10. INVESTIGATIONS OF IMAGE DETECTORS

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The basic requirement of an astronomical radiation detector is that it should make the best possible use of the available photons collected by the telescope; more precisely, it should transmit a high proportion of the relevant information content of the photon distribution. The Cambridge work has been aimed at investigating, both theoretically and practically, the relative efficiencies in this sense of radiation detectors including the eye, photographic emulsions and photo-electric image tubes.

The high quantum efficiency, linearity, freedom from early overload, and simplicity of response of photo-electric surfaces are all favourable to informational efficiency, but photocells are severely limited by their inability to measure more than one intensity at a time. Hence, special interest attaches to photo-electric image devices.

A telescope of 100 cm. aperture collects about 500 photons/sec. from a star of 18^m. If these could be used to full advantage, they would yield $500 \log_2 e \simeq 700$ bits of information per second. But if it is necessary to measure quantities to '1% accuracy', and coding of the information ahead of the detector is not possible, the information rate is reduced to about 0·66 bits/sec. Measurement in three colours on this basis to 1% accuracy requires 1 min. of telescope time, and spectrometry of 1000 resolved elements to 1% requires 5 hr.

The rate of gain of information is further reduced by many circumstances. Aberrations and seeing effects reduce the information content of images. Systematic errors reduce the significance of measures. Point by point measurement of a spectrum makes use of much less than the full information capacity, both because of statistical correlations along the spectrum and because a great deal is known in advance about the possible form of spectrum. This inefficiency is especially marked when a whole spectrum is observed solely in order to determine radial velocity or spectral type. If the points of a spectrum, or the magnitudes in different colours, are measured one at a time instead of simultaneously, a further large reduction in the utilization of photons occurs.

In addition, radiation detectors respond effectively to only a fraction of the available photons. It is the ability of a detector to use a high proportion of these photons that is properly referred to as 'sensitivity'. Following Rose(1) the fraction of the photons effectively used is called the 'equivalent quantum efficiency' ϵ_e; more precisely, ϵ_e is defined as the ratio of the number of photons necessary in principle to make a given measurement, or record a given image, to the number that the detector actually needs in order to accomplish the observation. This measure of sensitivity is applicable both to single- and to image-detectors. For good modern detectors ϵ_e is of the order of a few per cent. For $\epsilon_e = 0{\cdot}01$ the time necessary to record 1000 spectral elements to 1% accuracy with a 100 cm. telescope working on an 18^m star becomes 500 hours. The time for 3-colour photometry is 10 min. for $\epsilon_e = 0{\cdot}1$, and nearly 2 hr. for $\epsilon_e = 0{\cdot}01$. It thus appears (in agreement with experience) that spectrometry is impracticable on an 18^m star with a 100 cm. telescope, but that 3-colour work may succeed if the photometer is carefully designed. It is interesting that a knowledge of the photon rates, of the amount of information in the observation and its coding, and of the equivalent efficiency of the detector, is sufficient to enable conclusions of this kind to be drawn.

In the examples we have discussed, it will be noted that the loss of information rate due to imperfection in the detector is less than 100 times, and the loss due to imperfect coding of data which are to be measured to 1% is nearly 1000 times. This illustrates the general conclusion that greater gains are possible in principle by increasing informational efficiency than by improving the sensitivity of present-day detectors. For this reason, considerable attention has been given at Cambridge to the design of observations. The 'multiplex' infra-red spectrometer(2) recodes the information in a way which allows all the spectral elements to be received by the detector simultaneously. The proposed 'radial velocity photometer'(3) aims at avoiding redundant measurement of spectral details known in advance, and at making full use of prior knowledge of stellar spectra in order to confine the information gained in the observation as far as possible to the actual parameters sought.

Although detector 'sensitivity' is only a means to the end of gaining information about the sky, it is nevertheless our main concern in this discussion.

The equivalent quantum efficiency is in general a function of brightness level, exposure time, image contrast and fineness of detail considered. Hence the order of merit of two detectors is not necessarily the same at all brightness levels, and in particular the 'faint limit' is not a reliable measure of the performance on brighter objects. The variation of ϵ_e for several detectors has been estimated by Rose(1) who finds that the eye, image orthicons and photographic emulsions all have maximum values of the order of $\epsilon_e = 0{\cdot}01$. The eye does not have an exceptionally high ϵ_e, but it is remarkable for the wide range (>15 magnitudes) over which its efficiency remains high. This fact suffices to exclude bleaching of visual pigment as a major mechanism of adaptation over this brightness range. Photography at constant exposure gives the sharpest fall of ϵ_e from its maximum value. A number of physiological data which we have studied appear to confirm the peak monochromatic value $\epsilon_e = 0{\cdot}01$ for the eye at normal brightness levels, rising to 0·05 towards 'threshold'.

The equivalent quantum efficiency of a photographic emulsion can be shown to be

$$\epsilon_e = \frac{\gamma^2}{G^2\,Q}, \tag{1}$$

where γ is the slope of the characteristic $D\,v\,\log Q$ curve, D is the density of the developed emulsion, Q the exposure in quanta/cm.^{2} incident, and the fluctuation of density in area A cm.^{2} is given by $\overline{\Delta D^2} = G^2/A$. For some emulsions the granularity can be estimated approximately by assuming that the grains occur at random and each have projected area equal to the mean value a. Then $G^2 = aD$ where D is measured in $\log_e$ units. This gives

$$\epsilon_e = \frac{\gamma^2 \log_{10} e}{a\,D_{10}\,Q}, \tag{2}$$

where D_{10} is in $\log_{10}$ units.

Equations (1) and (2) have been applied to data kindly supplied by Messrs Kodak, and indicate a peak monochromatic ϵ_e of 0·011 for a fast blue-sensitive emulsion having grains of mean projected area 1 μ^2. The peak occurs at $D_{10} = 0{\cdot}25$ above fog, and the total number $Q\epsilon_e$ of quanta which are effective reaches its maximum when $D_{10} = 0{\cdot}85$ above fog.

When the quantum characteristic curve and granularity are not known, ϵ_e can be estimated, making certain additional assumptions, from the formula

$$\epsilon_e = 200\,\frac{\gamma^2 R^2}{D_{10}\,Q}, \tag{3}$$

where R is the 'resolving power' in lines/cm. Peak monochromatic values estimated in this way for 1 sec. exposures lie in the range 2–5% for a wide variety of emulsions covering a range of 'speeds' in the ordinary sense of over 30:1. At 10^4 sec. exposure, the best emulsions appear, in agreement with experience, to be types II*a*–O and 103*a*–O for which $\epsilon_e \sim 3\%$. The numerical values of these estimates are not insisted upon.

The equivalent quantum efficiency of photo-electric image tubes can be estimated from the quantum efficiency of the cathode, the amount and randomness of electron multiplication, and the efficiency of signal evaluation. For an image orthicon with a Bi-Cs-O cathode having efficiency 0·07, multiplication in the image section of five times and fractional beam modulation 1/3, ϵ_e may be 1–2%. Photocathode-to-emulsion image converters may have ϵ_e values of 5–10%, allowing for the randomness of the blackening effect at the electron-sensitive emulsion.

Direct astronomical comparisons which we have made have generally confirmed that the eye, image orthicons and photographic emulsions have rather similar peak efficiencies.

At the brightness level most favourable to the image orthicon, the image on the monitor screen appears very similar to what can be seen directly in the eyepiece of the telescope used. We have found that the image orthicon can maintain high efficiency to smaller contrasts than can the eye.

Hiltner and Baum have reported in this Symposium estimates of $\epsilon_e \sim 0{\cdot}001$ for fast emulsions. However, their data agree well with our estimate $\epsilon_e \sim 0{\cdot}01$ when allowance is made for the difference between monochromatic and 'white light' values, for the distinction between root-mean-square and 'peak' noise, and for the distinction between the fractional error in the number of developed grains and the fractional error in the number of the photons which caused the grains to become developable.

An important apparent objection to believing that photography has an efficiency comparable to that of the eye is the difficulty of recording photographically what can be seen in the eyepiece. This difficulty may be in part due to the sharp dependence of the photographic ϵ_e on exposure. Moreover, equality of ϵ_e does not imply that a single photograph should be comparable with what can be gleaned visually over many hours. Photographs are often exposed to higher densities than the optimum. Emulsions have been improved from year to year, and older photographs do not represent the best that can now be done. In addition, some details seen visually fail to photograph because they do not exist. Taking all these factors into account, the apparent discrepancy seems to be accounted for, and some conclusions can be drawn as to the best methods of planetary photography.

Photographic reciprocity failure, although apparently a great hindrance to astronomy, is fundamentally necessary to protect the emulsion from fog resulting from thermal excitations during storage. For this reason, attention has been given to destroying this failure just before exposure, particularly by cooling. Argue (4) has obtained an increase in speed of 15 times for ½ hr. exposure by cooling HP3 plates with solid CO_2. However, some other emulsions appear to give smaller gains. Cooling may make it possible to use ordinary emulsions, including fine-grained types having good signal-storage capacity, in astronomical exposures.

Studies have been made of the technology of photo-electric image tubes with a view to understanding in more detail their possibilities and limitations. It is necessary to guard against the bias of the ordinary text-books towards the scanning and other standards of broadcast use. Many of the usual statements about storage, signal-to-noise ratio, scale effects, etc. need to be generalized for astronomical conditions.

It was decided to use image-orthicon camera tubes for experiments at the telescope. This choice was partly dictated by the desire to complement the excellent work on image converters in progress elsewhere. Some attention has been given, however, to the possibility of using image converters with storage phosphors as signal-generating tubes (5). We believe signal-generating tubes to have important advantages. They give rise directly to a wave-form which constitutes a measurement, whereas the output of image converters must be recorded and measured by a microphotometer in some manner. We have also found it a considerable advantage of television systems that the effects of adjustments are presented at once to the observer. The image orthicon has so far proved the most sensitive tube in practice, but the straight orthicon also deserves close attention. Redistribution effects make 'ionoscope' type tubes less suitable for astronomy. The intensifying image-orthicon reported in this Symposium by Morton is of great interest. Solid-state intensifiers are likely to become important.

The image-orthicon tests which we have made at the telescope date back to 1952, and an account of their history has been given elsewhere (6). These experiments have been made possible through the courtesy of Messrs Pye of Cambridge. Only frame times of 1/25 sec. or less have been available so far, and the objects viewed, which include the Moon, planets, and solar spectra, have been chosen to have a brightness which gives a good ϵ_e for this exposure time. With reservations, the results indicate the probable performance on fainter objects at longer exposure times. It has been confirmed that under favourable conditions the image orthicon can work with shorter exposures than photography, and can record more detail through seeing disturbances (5). Tubes with wide target-mesh spacings are best for planetary work. A good match between optical resolving power and the resolution of the tube is often attained with imaging at $f/40$ to $f/90$. A focal ratio of about $f/150$ is theoretically necessary to record all the detail that the optical image can contain.

The general conclusion from the work is that photo-electric image devices have great potentialities as primary receivers of radiation in astronomy. Nevertheless, photography, properly understood and used, can probably yield equivalent quantum efficiencies of over 1% and, consequently, the gains from photo-electric devices are likely to be useful rather than spectacular. Larger gains may be possible by improved design of observations.

REFERENCES

(1) A. Rose, *Advances in Electronics*, ed. Morton. Academic Press, N.Y. (1948), pp. 131ff.
(2) P. B. Fellgett, Proc. Columbus Symposium on Spectroscopy (Columbus, Ohio, 1952). Paper I, 1.
(3) P. B. Fellgett, *Optica Acta*, **2**, 9, 1955.
(4) A. N. Argue, *Observatory*, **74**, 213, 1954.
(5) P. B. Fellgett, *Vistas in Astronomy*, ed. A. Beer. Pergamon Press, London (1955).
(6) P. B. Fellgett, Proc. Manchester Symposium on Astronomical Optics. North-Holland Publishing Co., Amsterdam, 1956.

OTHER PAPERS AND DISCUSSION

Among the informal reports of research presented during the afternoon session, five are summarized on the preceding pages in papers **6**, **7**, **8**, **9** and **10**. The others, for which no manuscripts were prepared, included discussions by Morton, Lallemand, and Hiltner.

Dr Morton described in more detail some of the technical problems encountered in image tubes of the electron-storage type (see review paper no. 2) at the Princeton R.C.A. Laboratories. Among other things, he referred to a special orthicon-like tube in which a uniform background could be continuously removed at the same time as the signal was being accumulated. The electron-storage target of this tube consisted of an inner mesh conductor which was covered with an insulator of suitable leakage resistance and then with a conducting material in the interstices of the mesh. Under the action of an applied potential, a constant leakage current could be made to cancel background charges at the same rate as they were produced. Fellgett, however, questioned whether the weight given to a photo-event is truly independent of its time of occurrence.

There was a discussion (Morton, Redman, Hiltner, Fellgett, Ring) as to the practical importance of secondary multiplication of internal pre-target intensification of the signal in orthicon-like systems. Morton described the phosphor-photocathode intensifying pellicules used in the intensifier orthicon. P16, P11, and a special Ag-activated ZnS are used in conjunction with a cesium-antimony photocathode.

In response to questions raised by Hiltner regarding field emission, ion currents, and the possible advantages of excluding cesium, Morton described the means of reducing field emission, the use of a cooled charcoal trap to improve the vacuum, and the exclusion of cesium from unwanted areas.

In conclusion, Morton told about some new photocathodes recently developed at R.C.A. by A. H. Sommer (*Rev. Sci. Inst.* **26**, 725, 1955). These 'multi-alkali' cathodes, Sb-K-Na-Cs, are not only more sensitive than cesium-antimony cathodes, which have heretofore been the best available, but they maintain high sensitivity all the way from 3000 Å to 8000 Å. This is a development of far-reaching astronomical importance.

Prof. Lallemand showed again some of the slides used in his review paper in the