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On the Use of Electrical Ion Sources for Ion Tracer Experiments in the Magnetosphere *

by

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ABSTRACT

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Several authors have proposed that clouds of ions of a species which scatters visible light strongly be injected into space as 'probes' to study electric and magnetic fields there. The clouds, viewed from earth by scattered sunlight, would be generated by chemical or atomic explosions in space. The present paper examines the possibility of using an <u>electric ion source</u> in orbit around the earth to generate such 'probes' for magnetospheric studies of (a) electric fields, (b) ion diffusion, and (c) the distant magnetic field configuration. It is concluded that studies (a) and (b) can be done using an electric ion source whose construction is probably within the present state of the art. Study (c), however, requires an ion source whose development in a size and weight suitable for sending into orbit may be outside the state of the art.

Author

I. INTRODUCTION

It has been proposed that clouds of ions of a species which scatters visible light strongly be used as 'probes' to study the electric and magnetic properties of the solar wind [Biermann et al., 1961] and the topological nature of the earth's distant magnetic field [Harrison, 1962a, 1962b]. The ion clouds would scatter visible light from the solar radiation intensely enough so that their motions in the fields in space could be followed simply by observations from the ground.

Sodium clouds have been released many times by means of small chemical bombs to study ionospheric winds. Sodium clouds were released by this means also from two Soviet space probes [Schklovskii, 1961; Schklovskii et al., 1960] as means for precise tracking of the vehicles. The material released by chemical bombs consists largely of neutral atoms because the temperature of these detonations is relatively low. This feature limits, seriously, the utility of chemical bombs in producing clouds of ions, for one must rely upon solar radiation to ionize the neutral gas, and the photo-ionization must take place in a short time if the cloud is not to become too large and diffuse, by thermal expansion, to be a useful 'probe'. The cloud released at ~ 150,000 km from the earth by the Soviets, consisting of about one kilogram of neutral sodium atoms, ceased to be detectable against the night sky after expanding for about 280 seconds. At this time its diameter was ~ 1100 km. We may conclude from this example that fairly complete ionization of a neutral gas cloud must take place in a few hundred seconds, at most, if one is to achieve, by a chemical burst, an ion cloud small and bright enough to provide quantitative measurements of electric and magnetic fields in space. Thus, although several elements--the alkaline earths and the rare earth, europium--scatter visible light efficiently in their once-ionized state, the alkaline earth, barium, has generally been considered the one of these most appropriate for use in producing an ion cloud by a chemical burst, for its photo-ionization time in sunlight, τ_i, is shortest. Estimates of τ_i for barium range from ~ 100 seconds [Harrison, 1962a; Biermann et al., 1961] to ~ 2000 seconds [Foppl et al., 1965].

There are alternatives to relying on photo-ionization of an initially neutral vapor cloud to produce a cloud of ions. One of these, suggested by Harrison, is to use an atomic bomb to release the material in an ionized state and, furthermore, to impart enough kinetic energy to the ions so that they will overcome gravity and trace out magnetic lines of force to large distances from the earth (e.g., the kinetic energy of a barium ion with earth-escape velocity, 11.5 km/sec, is ~ 90 eV). A second alternative, that which is examined in this paper, is to produce and deploy the ions with an electrical source. This method offers the potential of developing the ion tracer technique as a <u>repeatable</u> experiment which could be performed at many times and places in the magnetosphere with a single orbiting vehicle to make detailed studies of electric and magnetic fields.

Three very important matters can, in principle, be studied by ion tracer techniques:

(a) Magnitudes, directions, and time-variations of electric fields in the magnetosphere.

(b) Ion diffusion rates and processes.

(c) Configuration of the high latitude geomagnetic field lines.

Present knowledge of the electric fields in the magnetosphere is based largely upon interpretations of magnetic disturbances caused by ionospheric currents. The weakness of these fields probably precludes their direct measurement in space by conventional instruments. Regarding (b), very little is known about diffusion and transport of ions along and across the earth's magnetic field. One can estimate the magnitude of such effects due to coulomb scattering but these probably are often quite overshadowed by the effects of other phenomena such as electromagnetic waves. Regarding (c), continuing magnetic field measurements with satellites will provide a generally improving picture of the magnetic field configuration, though satisfactory mapping of the greatly distorted lines of force from high latitudes may require many satellites and many years of such conventional measurements. A few visible ion clouds injected on various ones of these high latitude lines might clarify this picture in a short time.

We discuss, in this paper, two different types of ion injection experiment which might be conducted from a magnetically-oriented satellite carrying an electrical ion source in a circular near-polar orbit at ~ 6000 km.altitude to study questions (a), (b), and (c). (Magnetic orientation of the satellite would permit the ion beam to be aimed in any desired direction relative to the magnetic field.) This discussion is primarily for the purpose of examining the basic requirements of such experiments and illustrating that some experiments relevant to these questions can be done with electrical ion sources which can be developed within present ion-source technology. For purpose of illustration we shall consider injection specifically of barium ions.

II. MEASUREMENTS OF ELECTRIC FIELDS AND ION DIFFUSION

The electric field and ion diffusion measurements would be accomplished by injecting low energy ions whose drift velocity due to the gradient and curvature of the magnetic field is very small compared to that expected due to electric fields. Barium ions would have a kinetic energy of ~ 20 eV by virtue of the satellite's orbital velocity at 2 earth radii (R_e). Their energy and direction of ejection from the source would be controlled, however, so as to limit the cloud's spreading along the magnetic field lines. Under the competing actions of gravity and the magnetic gradient parallel to the lines the ions will spread out along the lines of force, and it can be shown that, for barium ions injected perpendicular to the magnetic field with kinetic energy W_o, within a few thousand kilometers from the earth's surface at high latitude, the kinetic energy parallel to the lines, $W_{\parallel}$, is:

$$W_{\parallel}(r) \approx W_o \left[1 - \left(\frac{r_o}{r}\right)^3\right] - \frac{90}{r_o}\left[1 - \frac{r_o}{r}\right] \tag{1}$$

where r_o is the geocentric distance at which injection takes place. $W_{\parallel}$ and W_o are in electron volts; r and r_o are in earth radii. With this equation one can determine the value of r at which $W_{\parallel} \rightarrow 0$, i.e., the height to which barium ions, injected with energy W_o at r_o, will rise or fall after injection. One finds that ions injected at $r_o = 2$ with energy near 15 eV will neither rise nor fall; by controlling their energy to within ~ 0.1 eV it should be possible to limit their total spread along the lines to ~ 100 km.

The radius of curvature of a 15 eV barium ion at $r = 2\ R_e$ is ~ 1.1 km. The speed of a satellite, V_s, in a circular orbit at this height is 5.3 km/sec. Thus a burst of ion current of intensity j amperes and duration Δt seconds from a polar-orbiting satellite will distribute $6.3 \times 10^{18}\ j\Delta t$ ions in a region ~ 2 km east-west, about 5.3 t km north-south, and ~ 100 km high. From a point on earth directly underneath it (the best position for viewing) this region subtends an angle of ~ 4 minutes of arc (i.e., ~ one-tenth the diameter of the full moon). The critical question is: How great must j be in order that a cloud filling this volume may be detected from the earth--preferably by photographic means--and is this current attainable with presently available ion-sources or with reasonable modifications thereof?

The rate of excitation of ions to a radiation-emitting state is given by:

$$\alpha_{exc} = \frac{\pi e^2}{m_e c^2} f_{mn} \lambda^2 \phi_\lambda u \qquad (2)$$

where e = electron charge

m_e = electron mass

c = velocity of light

f_{mn} = oscillator strength for the transition

λ = wavelength

ϕ_λ = solar photon flux per unit wavelength interval (continuum) outside the earth's atmosphere

u = residual intensity at bottom of the solar Fraunhofer line

Once-ionized barium (BaII), which will be used as the basis for the subsequent discussion, has a resonance line at $\lambda = 4554$ angstroms, for which the oscillator strength is ≈ 1. $\phi_{4554} = 5 \times 10^{21}$ (cm^2-sec-cm)$^{-1}$ and $u \approx 0.2$ at the bottom of the BaII Fraunhofer line [Utrecht Atlas, 1940]. The rate of excitation, α_{exc}, for BaII is, thus, ~ 1.8 sec^{-1}.

A high-sensitivity photographic film requires $\sim 10^9$ photons per cm^2 in the image to produce an appreciable grain density [Foppl et al., 1965]. With an image-intensifier telescope, however, one can obtain photographs with only $\sim 10^8$ photons/cm^2 at the image [Shklovskii et al., 1960]. The photon intensity at the image of a camera, I_i, is:

$$I_i = \frac{S}{4\pi w_s l_s F^2} \tag{3}$$

where S = source (cloud) strength (photons scattered/sec)

w_s = width of source (cm)

l_s = length of source (cm)

F = f/D of objective lens

Since $S \approx 6.3 \times 10^{18} \alpha_{exc} j \Delta t$ and $l_s = V_s \times \Delta t$,

$$I_i = \frac{6.3 \times 10^{18} \alpha_{exc} j}{4\pi w_s V_s F^2}$$

$F \approx 1.1$ is easy to achieve and using appropriate values for other parameters, we find

$$I_i = \frac{6.3 \times 10^{18} \times 1.8 \times j}{4\pi \times 2.2 \times 10^5 \times 5.3 \times 10^5 \times 1.21}$$

$$= 6.5 \times 10^6 \ j \text{ photons/cm}^2\text{-sec} \quad .$$

It is necessary to use a filter to limit the background light from the night sky. A filter of 30 angstroms bandwidth and 60% transmission is readily available [Schklovskii et al., 1960]. Thus, $0.6 \times I_i = 4 \times 10^6 \times j$ photons/cm^2-sec is the actual intensity at the image.

The exposure time required to photograph the cloud with an image-intensifier telescope would be $10^8/4 \times 10^6\ j = 25/j$ sec, while that with a regular telescope would be $\sim 250/j$ sec. The anticipated motions of the cloud are slow and exposure times as long as 25 to 250 seconds probably would not be extremely objectionable, so, from this standpoint, a current as small as one ampere would be adequate. However, a more fundamental requirement on j is that the cloud's surface brightness must be at least comparable with that of the (moonless) night sky against which it is to be observed. The night sky background, G, is $\sim 5 \times 10^4$ photons/cm^2-sec-ster-angstrom [Allen, 1955]. The ratio of cloud surface brightness, I_c, to sky brightness, I_s, is:

$$\frac{I_c}{I_s} = \frac{S}{4\pi\ G b w_s\ l_s} = \frac{6.3 \times 10^{18}\ \alpha_{exc}\ j\ \Delta\ t}{4\pi\ G b w_s\ V_s\ \Delta\ t} \qquad (4)$$

where b is the bandwidth of the filter used. Substituting values we find $I_c/I_s \approx 5.2\ j$. This ratio is independent of the distance to the cloud and we see that $j \approx 0.2$ ampere satisfies this relative brightness requirement.

Deterioration of the Cloud

Electric fields would be deduced by measuring the motions of the cloud both perpendicular to and parallel to the magnetic field lines. At the low altitude of the cloud (i.e., $\sim 2\ R_e$) the magnetic field is well known and it is thus possible to derive, from the $\bar{E} \times \bar{B}$ drift motions, the value of the electric field component perpendicular to the lines of force. Electric fields along the magnetic lines would cause the cloud to rise or fall and their values could be deduced from the direction and magnitude of this effect. A question of great interest and importance is, for example, whether the cloud will rotate with the earth and, if so, within what range of latitudes the electric field forcing this corotation exists.

In order for the ion cloud to be useful in making quantitative evaluations of such unknown properties of the magnetosphere, its lifetime against deterioration by better-known phenomena such as ion-electron recombination and diffusion by coulomb scattering, must be long--hopefully several hours. Of course, the diffusive behavior of ion clouds is an interesting study in itself and might yield valuable information regarding rapidly time-varying fields and wave phenomena. But, here, it must be ascertained that the cloud's lifetime against predictable loss mechanisms is adequately long to permit quantitative measurements of its behavior and to justify injection of ion clouds for the study of <u>unknown</u> phenomena.

A simple argument suffices to show that the life against recombination is adequately long. The electron density at 6000 km altitude is $\sim 10^3/\text{cm}^3$. (Note that the density of barium ions in the cloud is only

$$\rho_i = \frac{6.3 \times 10^{18}\ j\ \Delta t}{10^7 \times 2.2 \times 10^5 \times 5.3 \times 10^5\ \Delta t} \approx 5.4\ j\ .$$

For j in the range 1 to 10 amperes, $\rho_i = 5$ to 50 ions/cm^3. This is a small fraction of the ambient proton and electron density so the cloud will not seriously perturb its environment.) The velocity of the ambient (1000° K) electrons is $\sim 2 \times 10^7$ cm/sec, so their flux, nv, is $2 \times 10^{10}/\text{cm}^2\text{-sec}$. Taking a recombination cross-section, σ_r, for BaII of 10^{-16} cm^2 (probably much too large) we have $nv\sigma_r = 2 \times 10^{-6}$ sec^{-1}. Thus, the lifetime against recombination is at least 5 days and probably much greater.

Estimates of the slowing-down and 'deflection' times of the cloud ions were derived from equations in chapter 5 of Spitzer [1956]. Here we will simply indicate the values of parameters used and the results of the calculations. The 'field-particles' consist of 10^3 electrons/cm^3 and 10^3 protons/cm^3, both at temperature 10^3 degrees K. The barium ions have, initially, 15 eV kinetic energy. Making use of Spitzer's equations (5-9), (5-18), and (5-22) and his tables 5.1 and 5.2, we find that t_D, the time for a 90° deflection of a barium ion, is $\sim 3.6 \times 10^5$ seconds, or about 4 days. But t_D varies directly with the third power of the ion velocity and as the ions are slowed down by coulomb interactions with the field particles, t_D shortens rapidly. Spitzer's equation (5-28) gives ~ 2 hours for t_s, the slowing-down time for the barium ions. This, then, is the effect most severely limiting the lifetime of the cloud. For, as the ions are slowed by coulomb interactions their deflection time decreases and they also fall to lower altitude where the field particles are even more numerous. We conclude, then, that useful cloud lifetimes of only an hour or so are possible in the experiment as described here. The lifetime could be increased by releasing the cloud at higher altitude.

III. TRACING OUT MAGNETIC FIELD LINES

To trace out high latitude magnetic field lines, using ions injected at low altitude ($2R_e$) it is necessary to give the ions energy enough not only to overcome gravity in rising to the high altitudes involved, but also to traverse the length of the lines in short times, thus minimizing the effects of electric field-induced drift during their traversal. Barium ions of 1 keV require ~ 1/2 hour to travel to the equator of a line of force reaching 8 R_e. We regard this to be a satisfactorily short time and, so, postulate the use of 1 keV barium ions for this type of experiment. The ions would be injected upward along the field lines with narrow angular collimation (pitch angle, α, less than 5°) wnd with good energy resolution (e.g., 1 ± 0.01 keV) to minimize spreading of the cloud, thus keeping it as small and bright as possible as it travels along the distant reaches of the lines of force.

To increase the cloud depth along the line of sight when it crosses the equator, ions could be injected continuously over a distance of perhaps 100 km (burst duration ≈ 20 seconds) as the satellite travels from high latitude toward low latitude. The ions, as they cross the equator, would then lie in a slab of line-of-sight depth ≈ 1000 km, and width ≈ 16 km, the latter dimension determined by the Larmor radius of the ions. Even with the high degree of angular collimation and energy resolution postulated above, the length of the cloud <u>along</u> the magnetic field would be no less than several hundred kilometers, and we assume 1000 km.

With the geometry of the cloud at its equatorial crossing thus determined, we now use equations (3) and (4) to determine the photon intensity at the image of an optical system and the ratio of cloud brightness to sky brightness. Taking $\Delta t = 20$ sec, $w_s = 16$ km, $l_s = 1000$ km, we find $I_i \approx 1 \times 10^5$ j photons/cm^2-sec. We find, also, $\frac{I_c}{I_s} \approx 0.1$ j. From these values we see that a current of 10 ampères is required to make the cloud as bright as the night sky. Furthermore, since the cloud, travelling ~ 40 km/sec, takes only ~ 25 sec to travel its own length (1000 km), exposure times for photography cannot exceed this value. We find that j must be ~ 40 amperes to meet this requirement.

IV. CONCLUSIONS

We have considered two basic types of ion tracer experiments whose performance would be of great value in studying the electric, magnetic, and electromagnetic character of the magnetosphere and have determined the ion current that is required if these experiments are to be done using an orbiting electric source of barium ions.

To measure electric fields at 2 R_e and, possibly, to study electromagnetic waves and ion diffusion phenomena there, we require that the source emit at least 1 ampere of ions, and preferably 10 amperes or more. The energy of the ions should be variable over a range from a few eV to ~ 30 eV. The energy should be controllable to ~ 0.1 eV and the energy spread at any particular setting should not exceed ~ 0.2 eV. The angular spread of the beam should not exceed 5° half-angle. With these specifications, the 10 ampere current, emitted for one or two seconds will produce a cloud of apparent angular size about one-tenth as large as the moon, 50 times as bright as the (moonless) night sky (when viewed through a 30-angstrom filter). This could be photographed, using essentially standard equipment, in exposure times of 3 to 30 seconds. The cloud should maintain its initial altitude, size, and shape for an hour or so if coulomb scattering is the principle deteriorating mechanism.

To trace out the distant magnetic field lines we require that the source emit at least 40 amperes of ions for burst periods of ~ 20 seconds. The ion energy should be ~ 1 keV with a spread no greater than 1% and an angular collimation of ~ 5°.

The low-energy source can be developed within the present state of the art, though achievement of the specified energy resolution, energy control, and angular collimation probably will present serious problems. The equipment, including power supply, would weigh only a few pounds. A single such source could be designed to provide hundreds of one- or two-second bursts, so that ion clouds could be injected and studied in a great variety of different locations and magnetospheric conditions with a single satellite. The high-energy source, however, represents an increase by a factor of ~ 40 over currents of 1 keV ions available from present single ion engines. Therefore we regard its development in a size and weight suitable for placing in earth orbit to be outside the present ion-engine technology.

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