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ELECTRON MULTIPLIER TUBES DEVELOPMENTS. UTILIZATION

By André LALLEMAND
Astronomer at the Observatory of Paris

Summary — Determination of the fluctuation in output current of an electron multiplier tube in terms of the number of stages and the multiplication factor of each stage, under ideal conditions. Other causes of current fluctuations are discussed along with the construction of a tube in which fluctuations are nearly eliminated. Results obtained are given as well as some ideas on the use of electron multiplier tubes: a high voltage feed. The multiplication obtained is determined if a galvanometer or amplifier is used as receiving apparatus. Use of multiplier tubes with a very stable balanced amplifier and use of a neon tube relaxation circuit are discussed.

Let us consider a photoelectric cell illuminated by a luminous flux, Φ_0. At saturation it supplies a current, $I_0 = K\Phi_0$. This current, often very weak, for example 10^{-15} amp. cannot be measured by direct methods. Amplification is necessary. Usually one uses a vacuum tube amplifier, but since this amplifier is sensitive to voltage and not to current one will change the current into a voltage drop, RI_0 across a load resistance, R. The larger the R the more advantageous the change, but with large R's certain difficulties arise: the response becomes slow and the grid current of the following amplifier tube interferes. We must therefore use special tubes called electrometric tubes. The current, I_0, is not a perfectly continuous current; it undergoes fluctuations or Shottky effect which are obviously amplified. In a fundamental manner these fluctuations limit the smallest measurable luminous flux. But there exists another source of very important disturbance in the load resistance, R, which behaves like a generator furnishing an e.m.f. of perfectly irregular character, i.e. that all the frequency components are equally probable and with the same amplitude.

If we consider the frequency interval, Δf, the mean square of the disturbing voltage or Johnson effect is:

$$\overline{E^2} = 4KTR\Delta f$$

K, Boltzmann constant: 1.380×10^{-23} W's per degree

R, the resistance in ohms

T, the absolute surrounding temperature

whereas the mean square of the current fluctuations of the photocathode is:

$$\overline{i^2} = 2eI_0\Delta f$$

$e = 1.60 \times 10^{-19}$ coulombs, charge of the electron.

It is necessary to compare the size of these two disturbances. In the load resistor the current, i, creates a difference in potential, iR, from which we obtain the relationship:

$$\gamma = \frac{\overline{i^2}R^2}{\overline{E^2}} = \frac{I_0R}{\dfrac{2KT}{e}} = \frac{I_0R}{5 \times 10^{-2}}$$

That is, the Schottky effect is equal to the Johnson effect when $\gamma = 1$, if the current furnished by the cell produces a voltage drop of 5×10^{-2} V. across the resistor.

Thus the smallest measurable flux is always masked by the Johnson effect of the input resistor.

We must therefore try to amplify the current without using any load resistance. This can be done by means of an electron multiplier.

If I_0 is the photocathode current, n the number of multipliers and δ the multiplication factor, the current furnished by the multiplier tube is

$$I = I_0\delta^n.$$

But this current is composed of fluctuations. We shall try to calculate the smallest measurable luminous flux by assuming ideal conditions where no other sources of disturbance exist other than those produced by the granular nature of electricity.

Let us proceed as follows:

1) The electronic emission arising from any multiplier follows Schottky's law

$$\overline{i^2} = 2eI_0\Delta f$$

2) The Schottky effect is multiplied by the successive stages, like any signal (all frequencies are equally amplified) so that if I_0 is the current arising from the photocathode, its fluctuation is given by:

$$\overline{i_0^2} = 2eI_0\Delta f$$

At the output of the first multiplier the current is $I_1 = \delta I_0$, its fluctuation

$$\overline{i_1^2} = 2e\delta I_0\Delta f + \delta^2(2eI_0\Delta f) = 2eI_0\Delta f(\delta + \delta^2).$$

At the n^{th} multiplier the output current fluctuation is:

$$\overline{i_n^2} = 2I_0\Delta f[\delta^n+\delta^{n+1}+\dots\delta^{2n}]$$
$$= 2I_0\Delta f\delta^n(1+\dots+\delta^n) = 2I_0\Delta f\delta^n\frac{1-\delta^{n+1}}{1-\delta}.$$

The disturbance at the input is given by:

$$\overline{i_0^2} = 2eI_0\Delta f,$$

The signal at the input is given by: x,
The disturbance at the output is given by:

$$\overline{i_a^2} = 2eI_0\Delta f\delta^n\frac{1-\delta^{n+1}}{1-\delta},$$

The signal at the output is given: $x\delta^n$,
From which:

$$\frac{\left(\frac{\text{signal}}{\text{noise}}\right)_{\text{input}}}{\left(\frac{\text{signal}}{\text{noise}}\right)_{\text{output}}} = \left(\frac{1-\delta^{n+1}}{\delta^n(1-\delta)}\right)^{\frac{1}{2}} = A.$$

This equation permits us to calculate the disturbance brought about by the multiplier system.

Let us take several numerical examples:

$\delta = 2$	$n = 1$	we find	$A = \sqrt{1.5}$
$\delta = 2$	$n = 7$	"	$A = \sqrt{2}$
$\delta = 4$	$n = 1$	"	$A = \sqrt{1.25}$
$\delta = 4$	$n = 7$	"	$A = \sqrt{1.3}$

The signal to noise ratio at the input is always larger than the signal to noise ratio at the output. A multiplier tube cannot improve the signal to noise ratio of a photosensitive layer. The larger is δ and the fewer the multiplications, the less the disturbances are. But practically speaking the supplementary disturbances produced by this manner of amplification are negligible as soon as $\delta>2$ no matter how many stages there are (under the ideal conditions which we have assumed).

The great value of the electron multiplier tube is that it makes it possible to measure very weak photoelectric currents without adding any large amount of disturbances to them. But if we are working with luminous fluxes of sufficient intensity to be able to measure these currents without amplification, or if the photoelectric current produces a drop in voltage greater than 5×10^{-2} V in the load resistance, the multiplier tube ceases to be of any value.

We shall show later, that a high multiplication cannot compensate for the weak sensitivity of the photocathode.

We have assumed ideal conditions. Unfortunately the multiplier tube possesses other sources of disturbance and the research which we have undertaken had as its aim the cancellation or reduction of these disturbances while conserving a large enough factor δ and a high total multiplication.

It is essential to have a photocathode of high efficiency, yet it is a difficult matter to produce very sensitive photocathodes. It is hardly likely that one will obtain optimum activation in the same tube for the photocathode and the multiplier target. We have thus chosen for multiplier targets a silver-magnesium alloy which can be activated separately, in part, outside the cell. When the activation is finished we can focus all our attention on the creation of the photocathode. We can thus obtain a sensitivity with a luminous source at 2500°K of 80-100 μA per lumen for the antimony-cesium cathodes. The Ag-Mg alloy possesses several advantageous properties also: it is not photoelectric and its thermal emission at ordinary temperatures is nil.

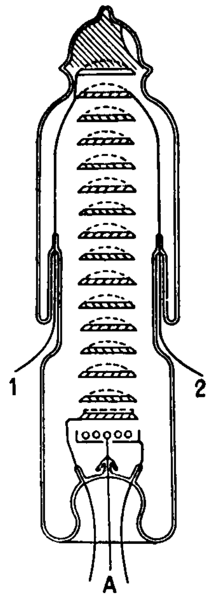

Fig. 1.

The arrangement to be used should be such that the desired paths of the electrons should be affected as little as possible by stray magnetic and electrical fields. The stray electrostatic fields which are produced in the interior of the cell are particularly disastrous and are often produced by dielectrics which are in the vicinity of the targets (wall of the cell, mica separators, glass support stems). They become charged to unknown potentials and create uncontrollable fields. We thus decided to choose a mounting in which all these insulators were eliminated (except of course the wall of the tube whose action will be minimized).

The multiplier targets are made of semi-transparent screens (Fig. 1) placed one behind the other at as small a distance as possible. Even when strongly deviated from their course, the electrons cannot miss the targets; they are focussed toward the axis by giving the targets suitable shapes like that of a basin whose curvature was determined empirically by tracing the trajectories of the electrons through fluorescence, in order to insure a sufficient concentration without losing electrons nor creating an excess charge in the center of the targets. Another advantage of this design is that the mounting need not be very precise, thereby permitting elimination of the glass or mica separators. The multiplier electrodes are mounted increasingly close together so as to augment the extraction field of the secondary electrodes. The anode is well protected by a guard ring.

We were obliged to change this device for several reasons:

1) Great difficulty in procuring suitable silver-magnesium sheets.

2) The extraction of secondary electrons was not good.

3) It was found to be difficult suitably to activate a sheet.

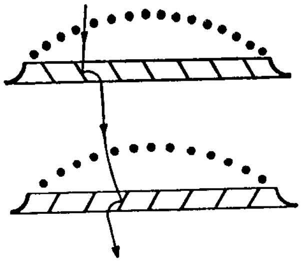

Fig. 2.

We created a mounting as shown in diagram 2. The multiplier parts are formed from parallel and inclined plates. A loose grill of fine wires permits focussing and extraction of the secondary electrons. A study of the electronic trajectories was made by the rubber membrane method.

We kept the advantages of design 1: ease of mounting, insensitivity to magnetic disturbances and omission of separators. In addition we have better extraction and more easily produced activation.

We have thus been able to make cells of 7, 12 and 18 stages.

We admitted, for the ideal case, that the non-illuminated cell supplies no current. In reality this is not the case because in the dark the cell always has a weak current known as the residual current. On it depends, when the mounting has been done correctly, the smallest measurable luminous flux. The various causes for this current have been well presented by Rajchmann. This current originates from:

1) The ionic reaction. Although the vacuum in the cell is good there are always some ions tending to rise toward the photocathode which they bombard, and thus provoke a multiplied electronic emission normally contributing to the residual current. One must prevent the ions from reaching the photocathode. In our mounting they are efficaciously stopped by the multipliers themselves.

2) The cold emission. These are the electrons which are torn away from the different electrodes by the electric field. In order to avoid it one must eliminate all unevennesses or points. The arrangement of the supports is such that the electrons torn from the edges of the electrodes cannot participate in the multiplication process. It is necessary that two conductors or two electrodes carried at two very different potentials be separated as far as possible one from the other. This we have found the best in our large 18 stage tube.

3) The current of ohmic origin. In our mounting it can only be produced in the foot of the cell. Since experience has shown that it is of superficial origin, we have lengthened the escape lines to a maximum from one electrode to another, as is done for high tension insulators. It is well to note that a multiplier tube utilizes very high voltages in relation to the weak intensities brought into play, and it is not reasonable to reduce the dimensions of the cell too much, which necessarily leads to insufficient insulators and gradient potentials which are too high and sources of parasitic emission. The last source of residual current is found in the thermic emission of the photocathode — it is linked to the extraction work of the layer, i.e. to its sensitivity limit toward the infra-red, and the antimony-cesium cells which are much less sensitive toward the red than

the cells of the type Ag-Cs^{2}O-Cs have a much smaller thermic current. We hope to develop layers of very low sensitivity to the long wavelengths of the spectrum, having a very weak thermic emission. In this case we must avoid the presence of oxygen in the layer to a high degree.

These different studies and adjustments have brought about the following results:

Antimony-cesium cell — Light source: tungsten filament lamp at 2500°K (temperature of color). Cells at room temperature (20°C.)

No. of cell	No. of stages	Sensitivity of the photocathode	Residual current at 120 V.	Multiplication at 120 V.	Lumens giving a current equal to the residual current
A 11	7	88 μ A/lumen	3.7×10^{-10}	1215	3.5×10^{-9}
B 24	7	103 "	1.5×10^{-10}	2080	6×10^{-10}
A 19	12	66 "	128×10^{-10}	100 000	3×10^{-9}
BG 1	17	67 "	30×10^{-10}	850 000	5×10^{-11}
BG 3	19	60 "	1.3×10^{-6}	3 700 000	5.8×10^{-9}
1953			1.3×10^{-8}	50,000	

Considerations as to the Use of Multiplier Tubes.

The supply voltage of the different stages constitutes an essential problem since the multiplication factor, δ, varies quickly with the voltage. If one desires coherent results a constant feed voltage is necessary. This source is the more easily realized the fewer stages the cell possesses. This is why one must limit oneself to the number of indispensable multiplier stages. The simplest source consists of a battery of the voltaic pile type. These batteries feed the multiplier directly without need of a voltage divider. One must take care to introduce a protective resistance of about 50 K Ω for each multiplier in order to avoid serious annoyance in case of short circuits. If one wants a feed taken directly from the power line one can use rectified and filtered current to feed a chain of neon lamps in series with a large stabilizing resistance. The desired voltages can be taken directly from the terminals of the lamps, this arrangement having the inconvenience that one cannot regulate the applied voltage applied to each multiplier except by steps of about 60V which represents the voltage drop in each lamp.

When the luminous flux to be measured is sufficiently intense or when the multiplier tube possesses enough stages, one can measure the current with the aid of a galvanometer. The multiplication factor which the cell must possess in order to attain the maximum sensitivity limited by the Schottky effect is interesting to calculate, for a given galvanometer. If I_0 is the current in amperes supplied by the photocathode, τ, the time constant of the circuit, usually given by the period, θ, of the galvanometer:

$$\tau = \frac{\theta}{2\pi}$$

and e the charge of the electron in colombs, then one can show that:

$$\bar{i}^2 = e \frac{I_0}{2\tau},$$

$\bar{i}^2$ being the mean square of the fluctuation of current, I_0.

The minimum current, I_0, will be the thermic current of the photocathode at ordinary temperature; its order of magnitude can be taken equal to 10^{-14} or 10^{-15} Amps. Let us take $I_0 = 10^{-15}$ Amp, $\tau = 2$s,

$$\bar{i} = 0.6 \text{ x } 10^{-17} \text{ Amp.}$$

Let us take a galvanometer whose sensitivity is 10^{-10} Amp/mm at 1 m. So that the inevitable fluctuation of the current gives a zero fluctuation of the 1 mm galvanometer, the coefficient of multiplication of the cell must be:

$$M = \frac{10^{-10}}{0.6 \text{ x } 10^{-17}} = 1.7 \times 10^{7}$$

which is quite difficult to obtain without other disturbances.

If one cools the cell the situation is even more critical.

Thus one often resorts to amplifying by tubes if one wishes to obtain all its sensitivity from the cell. Assuming this to be the case, letting R be the value of the load resistance, Δf the band width of the amplifier. The fluctuation found at the output of the multiplier is:

$$\bar{I}_f^2 = 2eI_0\Delta f M^2$$

The Johnson effect in the resistance is 4 $KTR\Delta f$ and one should obtain:

$$2eI_0\Delta f M^2 R^2 \geq 4KTR\Delta f.$$

$$M^2 \geq \frac{2KT}{e} \frac{1}{Ri} \quad \text{with} \quad \frac{2KT}{e} = 5 \times 10^{-2} \text{ Volts}$$

Let us suppose a cell at ordinary temperature to have $I_0 = 10^{-15}$ Amp. Let us take $R = 10^6 \Omega$, which produces no difficulty due to the grid current and the stability of the amplifier. We thus find

$$M \geqq 7 \times 10^3.$$

We see that in this case an amplification of 10,000 is largely sufficient. Naturally the amplifier itself must possess an amplification sufficient to make its fluctuations apparent at the output terminals of the apparatus.

If the cell can be cooled I_0 diminishes; here one would have to increase the number of multipliers of the cell.

We have tried to find what multiplication was necessary to permit the attainment of the ultimate sensitivity of the photocathode. For multiplication permitting correct measurement of the photocurrents without adding disturbances to them, let us assume I_φ the photoelectric current of the photocathode. I_Φ the current at the output of the multiplier. The signal is:

$$I_\Phi = I_\varphi \times M$$

The current of thermic origin is i; at the output it causes a residual current $I = i \times M$.

At the output we will have the following fluctuations:

$$M|2e(i+I_\varphi)\Delta f|^{\frac{1}{2}}$$

and the relationship

$$\frac{\text{signal}}{\text{noise}} = \frac{I_\varphi M}{M|2e(i+I_\varphi)\Delta f|^{\frac{1}{2}}} = \frac{I_\varphi}{|2e(i+I_\varphi)\Delta f]^{\frac{1}{2}}}.$$

M disappears as one might suppose, and we see that this ratio increases:

1) If I_φ increase, i.e. for a given luminous flux, if the sensitivity of the photocathode increases.

2) If i decreases;

3) If Δf decreases.

Thanks to the use of the silver-magnesium alloy, very sensitive photocathodes can be produced (100 μAmps per lumen and more). Moreover, this alloy furnishes multipliers which themselves do not possess any thermic emission, just as we had supposed.

i can be rendered smaller by cooling the layer. One can also make it smaller by electronic optic methods.

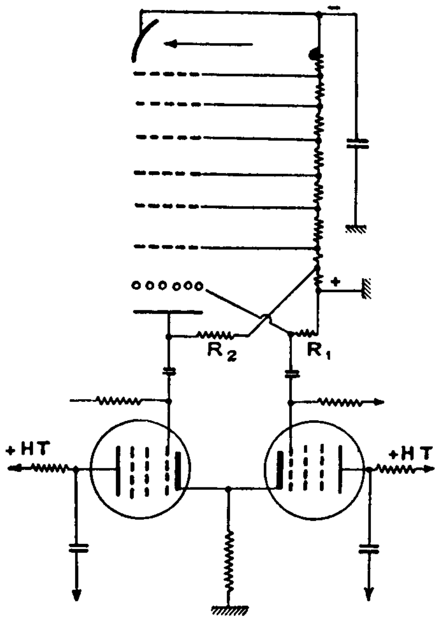

Fig. 3.

Improvement in the $\frac{\text{signal}}{\text{noise}}$ ratio can be obtained very efficiently by reducing Δf. This possibility has not yet been investigated thoroughly because it involves delicate mountings. The modulation frequency must not slip during the measurements in relation to the passing frequencies of the amplifier.

When the frequencies to be amplified are low, for example of the order of 1 cycle per second, it is difficult to create a stable amplifier. Under these conditions the multiplier tube permits the use of a balanced amplifier which is much more stable (Fig. 3). The amplifier consists of a common resistance in the cathode circuit which contributes a great deal to the stability. The application of signals of equal amplitude and 180° out of phase to the two grids is easily produced by taking one signal from the multiplier anode and the other from the last diode, the amplification, δ, of this plate being always high enough (of the order of 5). The two currents, out of phase by 180° furnish voltages of the same amplitudes in the load resistance R_1 of the anode and R_2 of the diode by taking:

$$\frac{R_2}{R_1} = \frac{\delta}{\delta - I}$$

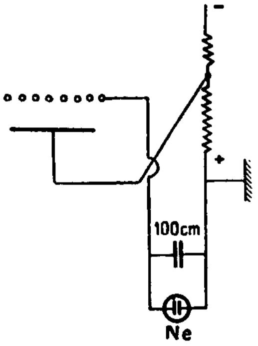

Fig. 4.

Let us note another circuit which is very simple and sensitive (Fig. 4). The output of the multiplier is applied to a condenser of small capacity (100cm), well isolated and shunted by a neon lamp. The multiplier current charges the condenser which discharges into the lamp when the illuminating voltage is reached. Thus, in a given time period, we have a certain number of flashes which are sufficient to be counted in order to have a measure of the luminous flux. This count can perhaps be made automatically by amplifying without special precautions that current which is furnished by the lamp and thereby activating a small telephonic counter. The sensitivity can be diminished by increasing the capacity of the condenser.