Rate of loss of terrestrial atmosphere from earthquake motions is estimated. Some of this atmosphere ionizes as it is blown off through the magnetosphere, and the amount so ionized seems to be abundantly ample to account for C, N, and O found in the Van Allen belt.

1. Introduction

The earth is peculiar in that "rare gases" are rare on earth but not on a cosmic scale as has been remarked by Russell and Menzel. From this fact valuable deductions have been made concerning the formation of the present day atmosphere of the earth by Suess and independently by Brown.

Their deductions are two-fold: (i) in the process of the earth's formation, some mechanism operated such as to prevent retention of any substance that was mainly gaseous at that time; and (ii) the earth's atmosphere today is almost entirely of secondary origin and was formed by chemical processes taking place after formation of the earth. Components of the secondary atmosphere must have been chemically combined with solids during the time that the first atmosphere was lost.

Furthermore, the earth has lost considerable amounts of N, O, and C, relative to cosmic abundances, although not as much by such severe fractionation as that of the rare gases. For example, the cosmic ratios of N and O relative to Si are $\sim 10^{-5}$. If their loss had been as severe as that of Ne, the ratio would have been $\sim 10^{-10}$ (see ref. 3, page 264). In a reducing environment, all the three elements would be gaseous, N as NH$_3$, O as H$_2$O, and C as CH$_4$.

Thus, we may conclude that some mechanism may have operated to remove gases from the earth even after formation of the solid earth and loss of the primary atmosphere, but presumably when N, O, and C were not gaseous.

This mechanism cannot have been thermal escape, as has been pointed out by Spitzer. For example, he finds that at 2000°K the time of escape of He from the earth is $2.4 \times 10^7$y and for N it is $3.9 \times 10^{16}$y. Although the present day fractionation of He reflects continued thermal escape, that of N and O cannot be affected by thermal escape in $4.5 \times 10^9$y, the life of the earth.

In the present paper we discuss a shock-wave mechanism to blow gases off the top of the atmosphere in amounts independent of the molecular weight of the gas. This mechanism blows off whatever gases occupy the top of the atmosphere; hence, the effect of molecular weight enters only as a secondary effect in populating the top of the atmosphere by thermal fractionation.

In particular, heavy gases such as Ne, N$_2$ and O$_2$, CO$_2$ and CH$_4$, which are otherwise unable to escape from the earth in its lifetime, may be blown off the top of the atmosphere by shocks evolving from small motions of the earth's surface at the base of the atmosphere. In this sense, a moving portion of the earth's surface may be considered as a piston which, pushing the atmosphere above it, produces a shock front moving radially upward with supersonic speed. The specific energy of the shock front as it moves into the logarithmically decreasing atmosphere is contained in decreasing amounts of mass, so that finally gas molecules in the shock reach escape velocity and are blown off the earth.

Piston motions of the earth's surface have been caused during the life of the earth by natural phenomena such as (a) earthquakes, (b) volcanic explosions which produce caldera like Krakatoa, Crater Lake, Valle Grande, etc., and (c) meteoritic collisions such as Tunguska and Canyon Diablo. Atmospheric shocks also originate from meteors burning up in the atmosphere without reaching the earth's surface, and from lightning bolts.

Estimates are made, in this work, of the mass of atmosphere lost from the earth during its lifetime by atmospheric shocks produced by some of these phenomena.
2. Evidence for Ionospheric Disturbances Caused by Natural Phenomena

The technique of reflecting ionosonde radiation at decametre frequencies from the ionosphere and study of the consequent Doppler shifts have been in existence for several years so that there exists considerable literature on it. The Doppler shifts are caused by reflection from wave motions of ionized layers of the upper atmosphere.

Atmospheric displacements associated with the pressure waves increase as the density decreases, so that displacements of the order of millimetres at the earth's surface are amplified to kilometres in the ionosphere, moving contours of constant electron density up and down. These motions cause time dependent Doppler shifts of reflected decametre radio waves from ground stations beamed at the ionosphere.

Documented causes of ionospheric motions producing Doppler shifts include:

(i) High altitude nuclear explosions.\(^5\)
(ii) The Alaskan earthquake of 1964, observed by the ionosonde at the NBS Laboratories in Boulder, Colorado.\(^6\)
(iii) The Japanese earthquake\(^7\) of May 1968 and the Kurile earthquake\(^8\) of August 1969, both detected with the Doppler ionosonde at the University of Hawaii.
(iv) The Peruvian earthquake of 31 May, 1970 detected at Westwood, New Jersey by the Doppler ionosonde array of Teledyne Isotopes.\(^9\)
(v) The Apollo launches at Cape Kennedy, detected by the Teledyne Isotopes' array at Westwood, New Jersey.\(^10\)
(vi) Meteor trails at \(\sim 100 \text{ km altitude.}\)^{11}

The 5 Mc radio signal at Hawaii was Doppler-shifted peak to peak by \(\sim 3 \text{ c/sec}\) when the seismic waves arrived there after travelling 5000 km from the Japanese quake of magnitude 8.2. (A shift of similar magnitude\(^9\) was observed over Westwood, New Jersey, from the Peruvian quake of magnitude 8.2, using a radio signal of \(\sim 5 \text{ Mc.}\) Thus, \(\Delta u/\nu \sim 10^{-4}\), so that the velocity of vertical motion of the ionosphere at 200 km (5 Mc) is \(10^{-6} \text{ c}^* = 3 \times 10^4 \text{ cm/sec, where } c^* \text{ is the velocity of light.}\)

Taking the attenuation of energy in the seismic wave \(\rho (\text{distance})^3\) and the surface dimension\(^12\) of a magnitude 8 quake to be \(\sim 8 \text{ km}\), then above the quake epicentre, the ionospheric velocity should have been larger by a factor \(\geq (5000/4) \geq 1200\) and therefore \(\geq 360 \text{ km/sec, already larger than the escape velocity of } 11 \text{ km/sec.}\)

Roughly speaking, one expects that the atmosphere above the level at which the escape velocity was reached was blown off the earth by this quake for an area \(\geq 8 \text{ km} \times 8 \text{ km.}\)

3. Estimation of the Altitude of Escape

The escape altitude may be estimated using the Riemannian invariant\(^{13,14}\) \(R\), which for the propagation of an acoustic wave is the invariant quantity

\[
du + c (dp/\rho) = 0
\]

where \(c\) is the acoustic velocity, \(u\) is the velocity of an element of the fluid, and \(\rho\) is density of the atmosphere. When the effect of gravity \(g\) is included, the invariant becomes

\[
du + c (dp/\rho) + g dt = 0
\]

where the two values of the sign correspond to velocities of propagation of the disturbance, \(u \pm c\).

This invariant has been evaluated numerically (the acoustic velocity \(c\) varies rapidly and erratically with altitude \(h\)) using measured quantities\(^{15,16,17}\) for \(\rho (h)\) and \(c (h)\) from sea-level to high altitude. At each mesh point in the numerical evaluation, \(g \Delta t\) was computed as

\[
g (1 - 2h/R_0) [u (h) + c]^{-1} \, dh
\]

where \(R_0\) is the earth's radius. Assuming \(u (0)\) small compared with the acoustic velocity at sea-level, one finds that escape velocity is reached at 400 km altitude. This may be compared with the altitude of escape of \(\sim 140 \text{ km}\) estimated from the Doppler ionosonde evidence. It is possible that the difference is caused by imprecise knowledge of variability of temperature and pressure of the ionosphere. No correction has been introduced for attenuation in the calculation from the invariant, which could cause the computed value to be so much higher than the measured value.

It is likely that the measured altitude of escape is lower because in an earthquake the "piston", namely, the surface of the earth above the epicentre, moves up and down many times per second, creating a series of waves which overtake each other and result in a disturbance of increased velocity. Consequently, we take the altitude of escape estimated from the ionosonde data to be \(\sim 150 \text{ km}\) as representing the actual phenomenon.

For estimation of mass of material lying above 150 km one may take\(^{17}\) \(\rho (150 \text{ km}) = 2 \times 10^{-13} \text{ gm/cm}^3\), with a mean molecular weight of 23 g/mole, and\(^{16}\) \(T (150 \text{ km}) = 5000 \text{K, so that } 4 \times 10^{-4} \text{ g/cm}^3\) of atmosphere are blown off.

For an earthquake of magnitude \(m\), one expects that more than \((4 \times 10^{-6} \text{ m}^2) 10^{10} \text{ g of atmosphere are blown off, because the ground wave travels radially out in all directions from the region of the quake, and continues to couple to the atmosphere} \)
producing compression waves. This coupling has been shown to be particularly effective when the phase velocity of the surface waves is equal to the speed of sound in air. Because of this coupling of the atmosphere to the radially outgoing seismic waves, the effective area of the earth is probably much bigger than the above expression would indicate. On this account we assume the geometry to be one-dimensional and make no correction for radial divergence of air waves from the quake region.

The above expression may, therefore, underestimate the amount of blow-off by earthquakes, but another factor, hard to correct for, operates in the opposite direction. This factor is that for most quakes more energy goes into shearing motion than into vertical piston-like motion, a factor which would decrease the effective blow-off.

Propagation of shocks in exponentially decreasing atmosphere has been calculated by Grover and Hardy as a function of source characteristics such as strength of initial pressure pulse and time interval during which the pressure pulse is applied to the atmosphere. The asymptotic behaviour of the shock (i.e. its slope) is found to be virtually independent of source characteristics and to become well established after 2-3 scale heights. The initial shock velocity is amplified by a factor ~ 30 (the factor of importance in the present cases is ve/c ~ 30) in ~ 10 scale heights. Although their calculations assume strong shocks, the independence of amplification on pulse strength and duration argues for similarity to this case, and the length of 10 scale heights required for amplification by 30 corresponds to ~ 100-150 km altitude above the surface of the earth where shock velocity reaches escape velocity, in rough agreement with the altitude as estimated from the Riemann invariant.

4. Mass Blow-off by Earthquakes

The number of earthquakes per year \( N \) exceeding magnitude \( m \) is given by (ref. 12b, page 69)

\[
\ln n = 30.9 - 4.01m
\]

and the number of quakes \( dN \) between \( m \) and \( (m + dm) \) by

\[
-dN = 4.01 \exp(30.9 - 4.01 m) \, dm \text{ per year.}
\]

Using as the effective area \( S \) of earthquake motion corresponding to a quake of magnitude\( m \), \( S \sim (m)^2 \) \( \text{km}^2 \), the area of earthquakes per year is given by

\[
S_{\text{tot}} = \int S \, dN = - \int 4.01 \, m^2 \exp(30.9 - 4.10 m) \, dm \\
\sim 10^{14.0} \, m^2 \, e^{-4.01 m} \, \text{km}^2/\text{y}
\]

It may be debated whether earthquakes of very small \( m \) produce shocks at the top of atmosphere and what is the lower limit of \( m \) for such shocks. For this limit we may choose \( m = 4.5 \), knowing from personal observation that quakes of this magnitude can be heard as well as felt (indicating acoustic coupling with the atmosphere), for which

\[
S_{\text{tot}} \approx 3 \times 10^{47} \text{ cm}^2/\text{y}
\]

The mass expected to be blown off the earth per year corresponding to this area is then \( 1 \times 10^{14} \) g. In the life of the earth the mass loss is \( 4.5 \times 10^{14} \) g assuming that the earthquake spectrum and rate have been constant, but we have no evidence that this is so. Assumption is further made that the pressure of the earth's atmosphere has remained constant, but again without evidence. Rather on the contrary, the earth has had eras of enhanced volcanic activity, probably correlated with enhanced quake activity, judging from the fact that on the earth's surface at the present day, volcanic regions are earthquake-prone and vice-versa with a high correlation. In such eras, rate of loss of atmosphere from earthquakes could have increased.

Over the area of the earth, \( 5.1 \times 10^{14} \text{ cm}^2 \), the loss estimated for a cut-off of \( m = 4.5 \) corresponds to \( 900 \text{ g/cm}^2 \) in the lifetime of the earth, namely, approximately all of the present day atmosphere.

5. Blow-off by Volcanic Caldera Explosions

The explosion of Krakatoa caused the climate in the northern hemisphere to be chilled for 5-10 y after by stratospheric dust; observation of solar radiation at the earth's surface showed measurable attenuation. Similarly, eruption of Mount Agung in 1963 injected dust into the stratosphere causing an increased earth albedo and a cooling trend in climate of the earth's surface. At least three other eruptions since have thrown dust and volcanic gases to stratospheric heights. In such explosions large amounts of solid particles are thrown to > 22 km altitude, as shown by measurements of scattered sunlight, and therefore, must have initial velocities \( > 7 \cdot 10^4 \text{ cm/sec} \), namely, supersonic. Taking the result of Grover and Hardy that escape velocity is reached in ~ 10 scale heights or ~ 150 km, taking the incidence of volcanic explosions as 0-25 per year (ref. 20, page 402), and assuming somewhat arbitrarily their individual areas to be ~ (2 km)\(^2\), (more than an estimated 4 km\(^3\) of dust was blown into the stratosphere from Krakatoa, ref. 20, page 438), and also assuming that such an eruption produces ~ 3 explosions per min for 24 hr (ref. 20, pp. 80-88), one finds the atmospheric mass loss per year to be ~ 1.2 \times 10^8 g. Consequently, in the lifetime of the earth the mass loss would be ~ 5 \times 10^9 or \( 10^3 \) g/cm\(^2\), assuming frequency of large volcanic eruptions to have been
constant, and the pressure of the earth's atmosphere to have been constant.

6. Atmospheric Blow-off by Meteor Impact

The mass of low speed (~20 km/sec) micrometeorite material impinging on and vaporizing in the earth's atmosphere is \(1.2 \times 10^8\) g/day. Roughly speaking, an approximately equal mass of atmosphere is knocked on by this impacting material and reaches escape velocity. Thus, in the life of the earth about 400 g/cm\(^2\) of atmosphere would have been lost assuming that the flux of meteorites has been constant. Whipple estimated a similar loss of about 1/2 atm for the great rain of meteorites which must have struck the juvenile earth (judging from the crat ered surface of the moon).

7. Atmospheric Blow-off by Lightning

Estimates are very uncertain regarding the area of a lightning bolt for which atmosphere is knocked off by shocks. Evidence of ionospheric disturbance from electrical storms should be sought in the Doppler-shifted ionosonde records. Approximate assumptions can be made to obtain an approximate estimate; supposing each lightning stroke has an effective radius 1 m and length 1 km, and supposing 100 bolts per storm and 100 storms per day around the earth, one finds ~10 g/cm\(^2\) of atmosphere blown off in the lifetime of the earth.

8. Significance of Fractionations of Atmospheric Components

The fractionation factors of C, N, and O are (defining the fractionation factor as the cosmic abundance ratio of each element to silicon divided by the terrestrial ratio for that element) \(5 \times 10^{-5}\), \(9 \times 10^{-6}\) and \(3 \times 10^{-4}\), where their cosmic abundances are respectively \(1, 1\), and \(1\). That is, oxygen was lost much less than C and N from the secondary atmosphere. The time that this loss occurred may have been very early in the life of the earth, because most of the \(^{40}\)Ar from potassium decay, some 10% is still in the atmosphere today; that is, an earth of chondritic composition, in \(4.5 \times 10^9\) y, generates ten times the amount of \(^{40}\)Ar present in today's atmosphere, so that it must have been accumulating without much escape for most of 4 billion years, which then would seem to be the age of the present-day atmosphere. The implication is that the present rate and spectrum of earthquakes and volcanoes and incident meteorites have not been significantly different during this time and have not caused much loss.

But, of course, outgassing of argon may be very slow from the earth's interior, viz., perhaps, 10% has come out in \(4.5 \times 10^9\) y and the half-life to come out may be \(\sim 2 \times 10^{10}\) yr. Or, perhaps, outgassing has been rapid and some 90% of argon has been lost by loss of atmosphere. In either of these cases, no conclusion can be made about age of the present atmosphere.

But to account for the difference in fractionation between oxygen on the one hand and C and N on the other, there could have been cataclysmic processes after the secondary atmosphere was evolved which blew some atmosphere off the earth, and oxygen could have been much less in gaseous form than were C and N, and this can be the case in a reducing atmosphere, i.e., CH\(_4\), NH\(_3\), and H\(_2\)O where the water is already largely condensed, and its partial pressure is \(\sim 1\%\).

The picture that suggests itself is that after a secondary, reducing atmosphere had evolved and after the earth's surface had reached a temperature low enough to condense water, the earth was either seismically very active or subjected to meteorite bombardment or both, and most of the secondary atmosphere was blown off by the shock mechanism described above.

The estimated blow-off by earthquakes of \(\sim 1\) atm and by meteorites of \(\sim 2.5\) atm, are amounts sufficiently large as to suggest that indeed significant amounts of atmosphere may have been lost in the past, i.e., that the history of the atmosphere has not been that of slow, steady accretion. The amounts of volatiles being evolved today from volcanoes suggest much the same story when compared to the total amounts present on the earth's surface, namely, that gaseous nitrogen has been lost in considerable amounts relative to liquid water. Specifically, among the total volatiles today on the earth's surface, according to Rubey (ref. 27, page 9) are \(2.92 \times 10^4\) g H\(_2\)O/cm\(^2\) and \(7.8 \times 10^3\) g N/cm\(^2\) in the ratio \([\text{H}_2\text{O}]/[\text{N}]=370\) while in volcanic gases (Rubey, ref. 27 page 43), the ratio is \(\sim 10\). If volcanic gases had supplied all surface water, there should be \(2.92 \times 10^4\) g (N, C) per cm\(^2\) or 29 atm, and hence 28 atm could have been blown off by shocks.

If the amount of the earth's atmosphere (nitrogen and oxygen) has varied by large excursions in the past, then there may be other tests of this hypothesis to be sought out in the stratigraphy and structure of the continents.


Some of the atmosphere being continually blown off by shocks will be ionized on the way out from the earth and trapped in the magnetosphere. Using esti-
mates of MacDonald\(^2\) that a particle must spend about a week in the magnetosphere before becoming ionized, one finds a probability of about $10^{-3}$ for a particle of escape velocity to ionize while traversing the magnetosphere of ~ 10 earth radii. Assuming a residence time of ~ 1 week for a particle to remain ionized, one finds the average density of ionized air in the entire magnetosphere to be ~ 10 atoms/cm\(^3\) and the flux of ionized particles of escape velocity to be ~ $10^{7}$ cm\(^2\)/sec, averaged for the entire magnetosphere, including protons and ionized helium as well as C\(^+\), N\(^+\) and O\(^+\). These have, of course, energies only slightly above thermal\(^19\),\(^20\) initially, but may undergo local acceleration after ionization and trapping.

By the same mechanism of blow-off by atmospheric shock, hydrogen in the top of the atmosphere will be blown through the magnetosphere, and again about 1 % will become ionized and remain trapped. Taking the number fraction of hydrogen at escape altitude to be $10^{-7}$ (MacDonald, ref. 30, page 150), as being blown off, and to become ionized with probability~10\(^{-3}\), yields a flux of ~10 protons/cm\(^2\) sec averaged over the entire magnetosphere.

Local acceleration may increase the velocity and therefore the flux by factors as much as ~10\(^4\), to an average flux over the entire magnetosphere (of ~ 10 earth radii) of ~ $10^4$ proton/cm\(^2\) sec, more than sufficient to account for the observations of Van Allen et al.\(^21\) of average proton fluxes of ~0·1 proton/cm\(^2\) sec of energies 3·4—74 Mev.

The hypothesis that decay of albedo-neutrons created in the atmosphere produces the high-energy protons in the Van Allen Belt, has been unable to account quantitatively for the observed fluxes, and as an additional source, injection of solar neutrons has been hypothesized to make up the deficiency.\(^22\)

The present mechanism of population of the Van Allen Belt by atmospheric blow-off should likewise be considered, taking into account local acceleration in the magnetosphere as well as shock acceleration beyond escape velocity to bring protons to the observed high energies > 20 MeV.

10. Loss of Terrestrial Atmosphere by Solar Wind

The earth's magnetic field is thought to reverse every 100 million years or so, but the magnetic field vector is thought to swing around in such reversals without vanishing in magnitude. If it did go to zero, the solar wind, presently shielded from the earth by the magnetosphere, would come in and strike the earth's atmosphere. A rough estimate indicates that in a million years of zero magnetic field, the earth's atmosphere could be blown off by the present flux of solar wind, ~ $10^8$ protons/cm\(^2\) sec at 10\(^7\) cm/sec velocity. If geological evidence should be found indicating the possibility that the earth's atmosphere has been nil at past times of the order of millions of years ago, possible loss of magnetic field of the earth would have to be seriously considered. This new mechanism seems amply able to explain the observed fluxes of protons and C, N and O.

11. Possible Production of Rain by Earthquake Blow-off

The quake in northern Italy of Richter 6-5 to 6-9 and the quake in western Uzbekistan of Richter 7-2 in May 1976 were both followed by widespread torrential rainstorms. The dust blown off the earth's surface by these powerful quakes may well have nucleated condensation of atmospheric moisture, over large volumes of the atmosphere, thus causing the terrible storms. In each case there were damage and casualties from mud and rock slides.

References

2. Suess H, J. Geol., 51 (1949), 609.
The Riemann invariant is obtained from the convection equation and the equation of motion including gravity

\[ \frac{1}{\rho c} \frac{Dp}{Dt} + c \frac{\partial u}{\partial x} = \frac{1}{\rho c} \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} \]

and from it only slightly.

\[ Dp/DT = 1/c^2 \] 

\[ \frac{\partial}{\partial t} + \nabla \cdot u = 0 \]

and the equation of motion including gravity

\[ \frac{Du}{Dt} + \rho \frac{\partial u}{\partial x} + g = 0 \]

Adding Eqs. (5) and (6) one obtains Eq. (7) and subtracting Eq. (5) from Eq. (6) yields Eq. (8), as follows:

\[ \frac{\partial u}{\partial t} + (u + c) \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial \rho}{\partial x} + g = 0 \]

These equations represent disturbances propagating with velocities \( \pm (u + c) \) and can be written in the differential form:

\[ du \pm \frac{1}{\rho c} dp + g dt = 0 \]

The Riemann invariant is obtained from the continuity equation

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \nabla u = 0 \]

and the equation of motion including gravity

\[ \frac{Du}{Dt} + \rho \frac{\partial u}{\partial x} + g = 0 \]

where \( c \) is the speed of sound. Substituting Eq. (4) into Eq. (3) and multiplying by \( c/\rho \), one finds

\[ \frac{1}{\rho c} \frac{Dp}{Dt} + c \frac{\partial u}{\partial x} = \frac{1}{\rho c} \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} \]

or in the integral form, called the Riemann invariant:

\[ R = u \pm \int \frac{dp}{\rho c} + \int g \, dt \]

In using the integrated form, the integration must be stopped short of the pressure at which the mean free path approaches the magnitude of scale height. At 170 km altitude the mean free path is still small compared with scale height. Secondly, attenuation must be unimportant so that \( DS/DT \sim 0 \).

Attenuation of the pressure pulse and the shock wave in the atmosphere may be neglected from causes other than geometric. This is justifiable considering that Fehr has estimated attenuation of infrasound \( \sim 10 \) sec period) as less than \( 2 \times 10^{-9} \) db/km in the lower atmosphere, increasing to \( \sim 2 \times 10^{-9} \) db/km where the pressure has decreased to \( 10^{-6} \) atm, which extrapolates linearly to \( 2 \) db/km at \( 10^{-6} \) atm (or 170 km) (ref. 34). Thus by ending integration at 170 km we are still in the regime of weak shock, stopping short of the regions where changes in \( \Delta S \) become of major importance.

In a weak shock wave the entropy increase is a small quantity of third order with respect to the differences \( p_1 - p_0 \) or \( V_1 - V_0 \) which characterize the strength of the wave (ref. 14, pp. 64-67), and the appropriate equations are essentially those of a perfect gas, provided additionally that \( (\partial p/\partial V)_S \) be positive, i.e. the Hugoniot lies above the isentrope, but differs from it only slightly.