close to 100%, and the use of Eastman 103*a*-O emulsion. Owing to the proximity of the city lights of Los Angeles and Pasadena, the two Mount Wilson telescopes (represented here by the crosses) never actually reach the extrapolated thresholds necessarily assigned to them in this diagram. Although it is difficult to specify saturated thresholds with any precision, the results here seem to be nicely consistent with theory. It is certainly evident, for example, that the line of slope 5, representing the conventional 5 log f dependence for small telescopes, is grossly in error if extrapolated by the dashed line to long focal lengths. According to theory, the 2·5 log f dependence should commence when the focal length becomes long enough for the minimum image diameter to be determined mainly by seeing rather than by the resolving power of the emulsion, and this is indeed just what we observe.

Not only are we already up against the statistically saturated case in conventional photography, but we shall also need to beware of it in predicting the performance of image-tube systems. Merely increasing the quantum efficiency q of the receiver without increasing its storage capacity will gain *nothing* toward discriminating fainter images against the sky; an increase in q is only a practical convenience which (through method *a* or method *b*) makes the storing of more information feasible within reasonable exposure times. In principle, we should be able right now with no intensifying system to place a very fine-grain plate at the prime focus of the 200 in. telescope, expose it night after night to the same field, and eventually reach the same threshold of detection which an image-tube system would yield if its output were registered by method *a* on the *same plate*. In practice, of course, reciprocity failure and the cost of telescope time would make such a procedure abortive.

Another limitation is encountered if a photographic emulsion is used for registering a photo-electric image by method *a*, as, for example, in Prof. Lallemand's system. If electrons strike the emulsion with an energy of several kilovolts, they will produce the order of one blackened grain per electron, but they will not penetrate more than a few per cent of the thickness of a typical emulsion. Consequently, the maximum photographic density which can be produced by low-energy electrons is very low; it is scarcely more than the sky background density which one would like to attain in order to approach the limit set by statistical saturation. This means, of course, that the contrast between images and sky, even for bright stars, would be very weak. If electrons are accelerated to higher energies so that they penetrate deeper into the emulsion, they each expose several grains instead of one and they thereby use up the additional storage capacity made available to them without actually storing more information. As a consequence, the emulsion approaches statistical saturation sooner and with a less favourable noise level. One must therefore compromise between the desire to produce a reasonable range of densities and the desire to utilize as much of the storage capacity of the emulsion as possible before being limited by statistical saturation.

To summarize: the image-discrimination threshold of a picture-receiving system is readily predictable on the basis of known parameters. The roles played by the quantum efficiency and the storage capacity of the system are of primary practical importance in seeking a fainter threshold. Photo-electric image tubes offer very bright hopes for the future of this problem, and there are two general methods (*a* and *b*) by which the advantages of image tubes can be utilized.

4. IMAGE CONVERTERS IN STELLAR SPECTROSCOPY

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This paper is concerned primarily with the applications of image tubes to astronomical spectroscopy. The image tubes we now visualize may have their most extensive applications in that field. In this discussion we shall make the implicit assumption that a practical and efficient image converter or image-storage device is a reality and then explore the methods of application and the uses of such a device. To make such an assumption is in some respects equivalent to imagining that all photographic emulsions have suddenly become many (up to 100) times more sensitive and that the reciprocity failure of these emulsions has ceased to exist.

To appreciate the cause for enthusiasm concerning image converters, let us briefly consider the following. Under optimum conditions, approximately $1\cdot5\times10^6$ quanta are required to expose the fastest blue-sensitive emulsions to a photographic density of 0·6 within an area 100 by 100 microns. This area, which is approximately the same as that covered by the projected image of the slit of a typical stellar spectrograph, will yield a measure of the light intensity with an accuracy of several per cent—say 2·5. However, if the receiver had been perfect, that is, if it had registered one unit of information for each quantum, only $1\cdot6\times10^3$ quanta would have been required to give the same accuracy. It follows, therefore, that present photographic emulsions, remarkable as they are, operate at an efficiency of the order of 0·1%. On the other hand, photocathodes in the photocells and photomultipliers that are now employed in astronomical research operate at an efficiency of 10% or more; that is, on the average, one unit of information is obtained for every ten photons. Hence, it is obvious that a large gain in the speed of collecting information may be had if photocathodes can be used in place of photographic emulsions to receive spectra. As stated earlier, we shall assume that the necessary technical developments can be made.

In addition to the increase in speed over present photographic emulsions and the removal of reciprocity failure, the image converter has one additional advantage. For the spectroscopy of faint sources, such as extragalactic nebulae, fast spectrograph cameras are needed. Since a magnification (or demagnification) can be introduced electronically inside the image converter, the effective speed of a spectrograph camera can be varied beyond the limits ordinarily set by optical design. For example, a normal $f/1$ camera can be used with an image converter having an internal magnification of one-fourth to convert an $f/1$ camera to $f/0\cdot25$.

Two types of photocathodes are now commonly employed in photocells and are also used in image converters: one is cesium-antimony, Cs_3Sb, and the other is cesium-oxide on silver, $[Ag]$–Cs_2O–Cs. The cesium-antimony cathode has a maximum sensitivity near 4000 Å, 50% of maximum at 5300 Å and 3100 Å, and 10% of maximum at 6100 Å. The cesium-oxide-on-silver cathode has a broad maximum near 8000 Å, with a useful range from 6500 Å to nearly 1·2 microns. It is to be noted, therefore, that two photocathodes bridge the spectral region from about 3000 Å to 1·2 microns, which is also the region available for photography. It should be emphasized, however, that a minimum of sensitivity occurs at about 6500 Å and that the peak quantum efficiency of the infrared photocathodes (cesium-oxide on silver) is only about 1%. Hence, there is room for much improvement in sensitivity in the longer wave-lengths of the visible spectrum and in the infra-red.

We noted above that approximately $1\cdot5\times10^{10}$ quanta were required to expose an area of 1 cm.^{2} on the fastest blue-sensitive photographic emulsions. Suppose an image converter of the type discussed by Lallemand is employed with an emulsion of the same 'graininess' as the fastest blue plates. Such an emulsion requires about $1\cdot9\times10^7$ electrons with an energy of 15 to 20 kV. to expose the same area to the same density. If a cesium-antimony cathode with a peak quantum efficiency of 13% (as quoted by Zworykin and Ramberg) is employed in the image converter, it follows that $1\cdot5\times10^8$ blue photons are required to produce the $1\cdot9\times10^7$ electrons which in turn produce the necessary exposure. Hence, when the image converter is employed, only $1\cdot5\times10^8$ photons are required to expose the emulsion, whereas $1\cdot5\times10^{10}$ photons are required to expose the same emulsion without an image converter. It is from such considerations that a gain of 100 in speed is anticipated. Of course, instead of realizing the full gain as a shortening of exposure time, one can alternatively use a fine-grain emulsion to obtain a better 'signal-to-noise' ratio. This will increase the exposure time, but will also give more information per unit area of the emulsion.

Consider the following example: a spectrum of a 19th-magnitude star is to be obtained with a dispersion of 500 Å/mm. at the 100 in. telescope. Assume that the slit has an area of two square seconds of arc, that all the stellar radiation enters the slit, and that the magnitude of the moonless sky is 22·0 per square second of arc. Also, assume 50% efficiency for the spectrograph and 0·15 mm. for the width of the spectrum. The 19th-magnitude star will produce approximately 25 photo-electrons per second per 1000 Å (blue). The sky will produce approximately three photo-electrons per second for the same spectral region. It turns out that about $5{\cdot}7\times10^4$ photo-electrons would be required to expose the emulsion to a density of 0·6 and that the resulting exposure time would be 34 min. This figure is to be compared with an exposure of the order of 4000 min. (assuming no reciprocity failure) if unaided photography were used.

Unfortunately, this increase in speed of the order of 100 cannot, with present cathodes, be achieved at all wave-lengths. The cesium-oxide-on-silver cathode at its optimum wave-length (8000 Å) is about 40 times less efficient than the cesium-antimony cathode at 4000 Å, while the fastest infra-red photographic emulsions are only four times less sensitive than blue emulsions. Consequently, a gain of only 10 can be anticipated at 8000 Å unless more efficient infra-red-sensitive cathodes are found. Beyond 8000 Å, however, infra-red emulsions decrease in sensitivity much more rapidly than the cesium-oxide-on-silver cathode so that a gain of 100 again appears realistic at 10,000 Å.

Second in importance to the speed of an image converter is the resolution of such a device. If all photo-electrons were ejected from the cathode with the same velocity normal to its surface, an electron lens employing perfectly uniform magnetic and electric fields would yield a final image having the same resolution as the original optical image incident upon the photocathode. Actually, however, the photo-electrons are ejected with an energy spread of about 1 volt, which results in a loss of resolution. The diameter of the diffusion disk is given by $D=(V_0/V)\,d$, where V_0 is the normal component in the range of ejection energies, V is the accelerating potential, and d is the separation between the photocathode and the surface upon which the electron image is formed (the photographic emulsion in Lallemand's converter or the target in an image orthicon). For a typical image converter, $d\sim150$ mm., $V\sim15{,}000$ volts, and V_0 is assumed to be about 1 volt; then $D\sim0{\cdot}01$ mm. It appears, therefore, from this specific example, that sufficient resolution can be built into image converters. This figure represents the maximum theoretical resolution under the above conditions and it has been approached in actual production.

The size of the sensitive area will depend partly upon the type of image tube that proves most practical in the future. Nevertheless, a few general statements can be made. At present the photocathodes of image converters have a maximum diameter of about 30 mm. Image converters with larger cathodes can no doubt be made, but it is unlikely that image-converter cathodes with one linear dimension in excess of, say, 75 mm. will be constructed in the immediate future for astronomical applications. This finite size of the cathode handicaps the application of these tubes to dispersions higher than about 15 Å/mm.; multiple exposures will be necessary unless only a restricted wave-length region is of interest. However, high dispersion spectrographs of the future may employ an echelle in order to concentrate the spectrum on a rectangular area.

A photocathode is continuously ejecting electrons even when no radiation is falling on it. This thermal emission of electrons tends to fog the final picture and to reduce the contrast. If the exposure is short, the ratio of thermal electrons to photo-electrons will be sufficiently small so as not to be significant. A typical cesium-antimony cathode yields about 200 thermal electrons per sec. per cm.^{2} at room temperature. If the maximum allowable ratio of thermal electrons to photo-electrons is denoted by A, it follows that the maximum exposure time will be $A(N/n)m^2$, where N is the number of electrons required to expose 1 cm.^{2} of the emulsion to the density desired, n is the number of thermal electrons per sec. per cm.^{2} at the photocathode, and m is the magnification from photocathode to emulsion. Assume, for instance, that $A=0{\cdot}01$, $N=1{\cdot}9\times10^7$ electrons per cm.^{2} at the emulsion (as noted before), $n=2\times10^2$ thermal electrons per sec. per cm.^{2}

at the photocathode, and $m=1$. It follows that the maximum allowable exposure is about 1000 sec.

The maximum exposure time set by thermal electrons can be increased by a factor of 100 by reducing the temperature to that of solid CO_2, namely, -80°C. The refrigeration of photocathodes is already common practice in photo-electric photometry. Since the thermal emission of cesium-oxide-on-silver photocathodes (sensitive to the infra-red) is much greater than that of cesium-antimony cathodes, refrigeration is certain to be essential wherever infra-red cathodes are employed.

It is obvious from the preceding two papers that image tubes will be considerably larger and heavier than typical plate-holders for a spectrograph. The image converter with plate-exchanger as under development at Yerkes Observatory has a weight of about 5 kg. plus refrigeration equipment that may add another 2 kg. Overall dimensions are of the order of 20 to 30 cm. While some spectrographs would need to be considerably redesigned to accommodate heavy and bulky loads of that type in place of conventional plate-holders, others such as the Cassegrain spectrograph at the McDonald Observatory and the coudé spectrographs elsewhere can adapt an image converter with only minor alterations.

The adaptation of image converters to small fast spectrograph cameras should not be difficult if one additional reflection is introduced. Then the cathode can be placed either at the centre of the mirror or at the side of the optical bundle. With a design of this type, the whole camera in some cases may have to be refrigerated. As pointed out above, the image converter provides an independent means of altering the speed of a camera by electron-optical demagnification.

If the anticipated gain of image tubes can be realized in practice, the new fields of research open to the stellar spectroscopist seem limited only by the imagination of the observer. One obvious field of application is the observation of red-shifts of faint extragalactic nebulae where the discrimination of the nebular spectrum from that of the night air-glow must be improved. Other obvious applications include higher dispersion spectra of moderately faint objects (particularly in the infra-red region), low-dispersion spectra of stars which are too faint to be reached by present conventional methods at all, and the spectroscopic observation of rapidly varying phenomena. The two-dimensional spectral classification of stars down to 16th or 17th magnitude should provide opportunities in the study of galactic structure not dreamed of a decade ago. The classification and analysis of spectra might even be extended to the brighter stars of neighbouring galaxies.

In some applications, such as high-dispersion spectra, the full gain of 100 in speed can be anticipated, but in some other applications, such as the determination of line intensities or the discrimination of nebular spectra, the gain manifests itself as a ten-fold (square root of 100) increase in accuracy or detectability. In any case, it appears to be a safe prediction that image tubes will stimulate new life in stellar spectroscopy.

5. THE APPLICATION OF IMAGE TUBES TO THE PHOTOGRAPHY OF PLANETS

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The advantages of photographic observations over visual observations are unequivocal in such fields as astronomical photometry and spectroscopy, but up to the present time it has been impossible to record photographically all of the fine detail of planetary features which the human eye has been able to detect. In the case of the planet Mars, for example, the failure of photographs to record the detail which can be observed