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## abstract

*The inter-relationship between dark current, dark count rate and photomultiplier gain is explained, using the results obtained from measurements on a relatively large sample of photomultipliers. The absolute manner in which the known sources of background contribute to the dark count and dark current parameters is examined. Practical recommendations, based on tube measurements, are given which help provide optimum performance for DC detection and photon-counting applications.*


## 1 introduction

The ultimate detectivity that can be achieved with photomultipliers is determined by two considerations. The first of these is a theoretical argument and is a direct consequence of the statistical nature of both optical radiation and the secondary emission process which provides the high gain unique to photomultipliers. Key papers by Oliver and Pike (1968), Young (1969) and Robben (1971) give the theoretical justification in favour of photon counting as the preferred method for measuring low light fluxes. The second factor is a practical one which concerns the nature of the photomultiplier background. The term background refers to the anode signal measured when the tube is in complete darkness. The dark current is the appropriate parameter where DC or narrow-band detection is under consideration, whereas, for the pulse-counting technique, the pulse height spectrum together with the integral rate of dark counts is relevant.

The basic processes contributing to background were already well known some twenty years ago from the studies of Baicker (1960), Sharpe and Stanley (1062), Young (1966, 1969) and Krall (1967). Detailed studies on particular photomultiplier types have been reported by Barton et al (1964), Gadsden (1965), Oliver and Pike (1968) and Coates (1971, 1972). These studies, by providing a better understanding of the sources of background, have undoubtedly led to the manufacture of better photomultipliers. Two aspects of background performance, of direct relevance in the use of photomultipliers, have been noted by the more critical users of photomultipliers, although not fully explored in the scientific literature. The first concerns the observation that the dark current seldom varies linearly with overall gain: a relative improvement or deterioration with increasing gain may be observed. Secondly, there is poor correlation between the dark current and dark count parameters measured in the same tube. This is particularly evident when a set of photomultipliers is graded in accordance with either dark current or dark counts – the two groups of data do not always agree.

If it is assumed that dark current is solely derived from the emission of single electrons from the photocathode, then the anode current $I$ and the total dark count $N\,s^{-1}$ would be related as follows:

$$I = Ne\langle g\rangle \qquad ...(1)$$

where e is the electronic charge <g> is the mean multiplier gain obtained from the single=electron distribution measured with the photocathode illuminated with single photons (Wright 1981). Assuming further that $N$ is independent of gain, then following Sharpe and Stanley (1962) we may use equation (1) to check on the departure from ideal performance by noting that $I/\langle g\rangle$, the effective cathode current, should remain constant as <g> is varied. However, it is known from the references already quoted that

(i) dark counts vary with applied voltage;
(ii) the dark count is not solely derived from the emission of single electrons at the cathode;
(iii) the anode current $I'$ comprises a pulsed component $i_q$ from the electron multiplication process and a direct current $I'$ from leakage within the photomultiplier.

It is shown that individual tube behaviour can always be explained in terms of these three considerations, in particular the inter-relationship between dark current, the dark count rate and the photomultiplier gain. With the exception of Barton et al (1964) and Sharpe and Stanley (1962), most investigations have been confined to the measurement of samples containing between one and three tubes only. Photomultipliers exhibit a wide variation in the nature and quality of their performance and it is therefore unwise to generalize on the basis of a very small sample. Results of measurements on thirty-two photomultipliers of various types are reported in this work for the purpose of providing a more reliable description of the range of tube behaviour.

In order to quantify the contributions from the constituents of the photomultiplier background, it was found convenient to subdivide the spectrum into four regions as describe in section 3. Three photomultipliers were selected for detailed measurement, including the effects of cooling on the background spectrum. This provided further information on the sources themselves, but more importantly, led to a better understanding of the practical limits attainable in low light level detection. The final section, by providing a better understanding of tube selection criteria, helps categorise photomultipliers suitable for photon counting and for DC detection. Practical guidance and means of optimizing the performance of a given photomultiplier conclude this study.

## 2 experimental apparatus and procedure

The term dark count has meaning only when lower and upper acceptance thresholds have been specified. Threshold levels are ideally measured in coulombs when referring to pulses but other derived quantities, such as peak voltage or current, may be appropriate depending on the details of the instrumentation. In this work there was considerable advantage in using scale with units in photoelectrons equivalent' by referring to the photocathode, results may be expressed independently of multiplier gain, g. Certain type of photomultipliers provide a peaked output pulse height distribution under single photon excitation, in which case, the peak is taken as one photoelectron equivalent. Photomultipliers with a venetian blind multiplier, for example, do not in general resolve a single electron peak and for tubes of this type is is necessary to base the scale on the man multiplier gain <g>. Fractional and multi-electron pulses arise as a consequence of the statistical nature of g. Small pulses are also produced, for example, when the point of initiation is a dynode; multi-electron pulses are generated by ion bombardment of the cathode (Barton et al 1964, Morton 1967, Coates 1973 a, b).

Measurements of pulse height spectra were made with a charge-sensitive multichannel analyzer (Tracor Northern TN 1705). The instrument was calibrated in terms of picocoulombs per channel, as described in a previous paper (Wright 1981). The contribution to the dark current from the pulses in the spectrum may be assessed from the following relationship

$$iq = \int_0^\infty n(q)q \, dq \qquad \text{...(2)}$$

where *n(q)* is the number of pulses per second with charge between *q* and *q + dq*. The calibration accuracy of the analyzer allows the conversion in (2) to be made with an uncertainty of about 5%. The multichannel analyzer was also used to measure the multiplier gain of each photomultiplier. This is not straightforward, but it has been shown that the mean multiplier gain, <g>, can be measured with an accuracy of about 10% (Wright 1981). The multichannel analyzer incorporates a preamplifier of variable gain with a maximum sensitivity of 0.025 pC per channel. Increasing the preamplifier gain to provide more than this sensitivity led to an unacceptable level of noise and hence dead-time. The lowest gain at which N could be measured was, therefore, restricted to 5 x $10^6$. The range of the analyzer was such that photomultiplier gains up to $10^8$ could be measured directly. Having measured the gain at a particular operating voltage, an extended gain-voltage calibration was then obtained using a single-photon source of fixed intensity and a Keithley Picoammeter (type 160B). The intensity of the light source as adjusted to give an anode current of ~1 μA at a voltage for which <g> was already known. The measured variation of current at a function of EHT about this voltage ws taken to be directly proportional to the variation in gain.

Measurements were made on thirty-two photomultipliers incorporating various types of multiplying structures and photocathodes. The details of the tubes tested are given in the table 1. The apparatus was arranged so that the photomultiplier output could be connected to either the multichannel analyzer or to a picoammeter by a simple switching arrangement. All photomultipliers were tested in a linear voltage divider chain, decoupled on the last three stages and with the cathode at high negative voltage. A more stable configuration is undoubtedly that with the cathode at earth potential, but the need to measure dark current favoured the use of negative high voltage. As a precaution against high variable dark counts, every tube was externally covered with a conductive coating of aqadag and maintained at cathode potential. External leakage effects were kept ot a minimum by ensuring that each tube base and socket were scrupulously clean prior to measurements. Cleaning with alcohol followed by distilled water ws adopted for this purpose.

The photomultipliers under test were stored and measured in a temperature controlled dark box (20 ± 1°C) and always allowed at least two weeks dark adaption. Ideally a tube should be run continuously until such time as the dark current stabilizes and only then should measurements be taken. The period required depends on the individual tube and can vary from a few hours to many weeks. In most instances, only an hour was allowed after application of the high voltage. While this is admittedly not ideal, it was adopted as a practical expedient because of the number to be tested.

A preliminary experiment was carried out to check the degree to which photomultipliers follow ideal behaviour stated in equation 1). The points linked by straight line segments, shown in **figure 1**, refer to the same photomultiplier operated within the gain range 5 x $10^6$ to $10^9$. An ideal tube is represented by a single point lying on the straight line of the slope e. The coding symbols refer to the lowest gain at which each tube was operation (5 x $10^6$) with the arrow indicating the path taken with increasing gain. There is no common pattern: for some tubes the arrow points towards ideal behaviour with increasing gain whilst in other the reverse is true. The 9798 type photomultiplier conforms best to ideal performance because the low work function of the S20 photocathode provides copious thermionic emission at room temperature, and for tubes of this type the assumptions implicit in equation 1) are not unreasonable. For the majority of tubes, however, equation 1) is a gross oversimplification of real photomultiplier behaviour.

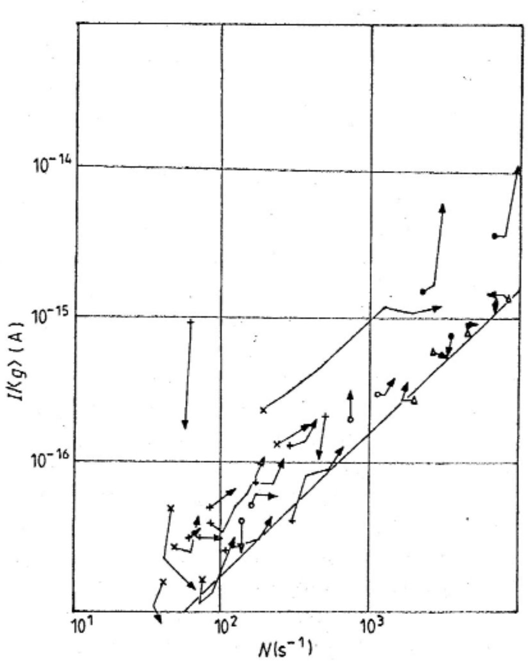


**figure 1** the equivalent cathode current, I<g>, measured over a range of multiplier gains from 5 x $10^6$ to $10^9$. Data points linked by straight line segments refer to the same photomultiplier. *N* is the integral number of background pulses of amplitude between 0.2 and 10 photoelectrons equivalent. The method of gain assignment <g> is described in section 2. ∆, 9798; ●, 9811; x, 9813; +, 9814; ○, 9954.

**table 1** summary of the photomultipliers tested

| Type | Number Tested | Cathode Type | Diameter (in) | Multiplier Stages | V(k-$d_1$) |
|---|---|---|---|---|---|
| 9814 | 8 | Bialkali | 2 | LF 12 | 300 |
| 9813 | 5 | Bialkali | 2 | LF 14 | 300 |
| 9811 | 4 | S11 | 2 | LF 12 | 300 |
| 9954 | 6 | RbCs | 2 | LF 12 | 300 |
| 9798 | 4 | S20 | 1 | BG11 | 150 |
| 9635 | 5 | Bialkali | 2 | VB13 | 150 |

LF, linear focus; BG, box and grid; VB, venetian blind

## 3 sources of background

Pulse height distributions were recorded for twelve photomultipliers, a representative selection of which are shown in **figure 2**. For convenience, four pulse height regions have been defined: A<0.5, 0.5<B<2, 2<C<15 and D>15 photoelectrons equivalent. Each tube was measured over a range of applied voltages to check how the spectral content of the background varied with gain. In general, dark counts increase with gain for most photomultipliers, as previously observed by Coates (1972), for example. This is particularly noticeable in regions A and B, and to a minor extent in region C, whereas the counts in region D are independent of gain. In contrast, the pulse height distribution for single photon excitation does not change significantly with gain as can be seen by comparing **figure 3b** with **3a**.

Small amplitude pulses (region A) occur in the signal and in the background spectra. A proportion of these can therefore be accounted for in terms of the statistical nature of the photomultiplier gain. Sharpe and Stanley (1962) have shown that the side walls between the window and the first dynode contribute to the background. It is likely that a proportion of these electrons do not focus onto d1 but skip d1 landing on $d_2$ or $d_3$. Alternatively they land on the edge of d1 producing secondaries which are inefficiently collected by $d_2$ - the so-called edge effect mentioned by Oliver and Pike (1970). Contributions from thermionic electrons originating that the dynodes, and secondaries generated from ion impact on the dynodes, together with photoemission from internal light generation (Krall 1967) must also be considered.

The events in region C of **figure 3b** are most certainly signal-induced afterpulses. There is considerable literature on this subject and reference to the work of Allen (1952), Barton et al (1964), Morton et al (1967) and Coates (1973) can be made for further details. Comparison of figure 3a and b shows that pulses in region C account for 15-20% of the total background counts whereas the corresponding number in the signal spectrum is only about 1% of total. This implies that only a very small proportion of the pulses in region C of this background spectrum are signal-induced by pulses in region B.

It is well known from the work of Sharpe and Stanley (1962) and Jerde et al (1967) that 40K, U, and Th contaminants in the glass contribute to region C. The group of two photomultipliers (serial numbers 6670, 6777 in **figure 2** have windows made from a high-pottassium-content glass (8% $K_2O$) and consequently show a relatively high

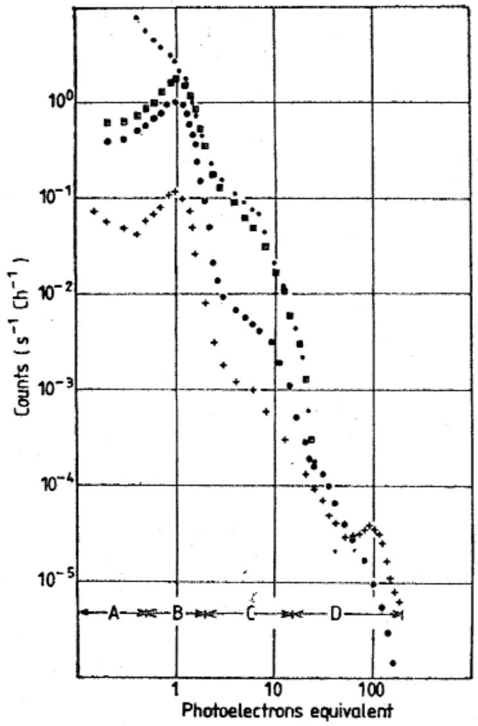


**figure 2** background pulse height distributions for four photomultipliers at 20ºC. ●, 9814 6777; ⊡, 9814 6777; ⊙, 9813 12123; +, 9813Q 4282. Regions A, B, C and D are defined in the test. Serial number 6670 is an example of a photomultiplier with an excess of small pulses in the background. The magnitude of the contributions in region C is a measure of the $^{40}$K content of the window material. Serial number 4282 has a quartz window and is free from this radioactive contaminant but shows a well resolved cosmic ray peak at 80 photoelectrons equivalent.

proportion of counts in region C. Serial number 12123, has a Pyrex window containing only traces of $^{40}$K whereas serial number 4282, with a quartz window, is free from radioactive contaminants. That 40K is indeed the major contributor to region C was readily established by placing serial number 6777 in contact with a NaI (T1) crystal assembly with identified that isotope through the appearance of g ray peak at 1.46 MeV, 89% β decay fraction) which gives rise to the counts in region C. Further to this experiment, the window of serial number 6777 was optically coupled to that of the quartz photomultiplier serial number 4282. A substantial increase in region C counts by a factor of 50 was now observed in serial number 4282, as expected. In addition, the counts in regions A and B increased by 40 s-1 showing that sources that contribute to region C also contribute single photoelectron counts, although referring to 3a and b, the converse does not apply. The observations suggested that further information relating to source contributions could be gained by studying the effects of cooling on background spectra.

Distributions were recorded for three photomultipliers using a cooled housing (Model Fact 50,

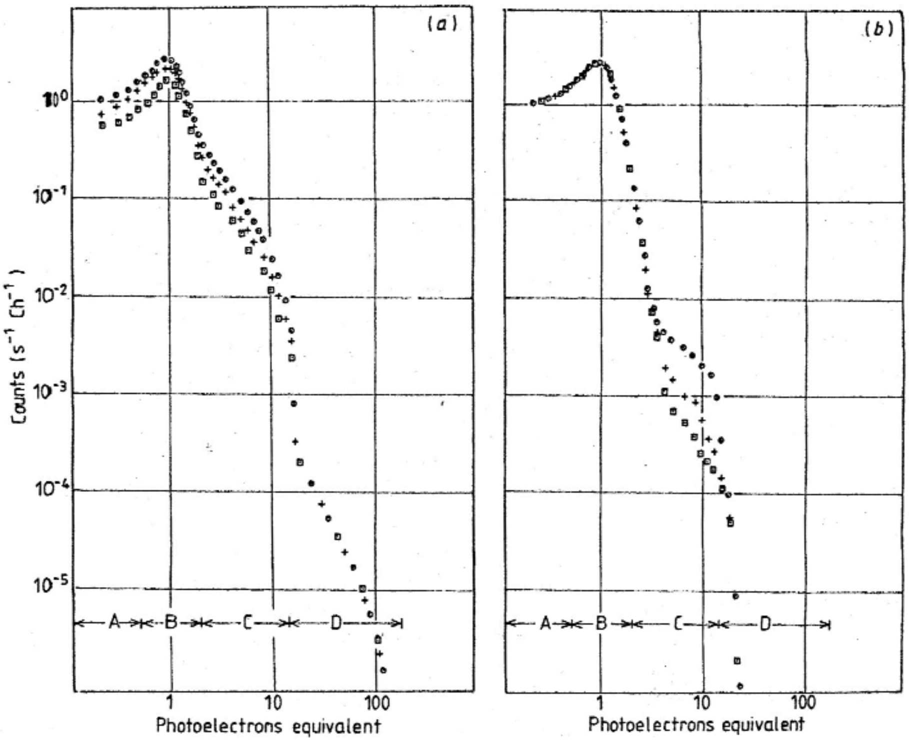


**figure 3** pulse heigh distributions for a 9814 6777 operated at three gain settings: ⊡, $\langle g \rangle$ = 6 x $10^6$; +, $\langle g \rangle$ = 5 x $10^7$; ⊙, $\langle g \rangle$ = 2.8 x $10^8$. (a) Backgound distribution at 20°C exhibiting an increase in region aA, b and c with gain. (b) Single photon excitation. The relative proportion of counts in C, compared with the single electron peak, is two orders of magnitude less than in the corresponding bacground spectra. Note the absence of region D in (b).

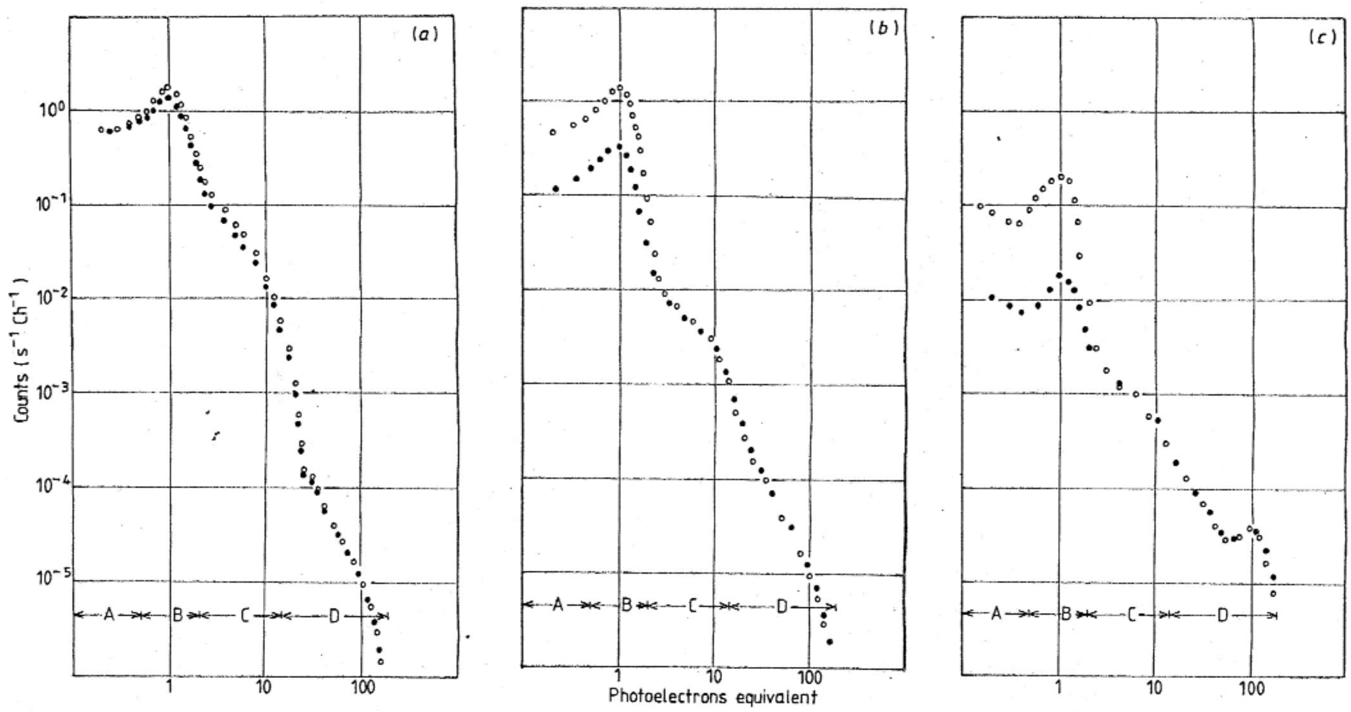


**figure 4** the effect of cooling (○, $T$ = +25°C; ●, $T$ = -25°C) on the background for the photomultipliers; (a), 9814 6777; (b), 9813 12123; (c), 9813Q 4284. The spectrum in (a) shows little change on cooling because the background in this photomultiplier is erived largely from the presence of $^{40}K$ in the window material. (b) is an example of a tube made from low-background glass; the integral counts decrease from 50 $s^{-1}$ to 20 $s^{-1}$ upon cooling. (c) is representative of an exceptional quartz photomultiplier with dark counts of ~10 $s^{-1}$ at 25°C reducing to ~1.5 $s^{-1}$ at -25°C.

Electron Tubes, Gencom Inc.) operated at temperature of +25°C and -25°C. The background spectra in **figure 4** show that the spectral content in regions A and B, decreases substantially upon cooling in figures 4b and c but considerably less so in 4a - a result of the $^{40}K$ contribution which is temperature independent. Again referring to regions A and B, the reduction in count rate with temperature if **figures 4b** and **c** is characteristic of thermionic emission, although Young (1969) has suggested that there are possibly other temperature-dependent sources which contribute.

The spectrum in region D is independent of temperature in all three photomultipliers. These very large pulses are a direct consequence of the passage of relativistic cosmic rays (mainly muons and electrons) through the photomultiplier window (at a rate of about 15 $min^{-1}$ for a 51 mm diameter tube). This aspect of photomultiplier background has been covered in detail by Young (1966). It is interesting to note that the photomultiplier with a quartz window (**figure 4c**) gives a peaked response at 80 photoelectrons whereas those with glass faceplates only exhibit a shoulder in region D. This can be explained in terms of the superior transmission of quartz for the uv-rich Cerenkov emission.

## 4 relationship between dark current and dark counts

In order to explain why most of the experimental points in **figure 1** generally lie above the line representing ideal behaviour, the spectral content of the dark counts must be taken into account. A term representing the contribution from leakage currents flowing into the anode, due to the applied biasing voltages on the dynodes, must be including. If I' represents this components, including any other source in the photomultiplier, responsible for a DC contribution, then

$$I = i_q + I'$$

$$I = \int_0^\infty n(q)q\,dq + I' \qquad \text{...(3)}$$

**Figure 2** illustrates the wide variation in the background spectra from one tube to another and helps to explain how the multi-electron pulses can make a significant contribution to iq. Plotting n(q)q dq against q shows the extend to which regions A, B, C and D contribute to the dark current.

The leakage component $I'$ may be estimated with reasonable accuracy in the following way. Shorting the cathode $d_1$ and $d_2$ together, while maintaining the same voltage distribution on the remaining dynodes, reduced the contribution from $i_q$ to negligible proportions. This was checked by noting that the pulse height distribution measured under these conditions consisted of very few pulses. The measured dark current is taken to the be same as $I'$ in equation (3). This is of course an underestimate because the photomultiplier operating conditions have been altered and any signal-induced leakage due to the cathode emission is also removed. However, there is no other obvious way of deducing $I'$.

The contribution from the dark pulses, taken from **figure 5a**, are shown in **5c** (circles). Adding to these, the measured I' (squares), gives the full curve. The agreement between the observed total dark current (small dots), and that predicted (full curve) is remarkably good when allowance is made for the uncertainty in the charge calibration of the multichannel analyzer and the assumption inherent in deducing $I'$. The same procedure has been adopted in arriving at the results in **figure 5d** where theory and experiment again agree rather well. As mentioned earlier, pulse height distribution (and hence iq) could not be measure for $g < 5 \times 10^6$. Values of iq deduced from an extrapolated curve were therefore assumed in the low-gain region of **figure 5c** and **d**. The results shown in figure 5e and f indicated that N approaches an asymptotic value as $g \rightarrow 0$ and so the extrapolation is not unreasonable.

$I/\langle g\rangle$ has been plotted against $\langle g\rangle$ in **figures 5e** and **f** for the same two photomultipliers. Referring to serial number 6777 we see that $I/\langle g\rangle$ is essentially constant over a wide range of gain extending from $10^6$ to $5 \times 10^7$. The other curve in **figure 5e**, showing the dark count rate increase with applied voltage, accounts very nicely for the upward deviation of $I/\langle g\rangle$ for serial number 6777 at the higher gains. Departure from ideal behaviour is also apparent for $g < 10^6$. The dark current is leakage dominated in this region and virtually independent of the dark count rate. In contrast serial number 12123 is leakage dominated for all $g < 10^8$ and only approached ideal performance when $g > 10^8$.

The complete set of thirty-two phototubes of six different types, were measured with the results obtained in **figures 6a-f**. The majority of curves are consistent with a typical behaviour pattern: a curve with a broad minimum lying between $\langle g\rangle = 5 \times 10^6$ and $10^7$. The exceptions are worthy of note.

(i) serial number 6680 (**figure 6a**) is an example of a tube with exceptionally high leakage, accounting for the major component of dark current up to $g \sim 10^7$. Although very poor with regard to dark current, the dark counts at 65 $s^{-1}$ for this tube were voltage independent up to $g = 7 \times 10^7$.

(ii) serial number 11086 (**figure 6a**) has a low leakage current component. The dark counts for this tube vary from 100 at $g = 10^7$ to 440 $s^{-1}$ at

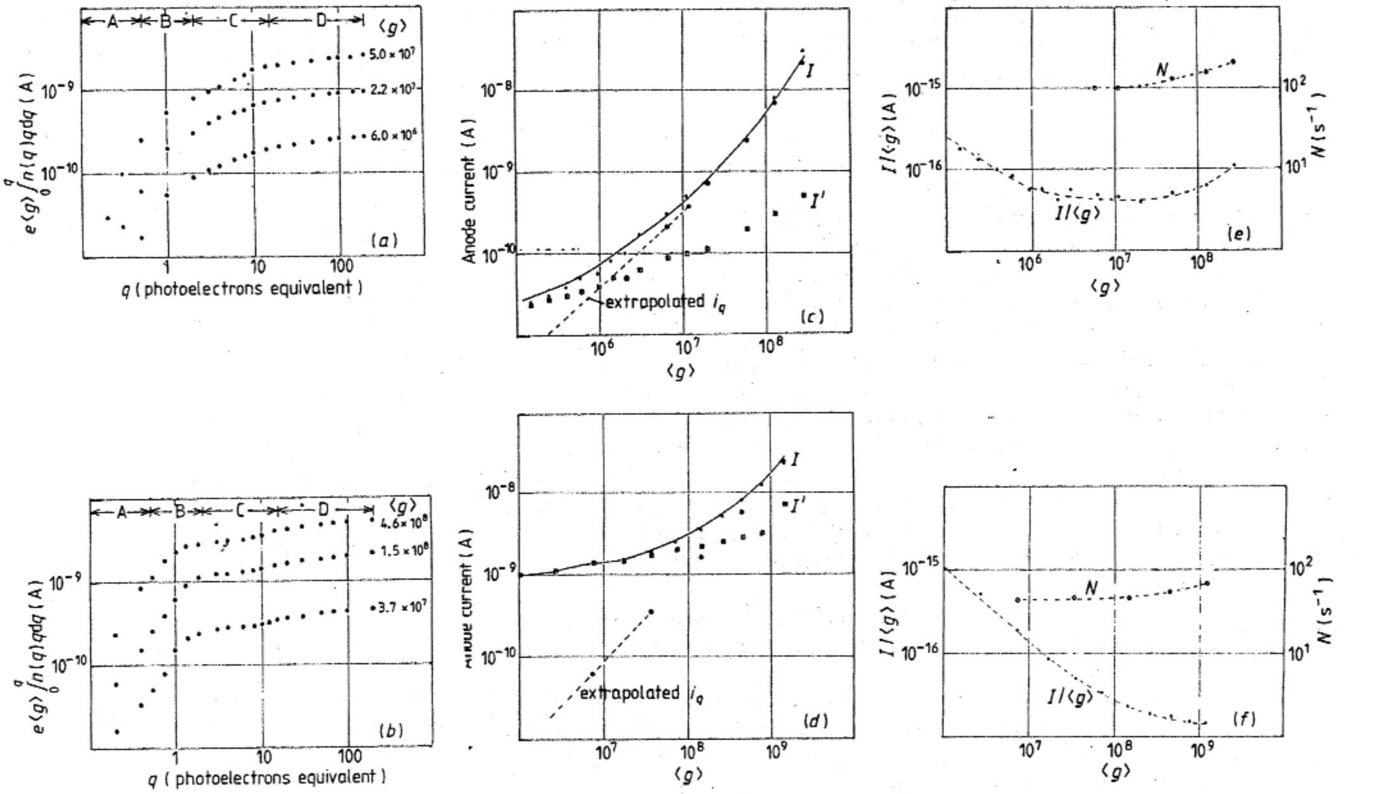


**figure 5** illustrating the absolute contributions made by regions A, B, C and D to the dark current: (a), (c), (e), 9814 6777; (b), (d), (f), 9813 12123. the photomultiplier in (a) is characterised by a significant contribution from region C, while that in (b) has a lower proportion of large pulses. The contribution to the dark current, derived from dark counts, is given by the asymptotic value of the function $e\langle g\rangle \int_0^q n(q)q\,dq$. $i_q$ values so derived are used in (c) and (d) (circles) which illustrate how the measured dark current can be accounted for in terms of $i_q$ and $I'$. The measured dark currents can be expressed as equivalent cathode currents, $I/\langle g\rangle$, as in figures (e) and (f); an ideal tubes is one for which $I/\langle g\rangle$ = constant. The variation of count rate, $N$, with gain is also shown in (e) and (f).

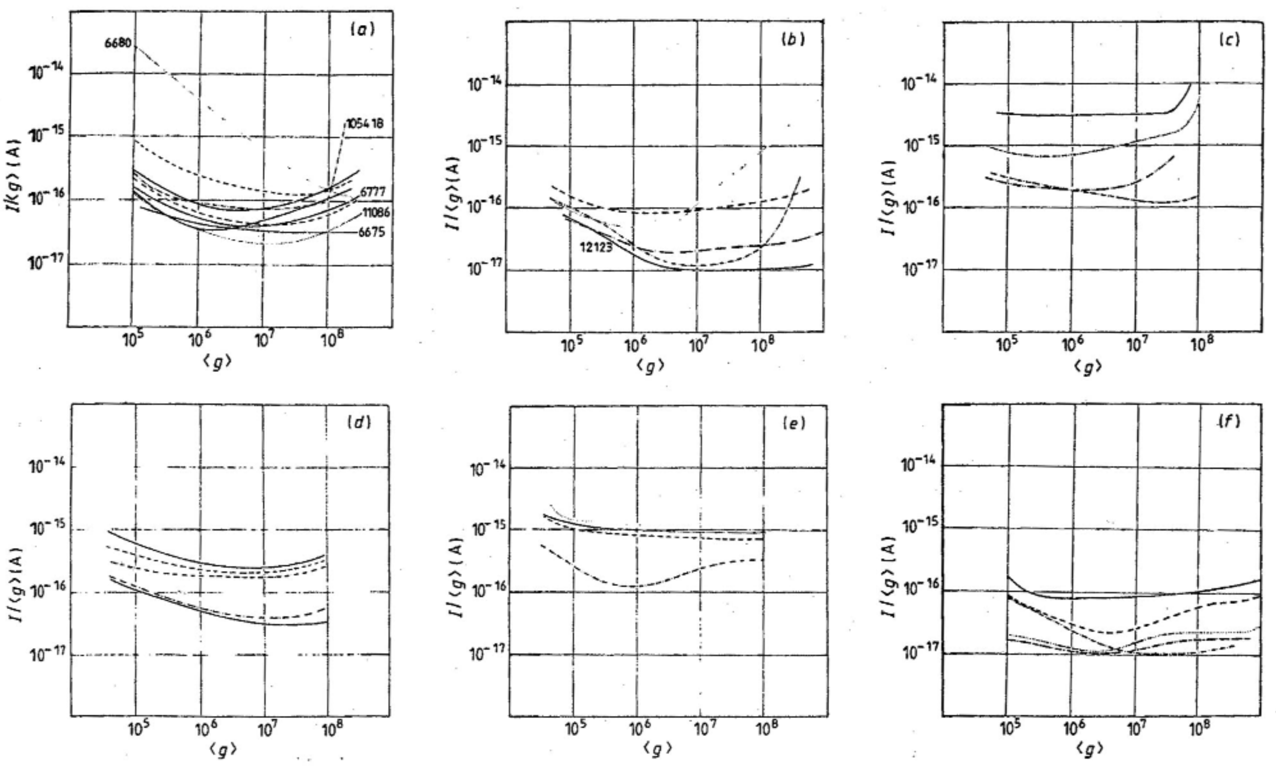


**figure 6** equivalent cathode currents plotted agains multiplier gain for the set of photomultipliers tested: (a), 9814; (b) 9813; (c) 9811; (d) 9954; (e) 9798 and (f), 9635. The serial numbers of tubes referred to in the text are indicated on the curves.

$g$ =3 x $10^8$ which explains the turn-up in the curve at high gain.

(iii) the curve representing serial number 6675 remains flat between $10^7 < g < 3 \times 10^8$. This is because the dark counts do not increase with gain.

(iv) an example of a photomultiplier suffering from excessive light generation is that of serial number 105418. Light feedback sets in at $g > 10^8$.

The variation of darks with $<g>$ for the tubes referred to in (i)-(iv) are shown in **figure 7**.

Comparing the results in **figures 6a** and **b** we note that three of the tubes with 14 stages of gain operate satisfactorily up to $g$ ~$10^9$. The limiting gain for the 9814s is typically 3 x $10^8$ and beyond this gain, light feedback sets in.

The best tube in **figure 6b** has $I/<g>$(min )= $10^{-17}$ whereas the corresponding figure for the 9814s is 2 x $10^{-17}$. The minimum values attained by the S11 and S20 tubes (9811) and (9798) (**6c and e**) lie in the range $I/<g>$ = $10^{-16}$ to 3 x $10^{-15}$. This is because the background counts are an order of magnitude higher than those for the bialkali photomultipliers.

The 9635 venetian blind tubes behave in a similar way to the 9813 photomultipliers. Three of the samples attain very low values of $I/<g>$ at the minimum and all perform satisfactory at high gain.

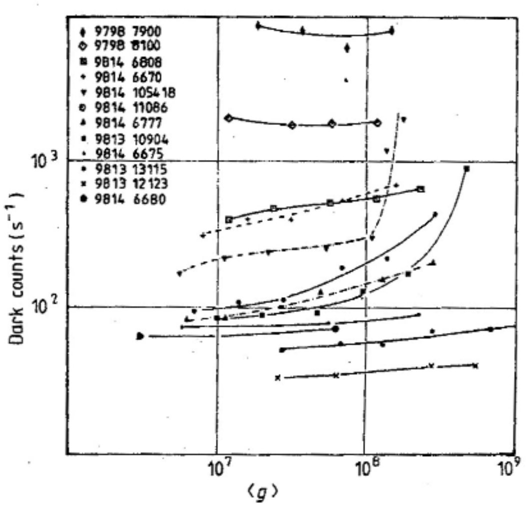


**figure 7** the variation of dark counts with gain for a set of selected tubes. The steep rise in count rate exhibited by 105418 is symptomatic of light feedback

All the photomultipliers in **figure 7** show an increase in background counts with gain, particularly at gains in excess of $10^8$. We have no means of determining whether this occurs as a consequence of the higher voltages applied to the tube or whether the increase in counts relates to the signal current density in the tube, which naturally varies proportionally with $g$. It seems reasonable to assume that the counts continue to decrease slowly as $g$ is reduced below 5 x $10^6$, perhaps approaching the true thermionic emission rate from the cathode as $<g> \rightarrow 0$. Taking an asymptotic value of 100$s^{-1}$ as representative of a good bialkali tube (see **figure 7**), which is an equivalent cathode current of 1.6 x $10^{-17}$ A, we note from **figures 6a** and **b** that even for the best tubes $I/<g>$ tends to be an order of magnitude higher than this value at $g$ = $10^5$ for example. Furthermore, $I/<g>$ is varying something like $1/<g>^{½}$ as $g$ 0. If it is assumed that $I'$ is purely due to ohmic leakage, then $I'$ would be proportional to V and since $g \propto V^{10}$ in the region of interest, $I'/<g>$ will vary as $<g>^{-0.9}$. Two tubes that perform poorly at low gain, serial numbers 6680 and 12123 from **figures 6a** and **5f** respectively, both vary as $<g>^{-0.8}$, supporting the view that these two tubes suffer from having an ohmic leakage path somewhere in the dynode stack. The majority of tubes vary approximately as $<g>^{-0.5}$ in the region of $<g>$ = $10^5$ and ohmic leakage alone clearly cannot account for this magnitude of dark current.

Serial number 12123 is an interesting example of a photomultiplier that improved with continuous operation. Because of the high leakage current, this tube was left with the voltage applied for two days and then remeasured with the results shown in **figure 6b**. Comparing $I/<g>$ value at $<g>$ = $10^5$ in **figures 5f** and **6b** we note an improvement of two orders of magnitude in the leakage. Similar treatment applied to number 6680 did not result in the same degree of improvement and it seems plausible to attribute the behaviour of these tubes to the existence of a low resistance leakage path which cleared itself in the one tube but not in the other. The fact that photomultipliers tend to improve after a continuous period of operation is well known to most users.

## 5 conclusions and implications for low light level measurements

This work shows that the suitability of a particular tube for low light level applications is best ascertained by a measurement at the intended operating gain. In fact, there is an optimum gain, for which a photomultiplier will provide the best signal to background ration (S/B). A tube which performs well at low gain will not necessarily do so at a higher gain and vice versa. The dark current does not correlate well with the dark count rate except under high gain condiditions where the DC component is usually a negligible proportion of the total dark current. Examination of the set of curve in figure 6 allows the following generalization to be made. The S/B ratio for DC detection is a minimum within the range 3 x $10^6 < (g) < 10^8$ for the most of the photomultipliers tested. The curves of **figure 6** suggest a simple but effective way of setting up a commercial detector system which includes ad DC amplifier of variable gain. The total gain in the system is the product of the multiplier gain and the amplifier gain and the experimentalist can choose the relative contributions from each. The optimum gain assignment is readily arrived at by plotting a family of

$I/<g>$ curves for various combinations of amplifier and photomultiplier gain. In fact it is sufficient for this purpose to plot $I$/(relative gain) since a knowledge of the actual gain is not required to optimize S/B - it is only the overall voltage at which the minimum of the curve is attained that is important. Relative gain can be measured as described in Section 2 by using a steady light source and varying the applied voltage.

Similar considerations apply in setting up a photon counting system. The curves of **figure 7** indicate that the lower the photomultiplier gain, the better the dark counts. Photon counting systems are sensitive to electrical interference and it is therefore unwise to derive too high a proportion of the overall gain from the amplifier. The optimum gain assignment in this case is obtained by plotting a family of curves of dark counts against system gain. A photon counting system can be further optimized by careful selection of the upper and lower threshold levels which determine the actual rate of measured signal and background. **Figures 2, 3** and **4** suggest that the lower acceptance level for pulse counting should be set at ~0.3 and the upper at ~3 photoelectrons equivalent to eliminate the majority of small and large amplitude pulses in the background while sacrificing very little counting efficiency with respect to signal. This manner of S/B optimization is of course not possible in DC detection where all contributions to the dark current have to be accepted. We note from **figure 5a** that small amplitude pulses barely contribute whereas those from C and D can account for 20-30% of I. For an exceptional photomultiplier, such as as the 9813Q 4282, the contribution from C and D exceeds that from A and B. Cooling this photomultiplier to -25°C reduces the rate from A + B to less than $1s^{-1}$ while C + D remains constant at about $1s^{-1}$; the dark current is now almost entirely derived from large amplitude pulses. It is not difficult to appreciate how a source of large amplitude but relatively infrequent pulses will lead to a dark current with high variance. This manifest itself most noticeably as 'kicking noise' in chart recordings of low level dark current.

The purpose of this study has been to gain an understanding of the constituents of the dark current in a photomultiplier. A simple model assuming a pulse like component and a DC component is sufficient to account for the magnitude of the dark current and its dependence on tube gain. This work also underlines the arguments in favour of photon counting for low level applications by showing for example how selected cooled photomultipliers can exhibit an effective cathode dark current of less than one electron per second. This is achievable with quartz windowed photomultipliers only; for those in low background glass the figure is about 10 $s^{-1}$ whereas those in glass envelopes have a high $^{40}$K content give rise to at least 40 counts $s^{-1}$. These figures apply to counting window corresponding to region B; considerable S/B advantage is always sacrificed by following the common expedient of using only a single detection threshold.

Finally, the notion that a particular photomultiplier type can be categorised in terms of quoted typical background performance figure seems spurious. The wide variation in the results of **figure 6** are taken in support of this view. In addition, it should be noted that the photomultipliers examined in this work had undergone the standard factory screening prior to measurement. Those with excessive dark and leakage currents had thus already been eliminated. It is undoubtedly more meaningful for photomultiplier manufacturers to classify tubes as 'good for low background counting' or 'suitable for low current measurements' or both.

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