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1. REPORT NUMBER

AFOSR-TR-85-0923

5. GPO ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

EARTHQUAKE LIGHT

5. TYPE OF REPORT & PERIOD COVERED

FINAL REPORT  
1 MARCH 1983 - 15 AUGUST 1986

6. PERFORMING ORG. REPORT NUMBER

MSA-FCR-36

7. AUTHOR(s)

W.G. McMillan

8. CONTRACT OR GRANT NUMBER(s)

F49620-83-C-0079

9. PERFORMING ORGANIZATION NAME AND ADDRESS

McMillan Science Associates, Inc.  
1100 Glendon Avenue, Suite 901  
Los Angeles, California 90024

10. PROGRAM ELEMENT, PROJECT, TASK  
AREA & WORK UNIT NUMBERS

ARPA Order 4700  
Program Code 3D60

11. CONTROLLING OFFICE NAME AND ADDRESS

Air Force Office of Scientific Research  
Building 410  
Bolling AFB DC 20332

12. REPORT DATE

15 August 1985

13. NUMBER OF PAGES

61

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING  
SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release  
Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

See Inside

19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Airglow; Atmospheric luminosity; Aurora; Earthquake light; Electromagnetism; Electron-acceleration mechanisms; Electron reservoirs; Geoelectricity; Geomagnetism; Geophysics; Ionosphere; Light flashes; Lightning; Luminescence; Magnetic fields; Mirror-point altitudes; Nuclear-explosion aurora; Piezoelectricity; Radon; Satellite observations; Seismology; Telluric currents; Trapped particle dynamics; Van Allen belts; VELA.

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FOSR-TR- 85-0923



MSA-FCR-36-DARPA

AD - A161385

**EARTHQUAKE LIGHT**  
**Final Technical Report**

15 August 1985

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ARPA Order No. 4700

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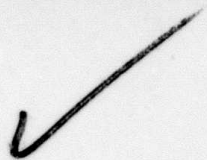
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER <b>AFOSR-TR- 85-0923</b>	2. GOVT ACCESSION NO. <b>AD-A161385</b>	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) <b>EARTHQUAKE LIGHT</b>		5. TYPE OF REPORT & PERIOD COVERED <b>FINAL REPORT 1 MARCH 1983 - 15 AUGUST 1986</b>
		6. PERFORMING ORG. REPORT NUMBER <b>MSA-FCR-36</b>
7. AUTHOR(s) <b>W.G. McMillan</b>		8. CONTRACT OR GRANT NUMBER(s) <b>F49620-83-C-0079</b>
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11. CONTROLLING OFFICE NAME AND ADDRESS <b>Air Force Office of Scientific Research /MP Building 410 Bolling AFB DC 20332</b>		12. REPORT DATE <b>15 August 1985</b>
		13. NUMBER OF PAGES <b>61</b>
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) <b>Unclassified</b>
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  <p style="text-align: center;">Approved for public release; distribution unlimited.</p>		
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## EARTHQUAKE LIGHT\*

W.G. McMillan

### ABSTRACT

The diverse manifestations of luminous phenomena associated with earthquakes are described and grouped into six categories according to their dominant common geophysical features: 1° Frictional heating at faults; 2° Burning gases--flames, plumes, explosions of combustible gases emanating from the ground; 3° Phosphorescence, including bioluminescence and triboluminescence; 4° General atmosphere luminosity or airglow; 5° Light flashes and lightning; and 6° Auroral effects. Phenomena in the first three categories are familiar in the laboratory and, although not unique to earthquakes, can obviously be stimulated or enhanced by seismic activity. They pose no significant scientific puzzle and are thus dismissed from further discussion.

Phenomena in the remaining categories are evidently of electromagnetic origin. An explanation of those in 4° and 5° is offered in terms of the acceleration of free electrons in the air by the geoelectric field, both electron number density and field possibly being enhanced by the earthquake. Those in category 6° resemble natural aurorae, but apparently utilize electrons stored in the natural reservoirs of the ionosphere (F layer) and Van Allen belt. The central questions are: on the one hand, how the thermal ionosphere electrons can be accelerated to energies high enough to excite emission of the air molecules; and, on the other, how the mirror points of the Van Allen electrons can be lowered into the atmosphere.

The phenomenologies of these two classes are treated in parallel, with subsections on proposed mechanisms, sources of charged particles, relevant geoelectromagnetic fields, motions of charged particles in these fields, expected alterations due to seismic activity, and estimated intensity and time dependence of the associated light production.

The treatment throughout is qualitative, and is intended to stimulate further theoretical and observational research.

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\*Sponsored by the Advanced Research Projects Agency (DOD), ARPA Order No. 4700, and monitored by AFOSR under Contract No. F49620-83-C-0079.

## 1. INTRODUCTION

### 1.1 Background and Motivation

Although the reality of various luminous phenomena attending (some) earthquakes appears to be generally accepted as an observational fact<sup>1</sup> by seismologists and is attested by thousands<sup>2-4</sup> of eyewitnesses and even numerous photographs,<sup>5-6</sup> there is little consensus on the description of these phenomena, much less any comprehensive theory of their causes. In part, this state of confusion arises because of the bewildering diversity of the luminous effects involved. Descriptions<sup>1-9</sup> range from: 1° scorching of vegetation near faults, as from frictional heating during displacement; 2° fires, flames, and airborne fireballs, as from the burning of combustible gases liberated through fissures in the earth (and reminiscent of the "will o' the wisp"); 3° surface phosphorescence of the ocean, as from marine protophyta stirred up in the wake of a ship; 4° general luminosity of the atmosphere, or air glow, near ground level; 5° flashes of light at the Earth's surface; 6° lightning bolts out of a clear sky; 7° fireballs

<sup>1</sup>J.S. Derr, Earthquake Lights: A Review of Observations and Present Theories, *Bull. Seis. Soc. of America* 63, 2177-2187 (1973); *USGS Earthquake Info. Bull.* 9, 18-21 (1977). See also the news note in *Geotimes*, Dec. 1977, pp. 31-32.

<sup>2</sup>K. Musya, On the Luminous Phenomenon that Attended the Idu Earthquake, 26 November 1930 (0430 hours), *Bull. Earthquake Res. Inst., Tokyo University* 9, 214-215 (1931); Investigations into the Luminous Phenomena Accompanying Earthquakes, *ibid.* 10, 666-673 (1932); On the Luminous Phenomena that Accompanied the Great Sanriku Tsunami in 1933, *ibid.*, *Suppl. 1*, 87-111 (1934).

<sup>3</sup>T. Terada, On Luminous Phenomena Accompanying Earthquakes, *Bull. Earthquake Res. Inst., Tokyo University* 9, 225-255 (1931); Luminous Phenomena Accompanying Destructive Sea Waves (Tsunami), *ibid.*, *Suppl. 1*, 25-35 (1934).

<sup>4</sup>C. Davidson, *Great Earthquakes* (Thomas Murby, London, 1937), pp. 254-260; Luminous Phenomena of Earthquakes, *Discovery* 18, 278-279 (1937).

<sup>5</sup>Y. Yasui, A Study of the Luminous Phenomena Accompanied with Earthquake, Part I, *Mem. Kakioka Mag. Obs.* 13, 25-61 (1968); Part II, *ibid.* 14, 67-68 (1971). Some of these pictures, taken by T. Kuribayashi, a dentist in Matsushiro, during the Matsushiro earthquake swarm of 1965-1967, are reproduced by Derr (Ref. 1).

<sup>6</sup>R.L. Williams, Science Tries to Break New Ground in Predicting Great Earthquakes, *Smithsonian* 14, 40-50 (1983). See also Ref. 13 below.

<sup>7</sup>P. Byerly, *Seismology* (Prentice Hall, New York, 1942), p. 76.

<sup>8</sup>C.F. Richter, *Elementary Seismology* (Freeman, San Francisco, 1958), pp. 581-2.

<sup>9</sup>Phenomena Preceding two Large Quakes, *Sci. News* 112, 408 (1977).



resembling ball lightning, especially in the neighborhood of mountaintops; 8° distant flashes resembling "heat lightning" on the horizon; 9° extensive illumination or glowing in the sky, which exhibits many of the forms, colors and time characteristics of the Aurora Borealis and Australis: light streamers, fans, beams, columns, etc.

A large factor contributing to this confusion is the dearth of scientific observations and measurements. Nearly all of the eyewitness accounts have come from untrained observers, and suffer from the large dispersion of eyewitness testimony<sup>3</sup> familiar in other contexts (e.g., traffic accidents)--but here, exacerbated by many different events occurring at different times and places, and viewed from different perspectives. Moreover, since the luminous phenomena are visible only at night, many witnesses will have been abruptly awakened by the earthquake, which may induce a degree of primordial excitement and mental stress since survival is likely to be uppermost in their minds. Combined with the propensity of the dark-adapted eye to exaggerate light intensities, these are scarcely optimal conditions for objective observation.

Since at least at present, the time and place of occurrence of an earthquake is quite unpredictable,\* it is difficult and expensive to provide continuously-recording instrumentation for effects that may be highly localized in time and area. Also there is evidence that some of these luminous phenomena are associated only with the fairly infrequent<sup>10</sup> large-magnitude ( $M > \sim 6$ ) earthquakes, and possibly with only a fraction of these that meet several special conditions to be discussed below. The opportunity for observation is further restricted, since few attendant luminous phenomena are evident for earthquakes occurring during daylight hours; and earthquakes with epicenters at sea

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\*But see the exceptional Chinese example described in Ref. 13 below.

<sup>10</sup>G. Kondo, Variations of the Atmospheric Electric Field at the Time of Earthquake, *Mem. Kakioka Mag. Obs.* 13, 11-23 (1968), records numerous changes in the electric fields associated with earthquakes of magnitudes I and II, but "Unfortunately there was no report on the luminous phenomenon through the period of observation."

far from land are likely to have few local observers. Finally, lacking a theory of the causes of earthquake light, there is little guidance as to what may be the critical physical parameters to instrument for.

In the face of these difficulties, it is indeed remarkable that there exist numerous photographs,<sup>5,6</sup> many in beautiful color, of earthquake lights--essentially all in category 9° above--i.e., an extended area\* of illumination in the night sky. Not surprisingly, these photographs were taken in Japan, where the devastation and frequency of large earthquakes places a high premium on their explication and prediction, and where the opportunity for observation is relatively high.

Historically China also has suffered very large earthquakes, some with great loss of life--as in the great Shenshi earthquake<sup>11</sup> of 1556 or the recent Tang Shan earthquake<sup>12</sup> of 28 July 1976, each of which killed over 800,000 people. Such catastrophes have placed high priority on earthquake prediction, in which Chinese seismologists have taken an important lead. A series of three major earthquakes<sup>13</sup> in August 1976 (the Sungpan-Pingwu events in Sichuan Province) were successfully predicted, and timely evacuations of population centers were carried out. But the concentration in the Orient of these large earthquakes, and of the associated research and analysis in the Japanese and Chinese literature, poses for Western scientists the additional problem of communication.

Although most of the recent literature on earthquake light comes from the Orient, observations of luminous phenomena attending earthquakes are by no means

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\*Since these photographs are presumably time exposures (in order to catch the transient effects in the act and to provide sufficient film exposure), they display only a time integral, and thus cannot reveal any rapidly-varying characteristics such as the flickering of auroral streamers.

<sup>11</sup>D. Shapley, Chinese Earthquakes: The Maoist Approach to Seismology, *Sci* 193, 656-7 (1976).

<sup>12</sup>Tang Shan Quake: Portrait of a Catastrophe, *Sci. News* 111, 388 (1977); *ibid.* 112, 408 (1977).

<sup>13</sup>R.E. Wallace and Ta-Liang Teng, Prediction of the Sungpan-Pingwu Earthquakes, August 1976, *Bull. Seis. Soc. Am.* 70, 1199-1223 (1980).

limited to Asia, nor to recent times. The excellent annotated bibliography compiled by Corliss<sup>14</sup> summarizes many historical observations, of which the following excerpts are quoted as illustrative of earthquake light phenomena:

Three major earthquakes of 16 December 1811 (ca. 0200 hours), 23 January 1812 and 7 February 1812, epicenters near New Madrid, Missouri - In Livingston County, according to Mr. Riddick, the atmosphere previous to the shock of February 8 was remarkably luminous, objects being luminous for considerable distances, although there was no moon. "On this occasion the brightness was general, and did not proceed from any point or spot in the heavens. It was broad and expanded, reaching from the zenith toward the horizon. It exhibited no flashes nor coruscations, but, as long as it lasted, was a diffused illumination of the atmosphere on all sides."

16 August 1906, Chile - "The sky all over Chile flashed with a quivering light."

31 December 1730, Tokaido, Japan - Luminous bodies in sky and luminous air.

21 October 1731, England - Quake followed by vivid lightning display.

2 April 1730, England - Multitude of blood-red rays converged from all parts of the sky.

13 December 1823, Bellay, France - The sky seemed to be on fire.

24 April 1836, Italy - Great beams of fire in the sky.

Ca. 1867, Algeria - Atlas mountains enveloped in a luminous atmosphere.

17 December 1896, England - Many reports of vivid light flashes from region of earthquakes.

June 1932, Mexico City - Dull red glow in the sky and lightning during shocks.

5 January 1968, Chiba, Japan - Fan-shaped light seen in sky.

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<sup>14</sup>W.R. Corliss, *Lightning, Auroras, Nocturnal Lights, and Related Luminous Phenomena--A Catalog of Geophysical Anomalies* (Sourcebook Project, Glen Arm, MD, 1982), Sec. GLD 8, pp. 110-115.

5 September 1975, Eastern Turkey - Sky brightening in direction of epicenter.

28 July 1976, Tangshan, China - A brilliant light seen for hundreds of miles around quake area.

13 April 1950, England - red rays seen converging at zenith.

Although earthquake luminous phenomena have thus been known for centuries, it is only recently that they have become an object of serious study. They are clearly not an essential accomplice of an earthquake, although in 1750 Stukeley<sup>15</sup> ascribed lightning as an earthquake cause rather than effect; and their lack of complicity as a causative agent of damage ranks their explication low on any list of practical priorities. Nevertheless, after centuries of observation the persistent lack of a suitable theory constitutes a first-rate puzzle and a worthy intellectual challenge.

But there are also good international-political reasons for seeking to understand these effects, particularly those resembling aurorae: as with other physical effects of earthquakes--seismic waves, acoustic waves, ionospheric perturbations, etc.--earthquake aurorae may contribute to the background of signals generated by natural events against which the signals generated by the explosion of nuclear devices must be discriminated. Although so far as the author is aware, no auroral effects have been observed in connection with underground nuclear explosions (which in the US are generally conducted in the hours of daylight), there were spectacular auroral effects attending the US high-altitude TEAK event<sup>16</sup> in 1962. These effects occurred both in the immediate vicinity of the explosion near Johnston Island and in the magnetic conjugate area over French Frigate Shoals.

<sup>15</sup>W. Stukeley, *The Philosophy of Earthquakes, Natural and Religious* (Corbett, London, 1756), pp. 22-26. [Cited by J.J. Lloyd in a Letter to the Editor re Earthquake Light, *Sci.* 193, 1070 (1976)].

<sup>16</sup>A.L. Cullington, A Man-made or Artificial Aurora, *Nature* 182, 1365-6 (1958). See also the collected symposium papers on the STARFISH high-altitude nuclear explosion over Johnston Island on 9 July 1962 in *J. Geophys. Res.* 68, #3.

The question thus arises whether the auroral effects from an earthquake could conceivably be misinterpreted as having been generated by an atmospheric nuclear explosion, with all the attendant international concern and finger-pointing. The controversy<sup>17</sup> surrounding the atmospheric flashes of 22 September 1979 and 15 December 1980 observed by the Vela Satellite detectors over the southern hemisphere underscores the importance of understanding the natural background against which such grave issues as nuclear test treaty violation or nuclear-weapon proliferation must be judged.

### 1.2 Classification of Earthquake Light Phenomena

In order to bring some order to this broad subject, it is useful first to classify<sup>18</sup> the earthquake light observations into as few categories as possible so as to display their common features and plausible causes:

1° Frictional heating: melted rock at fault displacements.--The high temperature from such a frictional source likely accounts for the scorched appearance of nearby vegetation.

2° Burning gases: fires, flames, some fireballs.--Just as the ground motion during an earthquake may release unusual amounts of radon trapped in the rock medium, the increased ground porosity and agitation may permit the escape of combustible gases such as methane (marsh gas) and hydrogen sulfide from underground gas deposits or decaying vegetation. Indeed, in many instances "sulfurous odors" are reported. The bubbling up of gases in water wells is often noted in association with seismic activity. When this escaping gas is ignited (for example, from sparks generated by frictional electricity or even spontaneously) it may burn at the fissure opening or as a cloud in the air well above the fissure, as does the detached flame of a bunsen burner under excessive gas speed. The burning<sup>19</sup>--or even

<sup>17</sup>Eliot Marshall, Scientists Fail to Solve Vela Mystery, *Sci.* 207, 504-506 (1980); "Flash" Near South Africa, Again, *Sci.* 211, 1020 (1981).

<sup>18</sup>An early attempt at such classification was made by I. Galli, Raccolta e classificazione di fenomeni luminosi osservati nei terremoti, *Bull. della Soc. Italiana* 14, 221 (1910) [cited by P. Hedervari, *Bull. Seis. Soc. Am.* 71, 371-4 (1981)].

<sup>19</sup>See, for example, D.P. Penhallow, A Blazing Beach, *Sci.* 22, 794-6 (1905), cited in W.R. Corliss, *Handbook of Unusual Natural Phenomena* (Sourcebook Project, Glen Arm, MD, 1977), pp. 134-6.

exploding<sup>20</sup>--of natural gases issuing from the ground is a fairly common occurrence even with no accompanying earthquake.

3° Phosphorescence: bioluminescence, triboluminescence.--There are many natural sources of bioluminescence, such as certain fungi, decaying vegetation, waterborne photophyta, etc., that can be stimulated or enhanced by agitation as might result from an earthquake. A critical study of these should allow their elimination as not being unique to earthquake motion. Triboluminescence--the luminescence associated with electric charge separation caused by friction and tearing processes--may well arise from certain types of earthquake motion. However, these would be expected to appear, if at all, only in the immediate vicinity of the ground, and to be highly localized.

4° General Atmosphere Luminosity or Airglow--enveloping mountains or observers at ground level, both during and preceding the earthquake.

5° Light Flashes and Lightning:--Earthquake light flashes and lightning strokes (and ball lightning?) presumably come from the discharge of large electric fields generated or triggered by the earthquake. Several source mechanisms have been proposed including triboelectricity generated by the friction attending earth movement, piezoelectricity generated by stress release, etc. Lightning strokes of whatever origin can, of course, be expected occasionally to set fires, as indeed was reported<sup>21</sup> for the Owens Valley earthquake of 1872.

6° Auroral Effects: Illumination originating in the sky.--Variously described<sup>21</sup> as distant sheet lightning; light flashes of considerably longer duration than ordinary lightning; sheets, pillars and beams of light, extending over considerable areas of the sky and sometimes appearing to converge toward a point. The colors span the spectrum of polar aurorae, with white and red being most frequently reported. In some cases earthquake sky light, occurring over either land or sea, has been seen from distances of a few degrees in latitude and longitude. Intensity has been reported variously as equivalent to full moonlight, and as sufficient to see objects in a room (presumably by light entering a window). A most puzzling feature is the observation that incidents of lightning and sky glow sometimes precede a

<sup>20</sup>Cf fires and explosions in Los Angeles' Fairfax district in late March 1985 caused by leakage from natural methane deposits through cracks in the ground, *Los Angeles Times*, 27 March 1985, p. 1.

<sup>21</sup>P. Byerly, Ref. 7.

large earthquake shock by as much as hours, days and even months.<sup>22</sup> Despite the lack of quantitative measurements by trained observers together with the danger of imaginative post-shock hindsight and the lack of a satisfactory scientific explanation, the sheer weight of evidence makes these precursor phenomena difficult to dismiss.

Concerning the first three of these categories, although there remain many questions of detail, there appear to be no fundamental puzzles in their physical explanations. All occur in other contexts--even in laboratory experiments--and it is relatively easy to see how an earthquake could enhance or trigger their appearance.

Far more interesting and challenging are the last three categories, in which the role and coupling of the earthquake motion to the light-producing mechanisms are far more subtle. But one aspect is clear: luminous phenomena originating in the atmosphere at both low and high altitudes must involve coupling with the electromagnetic field.

Before searching for this electromagnetic coupling it is first desirable to extract from the observations some hints and clues as to the identity and magnitude of the electromagnetic effects needed as a basis for an explanation.

### **1.3 Objective and Preview.**

Against the foregoing background the objective of this study is to develop a qualitative orientation and framework, together with order-of-magnitude estimates where possible of the relevant physical and geophysical parameters, for the various manifestations of earthquake light.

One of the impediments in this field may be its highly-interdisciplinary nature: we will find it necessary to draw upon some of the most subtle features of seismology, the geoelectric and geomagnetic fields, natural radioactivity of the earth and air, air

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<sup>22</sup>One of the most detailed accounts of light associated with three major earthquakes in China was kindly provided the author by Professor Qin Xinling of the Institute of Geophysics, State Seismological Bureau, Beijing, China. To make this interesting account available to western readers, a translation--prepared by Paul Pau and Qi-xun Xu, graduate students in the Department of Chemistry and Biochemistry, University of California, Los Angeles--is included here as an appendix.

ionization by  $\alpha$ -particles, electrical conductivity and discharge in gases, lightning, the kinetic theory of gases, electrodynamics, excitation and ionization of air molecules, light emission and intensity, trapped electrons in the geomagnetic field, natural and artificial auroras, etc. It is hoped that this review and analysis will help identify some of the outstanding questions and issues, and possibly serve to stimulate further instrumentation, observation and theoretical work.

Toward these ends, the remainder of this study is divided into three parts: Low-altitude earthquake light electromagnetic phenomena; earthquake auroral phenomena; and outstanding issues. The two phenomenology parts have parallel structures, with subsections on proposed mechanisms, the sources of charged particles in and above the atmosphere, the relevant geoelectromagnetic fields, the motions of charged particles in these fields, the expected alterations due to seismic activity, and the intensity and time dependence of the associated light production. The final part summarizes the results, identifies the outstanding questions and offers some suggestions for further theoretical and observational research.



## 2. LOW-ALTITUDE EARTHQUAKE LIGHT ELECTROMAGNETIC PHENOMENA

### 2.1 Proposed Mechanism

The sub-family of earthquake light phenomena that occur at or near the Earth's surface (categories 4° and 5° above) appear to involve essentially a common electromagnetic mechanism--of free electrons in the atmosphere accelerated by an electric field to energies sufficient to cause air glow, discharge flashes and even lightning-like strokes. Both of the important parameters--the number density of free atmospheric electrons and the local electric field--may be enhanced by earth movement: the former, by an elevated rate of release of radioactive gases (e.g., Rn<sup>222</sup>) into the air; and the latter, through the piezoelectric effect, alteration in telluric currents, etc. Changes in both parameters could be generated over extended periods of time through a series of small precursor quakes below the threshold of common notice. Both have "capacitance" or "reservoir" features: it may take considerable time for radon in the ground to diffuse to the newly-opened crevices and thence to the atmosphere; and for electric currents to flow in a poorly-conducting medium to neutralize the earthquake-generated electric field.

The basic physical mechanism postulated above for generating light in the atmosphere near the ground involves several considerations:

1° Between collisions with the air molecules the free electrons (of charge  $-e$  and mass  $m$ ) are subject to the acceleration  $a = -e \mathcal{E}/m$  due to the existing electric field  $\mathcal{E}$ .

2° In falling distance  $s$  down the field, the electron acquires kinetic energy  $e \mathcal{E} s$ .

3° When this energy reaches a value exceeding the first excitation potential of the air molecules, the next collision may be inelastic, elevating the electronic energy of the molecule to an excited state from which it can radiate and thus produce light, as in a glow discharge.

4° An inelastic collision with a somewhat more energetic electron can cause ionization of the air molecule, thus resulting in a second free electron--i.e., an electron multiplication.

5° When the electron multiplication rate exceeds their capture rate these secondary electrons cause both excitation and further ionization, and a veritable avalanche or cascade ensues; radiation by the many excited molecules causes a flash of light; and the enhanced conductivity of the high electron density may even allow passage of a lightning stroke.

6° In the absence of nearby thunderstorm activity, the light flashes and lightning-like strokes are self-limiting and of short duration, because the reservoir of separated charges is small and the conductivity of the air is low, so that lateral charge flow into the conducting channel is slow. Correspondingly, the energy released is small relative to a lightning stroke in a thunderstorm, which explains why one finds almost no mention of thunder associated with earthquake light flashes. But there are instances<sup>23</sup> reported of hissing sounds (as accompany a corona discharge), together with the odor of ozone or a "sulphurous smell."

7° Free electrons can be captured and effectively immobilized by various processes: recombination with positive ions in three-body collisions; capture by the oxygen molecule to form the negative oxygen molecule ion,  $O_2^-$ ; dissociative recombination, e.g., to form  $O+O^-$ ; radiative recombination, etc.

8° Just as with a lightning rod, elevated promontories--mountain tops--are likely to have greater local electric field strengths, and are thus more likely to exhibit the above effects than are the valley flatlands. Indeed, earthquake flashes and lightning are most often reported to occur on mountain tops.

There is thus a delicate interplay between the geoelectric field and the electron number density, whose characteristics determine the kind of luminous phenomenon produced--if any.

## 2.2. Charges in the Atmosphere

There are two natural sources of high-energy particles that produce charges through ionization of the air: cosmic rays and airborne radioactive nuclides. Since cosmic rays are almost completely absorbed before reaching the surface, charges in the atmosphere below one kilometer above ground level are produced mainly by airborne radioactive nuclides.

Leaving aside the perturbations on the natural radioactive background due to atmospheric nuclear tests, the main source of airborne radioactivity<sup>24</sup> is the emanation from the ground of the isotopes of the noble gas radon (atomic number 86) which arise as links<sup>25</sup> in the naturally-occurring radioactive decay chains: uranium/radium; actinium; and thorium. These long-lived precursors are chemically bound<sup>26</sup> in minerals, mainly as oxides, but occur also in ground water.<sup>27</sup> However, once the sequence of radioactive decays reaches a radon isotope this is no longer chemically bound, and can diffuse to the crystalite surface, thence to a channel, and--if it lives long enough--eventually to the atmosphere.

In the literature, the naturally-occurring radon isotopes are still often referred to by their historic names derived from the radioactive chains in which they occur, as shown in Table 1. Although the short lifetimes of  $Rn^{220}$  and  $Rn^{219}$  give them relatively

Table 1. Properties of Naturally-Occurring Radon Isotopes

Radioactive chain	Emanation	Nuclide	Half life $t_{1/2}$	Mean life $\tau$	Decay Mode	Energy (MeV)
Radium	Radon	$Rn^{222}$	3.823 <sup>d</sup>	5.515 <sup>d</sup>	$\alpha$	5.587
Thorium	Thoron	$Rn^{220}$	54.5 <sup>s</sup>	78.6 <sup>s</sup>	$\alpha$	6.405
Actinium	Actinon	$Rn^{219}$	3.92 <sup>s</sup>	5.86 <sup>s</sup>	$\alpha$	6.944

<sup>24</sup>J.A.S. Adams and W.M. Lowder, Eds., *The Natural Radiation Environment* (U.Chicago Press, Chicago, 1964).

<sup>25</sup>J. Mattauch and S. Flugge, *Nuclear Physics Tables* (Interscience, New York, 1946), p.76.

<sup>26</sup>K.S. Heier and J.L. Carter, *Uranium, Thorium and Potassium Contents in Basic Rocks*, Chapter 4 of Ref. 24.

<sup>27</sup>Ref. 24, Chapters 11-14.

high specific activities, the slow diffusion rate of radon out of the ground favors the longer-lived  $\text{Rn}^{222}$ , which thus constitutes<sup>28</sup> the principal airborne isotope, and the main source of atmospheric charges near the ground. The 5.6 MeV  $\alpha$ -particle emitted by  $\text{Rn}^{222}$  creates about  $1.6 \cdot 10^5$  ion pairs along its 7-cm range in air at STP. Although fast knock-on (delta ray) electrons are produced by  $\alpha$ -particles in the primary ionization process, these are soon slowed by secondary ionizing collisions with the air molecules. Ultimately the slowed electrons are captured, largely by oxygen, to form atomic or molecular ions. In turn these ions may combine with other molecules or even airborne particles to form larger charged aggregates.

The rate of radon emanation into the air over land depends upon many local environmental factors--concentration and depth of radionuclide precursors in the ground, diffusivity in soil or rock granules, soil porosity, fault zones, ground water content and movement, atmospheric pressure, rain, snow, etc. Surface emanation rates vary so widely with location, and measurements are so sparse that no reliable experimental average is available. In one detailed series of measurements in an undisturbed area of Yucca Flats in the Nevada Test Site, Kraner, et al.<sup>29</sup> found an emanation rate of  $0.4 \cdot 10^{-16}$  curie/cm<sup>2</sup>·sec. This translates to a flux of  $0.7 \text{ Rn}^{222}$  atom/cm<sup>2</sup>·sec.

The rate of production of ion pairs by radioactivity in the lower atmosphere has been estimated<sup>30</sup> as shown in Table 2. If the only source were the  $\alpha$ -particles from  $\text{Rn}^{222}$ ,

Table 2. Average Ion-Pair Production Rates Due to Radioactivity<sup>30</sup>

Height (km)	Ion Pairs (cm <sup>-3</sup> sec <sup>-1</sup> )
0	7.6
0.1	5.1
0.5	3.8
1	2.7
2	1.5
3	0.9
4	0.5
5	0.3

<sup>28</sup> But see the dissenting view of H. Israel, Ref. 24, pp. 313-4.

<sup>29</sup> H.W. Kraner, G.L. Schroeder and R.D. Evans, *Measurements of the Effects of Atmospheric Variables on Radon-222 Flux and Soil-Gas Concentrations*, Chapter 10 of Ref. 24.

<sup>30</sup> S.L. Valley, Ed., *Handbook of Geophysics and Space Environments*, Air Force Cambridge Research Laboratories (USAF, 1965), p.8-8.

the integral over a vertical column ( $\sim 8.0 \cdot 10^5$  ion-pairs/cm<sup>2</sup>·sec) would correspond\* to the disintegration of 5 atoms/cm<sup>2</sup>·sec or  $2.9 \cdot 10^{-16}$  curie/cm<sup>2</sup>·sec, some 7 times the Yucca Flats emanation rate. Considering all of the variables, these numbers appear to be reasonably consistent.

As with the emanation rate of Rn<sup>222</sup> from the ground, its measured concentration in the atmosphere is highly variable. For example, measurements by Gold, et al.<sup>31</sup> at ground level in Cincinnati spanned the range  $(1-10) \cdot 10^{-16}$  curie/cm<sup>3</sup>, which translates into  $(0.6-6)$  ion-pair/cm<sup>3</sup>·sec. Again this range is reasonably consistent with the estimated average in Table 2.

It is particularly noteworthy that, owing to the universal nocturnal temperature inversion<sup>32</sup> and still air at night, the continuing emanation tends to accumulate near the ground and thus leads to a build-up of radon concentration in the air toward morning.

Large changes in the emanation rate, especially as measured by the concentration of radon in well water,<sup>33</sup> have long been observed to accompany seismic activity. The emanation rate may either increase or decrease, depending presumably upon whether the earth movement enhances or impedes the diffusion in the ground (and ground water). Intuitively it might appear that a compression would decrease the porosity--unless an overcompensating fragmentation of the medium were to release more of the trapped radionuclides. Despite the high interest, the uncertainties in interpretation of changes in radon emanation rates have so far frustrated attempts to utilize such data as a reliable index<sup>34,35</sup> in earthquake prediction.

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\*Since the rate of disintegration of a radionuclide is given by  $-\dot{N} = N/\tau$ , where the mean life  $\tau = t_{1/2} / \ln 2$ , 1 curie ( $\cong 3.7 \cdot 10^{10}$  disintegrations per second) corresponds to  $1.76 \cdot 10^{16}$  atoms of Rn<sup>222</sup> ( $\tau = 4.77 \cdot 10^5$  sec). Thus 1 atom corresponds to  $0.567 \cdot 10^{-16}$  curie, which in turn corresponds to  $1.6 \cdot 10^5$  ion-pair/ $4.77 \cdot 10^5$  sec or 0.335 ion-pair/sec; and 1 ion-pair/sec corresponds to 3.0 Rn<sup>222</sup> atoms.

<sup>31</sup>S. Gold, H.W. Barkhau, B. Shleien and B. Kahn, *Measurement of Naturally-Occurring Radionuclides in Air*, Ref. 24, Chapter 22.

<sup>32</sup>R. Geiger, *The Climate Near the Ground* (Harvard U. Press, Cambridge, 1959), p.23.

<sup>33</sup>

<sup>34</sup>

<sup>35</sup>

But there seems little doubt that under appropriate conditions the agitation of the earth accompanying an earthquake--particularly one of large magnitude--can greatly enhance the local radon emanation rate and increase the radon concentration in the lower atmosphere.

### 2.3 The Normal Geoelectric Field

It is now well-established<sup>36,37</sup> that the negative charge on the surface of the Earth--averaging  $\sim 6$  faraday--is maintained by the lightning strokes in the approximately 2000 thunderstorms in progress around the globe at any instant. In these storms the cloud base generally develops a very high negative charge density which induces in the surface below a positive image charge, so that the lightning strokes convey negative charge to the Earth. The average charge conveyed per stroke is about 20 coulombs in a time  $\sim 100$  msec, with current  $\sim 200$  amps, though much larger strokes carrying as much as 1000 coulombs and 10 kiloamperes are not uncommon.

Although the breakdown field strength for air is frequently quoted as  $\sim 20$  kV/cm, a more representative average along the ground-to-cloud path is probably closer to 2 kV/cm. Even so, with the cloud base  $\sim 1$  km above ground level, the potential difference is  $\sim 2 \cdot 10^8$  volts! Thus a typical lightning stroke may release  $\sim 4 \cdot 10^9$  joules, equivalent to a ton of high explosive, at a peak power of 40 Gwatt.

Flights near the base of thunderstorms have also found<sup>38</sup> horizontal components of the electric field as large as 500 V/m. Undoubtedly these play a role in commandeering charge from regions of the cloud surrounding a lightning stroke, and thus increase the total charge transfer.

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<sup>36</sup>See, for example, R. Mühleisen, *Atmosphärische Elektrizität*, in S. Flugge, *Handbuch der Physik* (Springer-Verlag, Berlin, 1957), vol. XLVIII, pp. 541-607.

<sup>37</sup>M.A. Uman, *Lightning* (Dover, New York, 1984).

<sup>38</sup>S.L. Valley, Ref. 30, p. 8-7.

The average worldwide current of negative charge flowing from cloud to ground totals about 1800 amperes. This is counterbalanced by an equivalent but oppositely-directed conduction current carried by charges in the atmosphere.

There is general agreement<sup>36,39-41</sup> concerning the following fair-weather properties of the Earth's electric field. At the Earth's surface the electric field  $\vec{E}$  is oriented toward the nadir and has average magnitude 130 V/m, corresponding to a total charge  $Q \approx 6$  faraday--i.e., 6 moles of electrons. Charges in the atmosphere collectively produce a conductivity  $\sigma \approx 2.8 \cdot 10^{-14} / \Omega \cdot \text{meter}$ . This yields a vertical current density  $j \approx 3.6 \cdot 10^{-12}$  amp/m<sup>2</sup>, or a worldwide total current  $J \approx 1800$  amp. It should be noted that these are average values, since both  $E$  and  $\sigma$  may have large variations with both location and time even in clear weather.

One interesting piece of orientation concerns the characteristic time  $\tau$  of the charge leakage rate  $\dot{Q}$ . Since

$$-\dot{Q} = J = 4\pi a^2 \sigma = 4\pi a^2 \sigma Q / 4\pi a^2 = Q / (a^2 / \sigma) = Q / \tau, \quad (2.1)$$

the characteristic time for leakage (to  $e^{-1}$ ) of the Earth's charge (if unreplenished by thunderstorms) would be

$$\tau = a^2 / \sigma \sim 4 \cdot 10^3 \text{ sec. or } 66 \text{ min.} \quad (2.2)$$

Also, both  $E$  and  $\sigma$  vary strongly with altitude. For example, Figure 1 shows<sup>42</sup> the range of measured values of the electric field as a function of altitude. A rough analytic fit to the average electric field up to  $\sim 5$  km altitude is

$$\vec{E} = -\vec{r}_1 130 e^{-h/2.1}, \quad (2.3)$$

where  $h$  is in kilometers. The total potential difference  $\Delta V$  between the ground and ionosphere amounts to about 300 kilovolts. Employing the connection between the field

<sup>39</sup>J.A. Chalmers, *Atmospheric Electricity*, 2<sup>o</sup> Edition (Pergamon, Oxford, 1967).

<sup>40</sup>L.G. Smith, Ed., *Recent Advances in Atmospheric Electricity* (Pergamon, New York, 1958).

<sup>41</sup>S.C. Coroniti, Ed., *Problems of Atmospheric and Space Electricity* (Elsevier, Amsterdam, 1965).

<sup>42</sup>Ref. 30, p. 8-2.

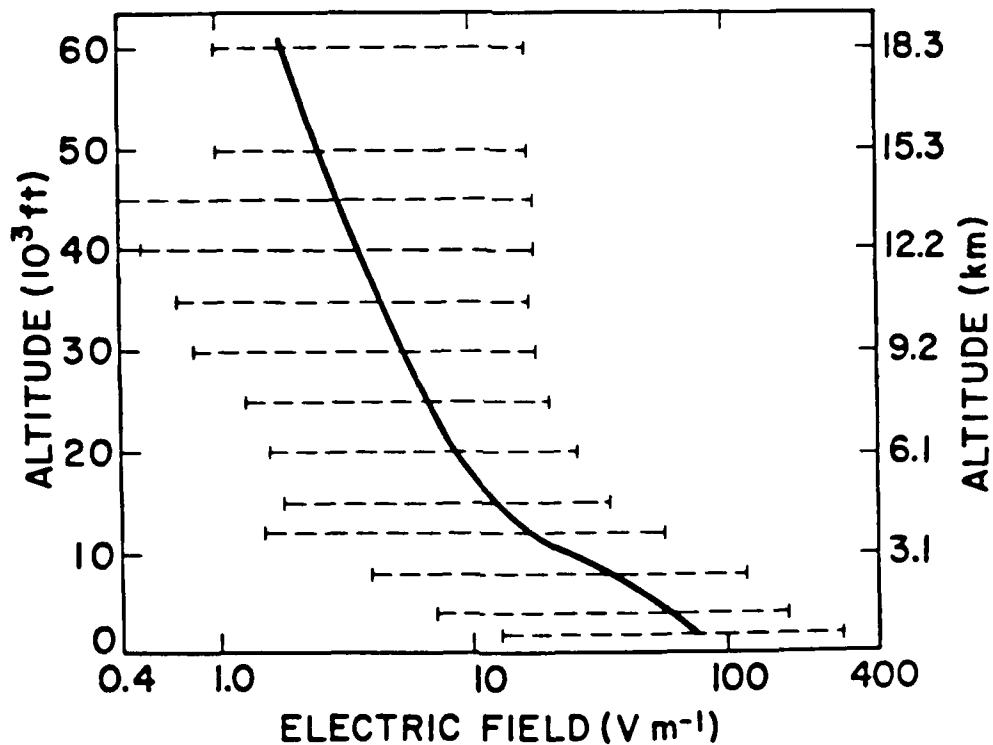


Figure 1. Average value and spread of observed electric field as function of altitude. [Taken from *Handbook of Geophysics and Space Environments*, S.L. Valley, Ed. (Air Force Cambridge Research Laboratories, Bedford Mass., 1965), p. 8-19.]

$\vec{\epsilon}$  and the net charge density  $\rho$ ,

$$\text{div } \vec{\epsilon} = \rho / \epsilon_0, \quad (2.4)$$

one obtains the charge density in terms of the magnitude of the electron charge  $e$  as

$$\rho/e = 2.7e^{-h/2.1} \text{ cm}^{-3}. \quad (2.5)$$

In other words, in the atmosphere at ground level there are fewer than 3 excess positive charges per cubic centimeter. Nevertheless, these are enough to cause the rapid decline in  $\epsilon$  with altitude.

Because of the frequent association of earthquake light phenomena with mountains, the electric field on promontories is of special interest. Unfortunately,



virtually no numerical data are to be found in the literature. Among the few qualitative statements, one of the most direct is from Mühleisen:<sup>43</sup>

Der Potentialgradient ist meist positiv (d.h. die Erdoberfläche erscheint negativ geladen) und hat am Erdboden in ebenem Gelände und bei Schönwetter Werte von 1 bis 3 V/cm oder 100 bis 300 V/m. In bewohnten Gegenden kann seine Grösse bis über 500 V/m ansteigen und ebenso in unebenem Gelände bei konvexer Krümmung, also auf Bergspitzen oder Bergrücken oder auch an der Oberseite von hohen Bäumen, Häusern, usw.

To gain some appreciation for the enhancement of the electric field by a promontory over that of a smooth earth, consider the model of two spheres of radii  $R$  and  $r$  ( $r \ll R$ ) bearing charges  $Q$  and  $q$  ( $q \ll Q$ ) such that they have a common electrostatic potential  $Q/R = q/r$ . The respective electric fields at the sphere surfaces are  $Q/R^2$  and  $q/r^2 = (Q/R^2)(R/r)$ . If this model were valid for a spherical "mountain" of radius  $r = 1$  km connected to the globular Earth of radius  $R = 6400$  km, the normal flatland atmospheric vertical potential gradient of  $\sim 130$  volt/m would correspond to over 800 kV/m on the "mountain." Although this model undoubtedly overestimates the effect, it nevertheless illustrates the great enhancement of the electric field on convex projections of small radii of curvature. Such large fields are manifested at sea in the corona discharge from the rigging of ships, known as St. Elmo's Fire; and of course this field enhancement and the consequent rapid charge leakage through air conductivity constitute the physical basis of Franklin's lightning rods.

It should be noted that although the mountaintop may be at high altitude, the geoelectric field measured in an aircraft or balloon at the same altitude but over a plain far below is not at all equivalent. The enhancement of the geoelectric field by a promontory derives from the compression and curvature of the equipotential surfaces immediately above it.

Whether the expected high charge-leakage rate from mountain tops makes a substantial contribution to limiting the Earth's total charge appears not to have been discussed in the literature.

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<sup>43</sup>Ref. 36, p. 542.

## 2.4. Electron Mobility in Air

The phenomena attending the conduction of electricity through gases<sup>44-47</sup> fall into several regimes distinguished by the charge, size and mass of the conducting particles, and the energy  $q\lambda$  that they acquire in falling one mean-free-path  $\lambda$  down the applied electric field  $\mathcal{E}$ . For a collision process having cross section  $\sigma$  the corresponding value of the mean free path  $\lambda=1/n\sigma$ , where the molecular number density  $n=p/kT$ . Thus it is customary to express the relevant parameters in terms of the ratio  $\mathcal{E}/p$ , measured in volts/cm·torr.

For our purpose we here consider only conduction by free electrons. The 5.5 MeV  $\alpha$ -particle from  $Rn^{222}$  has a range in air (at STP) of about 7 cm and produces about 0.16 million ion pairs. Initially each ion pair consists of a knock-on electron and an ionized air molecule ( $N_2^+$ ,  $O_2^+$ ) or atom ( $N^+$ ,  $O^+$ ), both having kinetic energies considerably above the ambient thermal value of 25 meV characteristic of  $kT$  at temperatures around 300°K. The average energy loss<sup>48</sup> of the  $\alpha$ -particle per ion pair formed is about 35eV, which is to be compared with the lowest ionization potential  $\sim 12$ eV for air molecules.

With their large masses and large collision cross sections, the ions are rapidly slowed to thermal equilibrium speeds. The thermalization of the free electrons, however, requires many more collisions with the air molecules owing to the inefficient energy exchange that is a consequence of the large disparity in masses: the average fractional loss in kinetic energy  $\epsilon$  of the electron in an elastic collision is given as the square root of the particle mass ratio:

$$-\delta\epsilon/\epsilon = 2(m_e/M_{air})^{1/2} \approx 1/117. \quad (2.6)$$

<sup>44</sup>L.B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (Wiley, New York, 1939); *Electrical Coronas* (U. Calif. Press, Berkeley, 1965).

<sup>45</sup>M.J. Druyvesteyn and F.M. Penning, *Rev. Mod. Phys.* 12, 85-174 (1940).

<sup>46</sup>J.M. Meek and J.D. Craggs, *Electrical Breakdown of Gases* (Clarendon, Oxford, 1953).

<sup>47</sup>S.C. Brown, *Conduction of Electricity in Gases*, Chapter 10 in *Handbook of Physics* (McGraw-Hill, New York, 1958), E.U. Condon and H. Odishaw, Eds.

<sup>48</sup>W. John, *Passage of Particles through Matter*, Sec. 8c, p. 8-38, in *Am. Inst. Phys. Handbook* (McGraw-Hill, New York, 1957), D.E. Gray, Ed.

Ultimately the slowed electrons are captured, mainly by the oxygen molecule, to form  $O_2^-$  or  $O + O^-$ .

For sufficiently high electron energy, besides the elastic collisions between the electron and the nitrogen or oxygen air molecules, certain types of inelastic collisions can occur that excite internal rotational, vibrational or electronic states of the molecule. Although, as shown in Table 3, the spacing between quantum levels for rotation and vibration is only a fraction of an eV, the cross section for such inelastic collisions is very small. Far more important are those inelastic collisions that can excite molecular electronic states, for these can result in light emission or electron multiplication.

Table 3. Excitation Energies (eV) of Air Molecules

Molecule	Rotation	Vibration	Electronic States				Ioniz. Potential	
			Ground	1°	2°	3°		4°
$N_2$	$2.46 \cdot 10^{-4}$	0.288	X. $^1\Sigma_g^+$	A $^3\Sigma_g^+(6.0)$	B $^3\Pi_g(7.3)$		15.377	
$O_2$	$1.78 \cdot 10^{-4}$	0.192	$^3\Sigma_g^-$	$^1\Delta_g(0.9)$	$^1\Sigma_g^+(1.6)$	$^3\Sigma_u^+(4.5)$	$^3\Sigma_u^-(6.0)$	12.075

Under a sufficiently high field the electron energy  $e \& \lambda$  gained between inelastic collisions can be large enough to cause collisional excitation of optically-emitting electronic states (e.g., the  $O_2$   $^3\Sigma_u^+$ ) or even ionization. Four observations are noteworthy in this context: first, such optical states lie well below the ionization potential; second, a single electron can be repeatedly accelerated, and so cause multiple excitations, until it is captured; third, since the probability of avoiding any collision over a distance of  $k$  mean-free-paths is  $e^{-k}$ , some few electrons may acquire much greater than average energy; and fourth, such high-energy electrons can cause ionization and thus multiply their numbers.

Starting with the electrons generated in the track of an  $\alpha$ -particle, we can thus distinguish with increasing field strength ( $\& \lambda$  or  $\&/p$ ) the following several regimes:

1° At small  $E/p$ , the  $eE\lambda$  product is too low to compensate for even the small electron energy loss in elastic collisions. The electrons thus progressively slow down and are ultimately captured. Although radiative capture is possible, it has such a low probability that electron capture produces little light.

2° At somewhat higher values of  $E/p$  the energy of the electron is maintained by the field, so that its lifetime (before capture) may be a large multiple of the collision time.

3° Increasing  $E/p$  still further produces a glow discharge, in which the electrons acquire sufficient energy between inelastic collisions to cause excitation of one or more molecular optical levels, but insufficient to cause ionization.

4° Finally a value of  $E/p$  is reached at which the electrons begin to multiply through ionizing collisions, and electrical "breakdown" occurs with the consequent passage of a spark.

Many of the experimental studies of the electrical conduction of gases have relied upon positive ion-bombardment of the cathode as the primary source of electrons. Moreover, as soon as light begins to be produced this may eject additional electrons from the cathode by the photoelectric effect. For these reasons, the electrodes have often introduced an undesirable complexity in the interpretation of laboratory conduction measurements.

One of the few studies that closely approximates the conditions of interest here is that of Klema and Allen,<sup>49</sup> who measured both the drift velocity and pulse height of electrons generated from the ionization by individual polonium  $\alpha$ -particles in various gases at pressures of 0.5, 1, 2 and 3 atmospheres. In argon, the pulse heights were constant over the range  $0.3 \leq E/p$  (volt/cm·torr)  $\leq 2.3$  (the highest value reported), showing that neither electron capture nor multiplication was occurring in this range.

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<sup>49</sup>E.D. Klema and J.S. Allen, Drift Velocities of Electrons in Argon, Nitrogen, and Argon-Nitrogen Mixtures, *Phys. Rev.* 77, 661-5 (1950).

The introduction of 1 per cent oxygen in argon at 3 atmospheres reduced the pulse height (owing to some electron capture), but increased the electron drift rate by more than a factor two for  $\mathcal{E}/p$  values below 0.15 volt/cm·torr. Above  $\mathcal{E}/p \sim 0.5$ , the pulse height declined owing to inelastic collisions and capture with  $O_2$ .

Noteworthy also were the low values of the field strengths at which discharges occurred in the various mixtures, as shown in Table 4.

The measured average electron drift velocities were typically 1 cm/ $\mu$ sec at  $\mathcal{E}/p \sim 0.4$  V/cm·torr.

If this drift velocity  $\delta \vec{v}$  were in the same direction as (i.e., additive to) the electron's random thermal velocity  $\vec{v}$ , the added average

energy increase  $\delta \epsilon$  ( $\sim m v \delta v_{\text{drift}}$ ) would be approximately 0.005 eV, bringing the total energy to  $\epsilon \sim 0.03$  eV; yet a value of  $\mathcal{E}/p \sim 1$  is enough to initiate discharge (Table 4), which clearly demands that some of the electrons acquire energies  $\sim 10$  eV, nearly  $10^3$  greater than the average.

A similar situation for high-frequency discharges was remarked by Brown:<sup>50</sup>

"If one calculates the maximum kinetic energy at the minimum field intensities for breakdown experimentally determined, one finds that this energy corresponds to about  $10^{-3}$  volt. Therefore, the energy of oscillation is insufficient to account for breakdown.

"A free electron in a vacuum under the action of an alternating field oscillates with its velocity  $90^\circ$  out of phase with the field and thus takes no power, on an average, from the applied field. The electron gains energy from the field only by suffering collisions with the gas atoms, and it does so by having its ordered oscillatory motion changed to random motion on collision. The electron gains random energy on each collision until it is able to make an inelastic collision with a gas atom. The fact that the electron can continue to gain energy in the field, on an average, despite the fact that

Table 4. Threshold Discharge Values of  $\mathcal{E}/p$  for Various Gas Mixtures

Mixture	p/atm	(V/cm)	$\mathcal{E}/p$ (V/cm.torr)
1% N <sub>2</sub> , 99% A	2	1280	0.84
	1	940	1.24
10% N <sub>2</sub> , 90% A	1	1360	1.79

<sup>50</sup> Ref. 47, p. 4-170.

it may move either with or against the field can be seen by showing that the energy absorbed is proportional to the square of the electric field and hence independent of its sign. The rate of gain of energy of the electron from the electric field  $E$  (rms) is  $P = e \mathcal{E} \langle v \rangle_{av}$ .

". . . The gas discharge breakdown occurs when the gain in electron density due to ionization of the gas becomes equal to the loss of electrons by diffusion, recombination, or attachment."

In this explanation for the high-frequency discharge, evidently collisions play an essential role in energy absorption from the field by destroying the electron out-of-phase correlations. Nevertheless, for the electrons to gain energy continually, whatever energy is lost in these collisions must be more than compensated by the increase in energy acquired between collisions. But obviously for a static field a different explanation is needed.

In qualitative terms, the problem can be formulated as a variant of the classical Einstein-Langevin theory<sup>51</sup> of Brownian motion, in which the course of a massive particle having large momentum is subject to frequent small random impulses from collisions with much-less-massive particles. Here, we have the opposite problem: a particle of small mass (the electron) under a small, steady external force, is subject to frequent large random impulses. The only similarity to the high-frequency case is that a steady increase in electron energy is possible despite the frequent large random impulses from collisions with the gas molecules. Unfortunately, this problem is not amenable to the standard<sup>52</sup> stochastic methods, which treat the collisional impulses as small perturbations. In the large volume of research<sup>53</sup> on the conduction of electricity by gases this fundamental problem appears to have been virtually ignored.

<sup>51</sup>See, for example, G. Marc and W.G. McMillan, *The Virial Theorem in Advances in Chemical Physics*, Vol. LVIII, (Wiley, New York, 1985), I. Prigogine, Ed., pp. 343-346.

<sup>52</sup>N. Wax, Ed., *Selected Papers on Noise and Stochastic Processes* (Dover, New York, 1954).

<sup>53</sup>There are many particularly informative papers in addition to the major reviews cited above (Refs. 44-47).

Despite this lack of a detailed theory, the experimental results quoted above for the high-frequency glow discharge and the low  $E/p$  threshold values for electrical breakdown (Table 4) show that free electrons can acquire energies  $\sim 10$  eV despite their continual deflection by inelastic collisions. This conclusion is what is needed to explain the earthquake luminous phenomena in the atmosphere near the ground:

1° Natural radionuclides (e.g.,  $Rn^{222}$ ) emanating from the ground--perhaps enhanced by the earthquake--provide the source of free electrons;

2° The electric field of the Earth--again possibly enhanced by the earthquake (e.g., by changes in rock stress coupled with the piezoelectric effect)--accelerates the electrons produced by  $\alpha$ -particle ionization;

3° Depending upon the number density of free electrons and the field strength, the electron-molecule collisions can result in luminous phenomena ranging from weak airglow, through brief light flashes to clear-air lightning-like strokes.

4° Because of the field-enhancement on promontories, these luminous phenomena may be expected to occur most frequently on mountains.

## 2.5. Earthquake Airglow Light Intensity

In assessing the possible magnitude of the earthquake airglow light intensity we take for comparison the intensity of moonlight from the full moon at zenith. This is  $\sim 10^{-6}$  times<sup>54</sup> the solar constant of  $1.35 \text{ kW/m}^2$ . If all of this energy were in the visible (e.g., 2-eV photons near the yellow sodium-D doublet), the intensity of full moonlight would correspond to  $\sim 10^{12}$  photons/cm<sup>2</sup>·sec or  $10^6$  rayleigh. This is about a factor of  $10^3$  greater than normal<sup>55</sup> airglow emission rates. These intensities are in qualitative agreement also with current light-amplification devices (e.g., the US Army's Starlight Scope) that provide amplification of illumination from normal night-time airglow by factors  $\sim 10^4$ , to yield images that are perhaps ten times brighter than full moonlight.

<sup>54</sup>Ref. 30, p. 10-28.

<sup>55</sup>R. Kauth, Chapter 5, Backgrounds, p. 106, in *Handbook of Military Infrared Technology* (USN Office of Naval Research, Washington, 1965), W.L. Wolfe, Ed.

Supposing the earthquake-stimulated airglow were to originate in a blanket 100 m thick and correspond to the fraction  $f$  of moonlight intensity, the rate of photon production required would be  $\sim 10^5 f/\text{cm}^3 \cdot \text{sec}$ . With the remarkable dynamic range of the human eye, an airglow intensity of 10-100 times normal background, i.e.,  $\sim 1$  per cent of full moonlight, would be clearly noticeable to the dark-adapted eye. This corresponds to  $10^3$  photons/ $\text{cm}^3 \cdot \text{sec}$  in a 100 m blanket, or  $10^2$  photons/ $\text{cm}^3 \cdot \text{sec}$  looking horizontally through 1 km of the luminous air.

Recalling from Table 2 that the average radon emanation rate corresponds to about 10 ion-pair/ $\text{cm}^3 \cdot \text{sec}$  in air near the ground, that the photon yield per ion pair is close to 1, and that the radon concentration can be much larger over ore-bodies rich in uranium and thorium, it seems clear that an earthquake-induced enhancement of the radon emanation rate could easily provide an adequate source of free electrons. Moreover, earthquake enhancement of the electric field--already abnormally large on promontories--could allow many cycles per electron of acceleration followed by an inelastic collision to excite an air molecule to an optically-emitting state. Even with the average ion-pair (electron) production rate of 10/ $\text{cm}^3 \cdot \text{sec}$  one needs only 10-100 photons per electron to explain the earthquake airglow.

Two additional contributing factors are noteworthy: first, the knock-on electrons in the  $\alpha$ -particle ionization wake are born "hot," and may be maintained at relatively high kinetic energies in a sufficiently strong electric field; and second, insofar as the free electrons avoid capture, their numbers--from the continuing emission of  $\alpha$ -particles--are cumulative, and may ultimately attain sufficient conductivity to support a flash discharge.

The discharge flashes and lightning-like strokes likely require higher than normal electric fields--perhaps in the range of 100 kV/m (cf. Table 4). As high as this figure sounds, it is still an order of magnitude less than the (admittedly extreme) estimate given at the end of Section 2.3 for the field on a mountaintop.



### 3. EARTHQUAKE AURORAL PHENOMENA

#### 3.1 Concept Outline

In seeking an explanation for earthquake light originating in the sky, (Category 6° of Section 1.2) one is led to a comparison with natural aurorae, to which these sky-light phenomena bear striking similarities: they occur over a considerable range of elevation angles above the horizon, often overhead; they may cover areas of several degrees in longitude and latitude; they exhibit many of the transient features of natural aurorae--sheets, fingers, converging streamers, flickering, etc.; and the range of colors reported are essentially the same as for polar aurorae. The designation as earthquake auroral phenomena thus seems appropriate.

Several key aspects, however, are different: earthquake aurorae are correlated with seismic activity--usually a large-magnitude earthquake; whereas polar aurorae are correlated in time with solar activity, specifically with solar magnetic storms and the arrival of copious numbers of high-energy charged particles. The earthquake aurora can appear at latitudes far below the normal auroral zones surrounding the Earth's magnetic poles; and their duration is much shorter.

Reasoning by analogy with polar aurorae, the excitation of the air molecules--whose radiation evidently constitutes the earthquake auroral light--presumably results from bombardment by energetic charged particles. Although at low altitude we could invoke as source of electrons the decay of radioactive gases--whose emanation from the ground is stimulated by seismic activity--this source cannot apply at high altitude. We are thus driven to examine ways of utilizing the charged particles already present.

There are two natural reservoirs of charged particles at high altitude: the ionosphere (e.g., the F-layer) and the Van Allen belts. The ability to excite radiation of the air places upon these particles three essential requirements: sufficient energy, sufficient air molecular number density, and sufficient numbers to account for the auroral light intensity. Upon examining, against these requirements, the characteristics

of the charged particles trapped in these reservoirs, particularly the limitations that preclude the generation of mid-latitude aurorae under normal conditions, it becomes clear what changes in properties--of either the particles themselves or their environment--might remove these limitations.

To extend our understanding, in this context, of the characteristics of the charged particles in these reservoirs and how these might be affected by an earthquake then involves a synthesis of several key aspects: the normal geomagnetic field; charged particle dynamics; possible electromagnetic influences; hypothetical coupling mechanisms to an earthquake; elimination and selection of most likely mechanisms through numerical evaluation. These aspects are treated in order in subsequent sections. A final section is devoted to a discussion of the intensity and time characteristics of earthquake auroral light based on the most promising mechanisms.

### **3.2 Two Electron Reservoirs**

#### **3.2.1 Ionospheric Electrons**

Electrons (and accompanying positive ions) in the ionosphere are produced by photoionization of the air molecules by solar radiation in the vacuum ultraviolet. (The ionization potential of the oxygen molecule, 12 eV, corresponds to the energy of a photon of about 1000Å wavelength.) Since most of these photoelectrons have insufficient kinetic energy to cause further ionization, they eventually become thermalized through collision with the air molecules, after which some may be captured to form negative ions or neutralize the accompanying positive ions. When photoionization ceases at sunset, recombination quickly causes the lower-altitude (D and E) layers of the ionosphere to disappear, leaving at night only the higher-altitude F layer. Since earthquake aurorae are visible only at night, it is this night-time F layer that has primary relevance.

Although the distribution of electron number density with altitude is a function of many variables--latitude, time of day, season, sunspot activity, etc.--this discussion is limited to the average properties, shown in Table 5.

Table 5. Average Properties of the Night-Time F-Layer

Altitude <sup>a</sup> of maximum electron number density	$4 \cdot 10^2$ km
Maximum electron number density <sup>b</sup> , $n_e$	$6 \cdot 10^5 / \text{cm}^3$
Molecular number density <sup>b</sup> , $n$	$3 \cdot 10^8 / \text{cm}^3$
Mean molecular weight <sup>b</sup> , $M$	20 g/mole
Atmospheric scale height <sup>b</sup> , $H$	70 km
Electron: temperature <sup>c</sup> , $T$	$1 \cdot 10^3$ °K
energy,	0.1 eV
speed, $v$	$2 \cdot 10^7$ cm/sec
mean free path	8 km
collision frequency, $\nu_c$	$1 \cdot 10^2 / \text{sec}$
plasma (angular) frequency, $\omega_p$	$3 \cdot 10^7$ radian/sec
gyration (angular) frequency, $\omega_g$	$9 \cdot 10^6$ radian/sec
gyration radius, $\rho$	2 cm

<sup>a</sup>K. Davies, *Ionospheric Radio Propagation* (Dover, New York, 1966), Figure 3.15, p. 128.

<sup>b</sup>*Ibid.*, Tables 1.3, 1.4, pp. 6-7.

<sup>c</sup>Ref. 30, Figure 12.15, p. 12-14.

As shown in Figure 2,<sup>57</sup> the electron number density in the night-time ionosphere declines more or less exponentially with altitude, but in two regimes of vastly different number-density scale heights: from 400-600 km, 125 km; and from 600-2000, ~2000 km or more.

As indicated in Table 5, the thermalized ionospheric electrons gyrate around the lines of force of the geomagnetic field, but also suffer frequent (elastic) collisions with the molecules of the tenuous atmosphere. Because of their low energy, these ionospheric electrons do not constitute a source of auroral excitation unless they can somehow be accelerated from thermal energy (~0.1 eV) to an energy (~10 eV) sufficient to cause electronic excitation of the air molecules. Conceivable mechanisms to achieve such acceleration are discussed in Section 3.5.1.

<sup>57</sup> Ref. 30, Figure 12-7, p. 12-7.

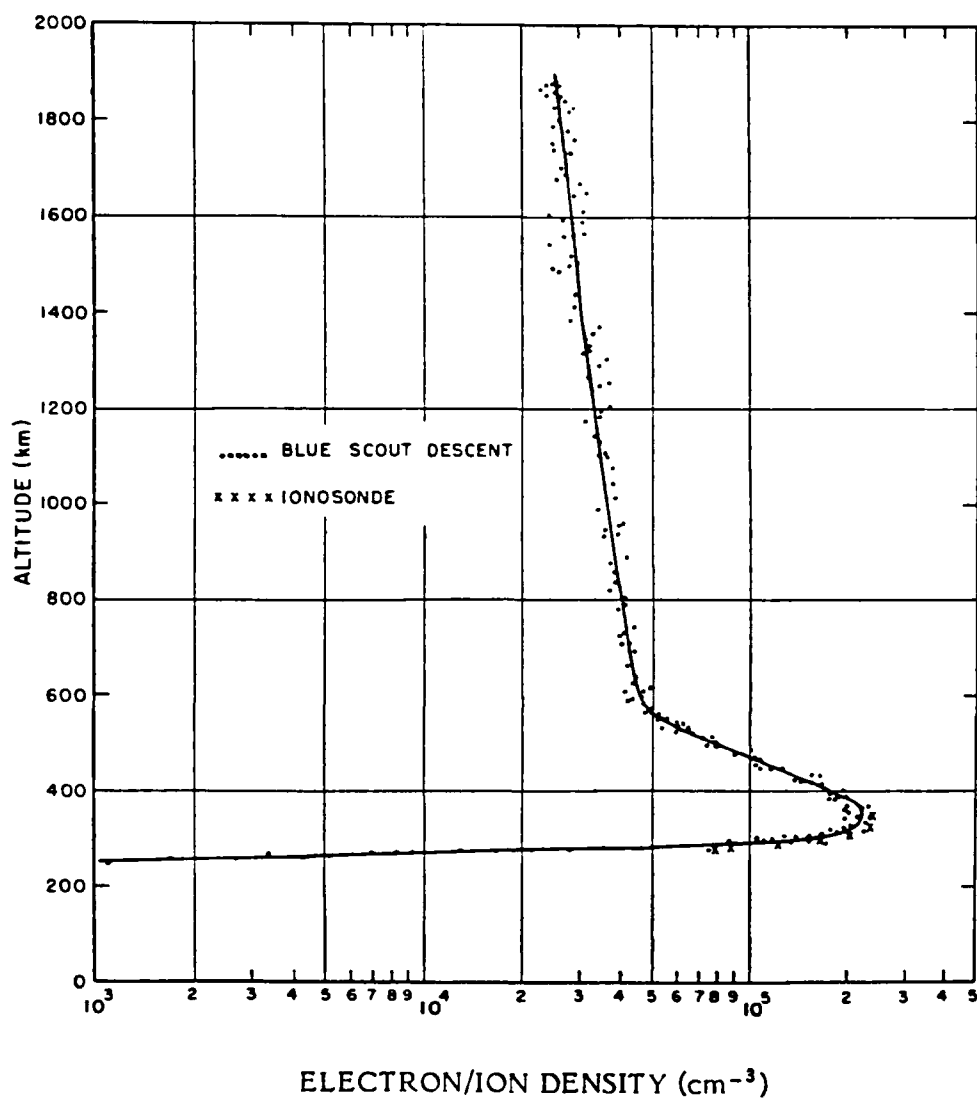


Figure 2. Night-time electron and ion densities as a function of altitude. (rocket flight at night from Cape Kennedy, Florida on 12 April 1961.) Positive ion densities from ion-trap probe and electron densities from rf impedance probe. [From R.C. Sagalvn and M. Smiddy, *J. Geophys. Res.* **69**, 1809 (1964).]

### 3.2.2 The Van Allen Radiation Belt

The second natural charged-particle reservoir at high altitude is the Van Allen radiation belt,<sup>58-61</sup> particularly the inner zone in which a maximum in the high-energy particle flux is centered around 1.5 earth radii (i.e., an altitude around 3000 km at the geomagnetic equator). As shown in Table 6., both electrons and protons in the MeV energy regime are present, but the particle flux is dominated by the electrons, particularly below L=1.5 earth radii.

Table 6. Omnidirectional Particle Fluxes and Energies on the Geomagnetic Equator<sup>59</sup>

Magnetic shell parameter (L)	Low-energy protons (E > 0.4 MeV)		High-energy protons (E > 15 MeV)		Electrons (E > 0.5 MeV)	
	Flux, cm <sup>-2</sup> sec <sup>-1</sup>	E <sub>0</sub> , MeV	Flux, cm <sup>-2</sup> sec <sup>-1</sup>	E <sub>0</sub> , MeV	Flux, cm <sup>-2</sup> sec <sup>-1</sup>	E <sub>0</sub> , MeV
1.25	4x10 <sup>4</sup>	2.2	1x10 <sup>4</sup>	20	4x10 <sup>7</sup>	0.9
1.5	1x10 <sup>6</sup>	2.2	1x10 <sup>5</sup>	13	6x10 <sup>7</sup>	0.4
2.0	1.6x10 <sup>7</sup>	2.1	7x10 <sup>4</sup>	8	3x10 <sup>6</sup>	0.13
2.5	1x10 <sup>8</sup>	0.6	8x10 <sup>3</sup>	8	2x10 <sup>5</sup>	0.33
3.0	2x10 <sup>8</sup>	0.4	2x10	7	6.7x10 <sup>4</sup>	0.42
3.5	1x10 <sup>8</sup>	0.34			3x10 <sup>5</sup>	0.5
4.0	3x10 <sup>7</sup>	0.3			10 <sup>6</sup>	0.4
5.0	4x10 <sup>6</sup>	0.13			2.5x10 <sup>6</sup>	0.35
6.0	9x10 <sup>5</sup>	0.11			9x10 <sup>5</sup>	0.25

The flux of medium-energy (e.g., 10 keV) electrons, particularly at low L values (<1.5) is not accurately known, in part because special instrumentation is required to distin-

<sup>58</sup>J.A. Van Allen, C.E. McIlwain and G.H. Ludwig, Radiation Observations with Satellite 1958, *J. Geophys. Res.* **64**, 271-286 (1959); J.A. Van Allen and L.A. Frank, Radiation around the Earth to a Radial Distance of 107,400 km, *Nature* **183**, 430ff. (1959).

<sup>59</sup>M. Walt, Van Allen Radiation, in *Encyclopedia of Science and Technology*, Vol. 14 (McGraw-Hill, New York, 1982), pp. 334-8.

<sup>60</sup>R.M. Buck, Energetic Electrons in the Inner Belt in 1968, *Planet. Space Sci.* **24**, 643-655 (1976).

<sup>61</sup>R.S. White, The Earth's Radiation Belt, *Phys. Today* **19**, 25-38 (1966).

guish electrons from the more penetrating protons, but mainly because it is highly variable. For example, in 1961 measurements at 1000 km altitude on an Injun rocket found a differential flux of  $\sim 10^{10}$  electrons/cm<sup>2</sup>·sec·keV at 10 keV energy; but in 1963 another measurement at L=1.55 found  $\sim 10^5$  electrons/cm<sup>2</sup>·sec·steradian·keV, or  $\sim 10^6$  omni. Taking a 10 keV-wide band centered on 10 keV gives for these two measurements a spread in intensity of  $10^{10} - 10^{14}$  eV/cm<sup>2</sup>·sec.

According to O'Brien,<sup>62</sup> at low altitudes the flux of electrons with energies  $\geq 40$  keV can change by a factor of  $10^6$  in about 30 seconds or  $10^3$  in less than 1 second. There is as yet no satisfactory explanation for the magnitudes and rates of these variations.

In the Earth's magnetic field the electrons undergo a superposition of three types of periodic motion: rapid gyration around a magnetic field line; oscillation parallel to the field line, with reflection at two mirror points symmetrically disposed at (geomagnetic) latitudes  $\pm \lambda_m$ ; and a slow eastward drift. The mirror points are determined by the pitch angle of the electron's helical path, those with smaller pitch angle (velocity vector nearly parallel to the magnetic field) mirroring at lower altitudes. Of course, those with mirror points within the sensible atmosphere eventually are removed from the radiation belt through collisions with the air molecules. Thus, those remaining have mirror points well above the atmosphere, and thus cannot contribute to an aurora without significant changes in energy or the confining magnetic field. As in the case of ionospheric electrons, we are thus again led to examine the physical mechanisms by which an earthquake might effect such changes. To this end we first summarize the relevant characteristics of the geomagnetic field and the dynamics of charged particles trapped therein.

<sup>62</sup> B.J. O'Brien, *Reviews of Studies of Trapped Radiation with Satellite-Borne Apparatus, Space Studies Reviews*, Vol. 1 (1962-3), p. 415, C.G. Jager, Ed. (\_\_\_\_\_, Utrecht, \_\_\_\_), cited in Ref. 30, p. 17-10.

### 3.3 The Normal Geomagnetic Field

For our purposes it is sufficient to use the approximate representation of the normal geomagnetic field source as a geocentric point magnetic dipole<sup>63</sup> of moment  $M = 8.05 \cdot 10^{25}$  gauss·cm<sup>3</sup>. By employing geomagnetic coordinates we can ignore the 11.5° inclination of the dipole to the earth's axis of rotation. With the possible exception of the South Atlantic (or "Brazilian") Anomaly, where the field lines sink to abnormally low altitudes, we will ignore also the small offset of the dipole center from the center of the Earth.

In geomagnetic coordinates the length of the radius vector  $\vec{r}$  from the dipole center to a given field line at latitude  $\lambda$  is given (in the ideal point-dipole approximation)

$$\text{by} \quad r/a = L \cos^2 \lambda, \quad (3.1)$$

where  $a (=6371 \text{ km})$  is the earth's radius. As used here, the parameter  $L$  introduced by McIlwain<sup>64</sup> is evidently the maximum altitude of the field line (at  $\lambda = 0$ ), measured in units of  $a$ . In these same terms the magnetic field is given by

$$\vec{B} = \vec{M}(3\vec{r}_1 \cdot \vec{r}_1 - 1)/r^3, \quad (3.2)$$

where  $\vec{r}_1$  is the unit vector along  $\vec{r}$ , and the period  $\cdot$  separating the vectors indicates a dyad. The field lines (which form closed loops since  $\text{div } \vec{B}=0$ ) thus converge toward the geomagnetic poles. The magnitude  $B$  of the field is

$$B = M(3 \sin^2 \lambda + 1)^{1/2}/r^3. \quad (3.3)$$

Since auroral light originates at altitudes  $\sim 70 \text{ km}$  ( $r/a \sim 1.01$ )--that being the depth of penetration corresponding to the "range" of the energetic Van Allen particles--the value of  $L$  characterizing the field lines involved can be calculated from Eq. (3.1) given the latitude  $\lambda$ . For example, if  $\lambda = 35^\circ$  (roughly the geomagnetic latitude of the Liaotung Peninsula in China where several major earthquakes have occurred during the

<sup>63</sup> Ref. 30, p. 11-1.

<sup>64</sup> C.E. McIlwain, Coordinates for Mapping the Distribution of Magnetically-Trapped Particles, *J. Geophys. Res.* **66**, 3681-3691 (1961). For the actual geomagnetic field  $L$  has a more complicated definition, but differs numerically by only a few percent.

last decade),  $L=1.49$  corresponding to an altitude of about 3120 km at the geomagnetic equator.

Another field-line parameter of interest is the inclination or dip-angle  $\psi$  from the local horizontal, for which

$$\sin \psi = 2\sin\lambda / (3\sin^2\lambda + 1)^{1/2}, \quad (3.4a)$$

or 
$$\tan\psi = 2\tan\lambda. \quad (b)$$

### 3.4 Trapped-Particle Dynamics

Both the ionosphere and the Van Allen radiation belts contain charged particles trapped on the magnetic field lines of the Earth's magnetic dipole. In the absence of collisions with air molecules, a particle of mass  $m$  and charge  $q$  undergoes three types of periodic motion,<sup>65,66</sup> whose periods are so vastly different as to make them essentially uncoupled and separable:

1. Helical cyclotron gyration about the field line, with angular frequency

$$\omega_g = |q|B/mc \quad (3.5)$$

and radius of gyration

$$\rho = v_{\perp} / \omega_g, \quad (3.6)$$

where  $v_{\perp}$  is the component of velocity normal to  $B$ . For near-relativistic electrons the gyro period  $\tau_g = 2\pi/\omega_g \sim 1 \mu\text{sec}$ , and  $\rho \sim 35$  meters.

2. Oscillation in geomagnetic latitude along the field line, with reflection or "bouncing" at the two mirror points (symmetrically disposed at geomagnetic latitude  $\pm\lambda_m$ ) where the convergence and increase of the magnetic field is sufficient to reverse the component of velocity  $v_{\parallel}$  parallel to the field line. For near-relativistic particles in the near geomagnetic field, this bounce period  $\tau_b \sim 0.1$  sec.

<sup>65</sup>H. Alfvén, *Cosmical Electrodynamics* (Oxford U. Press, Oxford, 1950).

<sup>66</sup>W.N. Hess, The Earth's Radiation Belt, in S. Flugge, *Handbuch der Physik*, Vol. XLIX/4 *Geophysics* (Springer-Verlag, Berlin, 1972), pp. 115-230. See also W.N. Hess, *The Radiation Belt and Magnetosphere* (Blaisdell, Waltham Mass., 1968).



3. A slow drift in geomagnetic longitude, westward for positive charges and eastward for negative. Again, for a near-relativistic electron the period of the eastward drift  $\tau_d \sim 1$  hour.

Apart from the slow longitudinal drift, the much more rapid particle motion resulting from the combined gyration about the field line and oscillation along the field line between conjugate mirror points can be visualized as a helical path on the surface of a Faraday tube of force in the form of a horseshoe-shaped cone that converges towards the Earth at both ends and has the field line as axis. This motion is best described in terms of the Alfvén<sup>65</sup> model, in which the "guiding center" of the particle motion progresses along the field line of force at such rate as to make the cyclotron orbit appear planar.

The principal results of the detailed mathematical analysis can be easily obtained from the theory of adiabatic invariants.<sup>67</sup> In a coordinate system in which the guiding center is (momentarily) at rest, the area  $\Delta S$  swept out by the particle radius vector  $\vec{\rho}$  (from the guiding center) in one cycle of gyration is intimately related to the azimuthal angular momentum  $P$  of the particle in its cyclotron orbit (i.e., Kepler's 2<sup>o</sup> Law), to the dipole moment  $\mu$  generated by the loop of current  $J$ , and to the total magnetic flux  $\Phi$  threading the cyclotron orbit:

$$\oint P d\phi = \oint \vec{k} \cdot \vec{\rho} \times m \vec{v} d\phi = 2m\oint (\vec{k} \cdot d\vec{S}/dt) d\phi = 2m\omega \oint \vec{k} \cdot d\vec{S} = (2q/c) B \Delta S \quad (3.7a)$$

$$\mu = J \Delta S / c = (e^2 / 2\pi m c^2) B \Delta S = 2r_e (B / 4\pi) \Delta S; \quad (b)$$

and  $\Phi = \int \vec{B} \cdot d\vec{S} = B \Delta S. \quad (c)$

Since the action integral (3.7a) is an (approximate) adiabatic invariant of the motion, so too are the dipole moment  $\mu$  and flux  $\Phi$ .

<sup>67</sup>T.G. Northrup, *The Adiabatic Motion of Charged Particles* (Interscience, New York, 1963); J.W. Chamberlain, *Motion of Charged Particles in the Earth's Magnetic Field* (Gordon and Breach, New York, 1964); J.G. Roederer, *Dynamics of Geomagnetically Trapped Radiation*, Vol. 2 of *Physics and Chemistry in Space*, J.G. Roederer and D. and Z. Zahringer, Eds. (Springer-Verlag, Heidelberg, 1970).

Although the magnetic force, being oriented always normal to the velocity vector, cannot change the total kinetic energy  $\epsilon$  of the particle, a nonuniform field can alter the partition of this energy between its transverse  $\epsilon_{\perp}$  and parallel  $\epsilon_{\parallel}$  parts. In terms of the instantaneous pitch angle  $\alpha$  between the particle velocity vector  $\vec{v}$  and field  $\vec{B}$ ,

$$v_{\perp} = v \sin \alpha, \quad (3.8)$$

and

$$\epsilon_{\perp} \equiv mv_{\perp}^2/2 = (mv^2/2)\sin^2\alpha = \epsilon \sin^2\alpha. \quad (3.9)$$

As the particle in its helical path approaches either of its mirror points the increase in the magnetic field  $B$  increases the transverse part of the energy  $\epsilon_{\perp}$  at the expense of the parallel part  $\epsilon_{\parallel}$  until at the mirror point (where  $B=B_m$ )  $\epsilon_{\parallel}=0$ ,  $\alpha=\pi/2$  and  $\epsilon_{\perp}=\epsilon$ .

Invariance of the flux  $\Phi$ , Eq. (3.7c), through the area  $\Delta S (= \pi\rho^2)$  immediately shows that for any given particle,  $\epsilon_{\perp}/B$  is a constant. Thus

$$\epsilon_{\perp}/\epsilon = B/B_m = \sin^2\alpha. \quad (3.10)$$

At the geomagnetic equator,  $\lambda=0$ , the pitch angle  $\alpha_0$  is given by

$$\sin^2\alpha_0 = B_0/B_m = \cos^6\lambda_m/(3\sin^2\lambda_m + 1)^{1/2}. \quad (3.11)$$

Specification of  $\alpha_0$  thus serves to determine the geomagnetic latitudes  $\pm\lambda_m$  of the mirror points; and specification of  $L$  determines the magnetic shell containing the line of force along which the guiding center moves. It is particularly noteworthy that the mirror point latitude depends upon only the equatorial pitch angle  $\alpha_0$ --i.e., it is independent of  $L$ , as well as of the particle energy  $\epsilon$ , mass  $m$  and sign of charge. This has the remarkable consequence that within broad ranges of the equatorial pitch angle  $\alpha_0$ , as shown in Table 7, the Earth's magnetic field--by most measures, of almost insignificant magnitude ( $\sim 0.5$  gauss)--has the capability of trapping, and turning around at the mirror points, electrons and protons having velocities approaching the speed of light.

The bounce period  $\tau_b$  for oscillation along the line-of-force between mirror points is given as the line integral

Table 7. Mirror-Point Latitude  $\lambda_m$  as Function of Equatorial Pitch Angle  $\alpha_0$ 

$L$ for $h=100\text{km}$	$\lambda_m$	$\alpha_0$	$\alpha_0$	$\lambda_m$
1.00	$0^\circ$	$90^\circ$	$90^\circ$	$0^\circ$
1.01	5	79.44	80	4.73
1.03	10	69.19	70	9.59
1.13	20	50.32	60	14.69
1.33	30	34.38	50	20.18
1.50	35.264	27.24	40	26.25
1.70	40	21.56	30	33.15
2.00	45	16.33	20	41.41
2.42	50	11.89	10	52.45
4.00	60	5.32	5	60.69
8.55	70	1.66	3	65.48
			2	68.68
			1	73.16

$$\begin{aligned} \tau_b &= ds/v_{||} = 4 \int_0^{\lambda_m} r d\lambda [(d \ln r / d\lambda)^2 + 1]^{1/2} / v \cos \alpha \\ &= (4aL/v) \int_0^{\lambda_m(\alpha_0)} d\lambda \cos \lambda \left[ \frac{4 - 3 \cos^2 \lambda}{1 - \sin^2 \alpha_0 (4 - 3 \cos^2 \lambda)^{1/2} / \cos^6 \lambda} \right]^{1/2}. \end{aligned} \quad (3.12)$$

The only virtue of this intractable integral is that its value is relatively insensitive to  $\alpha_0$ :  $\pi/\sqrt{18} = 0.7405$  for  $\alpha_0 = 90^\circ$  ( $\lambda_m = 0$ ), and  $\{[\ln(2\pi/3)]/2/3 + 1\} = 1.3802$  for  $\alpha_0 = 0$  ( $\lambda_m = 90^\circ$ ).

Thus, for a near relativistic particle ( $v \approx c$ )

$$\tau_b \sim 4aL/c = 0.085L \text{ sec.} \quad (3.13)$$

In the absence of an electric field, the longitudinal drift is a consequence of the inhomogeneity of the dipole field and the curvature of the lines of force. A drift period  $\tau_D \sim 1$  hour implies a longitudinal speed  $\sim 6^\circ/\text{minute}$  or, in midlatitudes,  $\sim 10$  km/sec. The significance of these numbers is that if the electrons in the reservoir immediately overhead are used up in producing an aurora, the supply is rapidly replenished. For

example, if the earthquake aurora extends over 1 degree in longitude (i.e., ~100 km in midlatitudes), the overhead reservoir will be replenished every 10 seconds. To determine whether this replenishment is rapid enough to keep the aurora going requires a detailed calculation of the intensity.

### 3.5 Ionosphere Electrons

#### 3.5.1 Acceleration Mechanisms

As discussed in Section 3.2.1, although there are large numbers of electrons in the F-layer of the ionosphere, their average energy is only about one per cent of that required to excite optical emission by the air molecules. Of course a maxwellian velocity distribution contains a few high-energy particles: at energies far above average, the fraction  $f$  whose energy exceeds  $\check{\epsilon}$  ( $\check{\epsilon} \approx kT\check{\xi}^2$ ) is given by

$$f \approx \int_{\check{\xi}}^{\infty} (\xi^2 - \frac{1}{2}) e^{-\xi^2} d\xi / \int_0^{\infty} \xi^2 e^{-\xi^2} d\xi = \check{\xi} e^{-\check{\xi}^2} / \Gamma(3/2)$$

or,  $f(\epsilon > \check{\epsilon}) \approx 2(\check{\epsilon}/\pi kT)^{1/2} e^{-\check{\epsilon}/kT}$ . (3.14)

With  $\check{\epsilon}/kT \sim 100$ , no calculation is necessary to see that electron-molecule collisions (as contrasted with capture or radiative recombination) contribute little to the night-time luminescence of the ionosphere. The problem then is to determine whether and how the electron energy might be increased by some phenomenon associated with an earthquake.

There are three physical mechanisms for increasing the energy of charged particles from a great distance: hydrodynamics, time-dependent magnetic fields, and both static and pulsed electric fields. (Static magnetic fields, even non-uniform, can cause acceleration of moving charges only in directions normal to the velocity vector, so that they do no work and impart no change in total energy.)

Although the surface motion from earthquakes can induce pressure and density pulses in the atmosphere<sup>68</sup> that ultimately reach the ionosphere, these appear much too weak to cause any significant electronic excitation.

In a time-dependent magnetic field  $\vec{B}(t)$ , if the rate of change is not so rapid as to invalidate the approximation of adiabatic invariance, the kinetic energy  $\epsilon_{\perp}$  is simply proportional to the field strength  $B$  (Cf. Section 3.5). Thus for an ionospheric electron to achieve an energy increase from ambient thermal ( $\sim 0.1\text{eV}$ ) to that required for excitation of an air molecule ( $\sim 10\text{eV}$ ) would require a 100-fold increase in the geomagnetic field. Since no such changes have ever been observed in the geomagnetic field, this mechanism<sup>69</sup> for generating earthquake aurorae utilizing ionospheric electrons thus appears to be out of the question.

As discussed in Section 2.3, the normal geoelectric field diminishes rapidly with altitude, but also the electron mean-free-path  $\lambda$  increases with decreasing molecular number density, so that the gain in kinetic energy  $e\mathcal{E}\lambda$  over one mean free path might appear significant. However, we note that apart from the very weak night-time high-altitude airglow (due to emission of the nitrogen molecule in the Vegard-Kaplan bands)--there is no significant amount of light generated in the ionosphere at night; and that the high geoelectric potential gradients invoked in Section 2.4 to explain earthquake light on mountains does not extend far above ground level.

Nevertheless, as Alfvén<sup>70</sup> has pointed out, even small changes in the geoelectric field may have large effects on low-energy electrons. The radius vector to the path of a

<sup>68</sup>R.W. Williams, Ref. 6, quotes C.F. Richter that "earthquake sounds" compared to "thunder, gunfire or heavy traffic . . . (are) produced directly by the transfer of elastic wave energy from the ground to the air."

<sup>69</sup>J.B. Cladis [Acceleration of Magnetically Trapped Electrons by Variations of Ionospheric Currents, *J.Geophys.Res.* 71, 5019-5025 (1966)] and W.L. Imhof, J.B. Cladis and R.V. Smith [Observation of an Energy-Selective Redistribution of Trapped Electrons in the Inner Radiation Belt, *Planetary Space Sci.* 14, 569 (1966)] have proposed an acceleration mechanism involving a periodic variation of the magnetic field in resonance with the electron motion. See also W.N. Hess, Ref. 66, pp. 168 ff.

<sup>70</sup>H. Alfvén, *Tellus* 10, 104-ff. (1958).

given geomagnetic field line--along which the ionospheric electrons are trapped--changes its length rapidly with change in geomagnetic latitude. Thus, for example, an electric field of only 1 millivolt/meter, directed upward along the magnetic lines of force over 100 km would increase the electron energy by 100eV. Should such an electric field act upon the electrons in the ionosphere the only impediment to their acquiring this magnitude of kinetic energy would be collisions with the air molecules. To assess this effect, Table 8 lists relevant information based on the US Standard Atmosphere<sup>71</sup> (1962) together with data on the ionospheric electrons.

Table 8. The Ionosphere Environment

Geom. Alt. (km)	Air <sup>a</sup> "Molecules"				Electrons <sup>b</sup>		
	Temp. (°K)	Number Density (cm <sup>-3</sup> )	Collision Freq. (sec <sup>-1</sup> )	Mean Free Path (km)	Number Density <sup>c</sup> (cm <sup>-3</sup> )	Collision Freq. <sup>d</sup> (sec <sup>-1</sup> )	Mean Free Path <sup>d</sup> (km)
300	1432	9.5·10 <sup>8</sup>	6.5·10 <sup>-1</sup>	1.8	2.0·10 <sup>5</sup>	30	7
350	1464	4.2·10 <sup>8</sup>	3.0·10 <sup>-1</sup>	4	2.3·10 <sup>5</sup>	13	16
400	1487	2.0·10 <sup>8</sup>	1.5·10 <sup>-1</sup>	9	1.9·10 <sup>5</sup>	6	36
500	1499	5.3·10 <sup>7</sup>	4.2·10 <sup>-2</sup>	30	0.9·10 <sup>5</sup>	1.7	120
600	1506	1.7·10 <sup>7</sup>	1.4·10 <sup>-2</sup>	100	0.5·10 <sup>5</sup>	0.5	400
700	1508	5.7·10 <sup>6</sup>	4.8·10 <sup>-3</sup>	300	0.4·10 <sup>5</sup>	0.2	1200

<sup>a</sup>Ref. 30, pp. 2-21,22 (rounded).

<sup>b</sup>The electron temperature measured by Nagy et al.<sup>72</sup> over Eglin AFB, FL at midnight on 24 October 1962 was essentially constant at 1000°K±10% from 250 to 500 km altitude. This corresponds to a mean speed of 2.0·10<sup>7</sup> cm/sec.

<sup>c</sup>Estimated from Figure 2.

<sup>d</sup>Based on a collision cross-section  $\sigma = 16\text{\AA}^2$ .

<sup>71</sup>Ref. 30, p. 2-5.

<sup>72</sup>A.F. Nagy, L.H. Brace, G.R. Carignan and M. Kanal, *J. Geophys. Res.* **68**, 6401-6412 (1963).

From the data in Table 8 one can draw the following inferences with respect to this proposed earthquake auroral mechanism:

1° Although the electron collision rates are not high, they are high enough to cause thermalization of the photoelectrons under normal conditions.

2° Reactions that reduce the number density of thermal electrons are slow: dissociative recombination with a molecular ion are infrequent because of the low ion density; radiative recombination is intrinsically slow; and electron capture by the neutral oxygen molecule requires a 3-body collision, which has low probability at the ambient low molecular number density. This explains the nocturnal persistence of high electron number densities in the F layer and above, in contrast to the rapid disappearance at sunset of the lower D and E layers.

3° Above 300 km altitude the electron mean free paths are long enough to allow increasing the kinetic energy by  $\sim 10$  eV or more in a suitably-oriented electric field of 1 mV/meter. (Note that the assumed cross section,  $\sigma=16 \text{ \AA}^2$ , corresponds to elastic rather than inelastic collisions; thus the effective mean free paths for energetic inelastic collisions are probably considerably longer than those listed.)

4° The rise time of the postulated electric field is not critical for the acceleration process. According to Eq. (3.12) the bounce period  $\tau_b$  for  $L=1.5$  is about 200 seconds for 0.1 eV electrons, 65 seconds for 1 eV, 20 seconds for 10 eV and 6 seconds for 100 eV.

5° However, the duration of the electric field should be long enough to allow the electrons, initially moving at 200 km/sec, to traverse a potential difference considerably greater than 10 V before they enter the atmosphere.

6° If initially a thermalized electron is moving up the potential gradient, its velocity will be rapidly reversed.

7° To produce auroral light over the earthquake epicentral area, the accelerated electrons must impinge upon the lower atmosphere.

8° If the optimal electric field direction were reversed the accelerated electrons would enter the atmosphere in the geomagnetic conjugate point.

9° An electric field that is not everywhere tangent to the magnetic lines of force will cause transverse diffusion.

### 3.5.2 Earthquake Coupling

Turning to the question of how an earthquake might produce in the ionosphere the small electric field under consideration, the piezoelectric effect appears to be a likely candidate. It is, of course, well known that changes in either the compressive or shear stresses can cause (equal and opposite) charges to appear on opposite faces of crystals of certain minerals--of which quartz is the most prominent example. The appearance of charges of magnitude  $Q$  separated by distance  $d$  constitutes formation of an electric dipole moment  $\mu=Qd$ . It is the electric field of this dipole that is here envisioned to cause acceleration of the ionospheric electrons. Figure 3 depicts in profile (but not to

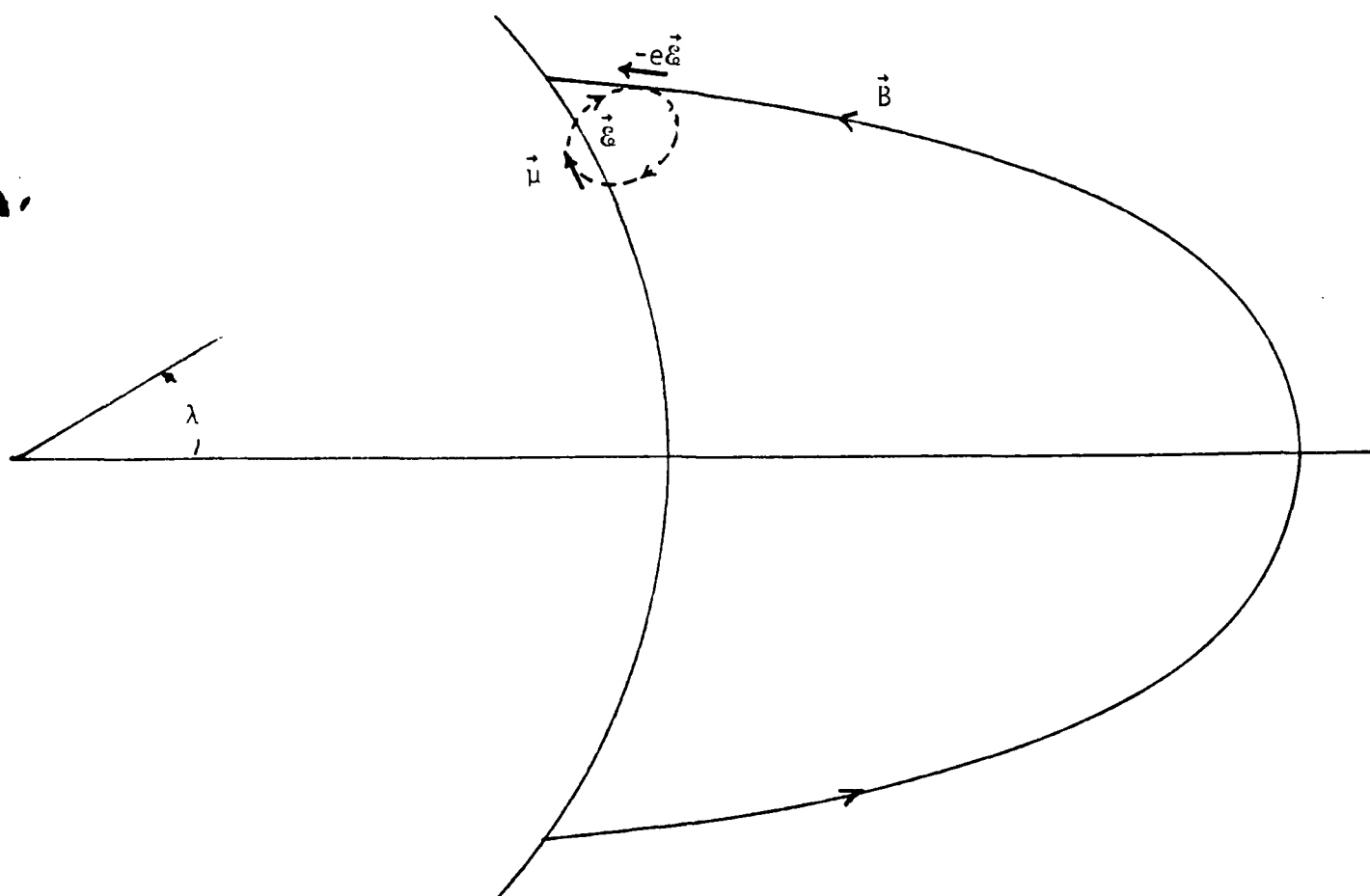


Figure 3. Profile of hypothetical piezoelectric dipole at earthquake hypocenter.



scale) such a piezoelectric dipole located at a hypocentral depth of perhaps 30 km, and so oriented as to accelerate the ionospheric electrons into the atmosphere over--and northward of--the epicentral area.

Besides having the necessary magnitude and direction aloft, the field of the electric dipole must not be inconsistent with observations at the Earth's surface. The requisite dipole magnitude can be estimated from the following crude model. As with its magnetic analog, Eq. (3.2), the field of an electric point dipole  $\mu$  is given by

$$\vec{\mathcal{E}} = \vec{\mu}(3\vec{r}_1\vec{r}_1 - 1)/r^3 \quad (3.15)$$

On the equatorial plane of the dipole,

$$\mu = r^3 \mathcal{E}. \quad (3.16)$$

Taking  $r=430$  km (i.e., an altitude of 400 km plus the 30 km depth of focus) and  $\mathcal{E} = 1$  mV/meter,  $\mu$  is  $2.7 \cdot 10^{15}$  esu·cm or  $9.2 \cdot 10^{-5}$  faraday·km. This means that if the "point dipole" extended over 1 km, the amount of charge transferred would be about  $10^{-4}$  faraday or 10 coulomb. (Of course these charges would be progressively neutralized by conduction through the rock.)

In this example the electric field at the earth's surface would be horizontal (along a meridian) and of magnitude

$$(1 \text{ mV/meter})(430/30)^3 \approx 3\text{V/meter}. \quad (3.17)$$

In comparison with the average vertical geoelectric field  $\approx 130$  V/m, this horizontal component would cause a tilt from vertical of only about one degree. Such small changes in the geoelectric field might well be masked by normal variations. In any event, they do not appear inconsistent with electric field variations measured<sup>73</sup> in conjunction with earthquakes.

### **3.5.3 Auroral Characteristics**

Given the favorable conditions assumed above of electric dipole size and orientation it is possible to estimate the resulting auroral intensity. To this end, it will

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<sup>73</sup> (Japanese reference)

be assumed that all of the ionospheric electrons in a given tube of force--both north and south of the magnetic equator--are accelerated downward into the atmosphere over the epicentral region. The cross sectional area of a given tube of force varies inversely with the magnetic field strength. Starting at  $35^\circ$  magnetic latitude on a line with  $L=1.50$ , this area approximately triples in reaching the maximum altitude  $a(L-1)=3170$  km. But the density of ionospheric electrons declines with altitude (Figure 2), so that for purposes of numerical orientation the product may be taken as roughly constant. Taking the total length of the tube  $\sim 4aL$ , the bounce period is  $\sim 1$  minute (corresponding to an average energy  $\epsilon \sim 1$  eV over the whole trajectory), the flux of electrons impacting the top of the atmosphere becomes

$$4aL n_e / \tau_b \approx 4(6.4 \cdot 10^8)(1.5) \cdot 10^5 / 60 = 6.4 \cdot 10^{12} / \text{cm}^2 \cdot \text{second}. \quad (3.18)$$

If these electrons--some of which would have energies  $\sim 1$  keV--produced an average of only a single photon each, the auroral light on the ground would be about double that of the full moon, and last for a minute or so. Replenishment of the electrons from the eastward longitudinal drift might prolong this somewhat, depending upon the effective lifetime and altitude reach of the electric dipole source.

Unique features of this type of aurora derived from ionospheric electrons include: 1) origination of the auroral light at altitudes considerably greater than for polar aurorae, owing to the relatively small electron energy; 2) location of the center of the auroral patch somewhat to the north of the epicenter; 3) considerable reduction in the density of the ionospheric electrons (that might be measured by ionosonde or observed in anomalous radio propagation).

### **3.6 Van Allen Electrons**

#### **3.6.1 Lowering the Mirror Point Altitude**

Electrons in the inner Van Allen radiation belt, which occupy the same region of B-L space as ionospheric electrons above the F layer, are distinguished by their much

higher energies and much lower densities. It is a curious coincidence that the measured energy flux (cf. Table 6) of these high-energy electrons ( $\sim 10^{13}$  eV/cm<sup>2</sup>·sec) is close to that of the ionospheric electrons obtained by multiplying the particle flux of Eq. (3.18) by an average electron energy  $\sim 10$  eV (after acceleration). The energy necessary to support a visible aurora is thus already present, but is normally unavailable because the electrons are trapped between conjugate mirror points at such high altitudes that collisions with air molecules seldom occur.

It might appear that this statement concerning sufficient energy is self-evident since high-energy particles confined to geomagnetic field lines are obviously responsible for natural aurorae in the polar regions. But a numerical evaluation shows that if the energy in polar aurorae had to come from trapped particles, the Van Allen belt would be quickly drained. Moreover, the particle flux in the Van Allen belt has been found to *increase*--rather than decrease--during periods of intense polar aurorae, showing that the high-energy particles responsible come from an outside source (e.g., blobs of solar plasma) rather than from the normal Van Allen population through some trap-release mechanism. The observed increase in this population is explained by the trapping of some fraction of the added particles (the "splash bucket" mechanism<sup>74</sup>). In the present context, however, we must examine those hypothetical mechanisms that relax the trapping constraints on the particles already present.

### 3.6.2 Earthquake Coupling

We are thus led to examine the possibility that the geomagnetic field can be modified over the epicentral region of an earthquake to open the trap by lowering the mirror-point altitude and thus allowing precipitation of the Van Allen electrons into the atmosphere. One might first suppose that the earth mass that suffers displacement by the earthquake carries with it a substantial magnetic dipole moment, which could result from the presence of magnetite rocks that carry permanent magnetization, or from magnetism induced by the Earth's magnetic field.

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<sup>74</sup> Ref. 66, p. 173 et seq.

But an immediate difficulty is encountered: although it may not be necessary to cancel the full geomagnetic field  $B$  ( $\sim 0.5$  gauss) in the Van Allen belt, it is necessary largely to cancel the gradient  $\nabla B$  that is responsible for the mirroring. Noting that  $|\nabla B| \sim B/R$ , and equating the gradients  $|\nabla B_{\text{geo}}(\text{at } R)|$  and  $|\nabla B_{\text{eq}}(\text{at } r)|$ , both corresponding to the altitude in question, leads to a value of  $B_{\text{eq}}(r')$  at ground level ( $r'$ ) that is untenably large:

$$B_{\text{geo}}(R)/R \approx |\nabla B_{\text{geo}}(R)| = |\nabla B_{\text{eq}}(r)| \approx B_{\text{eq}}(r)/r; \quad (3.19)$$

thus, 
$$B_{\text{eq}}(r') \approx B_{\text{eq}}(r)(r/r')^3 \approx B_{\text{geo}}(R)(r/R)(r/r')^3. \quad (3.20)$$

Using the geometry of Figure 3 with the exemplar distances adopted in Section 3.5.2, namely, radius from dipole  $r=430$  km, depth of dipole  $r'=30$  km,

$$B_{\text{eq}}(r') \sim (0.5 \text{ gauss})(430/6800)(430/30)^3 \sim 100 \text{ gauss}. \quad (3.21)$$

There seems no way to salvage this theory using as source a magnetic dipole displaced by the earthquake. The same conclusion applies (though with lesser force) to the magnetic field from telluric currents--e.g., those flowing to neutralize the piezoelectric dipole discussed in Section 3.5.2. The advantage of a current ( $J$ ) source over a magnetic dipole is that the  $B$  field, given for a long straight wire by

$$B_{\text{eq}} = 2J/\epsilon_0 r, \quad (3.22)$$

falls off with the inverse first power of the radius. Following the above procedure, the magnitude of  $B_{\text{eq}}$  on the Earth's surface for such a line-current source would be

$$B_{\text{eq}}(r') \sim B_{\text{geo}}(2r^2/r'R) \quad (3.23)$$

$$\sim (0.5 \text{ gauss})(2)(430)^2/(30)(6800) \sim 0.5 \text{ gauss}. \quad (3.24)$$

Again this appears to be much too large to have escaped notice of the many geomagnetic recording stations, especially in Japan.

It could be argued that less than complete cancellation of the geomagnetic field gradient would allow precipitation to begin for those electrons having lowest mirror points; and that, once begun, the unidirectional current of precipitating particles would tend to sustain itself by Lenz' law, and thus enhance the degree of  $\nabla B$  cancellation.

Indeed, by optimizing every parameter, one can make plausible a ground-level  $B_{eq}$  magnitude perhaps as low as  $10^3$  gamma (0.01 gauss). But this is still outside the magnetometer excursions that have been reported. The only other hope for this mechanism is that the magnetometers--which apparently have a low duty cycle--have so far missed making measurements at either the critical times or places.

It remains to examine the possibility of lowering the mirror altitudes of the Van Allen electrons by the same Alfvén mechanism discussed in Section 3.5.2. For electrons in the 1 MeV energy regime this does not appear promising: recalling Eq. (3.10), the magnitude of the electric field required to lower the mirror altitude to 100 km or below--an increase in the mirror-point magnetic field strength  $B_m$  by perhaps a factor  $\sim 1.75$  for particles with equatorial pitch angle  $\alpha_0$  near  $90^\circ$ --would require a similar fractional increase in  $\epsilon_{\parallel}$ ; but to double an electron energy already in the MeV range would require an electric field at least 1000 times greater than that postulated in Section 3.5.2. However, for electrons of 10 keV energy the conclusion is quite different.

To see this, it is illuminating first to calculate the rate of change of the geomagnetic field strength along a line of force. From Eq. (3.3), one obtains

$$d \ln B / d \ln r = -3(8 - 5 \cos^2 \lambda) / 2(4 - 3 \cos^2 \lambda). \quad (3.25)$$

Again using  $\lambda = 35^\circ$  ( $L = 1.49$ ) as example, this has the value  $-3.51$ . The fractional change  $\delta B/B$  in field strength corresponding to the fractional change  $\delta r/r$  in radius is given by

$$\delta B/B = (\delta \ln r)(d \ln B / d \ln r). \quad (3.26)$$

At 300 km altitude ( $r = 6700$ ) on the  $L = 1.5$  shell, this fractional change in field-magnitude ratio is  $-0.0551$  at  $\delta r = 100$  km,  $-0.110$  at 200 and  $-0.165$  at 300.

Following Alfvén's suggestion, we now examine what magnitude of electrostatic double layer would be required to change the mirror point altitude of a 10 keV electron by the amount  $\delta r$ . With reference to Eq. (3.10), at the "old" mirror point, where  $\epsilon_{\perp}$  was the total energy  $\epsilon$  (i.e.,  $\alpha = 90^\circ$ ), the new total energy is  $\epsilon + \epsilon'_{\parallel}$ , the parallel increment  $\epsilon'_{\parallel}$  arising by acceleration through the postulated electrostatic double layer. Thus, the

field magnitude  $B'_m$  at the "new" (lower) mirror point is given by

$$B'_m = B(\epsilon + \epsilon'_{\parallel})/\epsilon = B(1 + \epsilon'_{\parallel}/\epsilon),$$

so that  $(B'_m - B_m)/B_m = \delta \ln B_m = \epsilon'_{\parallel}/\epsilon = -0.0551 \delta \ln r$  (3.27)

or  $-\delta r = r(\epsilon'_{\parallel}/\epsilon)/3.51$ . (3.28)

Thus with  $\epsilon'_{\parallel}/\epsilon = 0.1$  (i.e.,  $\epsilon'_{\parallel} = 1$  keV for a 10 keV electron), the mirror point altitude is lowered by

$$-\delta r \approx 6700(0.1)/3.51 = 190 \text{ km.}$$

If the electrostatic double layer spans 100 km, the 1 keV energy increment employed in this calculation would correspond to a field strength of  $10^{-2}$  V/meter.

Evidence for the existence of such electrostatic double layers has been presented in the analysis by Albert and Lindstrom<sup>75</sup> of electron energy spectra measured during a Nike-Tomahawk rocket flight launched from Ft. Churchill on 16 September 1966:

"Fits to the experimental data indicate the presence of three double layers at altitudes of about 250, 270 and 280 km corresponding to  $1.0 \leq B_0/B_1 \leq 1.05$ . There is a potential difference of about 160 volts across each of the upper layers and about 80 volts across the lowest double layer."

Those authors further suggest that

". . . such double layers played a role in the production of a visible aurora observed during the fall of 1966."

As in the case of the low-energy ionosphere electrons, the Alfvén electrostatic acceleration mechanism seems the most promising basis for relaxing the trapping constraints on electrons with energies in the kilovolt regime.

Before embracing an exclusively geoelectric (i.e., electron-accelerating) mechanism to the total exclusion of lowering the mirror-point altitude by changing the geomagnetic field, it should be noted that electric fields produced by submarine earthquakes would be largely neutralized by the overlying seawater. Thus, earthquake

<sup>75</sup>R.D. Albert and P.J. Lindstrom, Auroral-Particle Precipitation and Trapping Caused by Electrostatic Double Layers in the Ionosphere, *Sci.* **170**, 1398-1401 (1970).

auroral effects produced at sea far from land must somehow depend upon changes in the magnetic field, whose propagation through the sea would be much less inhibited because of the low electrolytic conductivity.

### 3.6.3 Auroral Characteristics

In estimating the intensities of an aurora that might result from the Van Allen electrons in the 10 keV regime, a large uncertainty is introduced by the great variability in electron flux. In Section 3.2.2, the energy flux was estimated to range from  $10^{10}$  to  $10^{14}$  eV/cm<sup>2</sup>·sec. Using the method of Section 3.5.3, this energy flux translates into  $\sim 10^9$ - $10^{13}$  photons/cm<sup>2</sup>·sec, the upper end of which is again roughly comparable with the intensity of light from the full moon. This adds one more special circumstance--although perhaps not an improbable one--for an earthquake aurora to be produced by this source: namely, to be timed when the lower Van Allen belt is highly populated.

In comparison with the aurora discussed in Section 3.5.3, that from 10 keV electrons would have a much shorter rise time as well as a shorter duration. The speed of a 10 keV electron is about  $6 \cdot 10^9$  cm/sec. Again using as path length from the Earth's surface to the magnetic equator the order of magnitude  $4a_L$ , the transit time--a rough measure of the rise time of the auroral intensity--over this path would be about 0.5 second. The duration of the initial pulse might be four times as long, i.e., about 2 seconds. Since the replenishment time via longitudinal drift is of the order of 10 seconds, after the first pulse the intensity would likely drop to about 20 per cent.

Although none of the mechanisms considered in Section 3.6.2 appears promising to effect precipitation of the high-energy (MeV range) Van Allen electrons, it is conceivable that some sympathetic precipitation might be induced by the precipitation currents of those electrons with energies from 0.1 to  $10^5$  eV. In any event, the characteristics of an aurora from the MeV electrons would be strikingly different: the much greater energy of these electrons would carry them much deeper into the atmosphere, probably down to 60-70 km altitude; the greater speed of the electrons would narrow the band of arrival

times, and thus produce an initial flash with a rise time of the order of  $aL/c \sim 30$  msec, duration of the order of four times as long, and intensity perhaps 100-fold full moonlight. If the trap remained open, this flash would be followed by a continuing aurora of much lesser intensity, fed by new electrons drifting into the open precipitation channel. Vagaries of the time-perturbations of the electromagnetic field could simulate the transient effects of polar aurorae. And, of course, the spectrum of colors would be similar. These intensity-time characteristics might begin to simulate the appearance of a nuclear explosion in the atmosphere.

In all of the foregoing mechanisms for producing earthquake aurorae, the electrons are confined to the lines of the geomagnetic field. This implies that the center of the auroral patch would appear shifted somewhat to the geomagnetic north of the epicenter, to a distance given by

$$d = \Delta h \tan \psi \quad (3.29)$$

Here  $\Delta h$  is the altitude of a particular line of force over the epicenter, minus the altitude at which the electrons deposit their energy in the atmosphere; and  $\psi$  is the local dip angle of the line of force.

Such a displacement of the auroral patch was observed in the case of the Acapulco earthquake<sup>76</sup> of 11 May 1962, magnitude 7.0, the aurora from which was observed overhead in Mexico City. The relevant geographic and geomagnetic coordinates are shown in Table 9.

The epicenter of the quake was located ". . . nearly halfway between Mexico City and the famous resort town of Acapulco." From the coordinates in Table 9 it is seen that the geomagnetic longitude of Mexico City differs from that of Acapulco by only 0.5 degree. Taking literally the "halfway between" location, the distance of Mexico City from the epicenter would be 1.4 degrees or about 150 km. With the given dip angle, this

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<sup>76</sup> *Sci. News L.* **81**, 326 (1962).



translates to  $\Delta h \sim 150$  km. Assuming that the auroral light originated at 100 km altitude, the altitude of the (central) field line over the epicenter would be  $\sim 250$  km. This is not far below the altitude of the night-time maximum in the number density of F-layer electrons (Figure 2).

Table 9. Relevant Coordinates for the Acapulco Earthquake

	<u>Acapulco</u>	<u>Mexico City</u>
Geographic		
Latitude	16.9°N	19.5°N
Longitude	260.1°E	260.8°E
Geomagnetic		
Latitude	27.0°N	30.0°N
Declination	10°E	
Dip angle, $\psi$	45°	

#### 4. SOME OUTSTANDING ISSUES

The dearth of scientific observational data on earthquake light has allowed an unusual latitude of physical parameters in the foregoing theoretical treatment. This license has been deemed justifiable in order to arrive at models that may suggest critical measurements and further theoretical work.

##### 4.1 Low-Altitude Phenomena

With respect to the near-ground phenomena of Section 2 it would obviously be desirable to have more extensive measurements for both normal and earthquake conditions on

- \* the geoelectric field, especially on mountains
- \* the emanation rate of radon from the soil
- \* earthquake-induced EM fields and currents
- \* piezoelectric properties of rock materials
- \* electron number density in the low atmosphere
- \* rise time, duration and intensity of airglow
- \* energy in lightning-like strokes
- \* photographic images of airglow, columns, etc.
- \* continuous recording of  $\vec{E}$  and  $\vec{B}$  fields, especially in epicentral regions during earthquakes
- \* spectra of the various earthquake light phenomena.

On the theoretical side, a detailed treatment of the behavior of free electrons in a gas under static field strengths  $E/p \sim 1$  volt/cm.torr is necessary for a full understanding of the electrical conductivity, molecular excitation, electron multiplication and dielectric breakdown. The observational program outlined above should, of course, be accompanied with a corresponding theoretical effort.

##### 4.2 Auroral Phenomena

A simple but critical check on the proposed earthquake auroral mechanism based on the acceleration of ionospheric electrons into the atmosphere would be to make concurrent ionosound measurements of the critical frequency. This

frequency should drop dramatically as the ionospheric electrons are driven into the atmosphere. Though much more difficult and expensive, it would be useful also to have additional rocket probe data on the characteristics of the Alfvén electrostatic double layers. Since it would require a most improbable coincidence to correlate such measurements in time and place with an earthquake, consideration should be given to an analysis that would help guide a program of ground-borne measurements from which changes in the high altitude geoelectric field could be inferred.

Another promising observational avenue would be to examine what changes in satellite sensors would be necessary to provide information on earthquake auroral phenomena--rise time, intensity, area covered, etc.

The sketchy theory outlined in the present treatment has focused on electrons in narrow energy bands:  $\sim 0.1$  eV for ionospheric electrons, and  $\sim 10$  keV for Van Allen electrons. This leaves the possible contribution of the great majority of the Van Allen electrons, especially those in the MeV regime, in an unsatisfactory state.

Clearly the present treatment barely scratches the surface in explaining these fascinating geophysical phenomena. More data, as well as more theoretical work, are necessary to determine the degree to which aurorae from earthquakes might appear to resemble atmospheric nuclear explosions.

## APPENDIX A

Professor Qin Xinling, of the Institute of Geophysics, State Seismological Bureau (P.O. Box 2141, Beijing, China), kindly forwarded to the author an excerpt of a booklet entitled "Earthlight" written several years ago by an unidentified friend. Upon translation,\* this excerpt proved so interesting and informative that it is reproduced here. Three large earthquakes and their associated luminous phenomena are described.

Section 5. Liao-ning Province Quake, 4 February 1975, 19:36 hours,  
centered between Haicheng and Yinkou, magnitude 7.3 on the Richter scale.

During this earthquake the outstanding phenomenon was the widespread and intense light observed by many people in the quake area. The area in which the earthquake light was observed extended from Liaozhong in the north to Xinjin in the south and from Xiuyan in the east to Jinxian on the west. The light was observed mainly in the intersection of Haicheng and Yinkou, and Haicheng and Panjin. The location and movement of the earthquake light followed/were of the following general pattern.

The general features of the earthquake light reported were mainly individual flashes. One hour before the quake in Haicheng, Yinkou and Panjin, visibility was poor because of a dense fog, although the sky was not yet completely dark. No bicycles were allowed on the road and cars could barely navigate with yellow fog lights. But when the quake occurred the sky in the quake area became so bright that the roads and even things inside houses could be seen. Toward the east of the Haicheng Hotel people saw the sky light change from red to white. During the quake Rongtian Liu, a worker in the Liaohe hospital, saw a white light like an arc-welding light which lasted about one minute and was accompanied by a bad odor. A member of the Zhaoden commune saw from the southeast sky two bright white lights, like the headlights of a truck, which lasted about one minute. Then a loud noise was heard, and the light changed from a ray to a piece of light. A railroad officer in Jinzhou heard a loud noise from the ground during the quake and saw a pink light which lasted 4-5 seconds, like a fire accident.

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\*This translation was prepared by Paul Pau and Qi-xun Xu, graduate students in the Department of Chemistry and Biochemistry, University of California, Los Angeles

Over a long period of time numerous fireball flashes were observed in Haicheng, Yinkou and Panjin. Most of these were red but some were green, and resembled a signal rocket but without the tail. They issued from holes and craters in the ground from which sand and water were gushing. The fireball flashes were observed two types of areas: 1) On a plateau or mountain river; or 2) Areas not characterized by any special geological nature. A worker at the Jinzhou salt mine said: "When a light appeared from the east, we thought a car was coming. The light lasted almost a full minute, and its direction was straight up. But when we got there, we realized it was an earthquake light. After the light disappeared we saw a large round hole from which sand had been gushing. There was a lot of spring water around that smelled like beach mud. Next morning the hole was still steaming (streaming?), and continued until 10 February. Sugin Zhou, a member of the Guchengzi commune, recalled that ten minutes before the quake there was a fireball the size of a wok cover in the southwest direction toward Gongpiling. It resembled a burning charcoal fire rising from the earth's surface and illuminating the surroundings with a red light. During the quake, the food storage captain was on duty. He saw many fireballs, some close to the ground, some floating above the earth's surface; these were as large as basketballs, red in color and were rolling from west to east. They exploded on impact with other obstacles and with other. These lasted about 4-5 seconds. After the impacts the sky was red; then followed tornado-like sounds and vibrations. People in the Chagou commune saw fireballs flying all over the place.

These same kinds of fireballs were occasionally observed as long as two years before the quake. The night before the quake there were a lot of them. During the quake they appeared most frequently, and died out after the quake. Some could still be seen in April. In the 24 February quake, workers in Haomin Xu and Shi hai Hei were watching at night in the area most dense in fireballs. They noted fireballs in two places, in one of them four continuously and relatively bright; in the other place were three continuously and relatively dim. The former rose to 20 meters height/altitude? and then disappeared; the latter also disappeared. These two observations happened about 15 minutes apart.

Furthermore there was a kind of white light that flashed out from cracks in the earth. During the quake a crack developed that extended from Yidaogou to Yangjiabaozi, some 5.5 kilometers long, 10 centimeters wide and 2 meters deep. During the quake the local villagers saw very bright white flashes from the mountain. At that time a youth from Erdaogou was near an earth crack. He saw the white flashes coming from the crack, and lasting about one minute. A youth from Shuiyuan said that during the quake he was jogging and as he stepped on the cracks they flashed white light.

During the quake in Haicheng there also appeared column lights and ribbon lights. These kinds of lights were observed by fewer people. Some people at Jinxian Xingzhuangzi commune saw from the southeast direction a column light, fire-red in color. On top of the column there were flashes which flashed then disappeared. The second time around they saw about 5-6 green-white light columns each which emitted one flash and then disappeared. At Erjiegau, production farm workers saw on the morning of 3 February about 4 a.m. from the west of Erjiegau two flashes shooting to the sky, very narrow at the bottom but wider at the top. A quake worker, Haoding Gu, provided a detailed report about ribbon light. Before the quake he was working at Haicheng. On the evening of 4 February he and another worker were returning from Yingluo commune to Haicheng county by way of the north-south road. In the vicinity of the Zhuanwanzi brigade they saw earthquake light. Haoding Gu remarked that "the quake light appeared from the northern sky, a very intense white light. Visibility was about 10 kilometers. The quake light was ribbon shaped and stayed very close to the ground. Because the sky was very dark the quake light was very distinguishable from city lights. This light lasted about 2-3 seconds, during which period no notable flashes were seen. It suddenly disappeared, and then the earth began to shake.("?) Judging from the speed of the earthquake wave, the quake light and the quake occurred at the same time. The visible angle of the light was about 20-30°. Judging from visibility during the quake and subsequent investigation reports, the this ribbon-shaped light had an altitude of half a kilometer so it could be seen from far away.

#### Section 6. The 1976 Longling Yunnan Earthquake

On 29 May 1976 at 20:23 hours a quake of 7.3 magnitude on the Richter scale occurred at Longling, Yunnan province. A second shock of magnitude 7.4 occurred at 22:00 hours. During the first quake many people saw "fire-sky." During the second quake, more people saw quake light. Some quake workers even saw earthlight during the aftershock.

Earthlight was mostly seen in the areas of Pingda and Zhenan of Longling county, with some outside the boundaries; from Changning to Ruili, from Tengchong, Baoshan to Gengma, Shuangjiang. The boundary was about 200 kilometers square. In the quake area there seemed to emerge a certain pattern in the direction of the light, e.g., the light was observed in Longling from the west, in Mang city from the southeast, in Wanding from the southwest, Zhenan and Xiangda from the southeast, and in Huangyangba from the northwest. Observations from three communes bordering the quake area indicated from the direction of the light that its origin was in the quake area. According to the report

of Yuanjie Han, there were about 60 quake lights observed in two main categories: one was mainly individual flashes and "fire-sky"; the second category included fireballs from the earth and fan-shaped flashes. The day before the Longling quake, from 24:00 hours on 28 May to 01:00 hours on 29 May, nine workers on their way home after work at about midnight saw a white light like moonlight. This was so bright that they could see their way with it and later saw clearly things inside their houses. The light lasted about an hour. On 29 May one to two hours before the quake "fire-sky" appeared in the quake area. In this area everything--including people's faces--was glowing red. Although the sun was setting the light was not diminishing. As the light turned to blue color the quake occurred. People noted that this "fire cloud" was especially red. This phenomenon was different from the sunlight. First, the light was bright even indoors; and second, the light did not diminish when the sun set. The change in light was very sudden when it did disappear. The light indoors was darkened immediately. Third, in Yumingzhu, Yongde county, about 20 people noted some flashes similar in intensity to moonlight. The time of this occurrence was the same as when people in Pingda noticed quakelight. People in Jiufang commune also noticed earthlight from Pingda.

Just before and during the quake fireballs and fan-shaped flashes occurred in the quake area. For example, in Jinzhuping and Chaoyang areas, sounds were heard. In Jinzhuping, fire and light were coming out from earth cracks and even the rocks were red-hot. But not all observations were the same. On the highways and the bushy hill in front of the Luximang highway station, there were also glowing gases. But on contact they were not hot and there was no odor. Also ribbon-shaped lights were seen. These were mostly parallel with the ground or close to the ground or in the lower sky or near a mountain range. Investigators said these might be earth light. The flashes in the low sky and the ribbon-shaped lights were rarely seen.

#### Section 7. The 1976 Songpan, Sichuan Province, Earthquake

On 16 August 1976 in the areas of Songpan and Pinwu in the northern part of Sichuan province there was a quake of 7.2 magnitude. The intensity of the quake was 9 and its depth was 10-20 kilometers. This quake was accompanied by nearly 100 earthlight phenomena. Numerous fireballs were seen. This quake was rare in the history of our country. Fireballs were first observed on 18 March 1976 from the Jiaguan commune from 6-9 p.m. Fireballs of various sizes were reported seen from 37 places. From then on fireballs appeared first in the southern part of Longmen Mountain and gradually moved to the northern part. There were three intense periods of fireballs: 20-30 June, during which 60 per cent of the fireballs appeared on Dayi, Pujiang and

Chongqing (mountains?); 2) from 19-28 July, about 80 per cent of the fireballs appeared on Guan, Peng, Shifang and Mianzhu (mountains?); and 3) from 7-16 August, 90% of the fireballs appeared on Mianzhu, Deyang, An, Jiangyou, Qingchuan, Heishui and Maowen (mountains?). On the night of 16 July workers at the Jiangyou commune saw about 400 fireballs. After the quake the fireballs were even more numerous, distributed as in the third period, and diminishing after the quake.

In the quake areas the quake lights were numerous and strong. There was a quake report unit located in the Huangyang high school near the quake. They made an extensive record of the quake. The report of the teacher Fang Hua Wang was as follows:

"Before the quake the earliest quake light was observed on the evening of 1 April 1976, about 8:50 p.m. Light was seen from the northeast direction moving from east to west. During the same time there was a "rainbow" seen in the background. The whole valley shone bright. This lasted 2-3 seconds. Then there occurred light flashes at 4-5 minute intervals, with alternating strengths. This lasted about 40 minutes.

"On 5 April at 8:05 p.m. there was white light in the northern mountains. One could see the mountain clearly, but the light was not high.

"On 19 April at 10:00 p.m. there was white light from the northwest lasting about half an hour.

"In the latter part of June there were numerous quake lights. The most intense occurred during the evening of 23 June. Fan-shaped flashes were seen from the southern mountains from 9 p.m. onward. The light extended from earth to sky, with a high and uniform intensity. One could see clearly the mountains and the trees on the mountain-top. Flashes occurred intermittently, with varying directions. They started from the south but ended in the north after about one hour.

"In July the earthlight was seen even more frequently and was both more intense and of longer duration. In early July the light was seen every third night with one-minute intervals between flashes. In mid-July the lights occurred every other night with flashes at half-minute intervals. In late July the light was seen almost every night with 10-second intervals. The point of light lay in the northwest but then progressed to the north and then east. One strong flash would be followed by 2-3 weak flashes. On 4 August about 10 p.m. there suddenly appeared a yellow flash from the northwest direction. This died quickly. The light was 4 meters by 29 cm. Because of its sudden appearance, no one knew where it came from.

"On the evening of 11 August there appeared in the lower sky a red ribbon of light, extending from the northwest to the southeast. This disappeared quickly. This phenomenon appeared twice. After dark, about 9-10 p.m., we saw a dim white light in



the direction from northwest to southeast, and from south to north, but this lasted only a short time.

"On 16 August about 8 p.m., northwest of Huangyang, the people of Caoyuan brigade saw a very intense earthlight. The earth and half the sky were lit up. About 9 p.m. there was rain, after which the sky was dark and then the quake occurred. After the quake the flashes were numerous and very bright. Numerous fireballs appeared in the low sky. Five to six minutes after the quake people in the Longchi brigade, northwest of Huangyang, saw from the northwest mountains numerous lights, some like fireballs, some like rising flames, some like fire stars. The next day there were found on the mountain numerous holes about 2-3 inches long.

"In the area of Huangyang mountain, from early April on, earthlights were observed at distances of only about 10-20 kilometers. These seemed to occur just behind the mountain. But the quake light on 23 June was farther away. During April the sky was clear. From June to August there was little rainfall. This area had no high voltage wires and is not a natural gas area."

The abnormalities that preceded the Songpan quake occurred with special suddenness and usually first only in the immediate vicinity. These abnormalities became apparent only a few days before the quake. By contrast, during the Huangyang quake the earthlight phenomena were different. Not only did they appear earlier, but became more frequent and intense as the time of the earthquake approached. These observations should be studied.