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TRIGGERING AN AURORA

L. M. Linson and H. E. Petschek

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AVCO EVERETT RESEARCH LABORATORY
A DIVISION OF AVCO CORPORATION

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ABSTRACT

The suggestion is made that the creation of a significant enhancement of the ambient electron density at night in the lower ionosphere at auroral latitudes may trigger an aurora. The resulting increased drag affecting a sufficient number of magnetic flux tubes will disturb the natural convective flow in the equatorial plane of the magnetosphere around $L = 6$. Criteria which indicate the required size of the electron cloud ($\sim 10^3$ km^3), its density ($\sim 10^6$ electrons cm^{-3}), and its location (~ 115 km altitude) are discussed. Such a large electron cloud is also useful for studies of the physics of the ionosphere. The necessary energy requirement and a preliminary evaluation of several methods which might be used to produce the desired ionization are discussed.

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I. INTRODUCTION

The purpose of this report is to suggest that the creation of a significant enhancement of the ambient electron density at night in the lower ionosphere at auroral latitudes may trigger an aurora. Even if this ultimate objective is not accomplished, secondary objectives which have a scientific value could include studies of winds, diffusion, drifts, recombination, and effects on communications which would complement similar studies which have been conducted with the aid of smaller electron releases. We shall discuss the criteria to be applied and thus estimate the necessary energy requirement to trigger an aurora and give a preliminary evaluation of several methods which might be used to produce the desired electron cloud.

The principal observations during an aurora consist of emissions in the visible spectrum from excited molecular and atomic species and deflections in magnetic field intensities measured at ground stations. The latter are believed to be due to currents in the vicinity of 120 km altitude. The currents are the result of an increase in conductivity due to an enhancement of the ambient electron density. Both the molecular excitation and the ionization are caused by high energy electrons (around 10 kev) which precipitate along magnetic field lines from the equatorial region of the magnetosphere in the vicinity of L-shell equal to six. While it is not practical to consider supplying the energy which is dissipated during a natural aurora (of order 10^{10} watts for times up to 10^{4} sec) barring the use of nuclear explosives, it may be possible to trigger such an event by a more modest expenditure of energy.

The suggestion is made that one might trigger an aurora by increasing the electron density and hence the conductivity in the auroral zone where the currents are observed to flow. The increased conductivity would couple the magnetic field line motion more closely to the neutral atmosphere. The resulting disturbance in the magnetospheric convection may produce precipitation, as will be discussed below. Although the exact requirements are uncertain, a rough estimate indicates that an electron density of about 5×10^5 electrons cm^{-3} in a volume of about 100 km^2 by 20 km in height or $2 \times 10^{12} m^3$ should be sufficient to produce an observable effect. The above density is far above the ambient nighttime value and would have to be created in a time which several factors (to be discussed below) suggest to be of the order of a minute. Using an average ionization potential for air (I_{O_2} = 12.2 ev; I_{N_2} = 15.5 ev) of 15 volts, we easily arrive at a minimum energy requirement of 2.4×10^6 joules or a power requirement of 40 kwatt for 60 sec if the free electrons are to be created by ionizing the ambient air.

The release of electron clouds from rockets in the earth's atmosphere between 70 km and several thousand kilometers altitude has been carried out by a number of researchers in the past decade. While these electron clouds have been useful for ionospheric physics studies, they have exhibited no interaction with the magnetosphere because the releases have been smaller than the ones envisioned in this report and, more importantly, for the most part they have been neither at the right place nor at the right time. Most of the previous releases have been conducted at midlatitudes and predominantly near dawn or dusk and have succeeded in producing only on the order of 10^{21} electrons. We require on the order of

10^{24} electrons at auroral latitudes near midnight at an altitude of around 100 km. The few releases which have been carried out in the auroral zone for the purpose of mapping ionospheric electric fields have all been above 150 km in altitude which is too high to couple magnetic field lines with the neutral atmosphere.

Most previous chemical releases have relied upon photo-ionization by sunlight to produce large numbers of electrons. Since 120 km altitude at auroral latitudes near midnight is not in sunlight we have considered a number of different methods of achieving the desired degree of ionization. The most promising seems to be an extension of the present technique involving the release of chemically reacting products. Another possibility is the use of energetic (of order 100 kev) electron or ion beams to ionize the ambient air. Breakdown of the lower ionosphere using electromagnetic radiation or the use of x-rays to ionize the air do not seem as practical. Further study is required to determine the optimum method.

In Section 2 we shall discuss the relevant properties of the ionosphere during an aurora and give the criteria used which determines the required electron density, volume to be ionized, and time scale of the experiment. In Section 3 we give a preliminary evaluation of the several suggestions to produce the necessary ionization mentioned above and indicate the major uncertainty associated with each. Section 4 consists of a brief summary. In the Appendix we describe the calculation which is necessary to determine the efficiency of the ionization of air by using an energetic ion beam.

II. REQUIREMENTS FOR TRIGGERING AN AURORA

Aurorae typically occur in the auroral zone usually within a few degrees of 66° magnetic latitude and generally between the late evening and early morning hours local time. Although there is a wide variety of displays, generally they appear to be around 5 to 10 km in thickness in the N-S direction but often extend for several thousand kilometers in the E-W direction. Their lower edge of visible light and presumably ionization is generally at an altitude of around 100 ± 10 km. The fact that intense auroral breakups consistently occur in the same location and represent the rapid deposition of large amounts of energy indicates that they are produced by the onset of an explosive instability. It has been suggested [Axford, et. al., 1965] that the energy source of an aurora may lie in the sunward flow of high energy plasma in the equatorial plane of the magnetosphere around $L = 6$. It is likely that some type of disturbance of this flow in the equatorial plane is responsible for provoking the instability which results in an aurora. It may be possible to create such a disturbance by slowing down with respect to the flow a sufficient number of magnetic flux tubes; the method we suggest is to tie their feet in the ionosphere by increasing the ambient conductivity significantly. This has the effect of coupling the magnetic field lines more strongly with the neutral atmospheric particles and thus increasing their drag. An alternative view suggests that the increased conductivity will greatly alter the ambient or equilibrium voltage gradients which may result in the lowering of energetic particle mirror points and hence initiate increased precipitation which could then sustain the increased ionization. While it is not at all certain that increased ionization in the ionosphere will provoke an aurora, the possibility of doing so with reasonable rocket payloads or power requirements makes it too intriguing to be overlooked. Should such an attempt be successful, the opportunity then exists for increasing our understanding of auroral phenomena as well as on the dynamic aspects of the flow in the magnetosphere.

While the possibility of triggering an aurora provides an exciting goal, useful scientific information would also be available from such an experiment if this spectacular result is not achieved. At a minimum, the change in ionospheric ion density will locally modify the ionospheric current patterns. Measurement of these currents would provide some information about the interaction of the magnetospheric flow patterns with the ionosphere. One would also expect at least measurable changes in precipitation due to the disturbance of the field line motion. Monitoring of these changes would again provide information which may suggest interactions between the magnetospheric flow and natural ionospheric irregularities. Furthermore, ionization over such a large scale as 10 km would complement experiments which have been performed by chemically releasing smaller electron clouds at the same altitude range at various times of the day. As examples, investigations of electron diffusion rates, drifts and distortion of the electron cloud, recombination phenomena, and various decay modes of the electron density could be carried out as well as studies made of the effect of the ionospheric winds and the effect of the electron cloud on communications.

We now obtain an estimate of the size of the region to be ionized. The minimum scale size on which the equatorial flow as such can be disturbed is probably a gyro-diameter of a proton of typical energy (1 kev) in the earth's magnetic field at $L = 6$ ($\sim 100\gamma$) or about 90 km. The equivalent length in the ionosphere is reduced by the square root of the ratio of the magnetic field intensities which results in a value of around 4 km. Hence, tying an area of 10 km x 10 km will represent intercepting the flow over a length corresponding to 2 or 3 proton gyro-diameters in the equatorial plane. A substantiation of this estimate is the observed fact that aurorae are typically several kilometers in thickness, possibly indicating a tendency towards a minimum scale size. If one were to ionize a larger area, extending the long dimension in the N-S direction would intercept more of the equatorial flow and would probably increase the possibility of triggering an aurora.

The total amount of ionization which might be required to trigger an aurora is uncertain. The most reliable dimension of the ionization cloud is probably the 5 to 10 kilometer size in the N-S direction as described above. It would also seem that the scale size in the E-W direction should be larger than an equatorial proton gyro-radius and hence comparable to that of the N-S direction if the gyrating particles in the equatorial plane are to be prohibited from passing through the frozen flux tubes. The remaining uncertainties are the determination of the most appropriate altitude at which to create the ionization, the required vertical thickness of the ionization, and the required degree of ionization. We first discuss the appropriate criteria theoretically and then compare our deductions with observations.

The Pedersen and Hall conductivities, σ_p and σ_H, which are the conductivities perpendicular to the magnetic field and parallel and perpendicular respectively to the electric field, are given by

$$\sigma_p = \left[\frac{(\omega\tau)_i}{1 + (\omega\tau)_i^2} + \frac{(\omega\tau)_e}{1 + (\omega\tau)_e^2}\right] \sigma'$$

$$\sigma_H = \left[\frac{(\omega\tau)_i^2}{1 + (\omega\tau)_i^2} - \frac{(\omega\tau)_e^2}{1 + (\omega\tau)_e^2}\right] \sigma' \qquad (2.1)$$

with

$$\sigma' = \frac{n_e e}{B} = 2.7 \times 10^{-4} \left(\frac{n_e}{10^5 \mathrm{cm}^{-3}}\right)\left(\frac{B}{0.6 \text{ gauss}}\right)^{-1} \text{mho m}^{-1}$$

Above 80 km $(\omega\tau)_e \gg 1$ while $(\omega\tau)_i(\omega\tau)_e > 1$ above 95 km. Hence, above 95 km the Hall current is due predominantly to the electrons while according to Eq. (2.1) the Pedersen current in the N-S direction is predominantly due to ions. As it is difficult to create persistent ionization below about 95 km we shall take it to be a lower bound for our ionization cloud. An upper limit to the altitude above which we cannot tie the magnetic field lines to the neutrals is where $(\omega\tau)_i$ is of order unity or around 120 km for NO^+, as the ions rarely collide with neutrals at higher altitudes. If the criterion to be applied in order to achieve maximum effectiveness for line-tying magnetic field lines is that the Pedersen conductivity should be maximized, then Eq. (2.1) suggests that the ionization should be created at around 120 km altitude. The precise optimum altitude is uncertain but the above discussion indicates that close to but below 120 km is most appropriate. It is possible that the electron contribution to the Pedersen conductivity at these altitudes is considerably in excess of the value indicated by Eq. (2.1) due to anomalous or turbulent diffusion of electrons across magnetic field lines. Such increased electron diffusion is almost universally observed in laboratory plasmas when $(\omega\tau)_e \gg 1$. In this case the Pedersen conductivity would become less dependent on altitude and 120 km would remain only as an upper limit.

The requirement of a significant change in the Pedersen conductivity provides a criterion for determining the necessary height-integrated density in the ionization cloud. According to a model by Boström [1964] the height-integrated Pedersen conductivity is on the order of half a mho for the undisturbed ionosphere. According to Eq. (2.1) a height-integrated density of 4×10^{11} electrons cm^{-2} will increase the Pedersen conductivity by an order of magnitude above the ambient value. The thickness of this cloud of ionization is determined primarily by the requirement that the electron density be low enough so that the ionization will persist for times of the order of minutes. Experiments involving chemical releases indicate that electron densities on the order of 10^6 cm^{-3} persist for the required time [Marmo et al., 1961]. This fact indicates that the thickness of the ionization cloud should be several kilometers.

The theoretical discussion above agrees favorably with observations. In Fig. 1 is shown typical electron density profiles measured by rockets during discrete and diffuse aurorae [Baker and Ulwick, 1967]. Also shown for comparison are typical daytime and nighttime profiles. The distinguishing characteristic of the discrete aurora is the large enhancement

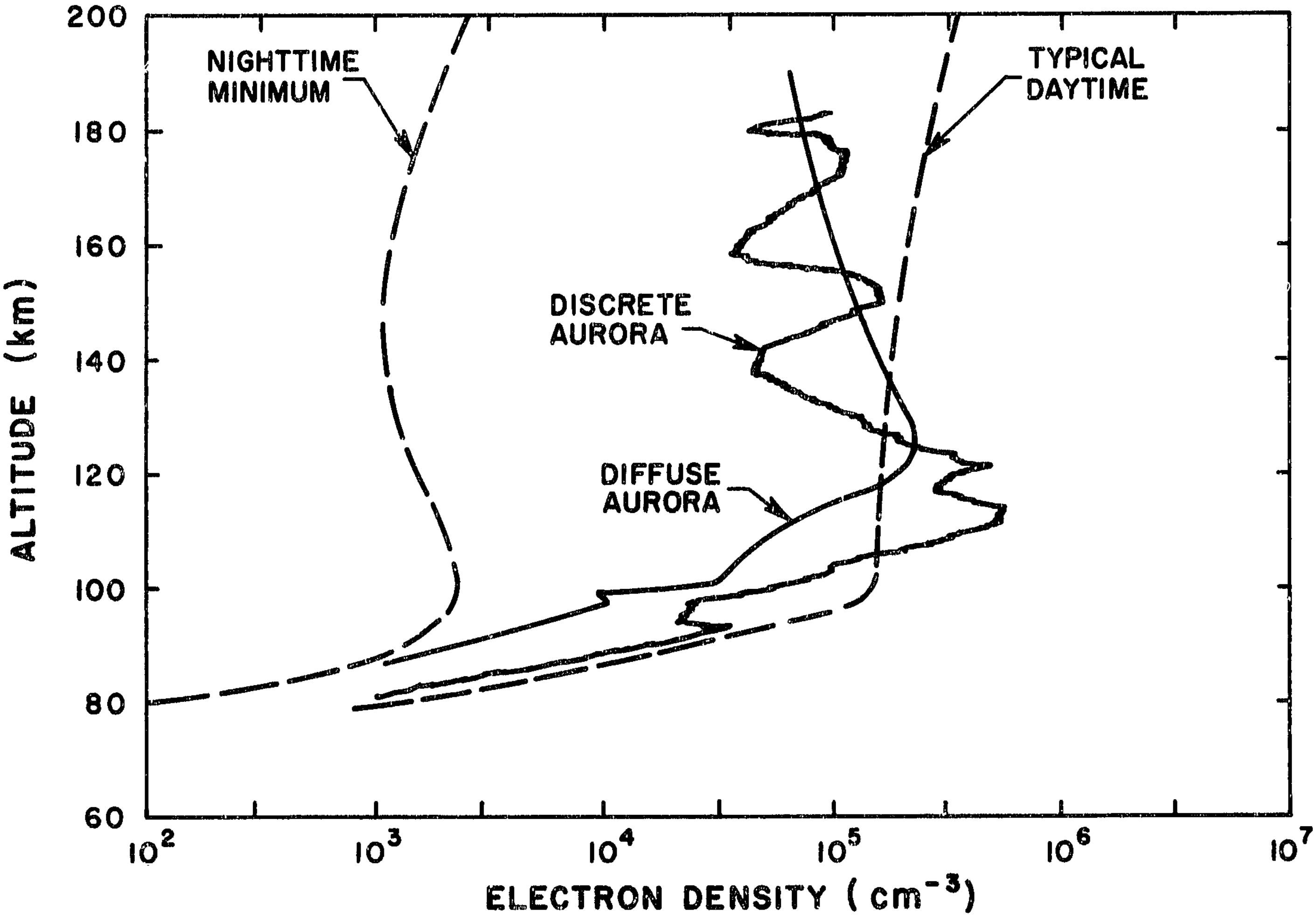

Fig. 1 Typical electron density profiles measured during discrete and diffuse aurorae [Baker and Ulwick, 1967]. The dashed curves represent typical daytime and nighttime profiles.

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of the electron density for about 20 km centered around 115 km. A value of 5×10^5 cm^{-3} seems typical and is occasionally exceeded by a factor of two or three. We thus reach the conclusion that ionization with a height-integrated density of order 10^{12} electrons cm^{-2} with an electron density of about 10^6 cm^{-3} at a height of around 115 km is created during a natural aurora. It may be more than a coincidence that the penetration depth of the precipitated 10 kev electrons corresponds to an altitude where the deposited ionization will have a maximum effect on the Pedersen currents and that the scale height is large enough so that the ionization is spread out which leads to a change of the Pedersen conductivity by more than an order of magnitude. Combining a height-integrated density of 10^{12} electrons cm^{-2} with a 100 square kilometer area leads to the previously mentioned requirement of 10^{24} electrons or about 2.4 Megajoules assuming a 100% efficiency for ionizing air.

The time limitations of the experiment require two considerations: a) the minimum length of time for which the regions of high electron density should be maintained; and b) the rate at which the electrons are to be created. An estimate for the former time is given by the time it takes the stopping of the magnetic flux tubes to be communicated to the equatorial plane. The appropriate speed is the Alfven speed which yields a time of about a minute for a lower limit. There is no reason to believe that the creation time of the cloud must be less than this limit.

The principal loss mechanisms of electrons in an electron cloud above 100 km are diffusion and recombination. When the source of electrons is ionization of the ambient air, the role of recombination is uncertain as both the effective electron temperature and the relative abundance of the dominant ionic species are unknown. However, an effective recombination coefficient in the range of 10^{-7} to 10^{-8} cm^3 sec^{-1} yields times for the electron density to decrease by a factor of two on the order of a minute. On the other hand, chemical releases involving different ions can increase the recombination time significantly leaving diffusion as the predominant loss mechanism. For instance, experiments conducted by detonating small canisters containing alkali compounds have shown [Marmo, et. al., 1961] that small electron clouds (scale size ~1 km) with densities in excess of 10^6 cm^{-3} have persisted near 115 km altitude for more than 10^3 sec. The conclusion was that the principle cause of decrease in electron density was diffusion with a diffusion coefficient of the order 10^7 cm^2 sec^{-1} indicated for electrons at an altitude of 115 km (varying inversely with the neutral density). A time in excess of 10^3 sec results for the density of a 100 sq. km. cloud to decrease by a factor of two.

There are two factors which set upper limits to the time during which the required ionization can be produced. Aurorae are observed to drift northerly at a rate of about 100 m sec^{-1} which indicates a time limit of about a minute for a 10 km region. In addition, the time to rise and fall 5 km freely under gravity is also a minute. Hence, the maximum time for deployment of the necessary ionization is of order 60 sec yielding a power requirement of only 40 kwatt for 100% efficiency of conversion of energy into ionization. In a chemical release there is no power requirement and the electron creation rate criterion is essentially inappropriate.

III. CREATION OF ELECTRON CLOUDS IN THE LOWER IONOSPHERE

We briefly discuss several possible methods which might be used to produce large electron clouds in the lower ionosphere.

A. <u>Production of Electron Clouds by Chemical Means</u>

There are two aspects to the problem of creation of large electron clouds by chemical means. First is the problem of creating sufficient numbers of electrons per gram of chemicals while the second problem is that of distributing the ionized material over the desired 2×10^3 km^3 volume.

Small electron clouds about a kilometer in diameter around 120 km in altitude and having densities of order 10^6 cm^{-3} have been produced by exploding small canisters containing an alkali metal. In a series of experiments summarized by Marmo, et.al. [1961], 50 moles of an alkali compound typically produced 10^{21} electrons for an overall yield of 3×10^{-5} electrons per atom. The primary reason for such low yields is that the canister used burst at around 300-500 atmospheres after only 3-5% of the chemical had reacted. The thermal coefficient of ionization (the number of electrons per reacted atom) was given as 10^{-3} after the rapid expansion at the thermal speed to the ambient pressure produced a cloud about 200 m in radius. If the chemical had undergone complete reaction (implying 5000 atm pressure), the temperature would have been higher yielding more electrons per atom in addition to increasing the number of atoms reacted.

Assuming a nearly 100% reaction and the same thermal yield results in a figure of 10^{-3} electrons per atom as a reasonable overall efficiency coefficient including recombination during the expansion. Since we require for our purposes about 2 moles of electrons, the weight of chemicals necessary is of order 300 kg, which is within the limits of feasibility for a modest sized program. Rosenberg and Golomb [1963] have reported a chemical yield of near 100% by adding a high explosive to cesium nitrate and aluminum. Best estimates indicate that around 2.5×10^{22} electrons were produced by detonating 18 kg mixtures at high altitude indicating that for our purposes we would require around a 700 kg payload.

More recent investigations [Friedman, et. al., 1963; Friedman and Macek, 1965] have reported much higher electron yields per gram of reactant achieved by burning strands of compressed material rather than by exploding canisters. Theoretical thermodynamic estimates predict yields for both systems on the order of 10^{20} electrons gm^{-1}. Experimental results obtained in the laboratory by Friedman, et. al. [1963] indicate that actual yields from the cesium nitrate and aluminum mixture were below the theoretical estimates by about a factor of four. Friedman and Macek [1965] reported experimental results almost an order of magnitude below theoretical estimates for the tetracyanoethylene, hexanitroethane and cesium azide mixture primarily because the actual temperature was below the assumed adiabatic value and the presence of unburned CN readily attached electrons. In summary, indications are that around 50 kg of material is sufficient to produce the necessary 10^{24} electrons for our purposes, an order of magnitude below the amount required by detonation.

We now turn our attention to the problem of spreading the desired ionization over the large volume required. In the earlier burst releases at high altitudes, the neutral clouds which were produced were observed to expand by diffusion to a size of 1 or 2 km in a minute. The electrons diffused more slowly and maintained a density of order 10^6 cm^{-3} which was observed to persist for 10^3 seconds. An ambipolar diffusion coefficient for the charged particles at 115 km is indicated to be about 5×10^6 cm^2 sec^{-1}. However, we cannot achieve our goals by just scaling up the number of electrons and the volume by a factor 10^3. If the electron diffusion is fast enough to spread itself over the desired volume in a time of order one minute, the magnetic field lines will not be tied by the resulting ionization. If, on the other hand, the electrons expand rapidly without diffusing, they are essentially moving field lines aside. It is possible that turbulent diffusion could be relied upon to distribute the charge component of the cloud rapidly and still allow the ionization to effectively tie down the magnetic field lines after its dispersal. The mixing of the ionized material must be accomplished by using a large number of small electron sources. Each of the smaller electron clouds thus produced could rapidly diffuse to produce a large volume of ionized air through which the magnetic field cannot move freely. Approximately twenty-five such clouds with a 1 km radius would be a minimum requirement for covering a 100 sq. km area with sufficient ionization. The scattering and ignition of a large number of chemical sources of electrons via a rocket payload should not be a difficult problem.

B. Ionization of Air Using a High Energy Electron or Ion Beam

High energy electron beams provide the most efficient method of producing ionization. Each high energy electron expends only 32 ev in ionizing an air molecule and hence, a 100 kev electron beam will produce approximately 3×10^3 ion-electron pairs resulting in an overall efficiency of 45% or a requirement of less than an ampere of current for a minute. From the standpoint of a low power requirement and the fact that the technology of electron guns is very advanced, the use of electron guns seems very promising. There is a possible charging problem in that a rocket which emits an electron current must reach some positive potential in order to attract to it an equal current from the surrounding medium. A preliminary investigation [Linson, 1967] indicates that a few kilovolts is sufficient and hence the beam energy is not significantly degraded. If more than one rocket is used, charging considerations are even less of a problem. A more serious and fundamental objection arises in that the earth's magnetic field limits the excursion of the beam perpendicular to the field. The gyro-radius of a 100 kev electron in a 1/2 gauss magnetic field is only 20 meters. While the rocket trajectory can be used to cross field lines in one dimension, it seems possible to produce only a thin vertical sheet of ionization but not a cubic volume of order 10^3 km^3. The only way of overcoming this limitation would be to use a number of rockets spaced close to each other so that these sheets of ionization could diffuse rapidly into each other. Based on the previously mentioned diffusion rates, four or five such sheets could be sufficient.

The advantage of an ion beam over an electron beam for creating a large volume of enhanced electron density is that its gyro-radius in the earth's magnetic field is larger, but it suffers from the relative disadvantage of a shorter range and a smaller fraction of its energy going into ionization. We shall show that, unlike electrons of comparable energy, the principal energy loss of a heavy ion at and below the several hundred kilovolt range is due to elastic collisions with neutrals which determines its range and results in the major part of its energy being used to heat the air. The charging problem is much less severe than in the case of an electron beam as a flux of low energy electrons can easily neutralize an ion beam.

The gyro-radius of an ion with M proton masses at an energy of E ev in a magnetic field of B gauss is

$$r_G = \frac{1.4}{B}\sqrt{M \cdot E}\ \text{m} = \frac{0.45}{B}\sqrt{M\left(\frac{E}{10^5}\right)}\ \text{km} .$$

For an ion of order 100 kev, a minimum mass of $M \simeq 7$ is indicated for a gyro-radius of about 2.5 km. A spinning rocket could ionize air in a circle with a diameter about 4 r_G by shooting tangentially instead of radially. A larger area could, of course, be ionized by using additional rockets simultaneously. The upper limit to the energy range which we consider for an ion beam is set by the limitations of ion gun technology. Breakdown considerations suggests that energies substantially greater than 200 kev are impractical.

Ions with energy E less than $E_c = 28 \times M$ kev have velocities less than that of the least bound (15 ev) electron in the N_2 molecule. At such velocities ions are not efficient ionizers and their principal energy loss is due to elastic collisions with neutrals. Experimental information on elastic scattering and ionization cross-sections of heavy ions at energies below E_c is presently meager but an area of increasingly active research. It is generally true that the elastic cross-section is a decreasing function of energy and is lower by more than one order of magnitude than that of typical ionization cross-sections which are increasing functions of energy below E_c. However, the energy loss in an elastic collision between heavy particles far exceeds the mean energy transferred in an ionizing collision. Indeed, we find that the energy loss rate, $\frac{dE}{ds}$, and hence the range, R(E), of a heavy ion is determined predominantly by its elastic collisions. The total number, N(E), of ion-electron pairs produced by a single ion is easily determined from a knowledge of the mean free path, $\ell(E)$, between ionizing collisions by the formula

$$N(E) = \int_0^E \frac{1}{\ell(E')} \frac{ds}{dE'} dE' \quad . \tag{3.1}$$

In order to obtain quantitative expressions for these variables, we have turned to a theory for elastic cross-sections due to O. B. Firsov [1958] and another theory for inelastic or ionizing cross sections [Firsov, 1959] by the same author. In the Appendix we discuss these theories, indicate their limitations and evaluate the mean energy loss in an ionizing collision and the mean free path $\ell(E)$ which allows us to evaluate the integral given by Eq. (3.1). Estimates of the range are also carried out in the Appendix and are shown in Fig. A.1 for an ion traveling through air at a density of 1.4×10^{12} cm^{-3}, typical for 115 km. The results of the calculations give the number of electrons produced as a function of energy and atomic number of the energetic ion. Some representative examples are shown in Fig. 2 from which we find that the number of ion-electron pairs produced per incident ion of atomic number Z and energy E ev in the 100 kev range is given very closely by

$$N(E) \simeq 400 \left(\frac{19}{Z}\right)\left(\frac{E}{10^5}\right)^{1.37} . \qquad (3.2)$$

Table I shows the results of the calculations for Cs^+ and Na^+. The general statement which one can make is that there is a distinct advantage in using small Z both from the standpoint of increased range and efficiency for producing ionization.

In the calculations in the Appendix we have neglected the effect of secondaries, double ionization, and stripping, each of which will increase the number of electrons produced. In particular, secondaries (both ions and electrons) can significantly increase the number of ion-electron pairs produced by as much as a factor of two or more in some cases. The energy loss due to ionization has also been neglected as being small; this approximation is worse for the more efficient low Z ions. It should also be stressed that Firsov's theory does not include any effects peculiar to the particular interacting pairs which depends on atomic structure. For instance, it is known experimentally that alkali ions ionize noble gases nearest them in atomic number more easily than the theory predicts [Flaks, et al., 1966]. In addition, there are peculiarities which the theory cannot anticipate, such as the fact that Na^+ is a less efficient ionizer than would be expected [Flaks, et al., 1966]. However, Firsov's [1959] theory does show general agreement with experimental results; a comparison of its

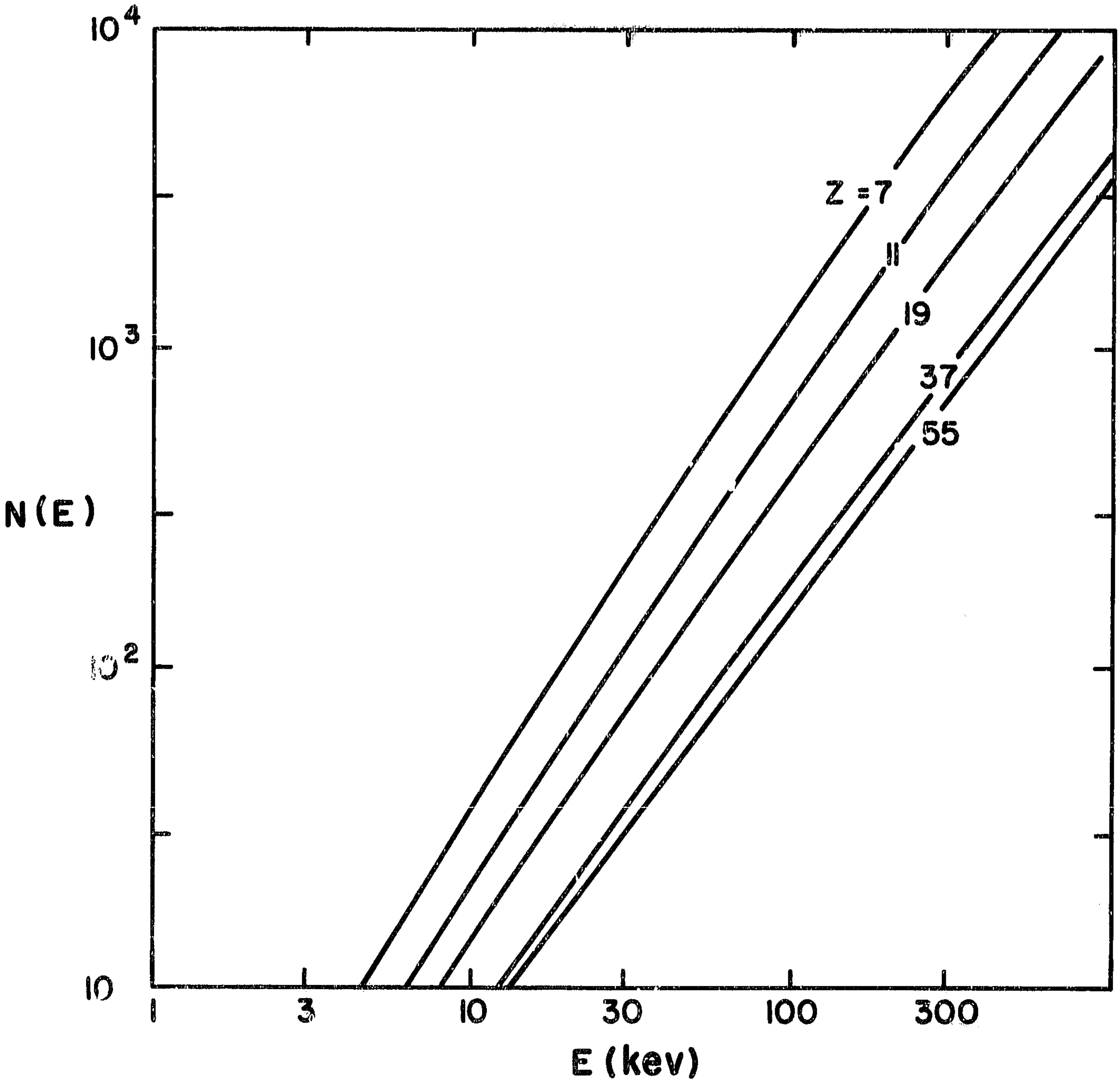

Fig. 2 Number of electrons produced by each ion as a function of energy for several representative ions.

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Table I. Characteristics of Heavy Ion Ionization

Energy	Ion	Range	Larmor Radius	Ion - e^- pairs	Energy/ electron	Efficiency
E ev	Z	$\sim .19 \frac{(Z+7)^{4/3}}{Z^2} \left(\frac{E}{10^5}\right)$ km	$.91 \sqrt{M \left(\frac{E}{10^5}\right)}$ km	$\sim 400 \left(\frac{19}{Z}\right)\left(\frac{E}{10^5}\right)^{1.37}$		$\sim \frac{114}{Z} \left(\frac{E}{10^5}\right)^{0.37}$ %
100 kev	Cs^+	1.5 km	10.5 km	150	670 ev	2.2%
100 kev	Na^+	7.1 km	4.5 km	700	140 ev	10.5%

predictions with experimental values is shown in Fig. A.2. There is no reason to choose alkali ions over any others; the choice of ion should depend on practical considerations such as ease of operation in a high voltage gun. It is obvious that higher energy at the same power is desirable both from the point of view of increased range and efficiency.

The use of an ion beam would require rockets. The payload is primarily determined by the weight of the energy storage devices. If an efficiency of 10% can be achieved, the figures given in the introduction indicate a minimum energy requirement of 2.4×10^7 joules. Present day technology indicates that a storage capacity approaching 10^5 joules/lb for special energy cells which can discharge their energy at a kwatt/lb is attainable. The minimum payload is thus indicated to be around 250 lbs without considering the practical aspects of energy storage and release and the equipment necessary for the creation of a high energy ion beam. Such a small payload makes this suggestion an interesting possibility.

C. Ionization of Air Using Electromagnetic Radiation

We are uncertain about the prospects of breaking down air at a pressure p of 4×10^{-5} mm Hg (the pressure at 115 km) and will confine ourselves to a few remarks which seem pertinent. The plasma frequency in an electron cloud of n electrons cm^{-3} is $f_p = 9 \times 10^3 \sqrt{n}$ cps. Radiation at frequencies f between $f_e = 1.3 \times 10^6$ cps which is the electron gyro-frequency in a magnetic field of 0.46 gauss and 9×10^6 cps which is the plasma frequency is reflected from an electron cloud of 10^6 cm^{-3} and cannot be used to break down air. Hence, we consider the two cases of radiation above and below these limits separately. Another important parameter is the elastic collision frequency of electrons with neutrals which is given approximately by $\nu \sim 3 \times 10^8$ p.

It appears that frequencies above 9 Mc are impractical. If a transmitter is carried by a rocket, breakdown would be most likely to occur near the transmitter where field strengths are the highest. Thus, a local, high density, electron cloud would be produced which would no longer absorb additional radiation when its plasma frequency exceeded the operating frequency. Transmission from the ground is also impractical as the most efficient energy transfer to the electrons occurs when the operating frequency is equal to $\nu/2\pi$. But this condition would be met at or below an altitude of 60 km for $f > 9 \times 10^6$ cps. Again, the air would break down (if sufficient power were transmitted) at a lower altitude than desired and the resulting electron cloud would increase in density until it would reflect the incident radiation.

In a magnetic field, a right-hand polarized wave commonly called a whistler due to its dispersion characteristics, can propagate below the plasma frequency if it is also below the electron gyro-frequency which is 1.3×10^6 cps for the ionosphere. The appropriate dispersion relation for whistlers, valid for frequencies above the ion gyro-frequency (about 400 cps), propagating at an angle θ with respect to the magnetic field, and obeying the condition $f_e^2 \sin^2\theta \ll 2\left|f_p^2 - f^2\right|$ is [Stix, 1962]

$$(kc)^2 = (2\pi f)^2\left[1 + \frac{f_p^2}{f(f_e\cos\theta - f - i\frac{\nu}{2\pi})}\right] \sim (2\pi f)^2\left[1 + \frac{f_p^2}{f(f_e\cos\theta - f)} + i\frac{f_p^2\nu}{2\pi f(f_e\cos\theta - f)^2}\right] \quad (3.3)$$

where the last expression is appropriate for $\nu \ll 2\pi(f_e \cos\theta - f)$. In Eq. (3.3) c is the speed of light and k is the complex wave number. At 10^6 cps the free space wavelength is 300 m and waves traveling within 40° of the magnetic field can propagate. The above dispersion relation tells us that the absorption of wave energy is increased as the operating frequency approaches the gyro-frequency from below. The absorption is also proportional to the ambient electron density and inversely proportional to the atmospheric neutral density. This fact indicates that if transmission is from the ground, maximum absorption takes place at the lower edge of the ionosphere (around 95 km) where $f_p \sim 10^6$ cps and $\nu \sim 10^5$. From Eq. (3.3) we obtain a typical absorption distance as

$$(\mathrm{Im}\, k)^{-1} \sim \frac{2c(f_e \cos\theta - f)^2}{\nu f_p^2} \sqrt{1 + \frac{f_p^2}{f(f_e \cos\theta - f)}} \sim 1 \text{ km}$$

for waves traveling parallel to the magnetic field at a frequency of 10^6 cps. As the electron density increases above 10^4 cm^{-3} this distance decreases which makes it difficult to penetrate the ionosphere significantly at modest power levels. A lower transmitting frequency increases the penetration but is difficult to focus due to its large free space wavelength.

The above considerations indicate that it would be difficult to create ionization at the desired altitude by electromagnetic radiation. We have not considered the problem of the coupling of the radiation into the ionosphere which is important as the power which is actually absorbed is reduced if the radiation is predominantly reflected from the bottom of the ionosphere. The possibility of irradiating the ionosphere from above where the collision frequency is less has not been investigated. Furthermore, we have not considered the important problem of breakdown of the air or the efficiency with which the absorbed radiation is converted into ionization. The possible use of electromagnetic radiation to accomplish our goal requires further study.

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IV. SUMMARY

From the previous discussion, we conclude that it is possible to produce sufficient numbers of free electrons on a large enough scale in the lower ionosphere to have geophysical effects. We expect that these effects will increase our understanding of the coupling between the natural magnetospheric convection and high latitude ionospheric processes and may achieve the ultimate goal of triggering an aurora. The most likely method for production of these electrons at 115 km appears to be either by chemical deployment or with the use of high energy electron or ion beams. On the basis of a production efficiency of 10^{19} electrons per gram in a chemical release, the requirement of 10^{24} electrons results in a payload of the order of 200 pounds. On the other hand, 50 pounds of batteries can store enough energy for an electron beam to ionize 10^{24} air molecules based on an energy storage capability of 10^5 joules per pound; the use of a less efficient ion beam would require 3 to 5 times this payload. The principal advantage of chemical releases is their simplicity. Alkali clouds also have the added advantage of having a significantly smaller recombination coefficient which results in a longer lifetime for the electrons. The use of electron beams probably would require more than one rocket in order to spread the ionization out over the required area. The efficiency of ion beams is increased by the use of ions of lower atomic number and higher energy. Increasing the energy of the beam not only increases its overall efficiency but also increases its range which allows more flexibility for operation at slightly lower altitudes. The possibility of using electromagnetic radiation in the radio frequency range needs to be investigated further.

It is possible that increased coupling of the magnetic field lines to the ionosphere could be obtained by producing ionization at lower altitudes. In support of this it has been reported that the lower edge of discrete aurora usually lies in the range of 100 ± 10 kilometers. The practical limitation for the maintenance of ionization is set by the decreasing lifetime of the electrons as one moves to lower altitudes. One would have to rely on initiating increased precipitation in order to maintain the ionization. Since the e-folding distance for the exponential atmosphere is 7 km, the use of high energy heavy ions for producing ionization much below the altitudes we have been discussing becomes impractical due to their shorter range. The use of chemical releases then appears to be the most promising method of producing large numbers of electrons at lower altitudes, but their successful deployment becomes more difficult due to slower diffusion.

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APPENDIX

We apply the theories of O. B. Firsov in order to obtain estimates for the elastic [Firsov, 1958] and ionization [Firsov, 1959] cross sections so that the integral given in Eq. (3.1) can be evaluated to give the total number of electrons produced by an energetic ion. In the following we consider collisions of an arbitrary ion $Z \geq 7$ with a nitrogen atom ($Z = 7$, $M = 14$). For elastic scattering, Firsov [1958] gives the expression*

$$\sigma_{el}(E) = 6.7 \times 10^{-16} \frac{Z(M+14)}{(Z+7)^{1/3}} \frac{1}{E} \left[\frac{E_o}{E} \ell n\left(1+\frac{E}{E_o}\right)\right] cm^2,$$

$$E > E_{min} = 0.34 \cdot Z \cdot (Z+7)^{1/3}(M+14) \text{ ev} \sim 10\left(\frac{Z}{54}\right)^{7/3} \text{kev} \quad (A.1)$$

$$E_o = 21 \times Z(Z+7)^{1/3}(M+14) \text{ ev} \sim 100\left(\frac{Z}{24}\right)^{7/3} \text{kev} .$$

The factor in brackets is unity for $E < E_o$ while for greater energies it gives the more rapid decrease than E^{-1} in the elastic cross section due to the coulombic character of the nuclear scattering. For $E < E_{min}$ the cross section rapidly approaches its gas kinetic value. The mean energy loss for elastic scattering is $2M_T M(M_T + M)^{-2}E$ where M_T is the

*Firsov introduces the function $\psi(Z_1, Z_2) \sim (Z_1^{2/3} + Z_2^{2/3})^{1/2}$. We find that ψ differs by less than 2% from $1.1(Z_1 + Z_2)^{1/3}$ for $1 < Z < 56$ and we use the simpler expression in the following equations.

mass of the stationary target particle. If the elastic scattering is assumed to be due to a hard sphere of cross sectional area given by Eq. (A.1), we easily obtain an energy loss rate roughly independent of energy of

$$\frac{dE}{ds} = 3.8 \times 10^{-14} n \frac{Z}{(Z+7)^{1/3}} \frac{M}{M+14} \left[\frac{E_o}{E} \ln\left(1+\frac{E}{E_o}\right)\right] \text{ev cm}^{-1} \tag{A.2}$$

where n is the density of neutral molecules (= 1.4×10^{12} at 115 km). Molecular scattering has been taken into account by doubling the atomic cross section given by Eq. (A.1). Neglecting the slowly varying factor in brackets, we obtain a pessimistic estimate for the range of a heavy ion at 115 km of

$$R = 0.19 \frac{(Z+7)^{1/3}}{Z} \frac{M+14}{M} E \quad \text{meters} \tag{A.3}$$

which is shown plotted as a function of Z in Fig. A.1. Note the substantial increase in range for $Z < 20$. The plot is shown for $Z \geq 7$ as Firsov's statistical theory is valid only for many electron atoms.

For ionizing collisions, Firsov [1959] calculates the energy transferred to the electrons in a single ionizing collision between heavy atoms or ions to be

$$\mathcal{E} = \frac{x\mathcal{E}_i}{[1 + 0.304(Z+7)^{1/3} r]^5} \text{ ev} \tag{A.4}$$

where r is the impact parameter in Å, $\mathcal{E}_i$ is the ionization energy of

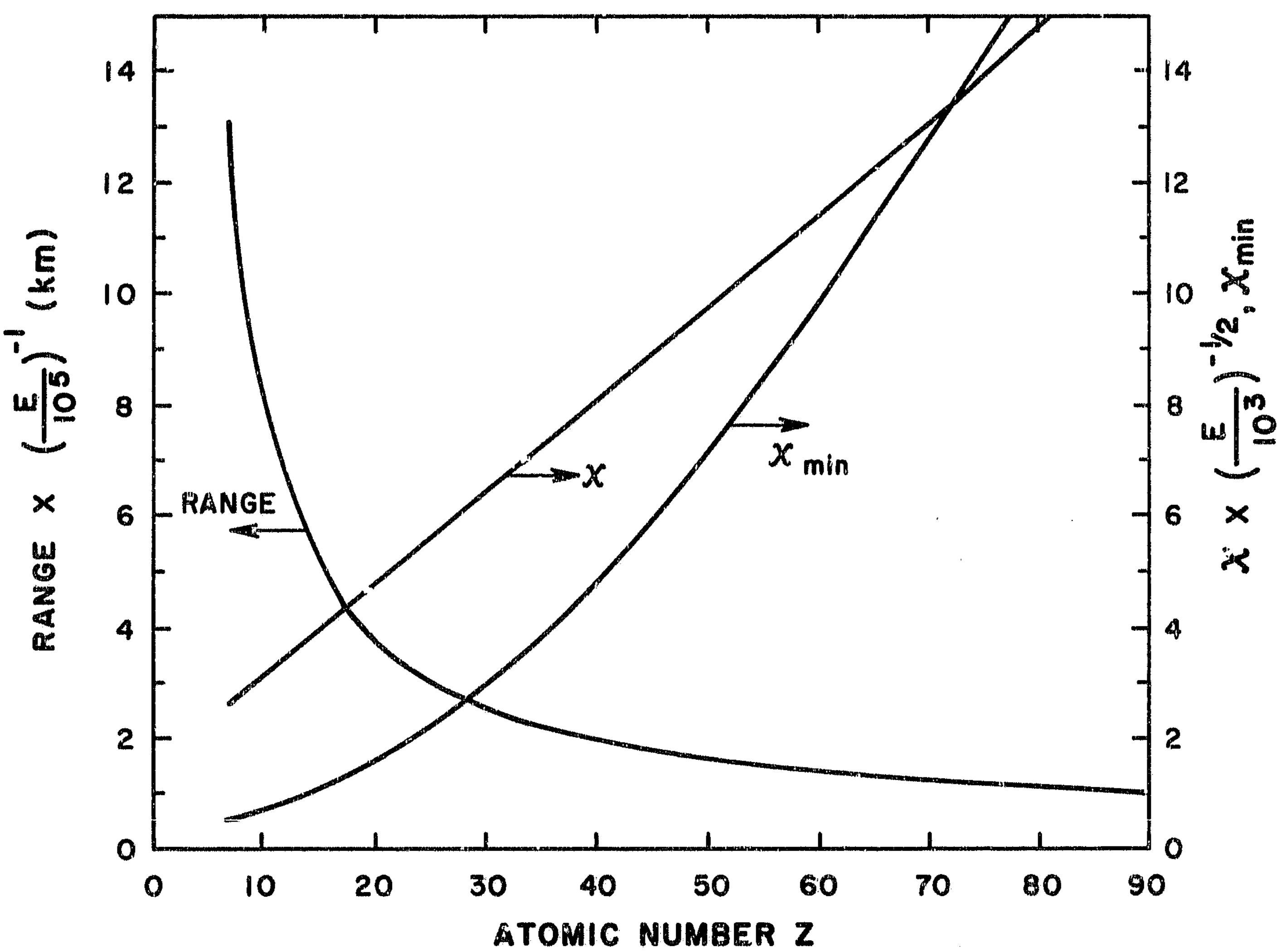

Fig. A.1 Range of a 100 kev heavy ion of atomic number Z according to Firsov's [1958] theory. On the right-hand scale are shown the parameter x for a 1 kev ion defined by Eq. (A.5) and the minimum value of x for the validity of the theory for the inelastic cross section [Firsov, 1959].

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the least bound electron which we take to be 15 ev, and x is the ratio of the velocity of the ion normalized by a characteristic velocity which can be expressed in terms of the energy as

$$x = \frac{5.94 \times 10^{-2} (Z+7)^{5/3}}{\mathcal{E}_i} \sqrt{\frac{E}{M}} \sim \frac{1}{6} (Z+9) \sqrt{\frac{E}{10^3}} \quad . \qquad \text{(A.5)}$$

$x \cdot (E \times 10^{-3})^{-1/2}$ is shown in Fig. A.1 as a function of Z. There is a lower limit to the energy for which we can expect Firsov's theory to be realistic as he assumes rectilinear motion for the nuclei. The maximum energy transferred in an ionizing collision is xE_i according to Eq. (A.4). If we arbitrarily demand that the incoming ion must itself have 5 times this energy in order to apply the theory, we obtain a minimum value of x given by

$$x_{min} = \frac{1.18 \times 10^{-3} (Z+7)^{10/3}}{M} \qquad \text{(A.6)}$$

below which we cannot expect the theory to be accurate. x_{min} is also shown as a function of Z in Fig. A.1 where the corresponding critical energy is seen to vary from around 100 volts for low Z to around 1.5 kev for heavy ions.

Firsov obtains a universal curve for ionizing collisions by arguing that as long as the minimum ionization energy is transferred, an electron will be ejected by the Auger process with a high probability. Setting $\mathcal{E}$ equal to $\mathcal{E}_i$ in Eq. (A.4) and solving for πr^2, we obtain Firsov's [1959] expression which when multiplied by two gives for the molecular ionization cross section

$$\sigma_i = 8 \times 10^{-16} \left(\frac{25}{Z+7}\right)^{2/3} [x^{1/5} - 1]^2 \text{ cm}^2 \quad . \tag{A.7}$$

In recent years there has been increased experimental activity in measuring cross sections for various interactions involving heavy ions in the kev range. We show in Fig. A.2 a typical comparison [Flaks, et al., 1966] of experimental values involving several combinations of incident and target particles with Firsov's universal curve. It seems as though the Firsov cross section predicts roughly the dependence on velocity and is within a factor of two of measured values for large energies. We shall make use of his expression for our analytic calculations.

We are now in a position to evaluate the mean energy loss $\bar{\mathcal{E}}$ in an ionizing collision as a function of x . After a simple calculation we obtain

$$\bar{\mathcal{E}} = \frac{x^{3/5} + 2x^{2/5} + 3x^{1/5} + 4}{10} \mathcal{E}_i \tag{A.8}$$

which is shown plotted in Fig. A.3. Since at worst only a few times the ionization energy is lost per ionizing collision, we see that heavy ion ionization is a relatively efficient process. The limitation which occurs is that elastic collisions are responsible for the energy loss of heavy particles.

Knowing the ionization cross section from Eq. (A.7) and the energy loss rate from Eq. (A.2), we can calculate the number of electrons produced by each primary heavy ion by using Eq. (3.1). The result can be given in the form

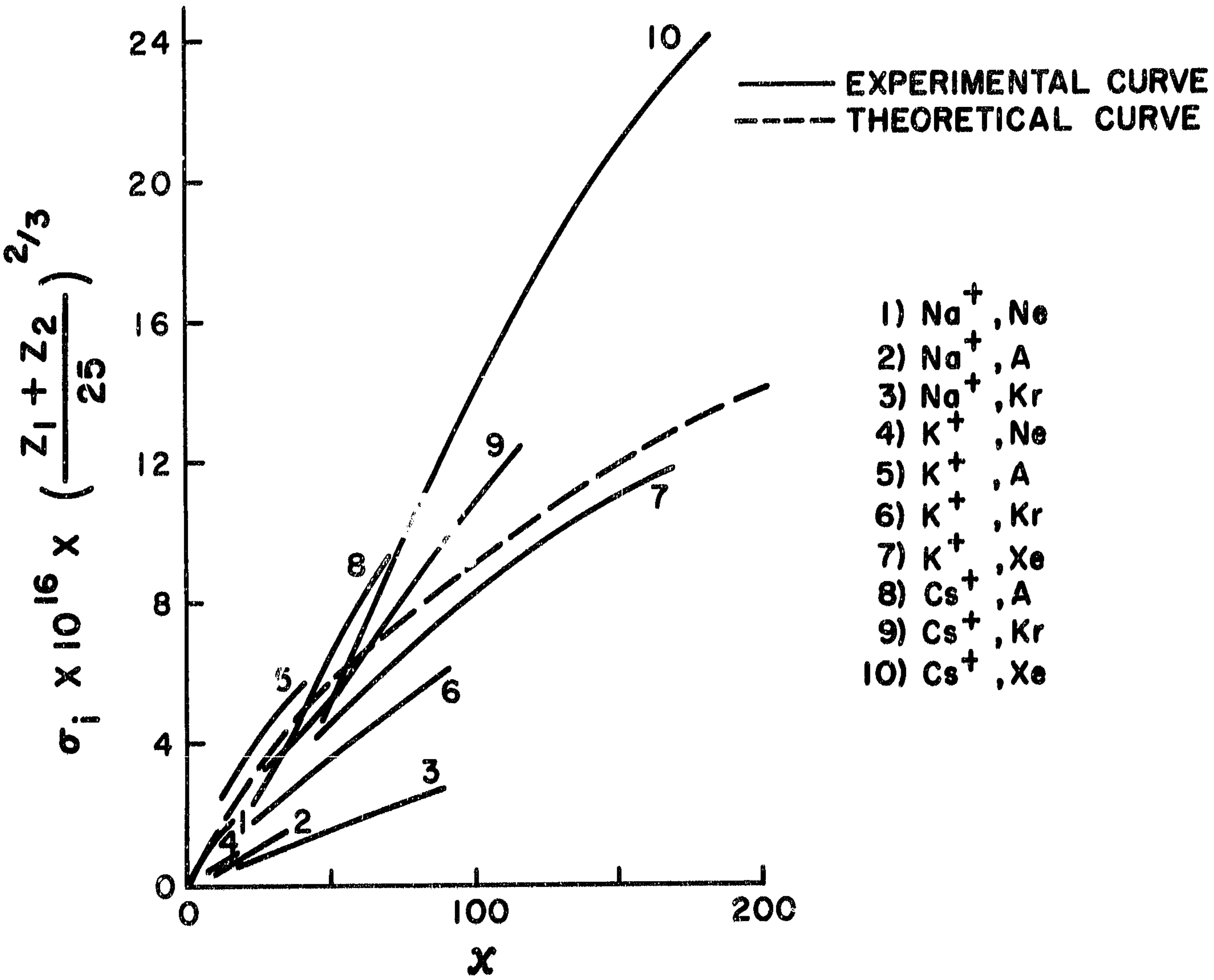

Fig. A.2 Comparison taken from Flaks, et al. [1966] of experimentally measured ionization cross sections for various interacting species with the universal (dashed) curve due to Firsov [1959].

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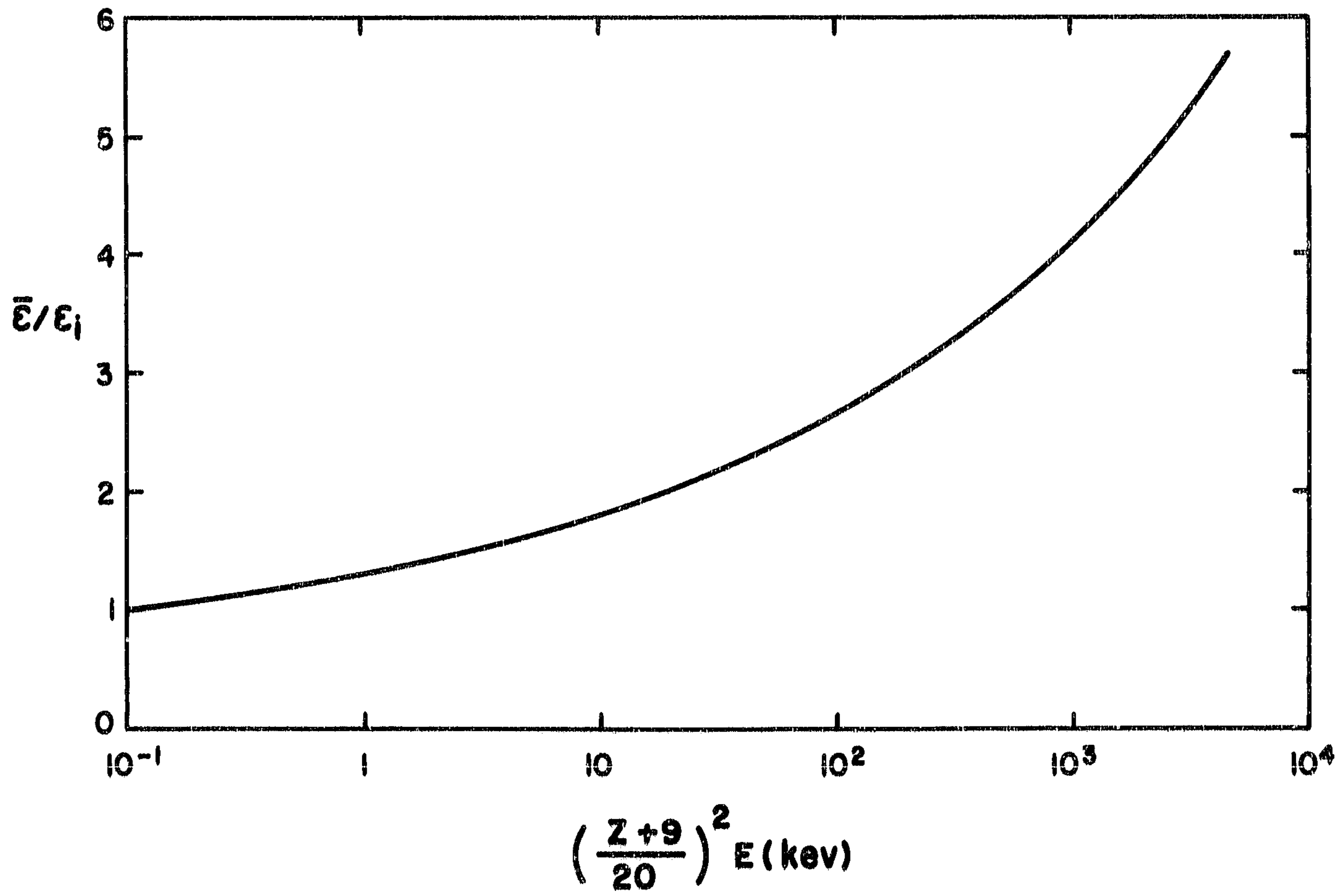

Fig. A.3 Mean energy transferred in an ionizing collision as a function of energy according to the theory of Firsov [1959].

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$$N(E) = \frac{(M+14)\,E}{M \cdot Z \cdot (Z+7)^{1/3}} \, F(x) \; ; \quad F(x) = 0.147\left[(x^{1/5} - 1)^2 + \frac{1}{5} - \frac{2x^{1/5}}{11} - \frac{1}{55x^2} \right] \tag{A.9}$$

which is shown as a function of energy for some representative ions in Fig. 2. This calculation of N(E) has neglected the contribution to the total number of electrons produced by secondaries (both ions and electrons) and has neglected the contribution of the energy loss due to ionization as being small compared to the elastic energy loss.

REFERENCES

Axford, W. I., Petschek, H. E. and Siscoe, G. L., "Tail of the Magnetosphere," J. Geophys. Res. 70, 1231-1236, 1965.

Baker, K. D. and Ulwick, J. C., Paper GA72 presented at the 48th Annual Meeting of the Amer. Geophys. Union in Washington, D. C., April 17-20, 1967.

Boström, R., "A Model of the Auroral Electrojets," J. Geophys. Res. 69, 4983-4999, 1964.

Firsov, O. B., "Scattering of Ions by Atoms," Sov. Phys. JETP 34, 308-311, 1958.

Firsov, O. B., "A Qualitative Interpretation of the Mean Electron Excitation Energy in Atomic Collisions," Sov. Phys. JETP 36, 1076-1080, 1959.

Flaks, I. P., Kikiani, B. I. and Ogurtsov, G. N., "Ionization of Gases by Alkali Ions," Sov. Phys. Tech. Phys. 10, 1590-1595, 1966.

Friedman, R., Fagg, L. W., Millar, T. K., Charles, W. D. and Hughes, M. C., "Study of Electron Generation by Solid Propellant Technique," in Progress in Aeronautics and Astronautics, Vol. 12, pp. 379-393, Academic Press, 1963.

Friedman, R. and Macek, A., "A Novel Chemical System for Generation of Electron-Rich Gases," Tenth Symposium (International) on Combustion, pp. 731-741, The Combustion Institute, 1965.

Hinteregger, H. E., Hall, L. A. and Schmidtke, G., "Solar XUV Radiation and Neutral Particle Distribution in July 1963 Thermosphere," Space Research V, pp. 1175-1190, North-Holland, 1965.

Linson, L. M., "Spherical Probe Characteristics at Large Positive Potentials in a Magnetic Field," Paper 5C-8 presented at Ninth Annual Meeting of the Division of Plasma Physics, Austin, Texas, November 8-11, 1967 (to be published).

Marmo, F. F., Pressman, J. and Aschenbrand, L. M., "Electron Clouds: A General Survey," Planet Space Sci. 3, 139-157, 1961.

Rosenberg, N. W. and Golomb, D., "Generation and Properties of High Altitude Chemical Plasma Clouds," Progress in Aeronautics and Astronautics, Vol. 12, pp. 395-408, Academic Press, 1963.

Stephenson, S. Town, "The Continuous X-Ray Spectrum," Handbuch Der Physik 30, 337-370, 1957.

Stix, T. H., The Theory of Plasma Waves, pp. 38-40, McGraw-Hill, 1962.