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Photon Counting in Astrophotometry. Fundamentals and Some Advices for Beginners

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Abstract

The beginners in astrophotometry are reminded of fundamentals of photon counting. Several advices for new users of electrophotometric technics are given.

1. A Photomultiplier

1.1. The structure of the photomultiplier

Among the photosensitive devices in use today in astrophotometry, a photomultiplier tube (PMT) still remains as a versatile device that provides sufficiently high sensitivity, ultrafast response and unsurpassed accuracy of light flux measurement. A PMT consists of a photoemissive cathode (photocathode), focusing electrode(s), electron multiplier (dynodes) and electron collector (anode), assembled in a vacuum tube (Fig.1).

When the photons from the light flux directed to the PMT strike to the photocathode, the photocathode emits photoelectrons into the vacuum. These photoelectrons are then

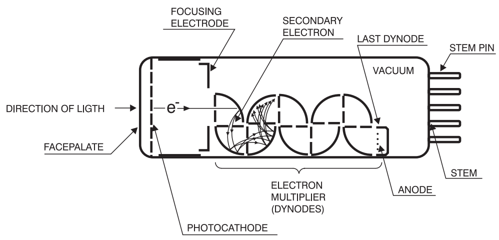

Figure 1. Structure of the photomultiplier

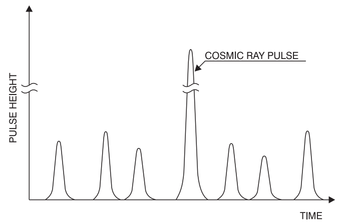

Figure 2. Diversity of PMT output pulse heights

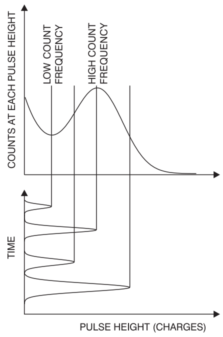

Figure 3. PMT output pulses and PHD

directed by focusing electrode voltage towards the electron multiplier where they are multiplied by the process of secondary emission (if proper voltages are supplied to the successive dynodes). The multiplied electrons are collected by the anode as an output signal. This signal can be detected as an electric charge, current or voltage pulses if the corresponding circuit is applied.

1.2. Electron multiplication process

The secondary emission process in the dynodes has a statistical character, i.e. the gain of secondary electrons has variance. Thus we can consider only the mean value of the secondary emission factor δ of each dynode. If there are n stages in the PMT, a single photoelectron from the photocathode is multiplied by δ^n to become a group of electrons which is a pulse output. The number of electrons in each group (pulse) is spread statistically (due to the variance of the secondary electron gain) and obeys Poisson distribution. This is why the values of output pulse heights at anode have a large variance (Fig.2). Heights of pulses plotted in a histogram are called the pulse height distribution (PHD)(Fig.3).

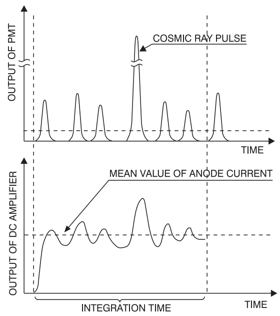

Figure 4. Analogue mode of PMT application

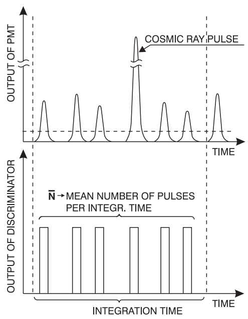

Figure 5. Single photon counting mode of PMT application

2. Single Photon Counting

2.1. Direct current mode

In the direct current (DC) application of PMTs (or analogue mode) (Fig.4) one measures the mean value of anode current containing the contribution of all pulses: their number and amplitudes. The mean value of anode current is proportional to the intensity of the light flux detected. It is clear that, due to the variance of the amplitude of the output pulse, the noise of the mean value of anode current is larger than the photon noise.

2.2. Photon counting mode

In the single photon counting (or digital) mode (Fig.5) we count the number of pulses per certain time interval independently of the pulse height (if their amplitude exceeds the discriminator threshold level). The number of pulses counted per time unit is proportional to the intensity of the light flux detected. We see that part of the PMT output noise caused by PMT itself is lower because the amplitude of the output pulses is not taken into account in this case.

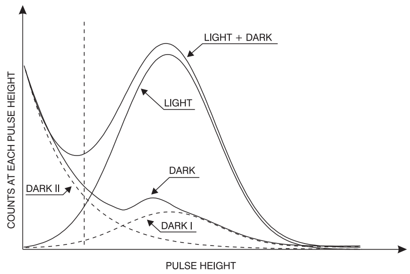

Figure 6. PHD of light and dark pulses of PMT output

Now we can state the first and the most important advantage of photon counting: single photon counting is not subject to the electron multiplication noise as the DC mode is.

2.3. Pulse height distribution

Let us consider more thoroughly the PHD and make some inquiries. It is well known that even if PMT is protected from the light, some signal (pulses) is produced at its output. It is the dark signal (by no means a noise as often it is called!). How does the PHD for the light differ from that for the dark signal? The heights of light pulses arisen from the photocathode are distributed according to the Poisson law. However, there is no possibility to measure directly the PHD for the light signal. This PHD could be derived only by subtracting the PHD for the dark signal from one for the summary of light and dark signals. The dark pulses have mainly two different sources: thermal emission from photocathode (the distribution has the same shape as in the case of light) and thermal emission from dynodes (which shows an exponential distribution of pulse heights) (Fig.6). Thus the PHD for the dark pulses is the superposition of these two components. How does the PHD change when the supply voltage is changed? Since the secondary emission factor is proportional to the voltage applied to dynodes, it is clear that the abscissa of PHD becomes a function of the supply voltage applied to the PMT (Fig.7). How does the PHD change when the incident light is changed? It is evident that the increase in light intensity is identical to the increase in the number of incident photons and leads to the increase in the number of output pulses. As the ordinate of PHD shows how often outputs corresponding to a given amplitude are produced, it is evident that the PHD curve rises when the incident light is increased (Fig.8).

3. Circuit Configuration

The simplest photon counting system consists of a PMT, amplifier, discriminator and pulse counter (Fig.9). For the supply of PMT and for the distribution of voltage to all electrodes, a high voltage (HV) power supply and an HV divider are necessary. The most

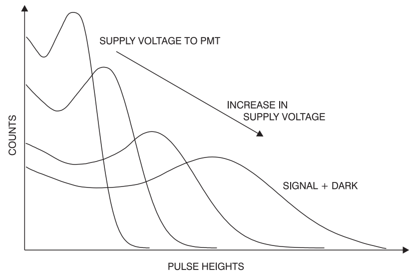

Figure 7. PHD of PMT when the supply voltage is changed

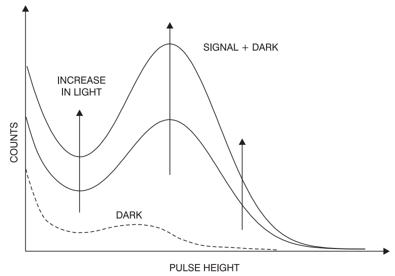

Figure 8. PHD of PMT when the incident light is changed

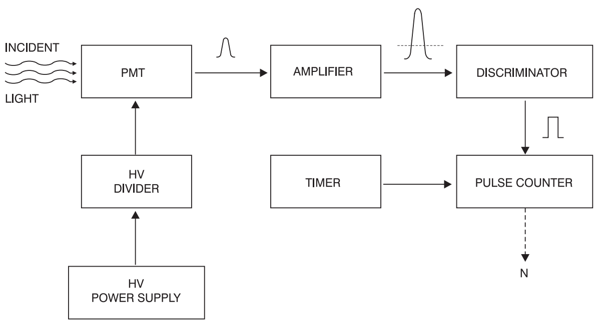

Figure 9. Basic configuration of the photon counting system

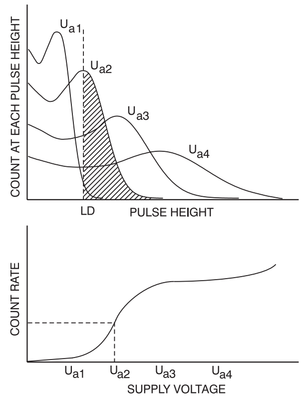

Figure 10. How is the counting characteristic got?

important element of the photon counting system is a discriminator. Each discriminator output pulse corresponds to each of the input pulses if its amplitude exceeds some amplitude level (discriminator threshold level) set. Output pulses have standard shape (uniform amplitude and duration) and are counted in the counter independently from their amplitude at the PMT output, providing in that way the main advantage of photon counting already mentioned. We can consider now the second merit of photon counting. Going back to the PHD for the light and dark signals (Fig.6) we see that, if the discriminator's threshold level is on the "valley" of PHD, we eliminate lower pulses which are originated mainly by thermal emission from dynodes. Thus, by using pulse amplitude discrimination, it is possible in photon counting to suppress part of the dark signal, i.e. to increase the signal to noise ratio.

4. Basic Characteristics of a Photon Counter

4.1. Counting characteristic

We should return to the PHD again to consider a counting characteristic which is the basic characteristic of a photon counter. The measurement of PHD using multichannel analyzers is a rather complicated and expensive way to investigate the photon counters. As the PMT's output pulse amplitude depends mainly on the voltage applied to the successive dynodes, there is a more simple and convenient method how to get some imagination about the PHD of the photon counter under investigation. Let us suppose that we have PHDs of the PMT for the same level of incident light measured at several successively increasing high voltages supplied to PMT (Fig.10). If the threshold of the discriminator is set at the pulse height LD, the top curves in Fig.10 show that at the voltage U_{a1} we will not count any pulses. At the voltage U_{a2} we will count approximately half of all pulses originating at the PMT anode. And finally, at the voltage U_{a4} we will count almost all pulses coming from the PMT. If we plot the dependence of the count rate

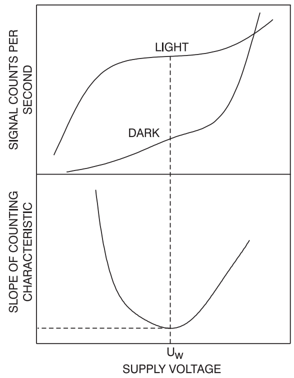

Figure 11. The definition of the "working point" of a photon counter

on the supply voltage (the bottom curve in Fig.10) we will have the main characteristic of the photon counter, i.e. the counting characteristic. It could be singled out three main parts of the counting characteristic: the initial rising part, plateau and the third region of signal increase at high values of supply voltage. It is clear that our goal is to reach the plateau in oder to count approximately all pulses caused by light photons striking to the photochatode of the PMT.

4.2. "Working point", or how to find the appropriate value of HV

If we plot the dependence of the counting characteristic's slope (for the pure light signal surely) on high voltage, we can see some minimum of this dependence (Fig.11). It is evident that we should seek to work at the value of voltage U_w where is the minimum of the slope. Here, at this "working point", all variances of high voltage, as well as of the gain of amplifier or of the level of discriminator threshold, have the least influence on the stability of light detection.

So, we have cleared up the third advantage of photon counting in comparison with the analogue mode: by setting HV in the "plateau" of counting characteristic it is possible to reduce the rate of change of the output signal with respect to variances of HV as well as of the electric sensitivity of all electronics and especially of an amplifier-discriminator.

4.3. Linearity of the photon counter (dead time)

Theoretically the photon counter is a nonlinear device, even at the low count rates. First of all it is related with the non-zero time resolution of the PMT and all successive electronic circuitries. On the other hand, due to the statistical distribution of photon arrival time, it can occur that two photons arrive very close to one another even at the low counting rate. In practice, unfortunately, one often reckons that photon counting is strictly linear in some dynamic range (the range of light flux intensities) and only at high

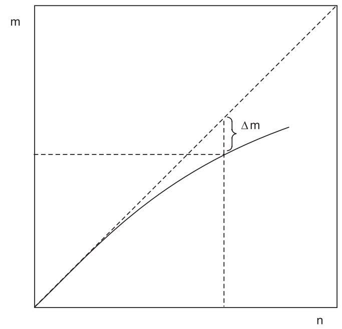

Figure 12. The dependence of the rate of counted pulses on the true rate of PMT pulses

counting rates the measured values should be corrected. It is not an exact way how to manage the photon counting. The best way is to investigate thoroughly this nonlinearity and to take it into account in every measurement (even at low counting rates). The recorded count rate m (in events per second) underestimates the true counting rate n because some pulses are too close to each other to be resolved. In a first approximation one can consider that, after the moment when the pulse is detected, the counter must wait some time before another pulse is detected. This time interval is called the dead time of the counter. We can find that, in a first approximation, the following relation between n, m and τ is valid:

$$n = \frac{m}{(1 - m\tau)} \approx m(1 + m\tau) = m + \Delta m. \tag{1}$$

It is seen from the formula (1) and the corresponding diagram (Fig.12) that some corrections are necessary, even in the middle of the dynamic range, if we are seeking to have precise measurements.

On the other hand, it is understandable that very precise measurements of the dead time value τ must be made if we want to use the dead time corrections and to perform measurements at comparatively high count rates. Photometric laboratory methods [1] of the dead time measurements are more preferable instead of those made by using the sky (calibrated stars or something like). However, it is absolutely unacceptable to measure the response time of electronics only and to evaluate the dead time by using only this response time value. On the other hand, even having quite an exact value of τ, the corrections should not exceed 10 or 15 percent, if we want to do good photometry.

5. Noise and an Integration Time

If N_s, N_d and N_b are the numbers of pulses counted during the integration time T of the light, dark and background signals, respectively, and if n_s, n_d and n_b are their intensities, the following relations are valid:

$$N_s = n_s T, N_d = n_d T, N_b = n_b T. \tag{2}$$

However, N_s cannot be measured, but it can be calculated according to ordinary measurement procedure: we measure $N_s + N_d + N_b$ and $N_d + N_b$ separately and then we can find the value of the light signal N_s:

$$N_s = (N_s + N_d + N_b) - (N_d + N_b). \tag{3}$$

N_s, N_d and N_b follow the Poisson distribution [2]. Because of this, their dispersions are equal to their mean values. Then we can find the mean square error (m.s.e.) of N_s:

$$\sigma_{N_s} = \sqrt{N_s + 2(N_d + N_b)} = \sqrt{T[n_s + 2(n_d + n_b)]}. \tag{4}$$

Then, the signal to noise ratio S/N is:

$$\frac{S}{N} = \frac{N_s}{\sigma_{N_s}} = \frac{n_s \cdot \sqrt{T}}{\sqrt{n_s + 2(n_d + n_b)}}. \tag{5}$$

Now we can find the integration time T necessary to achieve a needed S/N:

$$T = \frac{(S/N)^2 (n_s + 2n_d + 2n_b)}{n_s^2}. \tag{6}$$

We have above considered the case where the integration time T is the same for all values of N_s, N_d and N_b.

However, a better estimate of the optimum integration times may be achieved [3].

Usually in astrophotometry we do not measure the dark signal separately. Then the count rate of the star alone is

$$N_s = (N_s + N_{sky}) - N_{sky}, \tag{7}$$

where $N_{sky} = N_d + N_b$

and the corresponding m. s. e. is determined as

$$\sigma_{N_s} = \sqrt{\sigma_{N_s}^2 + \sigma_{sky}^2} = \sqrt{\frac{(N_s + N_{sky})}{T_{s+sky}} + \frac{N_{sky}}{T_{sky}}}. \tag{8}$$

If we denote the total integration time T_{tot} and the fraction of time spent on the measurement of the star k (k=$T_{star+sky}/T_{tot}$), then we have

$$\sigma_{N_s}^2 = \frac{N_s + N_{sky}}{kT_{tot}} + \frac{N_{sky}}{(1-k)T_{tot}}. \tag{9}$$

This error is minimal when the derivative with respect to k vanishes. Then one finds the condition

$$\frac{1-k}{k} = \sqrt{\frac{N_{sky}}{N_s + N_{sky}}}, \tag{10}$$

which allows us to make the best use of the given total integration time T_{tot}. For faint stars

$$(N_s + N_{sky}) \simeq N_{sky} \tag{11}$$

and thus star and sky integrations should be of equal duration. Here we can state one more advantage of a photon counter in comparison with the analogue mode: the simple increasing of the integration time can help us to increase the signal to noise ratio. In the DC mode the integration time is limited by instrumental causes.

6. Several Advices

Having in mind the properties of a photon counter considered above and our experience of many years we could formulate several advices or recommendations for the beginners in astrophotometry with photon counting.

1. If you have possibilities, select the best PMT from all available. For the selection, the tests, or evaluation of sensitivity and stability, should be taken into account. The counting characteristics should be used for the evaluation of the electron multiplication factor of the whole system of dynodes: it is clear that better is the PMT with higher factor of multiplication.

2. Choose a right HV value and check it every time when you change a PMT or amplifier-discriminator.

3. Do not change HV supplied to PMT without any serious reason.

4. Do not switch off the HV during the whole observational session, especially if you want to achieve exclusively precise results or want to accomplish absolute measurements.

5. Define the dead-time as precisely as possible and always use it for the correction of the data according to the formula discussed (independently on the counting rate).

6. After installation of your photon counter and photometer at the telescope, be sure that the mechanics and optics of your photometer is properly adjusted. The focusing of stellar images at the plane of apertures as well as the mechanical adjustment of the PMT to the position of the maximum signal output should be made. Then it would be very useful to evaluate the photometric sensitivity of your whole system. For this purpose, measure the counting rate by using the known star and compare it with the counting rate which you could expect taking into account the star's radiant effectiveness, the atmosphere transmission, reflection factors of the mirrors of your telescope, the transmission of the filter used and the conventional quantum efficiency of the PMT at the given wavelength. The measured and calculated values should differ not greater than 20 or 30 percent (if correct values of all factors mentioned are taken into account).

7. Acknowledgments

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