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ASTRONOMICAL PHOTOGRAPHIC RECORDING WITH AND WITHOUT ELECTRONIC LIGHT INTENSIFICATION

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The use of light amplifying systems for astronomical purposes has increased steadily during the past few years (Felgett, 1955; Gebel, Devol and Wylie, 1959; Hiltner, 1955; Lallemand, Duchesne and Wlerick, 1958; McGee, 1955). In view of questions that will arise, it appears worthwhile to analyze the limits attainable (1) by conventional photography, (2) by using grain counting for examination of a photograph, (3) by photography utilizing image converter intensification, and (4) by closed-circuit television type optical amplification, for obtaining photographs of faint celestial bodies, having an apparent magnitude comparable to that of the sky background. The factors determining the ability of these methods to detect celestial bodies are examined and since some of the factors depend on quantum statistics, the light flux is expressed in quanta throughout the paper. For determination of the statistical limitations the number of grains or electrons caused by star radiation per resolution element is compared with the number caused by the background radiation for an equal sized element. Some of the equations derived are approximations, because in this field of endeavor it is hardly possible to obtain precise equations considering all the existing factors, which are often uncontrollable and difficult to determine. Differences in color temperature of the radiation from a star and from the sky background, and failure of the photographic reciprocity law are neglected. For mathematical simplicity a rectangular intensity distribution for the star image is being substituted for the actual graded distribution where the two have the same volume. Some of the technical details involved are not further explained, since the treating of the mechanism of techniques is not the purpose of this paper.

SOME BASIC EQUATIONS

Quanta Supplied by Star

Under optimum conditions, a celestial body of apparent magnitude M , having the color temperature of the sun, will cause the arrival at normal incidence at the earth's outer atmosphere of an average number of quanta of light q per mm^2 per sec, where

$$q \approx \frac{2.7 \times 10^4}{2.512^M} \approx 2.7 \times 10^{(4-0.4M)} \quad (1)$$

counting all the quanta between 0.415 and 0.670 μ , which is essentially the visual range (Gebel, 1958).

If we define Q as the average number of quanta of light from the celestial body

arriving at the photosensor, that is at the photographic emulsion or photocathode in any of the systems of figure 1, in time t in seconds, we find:

$$Q \approx q \frac{\pi}{4} D^2 \eta t \approx 2.1 \times 10^{(4-0.4M)} D^2 \eta t \tag{2}$$

where D is the objective diameter in mm and η the transmission coefficient of the telescope and the atmosphere.

Quanta Supplied by the Background of the Night Sky

In analyzing the performance capability of any of these systems the background radiation of the night sky must be taken into account (Baum, 1957). The quanta of light received from this background can be computed on the basis of observations made with the 200 in, 15 m focal length telescope at Mt. Palomar. Here the size of the star image is determined by the "seeing," that is by the enlargement and the jittering motion of the image resulting from inhomogeneities and fluctuations of the atmosphere in the light path. Under favorable seeing conditions the star image produced by the Mt. Palomar telescope has a diameter of 0.1 mm, and the sky background radiation within an equal area is approximately equivalent to that from a star of the twenty-second magnitude (Ovenden, 1956). Hence, according to Eq (2), for the above situation the average number of quanta of light, Q_{bp} per mm² comprising the background radiation, received in the focal plane of the Mt. Palomar telescope, during t seconds exposure time is:

$$Q_{bp} \approx 2.1 \times 10^{(4-0.4 \times 22)} \times 5080^2 \cdot \left(\frac{\pi \cdot 0.1^2}{4}\right)^{-1} \eta_p \cdot t \approx 1.1 \times 10^5 \eta_p \cdot t \tag{3}$$

where η_p is the transmission coefficient of the Mt. Palomar telescope. If we use K^1 to account for the effects of geographic location, time and weather, then for any location and any telescope of focal length f in mm and time t in sec, we have:

$$Q_b \approx Q'_{bt} \approx \frac{1.1 \times 10^5 \eta_p}{\eta_p} t \left(\frac{15000}{f}\right)^2 \left(\frac{D}{5080}\right)^2 K^1 \eta \approx 9.7 \times 10^5 \left(\frac{D}{f}\right)^2 K^1 \eta \cdot t \tag{4}$$

where Q'_b is the number of quanta per mm² per sec from the background radiation, received in the focal plane.

THE CONVENTIONAL PHOTOGRAPHIC CASE (Fig. 1A)

The rate of arrival of quanta of light at the photographic emulsion, which in practice cannot be neglected because of failure of reciprocity at a low flux, is not considered in this analysis. It is assumed that the necessary time for sufficient exposure is available.

The probability of visually discriminating, in a developed photographic emulsion, between those resolution elements representing the star and those representing the background area is in the end basically determined by the ratio r of the flux of light received from the celestial body by each resolution element of the star area to the flux of light received from the sky background by each resolution element constituting the background area. Thus

$$r = \frac{Q R}{K^n Q_b} \tag{5}$$

where $K^n \cong 1$ and is the number of resolution elements of the photosensor covered by the image of the celestial body and R is the number of resolution elements per square millimeter, as determined by the optical system. Under optimum conditions the diameter of a resolution element is that of the disk of the diffraction pattern and R then depends on f . Obviously, the smallest effective size of a resolution element cannot be as small as one photographic grain, because of the initial background grains present in any emulsion and because of limitations

imposed by laws of statistics, which require a size permitting a considerable number of grains, depending on the contrast. For this reason, in astronomy, to obtain optimum performance the effective focal length of the optical system is arbitrarily increased beyond its initial length in order to increase the effective size of a resolution element to a desired value (Baum, 1957). For different emul-

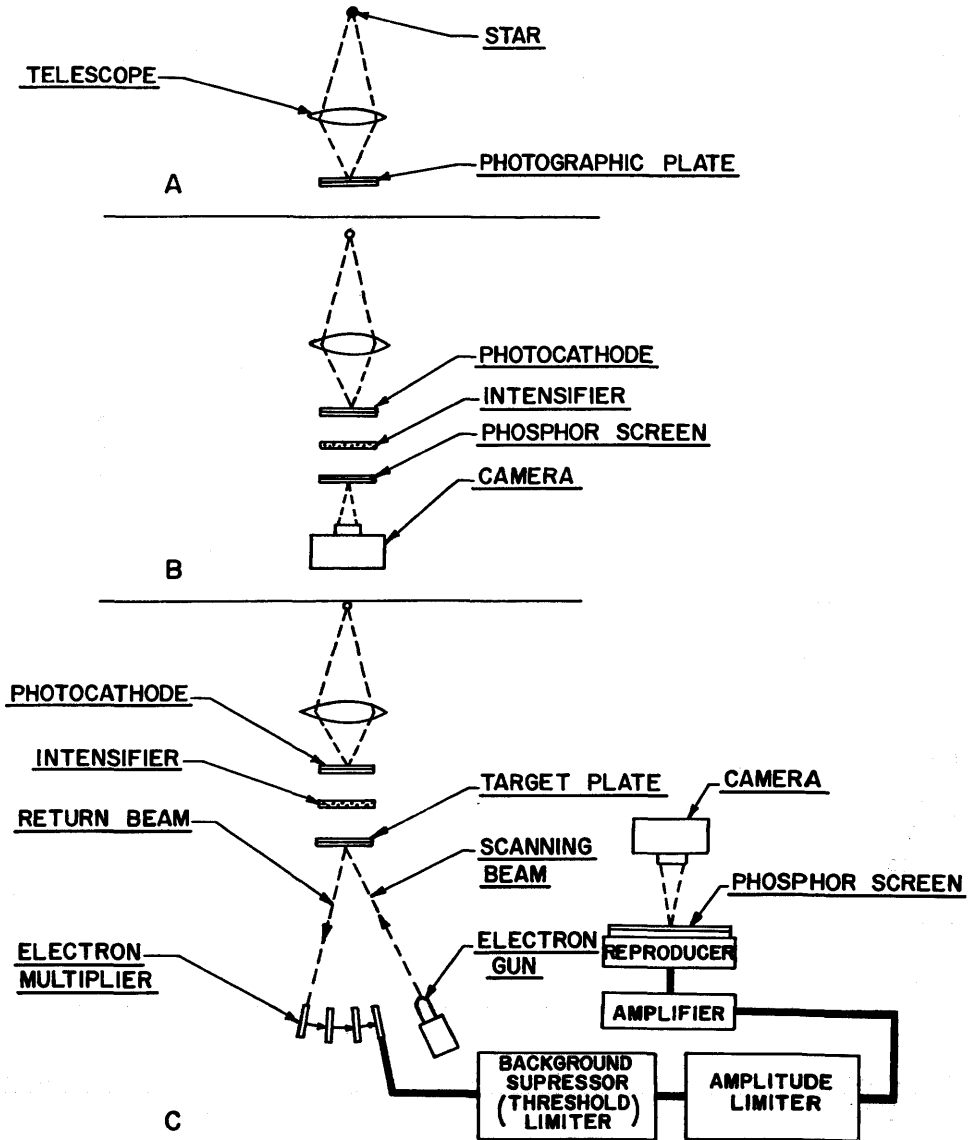


FIGURE 1. Basic schematics of recording systems.

sions and installations the smallest value of r that can be utilized, r_{min} , must be determined experimentally. If abundant exposure time is available, then a very fine-grained photographic emulsion can be used, which permits recording of small brightness differences. Here r_{min} may not be determined by the photographic

emulsion, but by the threshold in contrast discrimination of the human eye, which can detect, under the most favorable conditions, a contrast of about 0.02, giving r_{min} approximately the same value. If however the available exposure time is adequate only for a large-grained sensitive photographic emulsion, then the insufficient number of grains obtained may make, for statistical reasons as discussed in the grain counting section, photographic records impossible for r_{min} as small as 0.02. In this case the factor determining the value of r_{min} is the number of grains developed per resolution element rather than the threshold in contrast discrimination of the human eye. In such a situation the insufficient number of grains may require a value of r_{min} as large as 0.2 (Guderley and Lum, 1960).

From Eqs (5), (2), and (4) we find

$$\frac{2.1 \times 10^{(4-0.4M)} D^2 \eta t}{K''} =_{r_{min}} \frac{9.7 \times 10^5 D^2 K' \eta t}{R f^2} \tag{6}$$

Hence the limiting value M_L of the apparent magnitude of the celestial body that can be detected under the previous assumption is

$$M_L \approx 2.5 \log \frac{2.2 \times 10^{-2f^2 R}}{K' K'' r_{min}} \tag{7}$$

For a given system the terms f , R and K'' in Eq (7) are constants, and are related to each other. Assuming that any exposure time may be utilized, the faintest apparent magnitude M_L of the celestial body that may be detected depends only on r_{min} and the environmental effects expressed by K' . As anticipated, Eq (7) does not contain the exposure time. Under optimum conditions R is inversely proportional to f^2 , so that an increase in the focal length does not change the value M_L of the celestial body that may be detected, assuming r_{min} remains constant. However, an increase in f often increases M_L because, for statistical reasons, a smaller value for r_{min} may become possible.

The apparent diameter D_i in mm of the image of the celestial body at the focal plane is given by:

$$D_i = \alpha f \tag{8}$$

where α is the angle in radians subtended by the image at the objective. For a star, α is determined by the apparent oscillation of the beam of light from the celestial body combined with any increase in its true angular size due to scattering or haze.

Evidently, since K''/R is the area at the focal plane covered by the scintillating image of the celestial body

$$K'' = R \frac{\pi}{4} D_i^2 \tag{9}$$

therefore

$$K'' = \frac{\pi}{4} R \alpha^2 f^2 \tag{10}$$

and, substituting this in Eq (7)

$$M_L \approx 2.5 \log \frac{2.8 \times 10^{-2}}{r_{min} K' \alpha^2} \tag{11}$$

It should be noted, however, since by definition K'' can not be smaller than 1, Eq (11) holds only when

$$\alpha \geq \frac{1}{(\pi R)^{1/2} f} \tag{12}$$

Further, α can not be smaller than the diffraction pattern of the telescope, so that, in accordance with the well known diffraction equation,

$$\alpha \geq \frac{1.22 \times 10^{-3} \lambda_{max}}{D} \tag{13}$$

where λ_{\max} is the longest wave length of the light reaching the focal plane, in microns.

A. Numerical example:

Let us assume that a celestial body is to be photographed with a 15 m focal length telescope, using a commercial, medium speed photographic emulsion with grains having a projected diameter of approximately 1μ , that the seeing conditions result in an image subtending 1.5 sec of arc, or 7.3×10^{-6} radians, and for the time and place, $K^1=1.3$. Also assume an effective resolution factor of $R=1000$ elements per mm^2 and $r_{\min}=0.16$.

Using Eq (10), the number of resolution elements covered by the star image is,

$$K'' = \frac{\pi}{4} R \alpha^2 f^2 = \frac{\pi}{4} 1000 (7.3 \times 10^{-6})^2 (15000)^2 \approx 10$$

and Eq (11) yields

$$M_L \approx 2.5 \log \frac{2.8 \times 10^{-2}}{0.16 \times 1.3 (7.3 \times 10^{-6})^2} \approx 23.5.$$

This agrees with the limiting performance of the largest telescope in recording faint stars by conventional photography.

COUNTING THE GRAINS IN CONVENTIONAL PHOTOGRAPHS

Instead of visually perceiving the image of the celestial body by examining the photograph, grain counting or electronic translation may be used to establish its existence (Gebel, 1958).

The number of grains developed as a result of the combined light from the celestial body and the background radiation varies in a random manner, and for conventional emulsions it takes approximately 1000 quanta of light to lead to the development of one photographic grain. Therefore, assuming ideal conditions, the deviations in the number of grains developed at different resolution elements, which are assumed to follow a Poisson distribution, become the controlling factor.

Under this assumption the standard deviation from the average for the number of grains developed at the different resolution elements is equal to the square root of the average. The probability p of detecting a celestial body depends on the ratio r_G of the average number of countable grains N_s developed by the light from the celestial body within each resolution element to the standard deviation of the number of countable grains N_b developed by the background radiation per resolution element. Then

$$p = f(r_G) \tag{14}$$

where

$$r_G = \frac{N_s}{N_b^{1/2}}. \tag{15}$$

It is common practice to assume that detection of a celestial body may be possible if $r_G \cong 1$. For the ratio r as defined by Eq (5), we may also write

$$r = \frac{N_s}{N_b}. \tag{16}$$

Then by substituting N_s from Eq (15) into Eq (16) we find

$$r = \frac{N_b^{1/2} r_G}{N_b} = \frac{r_G}{N_b^{1/2}}. \tag{17}$$

Substituting r from Eq (17) for r_{\min} of Eq (11) we find for the grain counting device, as a theoretical limit under the previous assumptions,

$$M_L \approx 2.5 \log \frac{2.8 \times 10^{-2} N_b^{1/2}}{r_G K^1 \alpha^2}. \tag{18}$$

Further, if G_b is the maximum of the average number of countable grains per square millimeter of photographic emulsion which can be developed by utilizing optimum exposure time, A is the image area in mm^2 and, as before, the celestial body covers K'' elements of resolution we may write, using Eq (8),

$$N_b = G_b \frac{A}{K''} = \frac{G_b}{K''} \frac{\pi}{4} \alpha^2 f^2. \quad (19)$$

Substituting this in Eq (18) we find, for the value of the apparent magnitude of the faintest detectable star,

$$M_L \approx 2.5 \log \frac{2.5 \times 10^{-2} G_b^{1/2} f}{r_G K' K''^{1/2} \alpha}. \quad (20)$$

Obviously, in Eq (20) the value of M_L that may be detected must increase with G_b since this is the maximum number of countable grains which can be developed. For a fixed value of K'' and value of M_L also increases with f , because the larger area covered by the image of the celestial body results in a proportionally larger area for each resolution element and therefore a larger number of grains which can be found in each element.

B. Numerical Example:

Assume that the photograph obtained in numerical example A is evaluated by counting the grains. The emulsion was exposed to such an extent that 5×10^6 countable grains per mm^2 from the background radiation have been developed. Then if we select $r_G = 4$, the limiting apparent magnitude detectable by grain counting, using Eq (20), is

$$M_L \approx 2.5 \log \frac{2.5 \times 10^{-2} (5 \times 10^6)^{1/2} \times 15000}{4 \times 1.3 \times 10^{1/2} \times 7.3 \times 10^{-6}} \approx 24.6.$$

PHOTOGRAPHY ASSISTED BY THE IMAGE CONVERTER SYSTEM

In the image converter system, figure 1B, the image is focused onto a photocathode, and the emitted electrons are accelerated by an electrostatic field, multiplied by the intensifier screen and again accelerated and imaged onto the phosphor screen, from which the star image is photographed. Different types of intensifier screens are possible (Morton, Ruedy and Krieger, 1948; Wachtel, Doughty and Anderson, 1958). One type of converter uses an intensifier screen consisting of a thin phosphor layer which emits light when struck by the electrons and a contiguous photocathode which reconverts this light into electrons. The intensifier screen may be omitted if only a low intensification is needed. Alternatively, several intensifier screens may be used in series; some existing arrangements give an intensification of the order of 100,000 (McGee, Flinn, and Evans, 1959). At 300°K the dark current for commercially available image converter tubes is approximately equivalent to 5×10^{-8} ft-c photocathode illumination; for detection of a comparable illumination from the scene, the tube must be cooled. If we assume ideal conditions, namely that the system has a linear characteristic and that the contrast reducing effect of the photocathode dark current is avoided by cooling. Eq (7) and Eq (11) may be applied here also for obtaining photographs of celestial bodies for visual examination.

Then the advantage of using the image converter system consists of shortening the exposure time, avoiding the effects of failure of the photographic reciprocity law under some conditions in which this law would apply for conventional photography, and permitting the use of finer grained, but slower speed, photographic emulsions. The use of finer grained emulsions makes it possible to record smaller brightness differences, and when visually observing the photograph, to reach the threshold in brightness discrimination of the human eye (Gebel and Devol, 1961).

C. Numerical Example:

Assume the same telescope and the same atmospheric environment as used in numerical example A, with a light intensifying image converter tube capable of producing an effective gain in the photographic speed of 500. This makes possible use of a finer grained, but slower photographic emulsion with grains of 0.2μ projected diameter, a speed of about 2 ASA and $t_{\min} \approx 0.04$. Then, using Eq (11)

$$M_L \approx 2.5 \log \frac{2.8 \times 10^{-2}}{0.04 \times 1.3 (7.3 \times 10^{-6})^2} \approx 25.$$

THE SCANNING TYPE ELECTRONIC OPTICAL AMPLIFIER WITH A HIGH CAPACITY STORAGE TARGET PLATE

In figure 1C, the same photocathode and possible intensifier are shown as in figure 1B, but a target plate replaces the phosphor screen. Each electron striking the target plate ejects several electrons, and the positive charge image thus produced is stored and later neutralized by the necessary number of electrons from the scanning beam. The resulting variations in the return beam are amplified and modified electronically to produce a picture on the phosphor screen of a cathode ray tube reproducer.

To obtain the ultimate performance from such a system, it is necessary to abandon the continuous scanning customarily used in television. With the scanning beam turned off, the charge image is permitted to build up on the storage target plate in the pick-up tube used in this system, during a selected exposure time, which may be as great as an hour. The image is then removed by a single scanning operation and transferred to a storage reproducer, where it is displayed long enough to be photographed, and to be examined visually if desired (Gebel, 1961).

If a conventional linear electronic system is used for amplification and reproduction, the effect will be precisely the same as in the case of the image converter; however, when using a non-linear system, then by electronically suppressing a constant portion of the background signal and thus enhancing the contrast, we can detect visually from the reproducer screen star images otherwise impossible to perceive, because of the contrast threshold of the unaided human eye.

Since it is usually a constant portion of the background that is suppressed, the variations remain to be dealt with (Gebel, 1961). Even if the background brightness of the scene is uniform, deviations in the number of quanta or electrons in different resolution elements will occur as a result of random fluctuations in a number of items, as follows: (1) the number of quanta of light arriving during the exposure time at any resolution element of the photocathode which constitutes the original detector, (2) the number of electrons emitted by the primary photocathode at any resolution element, and (3) each other conversion taking place after the primary photocathode, but these may be neglected in a well-designed system. Irrespective of the origins of the deviations, the effect of electronic suppressions of a substantial portion of the background signal and the consequent contrast enhancement will be as illustrated in figures 2A, B, C and D, which show the intensity of one scanning line when sweeping across the target plate.

By suppression of a fixed amount from the electrical signal we may remove most of the background effects from the picture, as shown in 2B. Suppression of a larger amount of the signal can remove nearly all of the variation in it, over the area outside the boundaries of the image, as shown in 2C. Also, it is possible, by an amplitude limiting circuit, to remove most of the variations in the signal over the image of the celestial body itself, leaving the nearly perfect signal shown in 2D. The effects of electronic suppression are shown by figure 3.

In treating the performance capabilities of this kind of amplifier we take into account the effect of the dark current coming from the photocathode, which was

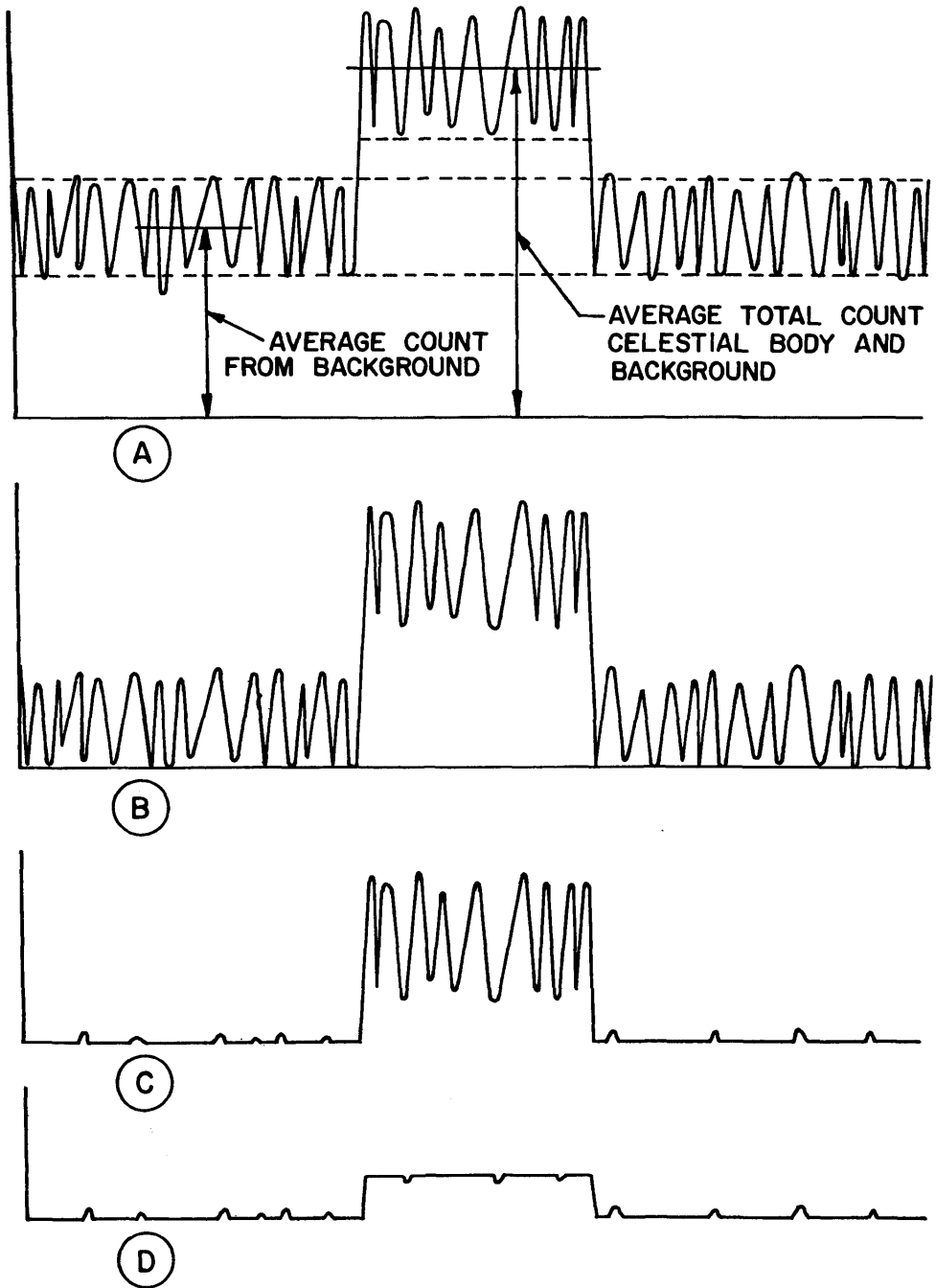


FIGURE 2. Successive modification achieved by electronic suppression.

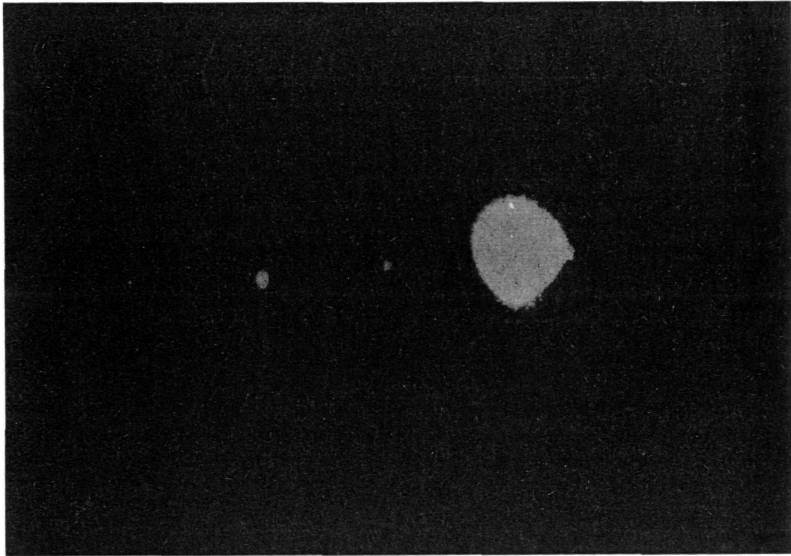
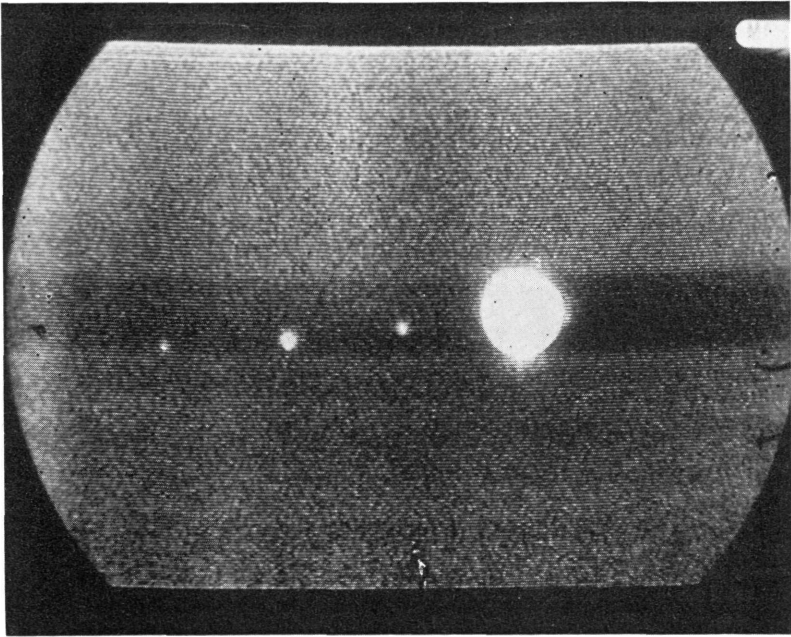


FIGURE 3A (top). Jupiter and four moons, taken at Wittenberg with a television type recording system in $1/25$ sec, showing effects of background fluctuations by suppressing at level as in figure 2B. Fluctuations in high lights not seen because of over exposure.

FIGURE 3B (bottom). Jupiter and four moons, $1/25$ sec exposure time, showing a more complete electronic suppression of the fluctuations using limiter action as in figure 2D.

referred to in the section dealing with the image converter. If the electron image has been intensified sufficiently by the time it reaches the target plate, the noise inherent in the scanning beam can be neglected. If I is the photocathode dark current emission in electrons per square millimeter per second, and η_c the efficiency of the photocathode, the effect of the dark current is equivalent to adding I/η_c quanta to the background. Since the quantum efficiency of the photocathode is considerably less than unity the statistical fluctuations in the photocathode emission substantially determine the limit in detection. The standard deviation σ_B which is the variation in photocathode-emission from the background plus the dark current is obviously

$$\sigma_B = \left(\frac{Q_b \eta_c + It}{R} \right)^{1/2}. \quad (21)$$

As explained before (Fig. 2B and 2C), it is possible to select an arbitrary threshold value and then to suppress any portion of the background signal or nearly the entire background signal including most of the variations in it. However, the variation given by Eq (21) represents the portion of the background signal from which it must be possible to distinguish the signal from the celestial body. In analogy with Eq (15), but taking r' as the ratio of the photocathode electrons per resolution element resulting from the light from the celestial body to the standard deviation of photocathode electrons from the combined background plus dark current per resolution element, we obtain:

$$r' = \frac{Q \eta_c}{K'' \sigma_B}. \quad (22)$$

The probability of detecting a celestial body is a function of the value of r' and, as in the photographic grain counting case, it is customary to assume that detection may be possible when $r' \cong 1$. Thus

$$\frac{2.1 \times 10^4 D^2 \eta \eta_c t}{10^{0.4M} K''} = r' \left(\frac{Q'_b \eta_c t + It}{R} \right)^{1/2}. \quad (23)$$

Hence,

$$M_L \approx 2.5 \log \frac{2.1 \times 10^4 D^2 \eta \eta_c R^{1/2} t^{1/2}}{r' K'' (Q'_b \eta_c + I)^{1/2}}. \quad (24)$$

Eq (24) is valid only as long as the device is capable of storing and integrating the charge image resulting from the photocathode emission. A sufficient number of quanta has to be collected to cause at least one photo electron or a certain number of photo electrons to satisfy r' . Thus, the exposure time must be chosen sufficiently long so that

$$\frac{2.1 \times 10^4 D^2 \eta \eta_c t}{10^{0.4M} K''} = Q_q \quad (25)$$

where

$$Q_q \cong 1 \quad (26a)$$

or

$$Q_q \cong r' \quad (26b)$$

which ever yields the larger value. Also, as in the conventional photographic case, the factors in this equation are not completely independent of each other; for example, a change in D or η will also affect Q'_b . The effect of the focal length is included in the term R .

Present high capacity target plate assemblies are capable of storing up to 1.8×10^{10} elementary charges per mm^2 (Gebel, 1961), which is approximately

equivalent to the storage capability of a photographic emulsion having grains with an average projected diameter of 0.1μ . Such an emulsion has a speed of only about 0.25 ASA. The photocathode used in the television device might have more than 150 times the quantum efficiency of such a photographic emulsion. Further, if the light flux is very weak the effective sensitivity will be reduced by failure of the reciprocity rule for photographic emulsions and, in addition recognition of the smallest brightness differences that are inherently detectable by such a film, as indicated by quantum statistics still require a complicated grain counting device. There is no failure of reciprocity at low light levels with photocathodes; under such conditions the quantum efficiency of the photocathode may be more than 500 times that of the emulsion. With the television type system, as a result of contrast enhancement and background suppression, any photographic emulsion, including large-grained emulsions, can be used to photograph images from the reproducer screen, of celestial bodies whose contrast with the sky background may be as low as the statistical fluctuations in the photocathode emission permit.

By substituting in Eq (24) the values of Q_b^1 from Eq (4) and K'' from Eq (10) we find

$$M_L \approx 2.5 \log 28 \left(1 + \frac{\frac{1}{I}}{9.7 \times 10^5 \left(\frac{D}{r}\right)^2 K' \eta \eta_c} \right)^{\frac{1}{2}} \frac{1}{\alpha^2 r^1 f} \left(\frac{\eta \eta_c t}{R K'} \right)^{\frac{1}{2}}. \quad (27)$$

For very large telescopes, or if the pick-up tube photocathode is sufficiently cooled, the term I may be neglected and the first parenthesis in Eq (27) becomes unity. Then, since f/D is the aperture number F of the telescope, we may write

$$M_L \approx 2.5 \log \frac{28}{r^1 F \alpha^2} \left(\frac{\eta \eta_c t}{R K'} \right)^{\frac{1}{2}}. \quad (28)$$

α in Eqs (27) and (28) is subject to the same restrictions as apply in the photographic case, Eqs (12) and (13). Also, the requirement of a minimum number of electrons applies here, as expressed by Eq (25). The target plate of the device is not capable of storing and integrating an infinite charge image resulting from the photocathode emission. The limiting magnitude that can be detected becomes increasingly faint, by the square root of the exposure time, until the charge limit is reached, making Eq (28) analogous to Eq (18).

D. Numerical Example:

Consider a closed-circuit television type light amplifier working with the same telescope and the same environment as in numerical example A. The primary photocathode of the pick-up tube is of the multialkali type with a quantum efficiency of $\eta_c = 0.15$. Also, $\eta = 0.5$, $D = 200''$. The aperture is then $F = \frac{f}{D} = 3$. To achieve an adequate probability of detection the numerical value of $\frac{1}{4}$ is chosen for r^1 . It is assumed that the storage target plate is of the high-capacity type and permits effective storage and integration for an exposure time of one hour; and also that the tracking of the telescope is accurate enough to keep the image stationary in the focal plane. The pick-up tube is an intensifier image orthicon and the scanning beam noise may therefore be neglected. The tube is sufficiently cooled to make the photocathode dark current negligibly small compared to the emission resulting from the sky background radiation. Only the resolution R of the optical system will be considered; it is assumed that the effective resolution of the light amplifier system is sufficiently better than R that it need not be considered. Using Eq (28) yields

$$M_L \approx 2.5 \log \frac{28}{4 \times 3 \times (7.3 \times 10^{-6})^2} \left(\frac{0.5 \times 0.15 \times 3600}{400 \times 1.3} \right)^{\frac{1}{2}} \approx 26.2.$$

CONCLUSIONS

The threshold in detection of faint celestial bodies in the presence of the sky background by visual observation of a photograph, using conventional photographic emulsions, is determined by either the properties of the photographic emulsion or the threshold in contrast discrimination of the human eye, whichever necessitates the greater brightness difference. A lower contrast threshold than perceivable by the unaided human eye can be attained by the use of a complex, opto-electronic counting device, which permits extraction of nearly all information resident in the photographic emulsion and its presentation in a new photograph. When an image converter tube is used to produce an intensified image for photograph, failure of reciprocity may be avoided, the use of a finer grained, but slower, emulsion is possible and, if the photocathode is cooled to substantially eliminate its dark current, a fainter celestial body may be detected under the same circumstances.

The closed-circuit television optical amplifier uses efficient background suppression and contrast enhancement, which is not possible with conventional photography or with a conventional image converter arrangement. Such a television system reproduces the viewed scene with an arbitrary contrast making possible visual observation and recording of scene brightness differences which are far below the threshold in brightness discrimination of the human eye. The statistical fluctuations in the combined photo-emission and photocathode dark current determine the theoretical limit for detection, and the detectable apparent magnitude increases almost with the one-half power of the exposure time. Practically, the limit for detection of such a device is determined by the maximum number of elementary charges that can be stored on the target plate.

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