
\]

Assuming the perturbations to be horizontal travelling waves of the form \( e^{i(kx - \omega t)} \), the dispersion relation is:

\[
\omega - kV_D = \frac{\psi_0}{\nu_i} \left[ \omega(i\omega - \nu_i) - ik^2 C_s^2 \right] \cdot \left( 1 - \frac{i\Omega_e}{\nu_e kL} \right)
\]

where \( V_D \) is the electron drift velocity in the \( x \) direction, and

\[
C_s^2 = K(T_e + T_i)/M_i
\]

is the acoustic velocity,

\[
\psi_0 = \frac{\nu_e \nu_i}{\Omega_e \Omega_i}
\]

and

\[
L = n_0 \left( \frac{dn_0}{dz} \right)^{-1}
\]
is the density gradient scale length. Breaking $\omega$ into real and imaginary parts,

$$\omega = \omega_k + i \gamma_k$$

(5.2.10)

and assuming that

$$|\gamma_k| \ll |\omega_k|$$

(5.2.11)

we obtain

$$\omega_k = \frac{k V_D}{1 + \psi_0}$$

(5.2.12)

and the growth rate

$$\gamma_k = \frac{\psi_0}{1 + \psi_0} \left\{ \frac{\Omega_e}{\nu_e} \frac{\omega_k}{kL} + \left( \omega_k^2 - k^2 C_s^2 \right) \frac{1}{\nu_i} \right\}$$

(5.2.13)

$V_D$ is the mean (eastward) drift of the electrons relative to the ions (ions and neutrals are taken to be stationary), and $\nu_{e,i}$ and $\Omega_{e,i}$ are the electron and ion (neutral) collision frequencies and gyrofrequencies. The term proportional to $C_s^2$ can be attributed to diffusive damping, which acts to oppose wave growth [Fejer and Kelley, 1980]. $\gamma_k$ is greater than zero when $V_D$ is westward and $L$ is upward.

A complete theory, including a zero-order ion drift velocity $V_i$ and an arbitrary $k$, results in the following expressions [Kagan and Kelley, 1998, Fejer et al., 1975]:

$$\omega_k = \frac{k \cdot (V_D + \psi V_{Di})}{(1 + \psi)}$$

(5.2.14)

$$\gamma_k = (1 + \psi)^{-1} \left\{ \frac{\psi}{nu_i} \left[ (\omega_k - k \cdot V_{Di})^2 - k^2 C_s^2 \right] + \frac{1}{Lk^2} (\omega_k - k \cdot V_{Di}) \frac{\nu_i}{\Omega_i} k_z \right\} - 2\alpha n_0$$

(5.2.15)
\[ \psi = \psi_0 \left[ \frac{k_z^2}{k^2} + \frac{\Omega^2}{\nu_e^2} \frac{k_z^2}{k^2} \right] \]  

(5.2.16)

where \( k_z \) is parallel to the drift velocity, \( k_x \) perpendicular. The most unstable waves propagate in a direction perpendicular to \( B \) and parallel to \( V_D \), in this case the x (east-west) direction. In these equations \( V_{Di} \), the ion drift velocity, could be due either to neutral winds or the ambient electric field [Kelley, 1989]. Eqn. 5.2.15 also includes a term proportional to the recombination coefficient \( \alpha = 3 \times 10^{-7} \text{ cm}^3/\text{s} \) which acts to oppose wave growth.

**Mapping Along Field Lines**

Before calculating the gradient drift growth rate in the observed \( E_z \) layer, we need to discuss mapping of the generated waves along the magnetic field lines. The growth rate for gradient drift instability was calculated in Eqn. 5.2.15 as a function of the wavenumber \( k \). In this section we consider the propagation of these waves along the magnetic field lines. If the plasma were perfectly conducting, the waves would map freely along the magnetic field lines. In reality, the ionospheric plasma has a finite anisotropic conductivity due to the Earth’s magnetic field, which restricts motion of ions and electrons perpendicular to the magnetic field lines. The conductivity also varies significantly with height, especially in the lower ionosphere. A “mapping” factor can be calculated using Ohm’s law [Farley, 1959, Farley, 1960]:

\[ J = \sigma_0 E_\parallel + \sigma_P E_\perp - \sigma_H (E_\perp \times \hat{B}) \]  

(5.2.17)

where \( \sigma_0 \) is the conductivity parallel to \( B \), \( \sigma_P \) is the perpendicular (Pedersen) conductivity and \( \sigma_H \) is the Hall conductivity. Setting \( \nabla \cdot J = 0 \), Eqn. 5.2.17 becomes:

\[ \nabla \cdot J = \sigma_0 \nabla_\parallel \cdot E_\parallel + \sigma_P \nabla_\perp \cdot E_\perp - \sigma_H \nabla_\perp \cdot (E_\perp \times \hat{B}) = 0 \]  

(5.2.18)
Assuming an electrostatic field, \( \mathbf{E} = -\nabla \phi \), and taking \( \mathbf{B} \) to be in the \( z \) direction, the Hall terms cancel:

\[
\nabla \perp \cdot (\mathbf{E}_\perp \times \hat{\mathbf{B}}) = \frac{\partial}{\partial x}(E_y B) - \frac{\partial}{\partial y}(E_x B) = -\frac{\partial}{\partial x}(\frac{\partial \phi}{\partial y} B) + \frac{\partial}{\partial y}(\frac{\partial \phi}{\partial x} B) = 0 \tag{5.2.19}
\]

Therefore,

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{1}{\sigma_P} \frac{\partial}{\partial z} \left[ \sigma_0 \frac{\partial \phi}{\partial z} \right] = 0 \tag{5.2.20}
\]

Farley (1959) defines a new coordinate system:

\[
x' = x \tag{5.2.21}
\]

\[
y' = y \tag{5.2.22}
\]

\[
dz' = \left( \frac{\sigma_P}{\sigma_0} \right)^{\frac{1}{2}} dz \tag{5.2.23}
\]

The “mapping factor” is \( \left( \frac{\sigma_P}{\sigma_0} \right)^{\frac{1}{2}} \), which describes the transformation into a coordinate system which has been compressed along the magnetic field lines. In this coordinate system the anisotropy in the conductivity perpendicular and parallel to the magnetic field has been removed.

In this coordinate system, Eqn. 5.2.20 becomes

\[
\nabla'^2 \phi + \frac{\partial}{\partial z'} \ln \sigma_m \frac{\partial \phi}{\partial z'} = 0 \tag{5.2.24}
\]

where \( \sigma_m \) is the geometric mean conductivity \( (\sigma_0 \sigma_P)^{\frac{1}{2}} \). Following Farley (1959), the geometric mean conductivity is modeled in the form:

\[
\sigma_m = C e^{a z'} \tag{5.2.25}
\]
where \( C \) and \( c_0 \) are constants (\( c_0 \) is the scale height of the geometric mean conductivity).

Eqn. 5.2.24 then becomes:

\[
\nabla'^2 \phi + c_0 \frac{\partial \phi}{\partial z'} = 0
\]  
(5.2.26)

The solution of this equation is then found to be:

\[
\phi = \phi_0 e^{i(k_x z' + k_y y')} e^{-\alpha(z' - z_0)}
\]  
(5.2.27)

where \( \phi = \phi_0 \) at \( z = z_0 \), and

\[
\alpha = \frac{c_0}{2} + \left( \frac{c_0^2}{4} + k^2 \right)^{\frac{1}{2}} \approx k
\]  
(5.2.28)

\[
k^2 = k_x^2 + k_y^2
\]  
(5.2.29)

since \( c_0 \approx 10^{-4} \), and for wavelengths on the order of 10 meters, \( k \approx 0.1 \).

This mapping factor describes how waves propagating perpendicular to \( \mathbf{B} \), in this case in the east-west direction, map along the magnetic field line. The mapping efficiency of these waves depends on the mapping factor \( \frac{\sigma_0}{\sigma_p} \) and the wavelength of the wave, as described by Eqn. 5.2.27. The mapping factor is plotted in Fig. 5-6, using the MSIS neutral atmosphere model and following the calculations of Kelley (1989). This number describes the extent to which the ionospheric medium is anisotropic with respect to \( \mathbf{B} \). Qualitatively, this mapping factor describes the transmission efficiency of electric field structures along the magnetic field lines. At low altitudes, the mapping factor is small and the amplitude of the electric field decreases quickly along \( \mathbf{B} \), according to Eqn. 5.2.27. As is the case with transmission lines, high-frequency waves are attenuated more than low frequency waves. Using Eqn. 5.2.14, large wavenumber (small wavelength) waves will be attenuated faster than low wavenumber (long wavelength) waves; the mapping of electric fields (along \( \mathbf{B} \)) varies with wavelength,
as given by Eqn. 5.2.27. Small scale structures (large k) do not map far along the magnetic field line, while larger scale structures (small k) can map long distances along the field line.

5.2.2 Application to Data

Growth Rate in E, Layer

Now, given the equations for generation of the gradient drift instability, Eqns. 5.2.14 and 5.2.15, and the conditions for mapping of the waves along the magnetic field lines, we can study the localized wave burst described in Chapter 4. The real part of the wave frequency is calculated using Eqn. 5.2.14 as a function of the wavenumber k. The drift velocity $V_D$ is the $E \times B$ drift of the electrons, which for an externally applied south-down electric field of 3 mV/m perpendicular to the 0.35 Gauss magnetic field, is $\approx 85$ m/s. The neutral wind velocity, and the ion drift velocity $V_{Di}$, are in the westward direction at 90 m/s. The atmospheric parameters used in for calculation of $\psi$ were taken from the MSIS neutral
atmosphere model [MSIS-E-90].

Looking again at Fig. 5-5, recall that the \( E \times B \) drift of the electrons is eastward for a downward electric field, corresponding to a net (relative) westward ion motion. This condition is unstable with respect to the gradient drift instability for a downward density gradient. A westward neutral wind also satisfies the conditions for gradient drift instability, as it results in a net westward displacement of the (collisional) ions, which are dragged along by the neutral wind [Kagan and Kelley, 1998]. The growth rate calculated from Eqn. 5.2.15 plotted as a function of wavenumber (and wavelength) is shown in Fig. 5-7. From these calculations, only waves with wavelengths longer than \( \approx 20 \) meters are excited. In Chapter 4 we determined the wavenumber spectrum of the downleg DC electric field channels, V12 and V34, and found that the peak power in the wave burst corresponded to a wavelength of approximately 20 meters. This agrees with the gradient drift instability calculations made here in which the shortest wavelengths excited by the instability are approximately 20 meters. Also plotted, in Fig. 5-8, is the growth rate vs. altitude for 30 meter waves, showing that gradient drift growth conditions are satisfied only for the top side of the \( E_s \) layer; the growth rate was calculated using the measured density profile of the sporadic E layer. Fig. 5-9 shows the same growth rate plot with the downleg HF data superimposed, confirming that no wave activity occurs outside the growth region. Although we consider only the downleg wave data for detailed wavenumber analysis in this section, since the upleg data is quite noisy due to contamination from sphere #2, the upleg and downleg profiles of the localization of wave activity are in good agreement.

The real part of the frequency calculated in Eqn. 5.2.14 is shown in Figs. 5-11 and 5-10, for \( V_D = 85 \) m/s (eastward) and \( V_{Di} = 90 \) m/s (westward). The phase velocity of
the wave [Pfaff et al., 1987] $V_\phi = V_d/(1 + \psi) \approx 3$ m/s, much less than the rocket velocity perpendicular to $\mathbf{B}$ in the frame of the neutral wind ($\approx 250$ m/s).

Mapping of Wave Burst Along Magnetic Field Lines

The minimum wavelength in the wave burst excited by the gradient drift instability is 20 meters. In this section we calculate the maximum wavelength in the wave burst using the theory describing the mapping of electric fields along magnetic field lines.

Fig. 5-12 shows the relative magnitudes of the wavelet components for the V34 downleg electric field channel; the wavelet components are altitude slices of Fig. 4-39. The peak wave power corresponds to 20 meter waves (solid line in Fig. 5-12), shorter wavelengths are suppressed, according to gradient drift theory. Longer wavelengths are also suppressed, since they map far enough along the magnetic fields lines to enter a region of negative growth. To determine the mapping efficiency for various wavelength waves, we compare
Figure 5-8: Growth rate vs. altitude, for 30 m waves.

Figure 5-9: Growth rate vs. altitude for 30 m waves, and HF34 showing downleg wave burst.
Figure 5-10: Real part of frequency vs. wavenumber and wavelength at 92.8 km altitude.

Figure 5-11: Real part of frequency vs. altitude, for 30 m waves.
a "mapping envelope" and the corresponding wavelet components for several wavelengths, plotted in Figs. 5-13, 5-14, 5-15. The mapping envelopes are derived from the potential of a point source at $z = z_0$, defined by Eqn. 5.2.27. The $z = z_0$ point was chosen to coincide with the wavelet component peak, to show the mapping of individual wave packets. The wavelet components are altitude slices of Figs. 4-38 and 4-39, showing the downleg electric field channel V34.

The mapping efficiency increases with wavelength, as the electric field strength is proportional to $\exp(-\alpha z')$ where $\alpha$ is approximately equal to $k$, as given by Eqn. 5.2.27. The 96 meter waves shown in Fig. 5-16 map several hundred meters along the magnetic field line. The actual mapping (determined by the wavelet components) is slightly longer than the predicted envelope at longer wavelengths, looking at the 48 meter and 96 meter waves of Figs. 5-15 and 5-16: "Anomalous resistivity" perpendicular to $B$, reducing $\sigma_P$, may be responsible for the increase in mapping efficiency at longer wavelengths (M.C. Kelley, pers. comm., 1999).

The region of growth for 96 meter waves is just a few hundred meters, as shown in Fig. 5-17. Long-wavelength suppression occurs when waves generated inside the region of positive growth map to regions of negative growth. Notice that no waves exist in the region of negative growth, as shown previously in Fig. 5-9.

**Height Integrated Growth Rate**

Calculation of the height integrated growth rate gives the predicted distribution of wavelengths of the gradient drift waves. The results of differentiating the growth rate (Eqn. 5.2.15) with respect to altitude and integrating over an altitude range proportional to the mapping
Figure 5-12: Wavelet components of V34 channel (downleg) for 12 meter (dashed line), 20 meter (solid) line and 48 meter (dotted line) waves.

distance for each wavenumber is shown in Fig. 5-18. The equations describing the height integrated growth rate and the altitude integration range are:

$$\gamma = \int_{z_1}^{z_2} \frac{\partial \gamma}{\partial z} dz$$  \hspace{1cm} (5.2.30)

$$z_1, z_2 = z_0 \pm 2 \left( \frac{2\pi}{k_L} \left( \frac{\sigma_0}{\sigma_P} \right)^{1/2} \right)$$  \hspace{1cm} (5.2.31)

where $z_0$ is the altitude of peak wave growth, determined by Fig. 5-8. The altitude ranges were chosen after studying the mapping of various wavelength waves, as described in the previous section; the altitude mapping of the waves is roughly twice the (parallel) wavelength of the wave.

Energy Power Law Behavior

The above calculations of gradient drift instability all employed the linearized plasma fluid equations. Non-linear gradient drift theory calculations have characterized the ($\delta E$) power
Figure 5-13: Electric field mapping of 12 meter waves (dotted line) and wavelet component of V34 downleg.

Figure 5-14: Electric field mapping of 20 meter waves (dotted line) and wavelet component of V34 downleg.
Figure 5-15: Electric field mapping 48 meter waves (dotted line) and wavelet component of V34 downleg.

Figure 5-16: Electric field mapping 96 meter waves (dotted line) and wavelet component of V34 downleg.
Figure 5-17: Growth rate vs. altitude for 90 meter waves.

Figure 5-18: Height integrated growth rate vs. wavelength.
spectrum of gradient drift irregularities and have determined a $k^{-3.5}$ power law behavior for short wavelength ($\leq 100$ m) waves [Keskinen et al., 1979, McDonald et al., 1974]. Dimensional analysis of the gradient drift instability has corroborated these simulations [Ott and Farley, 1974]. In Chapter 4, we plotted the power spectra of the upleg and downleg wave burst, and noted that the energy cascade from the peak in the spectral power (20 meter waves) followed a $k^{-n}$ power law ($2.5 \leq n \leq 3.5$) down to $k \approx 4$ rad m$^{-1}$, where the noise level was reached. This power law behavior is consistent with other rocket and radar measurements of the gradient drift instability [Pfaff et al., 1987, Kelley et al., 1995]. Since the linear theory predicts stability for wavelengths smaller than $\approx 20$ m, the strong implication is that nonlinear cascade populates linearly stable (shorter) wavelengths with energy. This is important since radar scatter operates in this regime, eg. $\lambda \approx 3$ m.

5.2.3 Gradient Drift Wave Summary

The localized wave burst on the topside of the sporadic E layer is an excellent example of a pure gradient drift instability. The growth rate as a function of wavelength in the wave burst was successfully calculated using a linearized theory; the peak power in the wave burst occurred at wavelengths near 20 meters, in agreement with the linearized gradient drift growth rate calculation. The maximum wavelength observed in the wave burst was determined by the mapping of the wave electric field along the magnetic field lines to regions of negative growth. Large scale structures (long wavelengths) map farther along magnetic field lines than small scale structures. Since the altitude range of positive growth was limited to just a few hundred meters, long wavelength waves which mapped to regions of negative growth were damped. The range of wavelengths observed in the wave burst, from 20 meters
to approximately 60 meters, can thus be explained by the short and long wavelength limits of the gradient drift calculations.

The wavenumber power spectra at short wavelengths obeyed a $k^{-3.5}$ power law, as predicted by non-linear gradient drift simulations and in agreement with other gradient drift measurements. This cascade of energy to shorter wavelengths, which should be stable with respect to the gradient drift instability, is important to radar scatter measurements which operate at short wavelengths. The population of short wavelengths by gradient drift waves may permit ground observation of this plasma instability.

5.3 Conclusions

The Sudden Atom Layer sounding rocket has resulted in several interesting data sets from the charged dust detector and electric field experiments. Ground and in-situ measurements of the ionospheric conditions at the time of launch make it possible to discuss these detector results in the context of sporadic atom layer and sporadic E layer formation and morphology.

The charged dust experiment has provided the first observation of charged meteoric dust in the tropical mesosphere, and as has been discussed throughout this thesis, the dust may play a role in the lifecycle of sporadic atom layers. Especially intriguing is the co-location of the charged dust layer and a peak in the in-situ sodium airglow. Many additional measurements are necessary to establish a conclusive link between mesospheric dust and Na$_s$, and though this particular measurement does not confirm any specific Na$_s$ theory, it does provide some evidence in favor of a dust mechanism in Na$_s$ formation.

The gradient drift induced wave burst detected by the electric field experiment is in itself an exciting measurement. This was a perfect example of a simple, stable, fairly weak
$E_s$ layer in which wave growth can be studied fairly accurately using linear gradient drift theory. For the first time we have shown that an outer scale limit occurs due to the mapping of long wavelength waves to the stable side of a layer.
Bibliography


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Appendices
Appendix A

Appendix - Dust Detector Design

A.1 Mechanical Drawings

A.2 Electrical Design
Figure A-1: Dimensions of detector electrodes.
Figure A-2: Dimensions of detector side pieces showing placement of screens.
Figure A-3: Top piece of grounded detector screen.
Figure A-4: Bottom piece of grounded detector screen.
Figure A-5: Top piece of biased detector screen.
Figure A-6: Center piece of biased detector screen.
Figure A-7: Bottom piece of biased detector screen.
Figure A-8: Preamp Schematic
Figure A-9: SAL Detector electronics block diagram
Figure A-10: Essential dust detector elements electronics block diagram
Appendix B

Appendix - Dust Particle Trajectories

Figs. B-1 through B-10 show sample dust particle trajectories for two snapshots of the electric field oscillation. The voltages in the detector model are: detector box and ground screens (physically connected to the box in the outlines of the detector below) at 0V. Starting from the top of the detector (looking from right to left below) the biased screens are: electron rejection screen at -1.5V, accelerating screens at +2V and +3V, anode at +5V. Trajectories are given for the case of the maximum electrode voltage (+/- 10V) and an intermediate voltage point (+/- 5V).
Figure B-1: Trajectory

Figure B-2: Trajectory
Figure B-3: Trajectory

Figure B-4: Trajectory
Figure B-5: Trajectory

Figure B-6: Trajectory
Figure B-7: Trajectory

Figure B-8: Trajectory
Figure B-9: Trajectory

Figure B-10: Trajectory
Figure B-11: Electron Trajectory

Figs. B-11 through B-15 show trajectories of plasma particles through the detector.
Figure B-12: Ion Trajectory

Figure B-13: Ion Trajectory
Figure B-14: Ion Trajectory

Figure B-15: Trajectory
Figure B-16: Trajectory

Trajectories of dust particles entering the detector at an angle with respect to the symmetry axis are shown in Figs. B-16 through B-21. A nominal dust particle of mass $\approx 6500$ amu (rammed kinetic energy of 20 eV) is used in the model.
Figure B-17: Trajectory

Figure B-18: Trajectory
Figure B-19: Trajectory

Figure B-20: Trajectory
Figure B-21: Trajectory