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THE SOURCES OF EARLY TELLER LIGHT*

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ABSTRACT

A semiquantitative description is given of what may be expected to give rise to the early Teller light. Several possible sources are considered, namely, band emission from excited molecules and continua due to recombination, bremsstrahlung, and Cerenkov radiation. It is shown that the band emission is strongly predominant.

INTRODUCTION

The gamma radiation from a bomb causes the air to glow brightly at considerable distances from the bomb. This phenomenon is well known by the name "Teller light." The glow is known to begin immediately (well within a shake) after gamma irradiation of the air, and has an apparent brightness of the order of that of the sun. Almost nothing is known quantitatively about the mechanisms involved in the air emission, but it is reasonable to assume that Compton electrons are primarily responsible. A few conceivable mechanisms are considered in this paper.

Assuming all sources are generated by the gamma-rays via Compton events, several things occur immediately following the ejection of a molecular electron by a gamma-ray. The Compton electron itself emits a visible light continuum through the bremsstrahlung and Cerenkov radiation processes in the air (the latter occurring for electron energies above 20 Mev). The Compton electron also ionizes and excites the air molecules, but in the Mev region this effect is relatively inefficient so that other processes, such as the Auger effect, contribute in producing ionizations and excitations at very early times, i.e., well within a shake. After several shakes, the primary Compton electron will have slowed down and begun to generate sources copiously through ionization and excitation.

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* A theoretical treatment of the time and space distribution of the air glow will be presented in a paper now being prepared by the author and J. P. Wesley.

In addition to the excitations that the primary Compton electron can produce, there are two other ways in which excitations can occur within a shake after the Compton electron is created. A molecule having a hole in its L shell can be left in the excited state of the ion. In particular, N_2 can become excited N_2^+ and emit the First Negative bands. The other possibility is that the hole occurs in the K shell, the highly probable result being the ejection of a monoenergetic Auger electron.[1] The Auger electron expends its energy, which is of the order of 400 ev for nitrogen and 500 ev for oxygen, producing excitations and ionizations, and traverses its range, which is about 10^{-3} cm, in a time of the order of 10^{-12} second, i.e., zero time for the present purposes. Excited molecules can also result from recombination of molecular ions and electrons into highly excited states, but this effect is relatively weak. This recombination also contributes to the continua.

After a time 10 to 100 shakes the streak pictures indicate very little emission, although it is known that complicated mechanisms exist which can replenish the excited states, in particular, the nitrogen afterglow, which is not well understood.

Using order-of-magnitude estimates, the relative importance of the various sources mentioned will be obtained. A mean energy of 2 Mev will be attributed to the gamma-rays (or Compton electrons).

BREMSSTRAHLUNG

The bremsstrahlung rate is given by Heitler[2] as follows.

The energy emitted per unit time, per unit electron current density incident on a single atom, and in the frequency interval $d\nu$ is

$$(20.5)(E_o)\left(\frac{Z^2 r_o^2}{137}\right)\frac{d(h\nu)}{T_o} ,$$

where E_o is the energy (including rest energy) of the incident electron, T_o is the electron kinetic energy, r_o is the classical electron radius (2.82×10^{-13} cm), and the number 20.5 has been estimated from Heitler's Fig. 14. The above expression is a cross section times an energy and gives, when multiplied by the atomic density and the electron velocity, the energy emission rate by a single Compton electron into the frequency range $d\nu$. Thus, if T_o = 2 Mev, E_o = 2.5 Mev, $d(h\nu)$ = 3 ev as the spectral interval available to detection, Z = 7, electron velocity = C, and the atomic density = 2×10^{19}, the emission rate becomes

$$\frac{(20.5)(2.5)(10^6)(49)(7.95)(10^{-26})(3)}{(137)(2)(10^6)}(2\times10^{19})(3\times10^{10})$$

$$= 1.3 \times 10^6 \text{ ev per second.}$$

If isotropic emission is assumed, the emissivity is this number divided by 4π, or 10^5 ev per second per steradian. If N_c = the density of Compton electrons, the emissivity becomes $10^5 N_c$ ev per second per cm^3 per steradian.

CERENKOV RADIATION

Cerenkov radiation can occur in air for electron energies above 20 Mev, and has the peculiar property of being sharply defined in directions of emission. The light is emitted in a cone of semi-angle θ given by

$$\cos\theta = \frac{1}{\beta\mu},$$

where $\beta = v/c$, v is the electron velocity, and μ is the index of refraction which for air at N.T.P. is 1.00029. The critical energy (E_c) is that for which $\beta\mu = 1$ and is 20 Mev for air at N.T.P. For energies considerably in excess of 20 Mev, the energy loss is independent of energy and is about 4 ev per $cm.^3$ This loss rate corresponds to 1.2×10^{11} ev per second.

The cone angle formula may be written, using $\beta \cong 1 - \frac{1}{2}\left(\frac{mc^2}{E}\right)^2$ and

$$\mu \cong 1 + \frac{1}{2}\left(\frac{mc^2}{E_c}\right)^2,$$

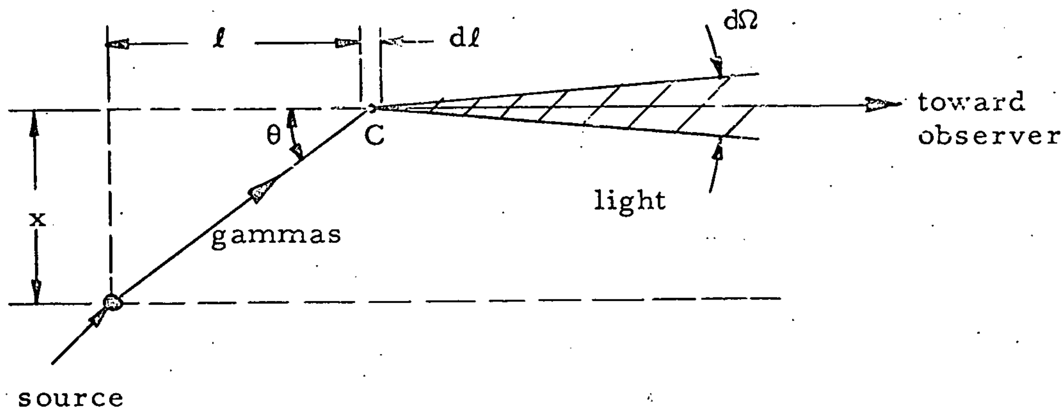
$$\theta^2 \cong \left(\frac{mc^2}{E_c}\right)^2 - \left(\frac{mc^2}{E}\right)^2,$$

giving the dependence of angle on energy. The range of θ is, therefore, as E goes from E_c to infinity,

$$0 \leq \theta < \frac{mc^2}{E_c} = \frac{1}{40}.$$

Since the gamma-ray distribution drops off rapidly with energy, the cone angles of significance are those which are << 1/40 radian. The

Compton electrons produced by gamma-rays in the vicinity of 20 Mev have, on the other hand, an angular distribution with a spread of the order of 0.1 radian about the gamma-ray direction. That is, the angular spread of the Compton electrons is greater than the spread in directions of emission from an individual Compton electron. Therefore, the Compton electrons can be considered as radiating in the forward direction only while their angular distribution governs the intensity observed, which is estimated by the following geometrical argument.



Let the remote observer receive light from points along a line-of-sight which passes within a distance x of the source. Consider a point C along the line-of-sight at which a gamma-ray from the source undergoes a Compton event. This gives rise to a Compton electron which has a probability $g(\theta)d\Omega$ of moving toward the observer and within the solid angle $d\Omega$. The light energy emitted into $d\Omega$ from a unit volume at C is proportional to the density of Compton electrons created at C with energies above 20 Mev, multiplied by the probability distribution function $gd\Omega$.

If the light emitted from unit volume at C into unit solid angle about the observer's direction is the "emissivity" j, the intensity observed will be given by the line integral (omitting retardations):

$$I = \int_0^\infty j(\ell)d\ell$$

Actually, the function g is energy dependent and integrations are required over both energies and angles, which are coupled through the conservation laws. A rigorous calculation would involve a complicated integration, the labor of which is unjustified for the present purpose.

An order of magnitude can be obtained by uncoupling the energy and angle integrations. It will be assumed that the intensity can be written approximately as

$$I_c = \int_0^\infty j\,d\ell \cong \frac{\epsilon S'}{4\pi\lambda'} \int_0^\infty \frac{d\ell\, g(\theta)}{(\ell^2+x^2)} = \frac{\epsilon S'}{4\pi x\lambda'} \int_0^{\pi/2} g(\theta)\,d\theta ,$$

where S' is the number of gamma rays of energy above 20 Mev emitted (in a short burst) by the source, λ' is the Compton mean free path for 20-Mev gamma-rays in air, g(θ) is the Compton electron angular distribution function corresponding to a 20-Mev gamma-ray, and ε is a mean Cerenkov emission rate for the Compton electrons (taken to be 1.2×10^{11} ev per second). The angle integral was evaluated roughly and has a value of about 4.

In order to make a comparison between the Cerenkov and bremsstrahlung intensities, it will be convenient to represent the bremsstrahlung effect in terms of an effective intensity observed along a line-of-sight characterized by the distance x. For 2-Mev Compton electrons the bremsstrahlung emissivity (isotropic), for one electron per cm^3, is 10^5 ev per second per cm^3 per steradian. If S is the number of gamma-rays above approximately 2 Mev emitted by the source, and λ is the 2-Mev Compton mean free path, the emissivity at a distance x is about

$$\frac{S(10^5)}{4\pi x^2\lambda} \text{ ev per second per cm}^3 \text{ per steradian.}$$

Multiplying this by x as an effective thickness gives an intensity:

$$I_b \approx \frac{S(10^5)}{4\pi x\lambda} \text{ ev per second per cm}^2 \text{ per steradian.}$$

Thus,

$$\frac{I_c}{I_b} \approx \frac{\frac{S'}{4\pi x\lambda'}(1.2 \times 10^{11})(4)}{\frac{S}{4\pi x\lambda}(10^5)} = \left(\frac{S'}{S}\right)\left(\frac{\lambda}{\lambda'}\right)(4.8 \times 10^6) .$$

Using the gamma-ray energy distribution function $N(E)dE \approx S_o E e^{-E}$ (E in Mev), we obtain

$$S' = S_o \int_{20}^\infty E e^{-E}\,dE = 21\,e^{-20} S_o \cong 4.2 \times 10^{-8} S_o$$

and

$$S = S_o \int_2^\infty E e^{-E}\,dE \cong 0.4\ S_o .$$

The ratio $\frac{\lambda}{\lambda'}$ is $\frac{(200)}{(1300)} = 0.15$.

Thus,

$$\frac{I_c}{I_b} \approx \frac{(4.2 \times 10^{-8})}{(0.4)} (0.15)(4.8 \times 10^6) = 0.075 .$$

The effect of Cerenkov radiation may, therefore, be comparable with that of bremsstrahlung in producing the continuum, since, considering the roughness of the calculation, they are not many orders of magnitude apart.

RECOMBINATION

Another contribution to the continuum at early times is made by the recombination of relatively slow (a few ev) electrons with ions. The fast Compton electrons themselves cannot participate but they produce at early times a few slow electrons in ionizing collisions with air molecules. The Auger electrons also make ionizing collisions. The electrons ejected from the molecules in the ionizing collisions will have a mean energy of only a few ev, regardless of the energy of the incident electron. The curves given by Mott and Massey[4] for atomic hydrogen show a peak energy for the ejected electrons of about 5 ev. This value will be assumed to be the right order of magnitude for the nitrogen and oxygen molecules. If these 5-ev electrons are assumed to come to thermal equilibrium instantly, the rate of recombination can be obtained using a recombination coefficient α extrapolated ($\alpha \sim v^{-1}$) from those calculated by Bates et al.[5] The value thus obtained for α is 10^{-13} cm^3/sec. There remains the task of estimating the initial density of electrons (and ions).

The number of ionizations produced in 0.1 shake by a 2-Mev Compton electron will be estimated using the cross section

$$\sigma \approx \frac{700}{2\times10^6} \frac{\ln(2\times10^6)}{\ln(700)} \sigma_o ,$$

in which σ_o is 1.2×10^{-16} cm^2, the cross section for the ionization of N_2 (or O_2) by 700-ev electrons,[6] and assuming that the cross section has the energy dependence for optically allowed transitions, i.e., $\sigma \sim \frac{\ln E}{E}$ (reference 6, p. 145). This gives a value $\sigma \approx 10^{-19}$ cm^2. Using 3×10^{19} for the molecular density and c for the electron velocity, the number of ionizations produced in 0.1 shake by a Compton electron is $3 \times 10^{19} \times 3 \times 10^{10} \times 10^{-9} \times 10^{-19} \cong 100$ ionizations.

The Auger electrons, on the other hand, will traverse their entire range in zero time and expend about 33 ev per ion pair. They can result only from inner-shell ionization in the Compton process, which occurs with a probability 2/7 for nitrogen and 1/4 for oxygen. An Auger electron from nitrogen occurs with a probability (4/5) (2/7) and can produce about $400/33 \cong 12$ ion pairs, while one from oxygen occurs with a probability (1/5) (1/4) and can produce about $500/33 \cong 15$ ion pairs. The average number of ion pairs produced by Auger electrons resulting from Compton events is therefore about 4 per Compton event. Thus, the primary Compton electrons and the Auger electrons cooperate in producing ionization at early times. For comparison purposes, the number 100 will be used for the number of unbound electrons per Compton event. If N_e is the electron (and ion) density at zero time in a plasma, the number of recombinations per second per cm^3 will be given by $N_e{}^2\alpha/(1+N_e\alpha t)^2 \cong N_e{}^2\alpha$; and if a photon of mean energy 3 ev is emitted per recombination, the emissivity will be

$$\frac{N_e{}^2(10^{-13})\,(3)}{4\pi} \text{ ev per second per cm}^3 \text{ per steradian.}$$

At a point where N_c Compton events per cm^3 have occurred, the recombination emissivity will be given, for 100 electrons per Compton event, by $2.4 \times 10^{-10}\, N_c{}^2$ ev per second per cm^3 per steradian. Dividing this number by the bremsstrahlung emissivity due to N_c Compton events per cm^3, which is $\approx 10^5\, N_c$, gives for the ratio of recombination and bremsstrahlung emissivities

$$2.4 \times 10^{-15}\, N_c\,.$$

But this number will usually be very much smaller than unity. Hence the role of recombination is minor in the production of the continuum.

BANDS

In time-resolved spectrograms, N_2 and N_2^+ bands appear prominently and occur, within the time resolution available, as early as any continuum. The early band emissivity can be estimated, therefore, if it is assumed to be proportional to the number of excitations of N_2 molecules that can be produced in, say, 0.1 shake. This number is to be divided by 1 shake, the order of magnitude of the lifetime of the upper state. Excitations can be produced in nitrogen molecules in the following ways:

1) Inelastic collisions with the primary Compton electrons.
2) Inelastic collisions with Auger electrons.
3) Direct excitation of N_2^+ through the creation of an L-shell vacancy in N_2 by a Compton event.
4) Electron-ion recombinations into highly excited states. This will be shown to be a negligible effect.

There are cross-section data available for the excitation of the N_2^+ First Negative bands by electrons of energies up to 200 ev incident on N_2. A paper by Stewart[7] gives the cross-section behavior as rising rapidly above 20 ev to its maximum value of about 10^{-17} cm^2 at about 100 ev, and subsequently dropping off slowly with increasing energy (only a 20% drop at 200 ev).

Since there are no such data available for the collisional excitation of N_2, and since N_2^+ bands are experimentally as prominent as N_2 bands, a calculation based on the excitation of N_2^+ only should give the right order of magnitude.

1) Assuming the excitation cross-section is (approximately)

$$\sigma \approx \frac{200}{2 \times 10^6} \frac{\ln(2\times 10^6)}{\ln(200)} (10^{-17}) \approx 3 \times 10^{-21} \text{ cm}^2 ,$$

(i.e., similar to the preceding ionization calculation) the number of excitations produced by the primary Compton electron in a time 0.1 shake will be given by

$$(3\times 10^{19})(3\times 10^{10})(10^{-9})(3\times 10^{-21}) \cong 3 .$$

2) The Auger electrons, however, have energies (400-500 ev) only slightly above those for which the measurements have been made. Moreover, the cross section drops off so slowly from 100 ev to 200 ev that the assumption of a constant cross section for energies up to 500 ev should not result in a gross overestimate. Therefore, the number of excitations produced by an Auger electron as it traverses its range is approximately

$$\sigma N_a R ,$$

where σ is the excitation cross section, N_a is the molecular density, and R is the range. Using $\sigma \approx 10^{-17}$ cm^2, $N_a = 3 \times 10^{19}$, and $R \approx 10^{-3}$ cm as computed from the Bethe energy-loss formula,[8] the mean number of excitations per Compton event is

$$[(4/5)(2/7) + (1/5)(1/4)]\ (10^{-17})\ (3 \times 10^{19})(10^{-3}) \approx 0.1 .$$

3) The creation of an L-shell vacancy in N_2 occurs with a probability $(4/5)(5/7) \approx 0.6$ per Compton event in air. The probability that the N_2^+ ion is left in the proper excited state is unknown, but the positions of the excited potential curves for N_2^+ suggest that it should be high. Thus, the number of excitations per Compton event due to this effect should be only slightly less than 0.6.

The total number of excitations of N_2^+ per Compton event, discounting the effect of recombination, is therefore a little under 4.

The N_2 emission, about which there exists little if any quantitative information, occurs strongly and concomitantly with the N_2^+ emission, and the number of N_2 excitations should not differ by an order of magnitude from the number of N_2^+ excitations. Hence, the number of excitations of both N_2 and N_2^+ will be (conservatively) estimated to be 5 per Compton event. Thus, if N_c is the Compton event density, the density of excitations resulting in band emission will be given by $5\ N_c$.

There remains the question of the excitations via electron-ion recombination, i.e., process (4). To conclude that this is a negligible effect, we need only to show that recombination proceeds at a rate much lower than the rate of radiative depopulation of the "initially" established excitations. The word "initial" is intended to be synonymous with "early" as used previously. Thus, if $N_e = 100\ N_c$ is the initial electron density as estimated in the section on the recombination continuum, and if $\alpha = 10^{-13}$ is the recombination coefficient, the recombination rate will be of the order of

$$N_e^2 \alpha = 10^{-9}\ N_c^2 \text{ recombinations per cm}^3 \text{ per sec.}$$

But the de-excitation rate will be, assuming an initial excitation density $5\ N_c$ and a lifetime of 10^{-8} seconds, of the order of

$$5 \times 10^8\ N_c \text{ de-excitations per cm}^3 \text{ per sec.}$$

The ratio of these is $2 \times 10^{-18} N_c$, which is expected to be very small compared with unity.

Therefore, the early band emissivity, assuming an energy 3 ev per photon, will be

$$\frac{(3)(5\times10^{8})N_c}{4\pi} \cong 10^{8} N_c \text{ ev per second per cm}^3 \text{ per steradian.}$$

SUMMARY

The early (within 0.1 shake) emissivities due to the various sources have been estimated as follows (in units ev per second per cm^3 per steradian, with N_c = the number of Compton events in air per cm^3):

Bands	: $10^8 N_c$
Bremsstrahlung and Cerenkov continua	: $10^5 N_c$
Recombination continuum	: negligible

On those spectrograms where a continuum appears (briefly), the ratio of energies in the bands and the continuum seems not inconsistent with the above.

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