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The Determination of the Dead-Time Constant in Photoelectric Photometry

E. PORETTI, Osservatorio Astronomico di Brera, Milano, Italy

It is a well-known fact that raw counts measured at the output of a photon-counting photometer must be corrected for the dead-time constant τ. This correction originates from the finite time interval necessary for the electrons to cross the photomultiplier tube and, overall, from the time necessary to the amplifier/discriminator electronic to record the output pulse. From a practical point of view, this means that the instrumentation cannot resolve two incident photons separated by a time shorter than τ since they will be counted as a single event. Hence, the output counts will always be an underestimate of the input value.

Photons are travelling clumped together in space and the correction term can be calculated by means of the Bose-Einstein population statistics. The probability density f(t) that two photons arrive separated by a time t is

$$f(t) = \lambda e^{-\lambda t}$$

where λ is the arrival frequency of the photons. n_τ, the number of photons which arrive in a time interval shorter than τ, is given by

$$n_\tau = N \int_0^\tau f(t)dt = N \int_0^\tau \lambda e^{-\lambda t}\, dt,$$

while N is the total number of photons arrived during the measurement time. If it is 1 s, we have $N = \lambda$. By integrating, we obtain

$$n_\tau = N(1 - e^{-N\tau})$$

and, if we indicate as n the photons actually counted,

$$n = N - n_\tau = \frac{N}{e^{N\tau}}$$

This is the relation between the number of incident photons N and the number of counted photons n. If we can suppose that $N\tau$ is small, we can approximate $e^{N\tau}$ with a McLaurin development stopped at the first order, obtaining

$$n = \frac{N}{1 + N\tau} \qquad N = \frac{n}{1 - n\tau}$$

The latter is the formula most widely used in data-reduction routines. The value of the τ constant is generally supplied by the manufacturer and it is reported in the users manuals without any further checks. In general this assumption is justified by the impossibility to perform accurate laboratory tests. In some cases, the dead-time constant is confused with the rise time (i.e. the time interval during which the output rises from 10% to 90% of peak output) and its value is therefore underestimated. In the dome, astronomers can directly calculate τ by measuring two standard stars, one much brighter than the other, and comparing the observed Δm with the expected one.

However, this method requires a very precise knowledge of the magnitudes of the two stars and of the extinction coefficient. Cooper and Walker (1989, "Getting the measure of the stars", Adam Hilger Publ.) report a method which seems to me much more practicable. The telescope should be pointed towards sunrise and, when the sky is brightening, sky measurements should be performed alternating two different diaphragms, one much smaller than the other; let α be the ratio of their areas. An upper limit should be fixed to satisfy the following conditions: it should not be too high to cause damages to the photomultiplier or, from a more formal point of view, to invalidate the McLaurin development, but it should not be too small to make the linear fit described below uncertain. Weighting these factors, we can establish a maximum rate of 1.2 10^6 counts per second. Sunrise should be preferred to sunset to better evaluate when this limit is reached and consequently not generate fatigue effects of the photomultiplier; as regards the observer's fatigue, moonlight can provide an alternative target . . . In any case, particular care must be taken to avoid expositions to very bright light sources. We have

$$N_l = \frac{n_l}{1 - n_l\tau} \qquad N_s = \frac{n_s}{1 - n_s\tau}$$

for the large and small diaphragm, respectively. In presence of a uniformly illuminated image (bright stars should be carefully excluded from the field of view), we can calculate

$$\frac{N_l}{N_s} = \alpha = \frac{n_l}{n_s}\frac{1 - n_s\tau}{1 - n_l\tau}$$

and by means of simple passages

$$\frac{n_l}{n_s} = \alpha + \tau\,(1 - \alpha)n_l.$$

In a n_l vs n_l/n_s plane the last equation represents a line: the ratio of the diaphragm areas α is the intercept, while the angular coefficient allows us to calculate τ.

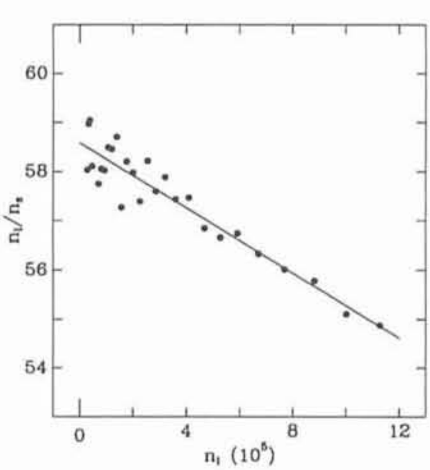

Figure 1.

Figure 1 shows the results obtained at the ESO 50-cm during sunrise on September 9, 1991 (B measurements carried out with an EMI 9789QB photomultiplier). The resulting value of the τ constant is 58 ($\pm$ 4) 10^{-9} s; a less precise, though in excellent agreement, determination (the maximum rate was only 5 10^{5} counts per second) was obtained on September 5, 1991: τ = 59 ($\pm$ 19) 10^{-9} s. The measure was repeated with the same instrumentation during sunrise on April 24, 1992, and the value of 58 ($\pm$ 6) 10^{-9} s was obtained.

These values are not much different from the value reported by the manufacturer (15 10^{-9} s): the 4:1 ratio causes deviations in limit cases only (0.005 mag between two stars with a luminosity ratio of 1:10 in the range $10^{4}-10^{5}$ counts per second). However, we notice that much larger deviations are expected for higher values of τ: if its value is 600 10^{-9} s, an underestimation by a factor 4 will produce a difference of 0.05 mag for the same two stars. Hence, the possibility of applying a well-determined value should not be overlooked by an accurate observer. This procedure also allows us to measure the area ratios with great precision: for example, in the figure the intercept value is 58.6 $\pm$ 0.1 (diaphragms # 1 and # 6).

Radioactive Isotopes of Cobalt in SN 1987A

I.J. DANZIGER, P. BOUCHET, ESO

The question of the main sources of energy input powering the late time (> 900 days) bolometric light curve of SN 1987A has continued to be debated up to the present time (> 1800 days). The nature of this energy input has been examined by determining by observational means the bolometric light curve and then comparing it with theoretical predictions. After day 530 when dust formed in the envelope most of the radioactive energy was released in the infrared region longward of 5 microns. This occurred because the optically thick dust proved very efficient at thermalizing the higher energy photons which emanated from the deposition in the envelope of γ-rays emitted as a result of β-decay of radioactive species.

Unfortunately, when the dust reaches a temperature of approximately 150° K, which it had by day 1316, the bulk of the radiation occurs at wavelengths longward of 20 microns, the longest infrared point measurable from ground-based observations. Thus astronomers using this technique are somewhat apprehensive about the accuracy of the derived bolometric light curve, for fear of course, that fitting theoretical black body temperatures and extrapolating into an inaccessible region may not account correctly for all the energy beyond observable reach.

The two groups studying this late-time behaviour, ESO and CTIO, have reported differences in 10 and 20 μ luminosities at approximately the same date (Bouchet et al. 1991; Suntzeff et al. 1991). In spite of these differences and the fact that they lead to somewhat different bolometric luminosities both groups agree that now there is radiation from SN 1987A in excess of what would be produced from the radioactive decay of ^{56}Co alone. Recently the CTIO group (Suntzeff et al. 1992) and others (Dwek et al. 1992) have ascribed this excess to the radioactive decay of ^{57}Co whose abundance would correspond to 4–6 times the amount expected on the basis of the solar values of the stable nuclides of mass 57 and 56. Other energy sources such as an embedded pulsar are also considered, but considerable weight is given to the fact that the observed light curves approximate in shape the decay curve of ^{57}Co with an e-folding decay time of 391 days.

The most direct method of determining the mass of ^{56}Co and ^{57}Co has been employed by the ESO group (Danziger et al. 1991; Bouchet and Danziger 1992) over the interval 200–600 days following the explosion. This involves the measurement of the Co II 10.52 μm line emitted in the nebular phase where the strength of this emission line is insensitive to temperature and comes from the predominant ion of cobalt during this time. This method allows the determination of ^{57}Co at much earlier epochs than the method based on the bolometric light curve, because at day 500 approximately half of the total mass of cobalt would be in the form of ^{57}Co even if the original 57/56 ratio were similar to that expected from the solar ratio of stable nuclides of the same mass. The detectable effect on the bolometric light curve occurs much later (> 1000 days) because ^{57}Co decays 3.5 times slower than ^{56}Co and also deposits lower-energy γ-rays in the envelope as a result of that decay.

At the Tenth Santa Cruz Workshop on Supernovae held in July 1989 (Woosley 1991), Danziger et al. (1991) announced that the ESO measurements pointed to an original ^{57}Co/^{56}Co ratio equivalent to 1.5 times the solar value of stable 57/56 nuclides. It was stated there and subsequently (Bouchet et al. 1991, 1992) that these results could not accommodate a value of this ratio as high as 4. In addition, this method also provided a determination of the original mass of ^{56}Co = 0.070 $M_\odot$ consistent with the value determined from the bolometric light curve by Suntzeff et al. (1991) and Bouchet et al. (1991) and others. This determination of the ^{57}Co/^{56}Co ratio was subsequently supported by the results of Varani et al. (1991) who used a near-infrared line of Co II at 1.5 μ, the effects of the temperature sensitivity on which were considerably reduced by comparison with an Fe II line of similar excitation level.

As a consequence of these observations the ESO group has always sought a different explanation for the excess in the bolometric luminosity at late times.

The other direct method to determine the mass of ^{57}Co (and also independently ^{56}Co) is to measure the flux of γ-rays produced by the radioactive decay. Because some γ-rays escape the envelope and some are absorbed to support the conventionally determined bolometric luminosity, the interpretation of any such measurement is somewhat model dependent. Nevertheless, the opacity of such an envelope to γ-ray penetration is thought to be well understood.

Therefore, it is of particular interest that recently, new results from the Oriented Scintillation Spectrometer Experiment on the Compton Gamma Ray Observatory have been announced by Kurfess et al. (1992) from observations made during the intervals days 1617 to 1628 and days 1767 to 1781. They report a detection of γ-ray emission from ^{57}Co in SN 1987A consistent with an original amount equal to 1.5 times the solar value of the ratio of stable 57/56 nuclides and inconsistent at greater than a 3σ level with a value of 5 times solar.

X-ray observations searching for comptonized γ-ray radiation (Sunyaev et al. 1991) from the KVANT-MIR Observatory had previously pointed to an upper limit of 1.5 solar.

One should note also that the most preferred values of the ^{57}Co/^{56}Co ratio