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LOS ALAMOS SCIENTIFIC LABORATORY
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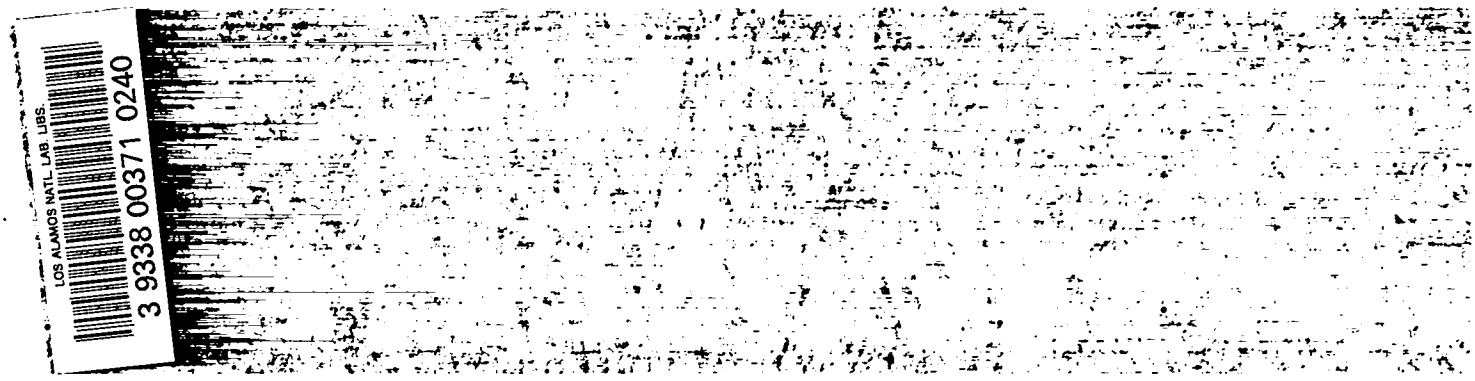

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ARTIFICIAL AURORA AND UPPER ATMOSPHERIC SHOCK PRODUCED BY TEAK*

by

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ABSTRACT

The northern branch of the artificial aurora and the features of the upper atmospheric shock produced by shot Teak exploded at 252,000 ft above Johnston Island are described and analyzed.

The correlation between the brightness-time history of the aurora and the decay of fission products is qualitatively good and a rather high conversion efficiency (~10%) for light emission is indicated. A pronounced slowing down of the upper shock was observed, which was caused by work against the geomagnetic field. The deep red appearance of this shock is believed to be due to excitation of the red auroral oxygen lines. The correlation between observed shock brightness and the light emission calculated on the basis of the computed shock temperature is discussed. The surprisingly high magnitude of the observed brightness of the front at plus 500 km is probably the result of interaction of the shock front with the compressed geomagnetic field.

It is evident that various geo-astrophysical phenomena can be simulated and explored by the release of known amounts of nuclear energy in space.

INTRODUCTION

During the Johnston Island phase of Operation Hardtack, two thermonuclear devices in the megaton yield range were exploded at high altitudes. Teak was fired at an altitude of 252,000 ft during the night of July 31, local time, and Orange was exploded the night of August 11 at an altitude of 141,000 ft. After Teak shot (and to a lesser extent after Orange) numerous local and world wide geophysical phenomena were observed. Two of these, the artificial aurora produced by fission betas and the propagation of the shock wave in the upper atmosphere will be described here. The observations were so interesting and spectacular that the usefulness of such energy sources for the study of natural geophysical and astrophysical phenomena appears evident.

THE TEAK AURORA

Within less than one second after the explosion a brilliant, purple colored auroral streamer emerged from the fireball in a northerly direction. The display was many kilometers wide and extended, with decreasing intensity, to a distance of the order of magnitude of 100 km. The axis of the streamer followed closely the earth's magnetic field at Johnston Island pointing 12° east of geographic north, and 30° down from the horizontal. After 5 sec, while the fireball and the bomb debris were rising, a second streamer started to emerge at the apparent origin of the first, becoming gradually longer and brighter. The two streamers together presented the appearance of a horseshoe, its

two parallel legs pointing away from the fireball in the direction of geomagnetic north. The upper leg of the horseshoe became gradually brighter relative to the lower. The flat plane of the horseshoe was inclined 40° to the vertical with the upper branch to the west; at late times, say plus 1 min, the shape of the configuration became indeterminate and the light faded. Figure 1 is a sequence of six pictures showing both the development of the aurora and of the rapidly rising fireball. The pictures were taken for the Department of Defense by Edgerton, Germeshausen and Grier (EGG) personnel from an aircraft flying approximately 80 miles NW from the burst at an altitude of 30,500 ft. Besides the horseshoe, one notices the doughnut shaped core of the fireball which is the site of the fission products and bomb debris.

While the general features of the aurora are rather clear cut, it is an interesting task to explain the time dependence of the formation of the horseshoe, the well defined bend and the orientation of the apparent "plane", i.e., the development first of the lower eastern leg and later of the higher western leg. The explanation must be consistent with the length and essentially parallel direction of both legs.

While many models have been proposed and discussed, it suffices here to state that the observed shape is primarily due to the transition from the early (1-5 sec) energy deposition in the mechanically still undisturbed lower atmosphere to the subsequent deposition in the higher, shock disturbed space. At the later times, when the

source of the fission betas has risen, it is the location of the radially expanding shock wave which delineates the areas of maximum energy deposition and brightness. In addition magnetic field distortions at the fireball edge contribute to the enhancement of the shape; also the relatively long lifetime of N_2^+ and resonance radiation in N_2^+ excited by fireball light and afterglow from longlived excited states of air constituents play a role. It is intended to discuss pertinent details elsewhere.

Of further interest is the brightness time history of the aurora. Histories of beta activity after fission are given by Way and Wigner[1] and by Present.[2] They are plotted in Figure 2 together with the photographically observed peak brightness of the aurora. The correlation is quite evident. The beta energy from fission products is also known, although less well; it ranges from 1 to 10 Mev during the time of interest. At plus 1 sec the disintegration rate feeding the northern branch of the aurora is of the order of magnitude of 10^{25} Mev betas/sec. Taking the precise auroral dimensions, the air density at the brightest spot and assuming a mean injection pitch angle of 30°, one arrives at a conversion efficiency of 10% for the photographically active emission (energy out over energy deposited). This efficiency is quite high and it appears that factors such as heating of the air, resonance radiation and, possibly, increased energy deposition in the shock compressed air at the location of

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[1] K. W. Way and E. T. Wigner, Phys. Rev. 73, 1318, (1948)

[2] R. D. Present, Phys. Rev. 72, 7, (1947)

the horseshoe bend and mirroring of particles contribute to the high brightness. In any case the injection efficiency of beta particles into the streamer must have been close to 100%.

The southern branch of the aurora was dimly visible from Johnston Island and clearly visible from the top of Mount Haleakala on Maui Island, Hawaii . See Frame 3 of Figure 3. The color was distinctly red, the wide arc pointing toward the burst location. Evidently at the altitude of the arc, >100 km, the light originated mainly from the 6300Å "forbidden" auroral oxygen line. This branch is responsible for the auroral display which was observed in the geomagnetically conjugate area near Apia in the Fiji Islands.[3]

No spectroscopic observations were made on the Teak aurora. All the spectroscopic equipment in the area was pointed at the fireball. However, a spectrogram was taken on Orange shot, after the fission products had risen toward the altitude of occurrence of natural aurorae. The spectrum was rich in N_2 second positive group, and N_2^+ first negative emission and resembled low altitude natural auroral spectra.

SHOCK PROPAGATION IN THE UPPER ATMOSPHERE

The behavior of the heated and shocked air in the immediate neighborhood of the Teak burst location was very much in line with expectation. To our knowledge no predictions were made as to the

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[3] A. L. Cullington, Nature 182, 1365 (1958) and H. Elliot and J. J. Quenby, Nature 183, 810 (1959)

expected shock propagation to large distances. Observers stationed near the Smithsonian Observatory on Maui Island at an altitude of about 9,000 ft, 1400 km from Johnston Island, noticed the very bright flash at shot time, originating from a spot below the horizon (the horizontal line of sight from Maui to the Johnston Island vertical intersects 113 km above Johnston). A series of pictures taken by John Champeny of Edgerton, Germeshausen and Grier at the Maui Observatory illustrates the subsequent development of the fireball (Figures 3 and 4). At plus 30 sec (Figure 3, upper right) a bright red hemispherical fireball had risen far above the horizon; it was followed by the appearance of the smaller slower rising "doughnut" or "smoke ring", the site of the bomb debris and fission products. The red shock wave expanded rapidly and at about plus 2 min (Fig 4, upper left) filled the field of view of the 50 mm focal length 35 mm camera. Champeny's pictures were analyzed photometrically at LASL.

At an altitude of 300 km, the shock velocity in the upward direction is 7.5 km/sec and the photographically observed surface brightness 5×10^{-7} watts/cm^2 ster in the red and 5×10^{-8} watts/cm^2 ster in the green. At an altitude of 500 km the apparent shock velocity has decreased to 3 km/sec and the observed surface brightness is now 8×10^{-8} watts/cm^2 ster in the red and 9×10^{-9} watts/cm^2 ster in the green. The red to green brightness ratio is 10:1.

While great care was exercised in the reduction of these data, one can not claim high accuracy. First, the edge of the shock front

is not very sharp in the pictures (nor can one expect a truly sharp front at these low air densities); second, it is not certain whether one really sees the front or, rather the somewhat slower radial mass motion; third, the error in timing might be appreciable, though not large; and fourth, the photometric brightness analysis of the film was not based on simultaneous development of the photometric calibration strip. Hence the errors might be rather appreciable, particularly for the higher altitude.

Nevertheless, on analyzing the data one encounters several interesting phenomena, which are of such magnitude that they cannot be explained by inaccuracies in data reduction.

a. Velocity of the Vertical Shock: Assuming pure hydrodynamic motion into an atmosphere of rapidly decreasing density and pressure, one would expect the upward shock velocity to increase. This was already pointed out by H. A. Bethe before the event. Using recent upper air density data, the increase should be twofold, while going from 300 km to 500 km. In reality the observed apparent shock velocity at 500 km is only 2/5 of that at 300 km. The hydrodynamic energy content (yield) of the upper sector of the 500 km fireball is very much smaller than of the 300 km fireball. Indeed the energy difference is of the same order of magnitude as the magnetic energy content of the space between the two radii. Thus T. Gold's suggestion that the energy is lost to the geomagnetic field seems to be supported. In fact it is above 300 km that the magnetic pressure becomes stronger

than the particle pressure. H. Kranzer elaborated on the interaction between the magnetic field and motion of the conducting fluid still further, suggesting that a convex plasma surface in contact with a magnetic field in a medium of lower density would lead to instabilities similar to Taylor instabilities. By means of these instabilities field lines which were originally outside the sphere can get inside. In this process an Alfvén wave will be produced and will carry off some of the original shock energy. It is further conceivable that these Alfvén waves, generated at the upper surface of the red sphere, could travel north and south to great distances and thus be responsible for much of the prompt and widespread radio interferences which occurred at shot time.

b. Brightness of the Shock: At 300 km and above one can assume that virtually all the significant mass density is due to atomic oxygen and that the observed red light is mainly emitted in the auroral oxygen lines at 6300Å and 6364Å after collisions of oxygen atoms with electrons. For the calculation of the lower limit of brightness one must take the normal night time electron density and a mean electron temperature equal to the shock temperature derived from the observed shock velocity. J. W. Chamberlain suggested to consider as the upper limit for the brightness the emission from oxygen in equilibrium, with the computed shock front temperature.

Applying strong shock theory one computes for the shocked gas a temperature of 2 ev at 300 km and 0.4 ev at 500 km. At the lower

altitude the shocked air approaches temperature equilibrium within a second or so. At 500 km only partial equilibrium is established immediately behind the shock, considering hydrodynamics only. Thus the total emission rate at one second after passage of the shock is for the case of non-equilibrium:

$$4\pi B = \alpha_{12}\, N_{(e)}\, N_{(0)}\, h\nu'\, (\rho/\rho_o)^2 LA$$

for equilibrium:

$$4\pi B = N_{(0)}\, \tilde{\omega}_2/\tilde{\omega}_1\, e^{-\frac{h\nu}{kT}}\, h\nu'((\rho/\rho_o)\quad LA$$

where

B = surface brightness in ergs/sec cm^2 ster

α_{12} = activation coefficient;[4]

$N_{(e)}$ = 2×10^5, electron density

$N_{(0)}$ = number of oxygen atoms per cc, 2×10^9 at 300 km, 10^8 at 500 km [5]

$h\nu'$ = photon energy in ergs

ρ = density behind shock

ρ_o = ambient density

L = 100 km, approximate optical path

A = 10^{-2} Einstein coefficient

$\tilde{\omega}_2/\tilde{\omega}_1$ = 5/9, statistical weight ratio

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[4] M. J. Seaton, J. Atm. and Terr. Phys. 4, 295 (1954)

[5] H. K. Kallmann, J. Geophys. Res. 64, 615 (1959)

The above numbers yield brightness values shown below together with the photographically observed values.

Altitude km	Brightness, watts/cm^2 ster		
	Non Equilibrium	Observed	Equilibrium
300	4×10^{-8}	5×10^{-7}	5×10^{-6}
500	3×10^{-11}	8×10^{-8}	5×10^{-9}

It is very interesting to note that the observed brightness at 300 km is bracketed by the two extreme computed brightness values; i.e., considering the circumstances, the observations are of the right order of magnitude. However, at 500 km the observed brightness is about 1,000 times the non-equilibrium brightness and even higher than the computed equilibrium brightness. Now, while it is understandable that the non-equilibrium case gives low values, it is not immediately obvious how complete temperature equilibrium could have been established during the period of photographic exposure. Thus one has to search for additional energy sources.

1. It is quite possible that the photographic observations do not delineate the shock front but rather the bulk of the outward flowing air. Material velocity is slower than shock velocity and consequently the computed temperatures would be too low by as much as factor five or more. 2. While the initial energy deposition by x-rays in the upward direction is small, there is a greater

contribution from the U.V. radiation emitted by the hot fireball; this contribution has not been calculated yet and though also small might not be negligible. Thus the ambient temperature at time of shock arrival could have been higher than the assumed temperature of ~2000° K. 3. It is conceivable, and in fact very likely, that the hydromagnetic instabilities which may carry off some of the missing shock energy produce enough turbulence and localized electric fields to yield additional excitation energy.

SCIENTIFIC APPLICATIONS

The geophysical phenomena described in the preceding pages are not the only ones observed after the Teak event. Extensive world-wide geomagnetic disturbances and long range communication interferences were reported in the literature.[6,7,8] Also the results of the subsequent Argus experiments are well known. It is therefore, evident that the release of energies of known composition in the upper atmosphere or in space can contribute substantially to our knowledge of the mechanisms of energy propagation in these regions.

The source characteristics exhibit similarities with natural sources. A nominal one megaton bomb exploded in near vacuum releases more than 50% of its energy in a thermal radiation pulse of about 1 microsecond duration, most of it at temperatures higher than 1 Kev;

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[6] S. Matsushita, J. Geophys. Res. 64, 1149 (1959)

[7] Obayashi, Coroniti and Pierce, Nature 183, 1476 (1959)

[8] N. B. S. Technical News Bulletin, 43, 121 (1959)

this energy is emitted in form of x-rays. The prompt neutron and gamma ray fluxes are of the order of magnitude of 10^{26} Mev neutrons and gammas each. The bomb material is expanding at a velocity of about 10^{8} cm/sec; the surface layers are moving somewhat faster and, given an iron atom, the kinetic energy at the surface would approach 2 Mev.[9] Finally, as we have seen, the release of fission product beta and gamma radiation is well known as function of time; at the end of the first minute, the total number of disintegrations transpired is roughly 10^{26}, giving an average of 1 Mev beta and 1 Mev gamma radiation per disintegration.

One sees that the explosion of such a source, producing photons and particles of widely varying energies and velocities, can simulate many phases of natural auroral phenomena. Some of these aspects have been discussed recently by Argo, Hoerlin, Longmire, Petschek and Skumanich.[9]

For example, one may be able to arrive at a better understanding of the long delay between the occurrence of the original solar event and the arrival of the auroral particles. Many theories have been proposed, such as those advanced by T. Gold[10] and E. N. Parker.[11] Gold's concept of particles moving through space together with magnetic

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9 Argo, Hoerlin, Longmire, Petschek and Skumanich, "Nuclear Explosions in Space for Scientific Purposes," Second Plowshare Symposium, San Francisco, May 13-15, 1959.

10 T. Gold, Nature, 183, 355 (1959)

11 E. N. Parker, Phys. of Fluids, 1, 171 (1958)

fields could be put to test. While solar gas masses are believed to shoot out from regions in the sun where the magnetic fields are strong, the man-made nuclear source could be born in the absence of strong magnetic fields by exploding in interplanetary space, let us say near the outer edge of the magnetosphere of the earth. One would be curious to learn the degree of guidance provided by the initially weak field for the various types of source particles. Most interesting would be the observation of their subsequent interaction with the geomagnetic field and their effects on the radiation belts. One would try to observe the formation and propagation of Alfvén waves and, finally, the collisions of the particles with the upper atmosphere.

ACKNOWLEDGEMENT

The reduction and analysis of many of the data discussed was done jointly by several LASL staff members. Franz Jahoda and Michael Cohen (LASL Consultant) contributed significantly to the analysis of the aurora; Andrew Skumanich and George Lamb took active part in the analysis of the upper atmospheric shock phenomena and Walter Gould did the major part of the photometric data reduction. Contributions by participants in the SANE Meeting were incorporated into the text.

Figure 1. Late phases of Teak fireball and formation of northern branch of aurora as viewed from aircraft flying NW of explosion. Horizontal diameter of fireball at +3.5 sec was ~30 km. (Photos by EGG under contract with DOD.)

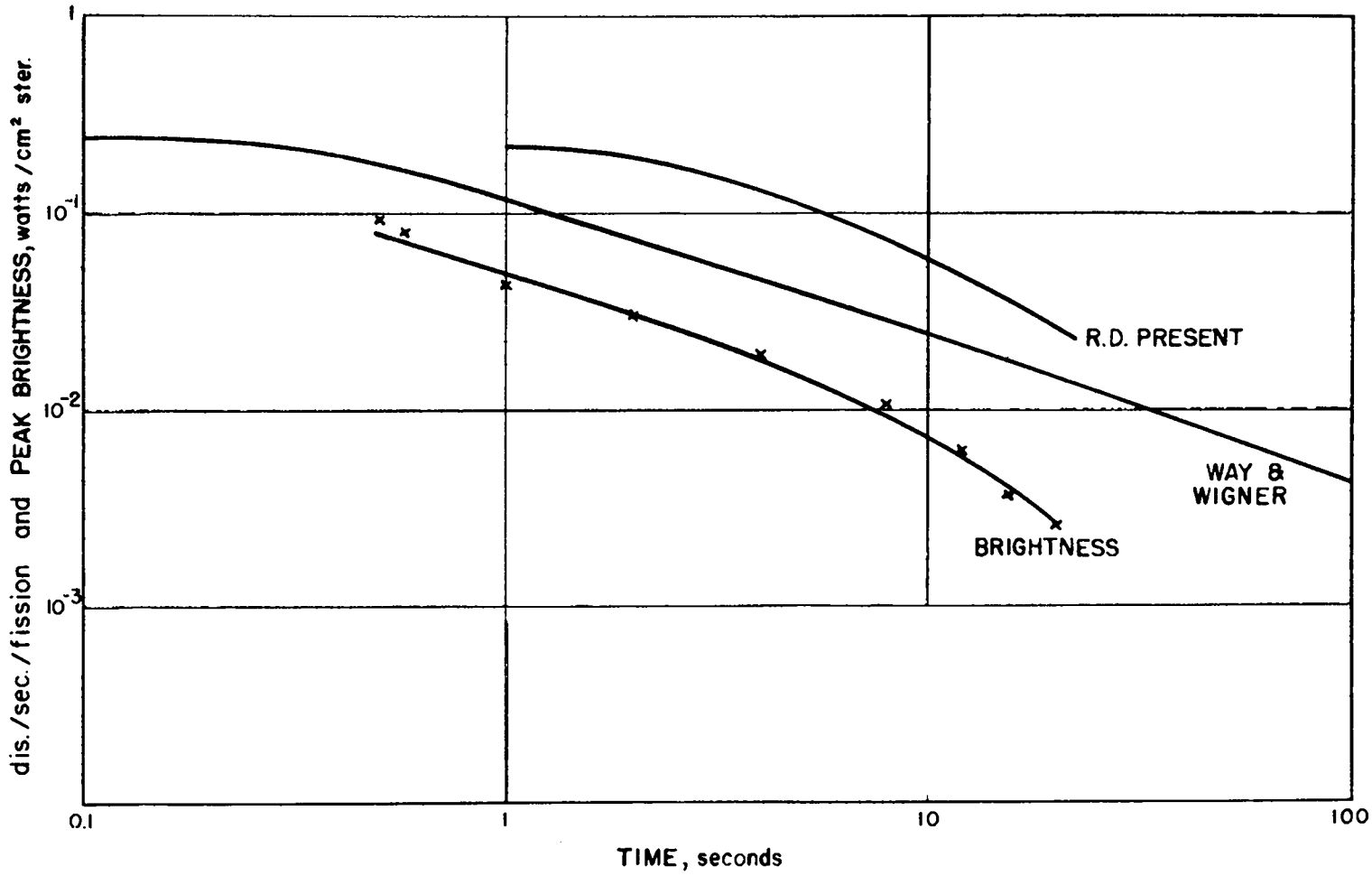

Figure 2. Peak Brightness of Aurora and Fission Decay Versus Time

Figure 3. Early development of the upper atmospheric shock as seen from Haleakala (~9000 ft above sea level) on Maui Island. (Photos by EGG under contract with DOD)

Figure 4. Late development of upper atmospheric shock and location of bomb debris, as seen from Haleakala. (Photos by EGG under contract with DOD).