An Apparatus for the Direct Determination of Slow Neutron Velocity Distributions

L. J. HAWORTH,* J. H. MANLEY, AND E. A. LUEBKE *
Department of Physics, University of Illinois, Urbana, Illinois
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Apparatus is described by means of which a modulated source of slow neutrons is produced and their intensity determined as a function of time. The deuteron beam of a high voltage tube is deflected by a modulated electrostatic field in such a way as to produce square bursts of fast neutrons of any desired length. After being slowed by hydrogenous material a selected beam of neutrons falls on a suitable detector at a measured distance from the source. Pulses from the detector are impressed on an oscilloscope screen, together with a sharply defined time scale and photographic records made. The time analysis of the neutron distribution is then made by a numerical count of the neutron pulses as a function of the time interval in which they occur.

METHODS for the direct determination of slow neutron velocity distributions are of extreme usefulness in determining the energy dependence of neutron reactions, particularly those involving resonance phenomena. Several investigators[1–4] have described such apparatus, that of Rasetti, Segrè, Fink, Dunning and Mitchell[1] being mechanical in nature, the others electrical. In each of the latter a burst of fast neutrons is created by allowing a beam of high energy nuclear particles to fall briefly on a target of suitable material. The neutrons are then slowed down by paraffin or other hydrogenous material and a selected beam is allowed to fall upon a detector at a measured distance from the source. Some method is incorporated for the determination of the number of neutrons reaching the detector in selected time intervals following the burst, the time intervals chosen being as short as is consistent with the neutron intensity available.

Alvarez[2] produced bursts of neutrons by modulating the oscillator voltage supply of a cyclotron with 60 or 120 cycle a.c., thus confining target current to a small part of the cycle. The counting interval was selected by a coincidence circuit rendered sensitive over any desired part of the cycle, the time being selected by a phase changing device.

Baker and Bacher[3] modulated the cyclotron source, producing better defined neutron bursts, and recorded the delayed neutrons by modulating the pulse amplifier in such a manner as to confine its output to the desired time interval.

Fertel, Gibbs, Moon, Thomson, and Wynn-Williams[4] (FGMTW) used a Cockcroft-Walton type linear accelerator and the D–D reaction, modulating the ion source. The time distributions of neutron intensities were obtained by photographing the screen of a cathode-ray oscilloscope with linear sweep on which the neutron pulses were impressed.

The following is a description of the application to the Illinois linear accelerator (see the preceding paper) of a method, similar to that of FGMTW, in which an attempt has been made to extend the accuracy and resolving power of the method to the farthest limit practicable with the available neutron intensity.

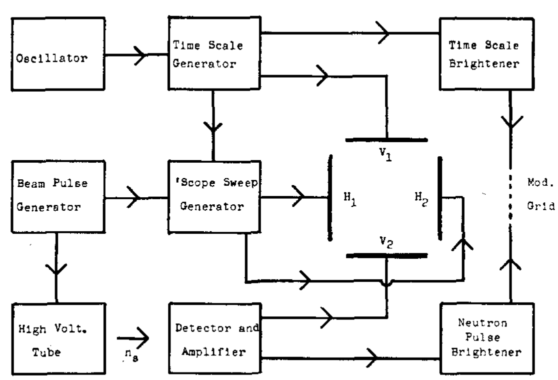
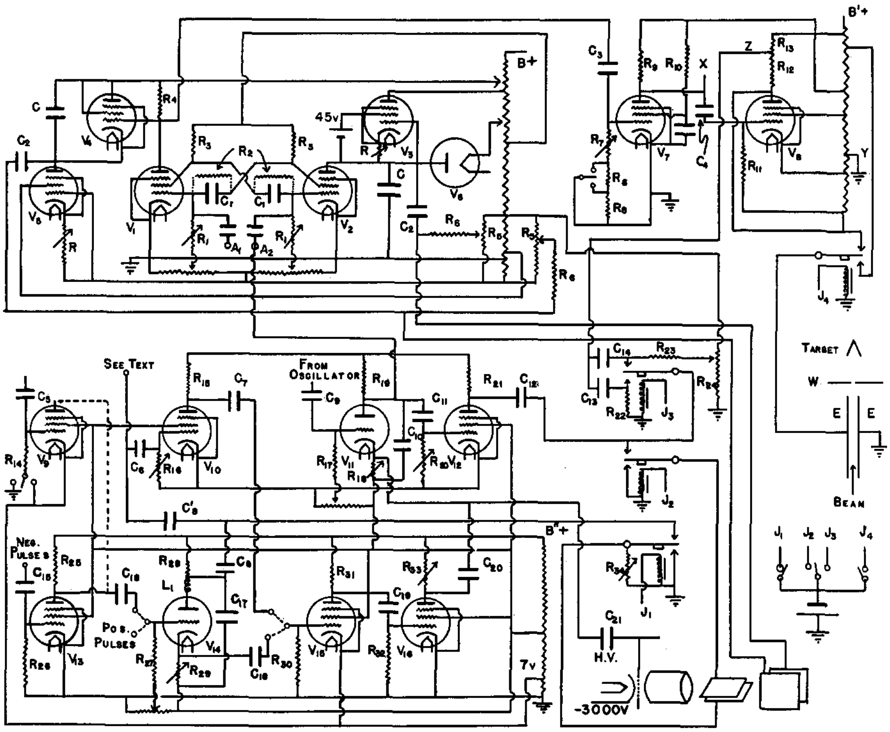


FIG. 1. Schematic diagram of apparatus.

* Present address: Radiation Laboratory, Massachusetts Institute of Technology.
[1] Rasetti, Segrè, Fink, Dunning, and Mitchell, Phys. Rev. **49**, 104 (1936).
[2] L. W. Alvarez, Phys. Rev. **54**, 609 (1938).
[3] C. P. Baker and R. F. Bacher, Phys. Rev. **59**, 332 (1941).
[4] Fertel, Gibbs, Moon, Thomson, and Wynn-Williams, Proc. Roy. Soc. **175**, 316 (1940).



V_1, V_2, V_4—6F6
V_6—80
V_8—6L6
V_{11}, V_{14}—884
All other tubes—6C6, 6J7G or equivalent
R_{18}, R_{29}—2.5 M
R_{10}, R_{13}, R_{33}—5 M
R_{12}, R_{15}, R_{20}—10 M
R_4, R_{21}, R_{31}—20 M
R, R_3, R_9, R_{16}, R_{19}, R_{21}, R_{33}, R_{34}—50 M
R_5, R_{24}, R_{25}, R_{26}, R_{27}, R_{28}, R_{30}, R_{32}—0.1 megohm
R_{14}, R_{17}, R_{22}, R_{26}—0.25 megohm
R_2—0.4 megohm
R_1, R_{11}—0.5 megohm
R_8—0.75 megohm
R_6, R_7, R_{23}—2 megohm
C, C_1, C_2, C_{10}, stepped
C_6, C_{11}—10 $\mu\mu$f
C_7, C_{18}—25 $\mu\mu$f
C_{13}, C_{15}, C_{16}, C_{19}—50 $\mu\mu$f
C_8, C_8', C_{17}—100 $\mu\mu$f
C_3, C_{12}—250 $\mu\mu$f
C_4, C_5, C_9, C_{20}, C_{21}—0.001 μf
C_2, C_{14}—0.1 μf
L_1—8 mh
J_1, J_2, J_3, J_4—relays
$B+$—500 volts
$B'+$—900 volts
$B''+$—350 volts

FIG. 2. Detailed circuit diagram. Filter networks are omitted for the sake of simplicity. Binding posts A_1 and A_2 are used when triggering the sweep circuit externally. See text.

APPARATUS

The electrical circuits are shown schematically in Fig. 1 and diagrammed in detail in Fig. 2.

In general the deuteron beam is deflected away from the heavy ice target and onto a tungsten plate W by a potential difference of several hundred volts between plates E_1 and E_2. At periodic intervals this potential is removed by a square pulse of controllable length developed in the deuteron "beam pulse" generator, thus allowing the beam to strike the target and produce a "square" burst of fast neutrons. This circuit is tripped by pulses from a trigger circuit forming an integral part of the oscillographic sweep generator, which thus determines the cyclical frequency of events. A master frequency, several times that of the neutron bursts, is generated in the stabilized audio-oscillator which serves to trip the time signal generator. The latter impresses linear time scale markings on the oscilloscope trace and also furnishes synchronizing pulses to the sweep circuit. The frequency of the master oscillator is chosen so that the time intervals marked on the oscilloscope are those into which it is desired to subdivide the neutron pulses being observed.

Neutron pulses produced in the detector are amplified by the appropriate circuits and impressed on the thyratron pulse sharpener which passes them on to the oscilloscope. The intensity of the pulse traces is increased by the "brightening" circuit so that they produce a photographic density comparable to that of the continuous baseline.

In the photographic record thus obtained each pulse is shown as a vertical line, lying in the interval corresponding to the time at which the pulse is delivered by the amplifier. (For a consideration of possible delays up to this point, see Discussion.)

The recording circuits, etc. are described in detail below. The sweep generator and the time scale circuit have been described previously by one of us (L.J.H.[5]) but brief descriptions are given here for completeness.

[5] L. J. Haworth, Rev. Sci. Inst. **12**, 478 (1941).

Master oscillator and time scale circuit

The master oscillator is of a standard stabilized type and is not illustrated in Fig. 2. Calibrated frequencies corresponding to time intervals of 50, 100, 150, 250 and 400 microseconds are available, selections being made by a rotary switch. The amplitude of the oscillator is increased by a one-tube amplifier which also serves as a buffer stage.

The Type 884 thyratron, V_{11}, is fired periodically by the signal from the oscillator. Negative pulses from its plate circuit are sharpened by pentode V_{12} and then impressed upon the oscilloscope plates to provide time scale markings. Because of the higher speed of the beam while tracing these lines some increase in intensity is necessary to make them comparable to the baseline proper. To accomplish this, positive pulses generated across the cathode resistor R_{18} are impressed on the modulator grid of the oscilloscope. Since the time constant of the cathode circuit is small, this pulse dies down almost immediately when the thyratron extinguishes. The brightening action therefore occurs only while the time scale pulse is rising, thus contributing to the effective sharpness.

The height of the time scale marks is controlled by R_{20} and their brightness by R_{18}.

Oscillographic sweep circuit

In general it is not desired to count the neutrons in all time intervals covering a cycle. For example, in many experiments one is not interested in the "tail" of very slow neutrons reaching the detector long after the original burst. In order to obtain the best available resolution on the oscilloscope screen it is therefore desirable that the unwanted intervals be not represented on the trace. This result is best accomplished by some sort of delayed action sweep. The circuit previously described[5] is of such a type.

The action of the circuit is best illustrated by Fig. 3 which shows the sweep voltage as a function of time. The triggering of the deuteron beam pulse is accomplished by a pulse from the sweep circuit at either t_1 or t_2. If at t_1, there is a controllable time delay from t_1 to t_2 before the sweep transit begins and the neutrons reaching the detector during this period are not recorded. The speed of the sweep then determines the interval $t_2 \rightarrow t_3$ over which the observations are made, following which there is a second delay until a new cycle begins at t_1'. If, on the other hand, the deuteron beam is triggered at t_2, the record begins immediately and all delay is subsequent to the sweep. Since it is often advantageous to be able to observe the length of the beam pulse on the screen, we have usually used the second described procedure. The connections in Fig. 2 are arranged accordingly.

The circuit may be arranged to trip only with external pulses or, with sufficiently small bias on V_1 and V_2, it can be used in a self-oscillating manner. We have usually used the latter arrangement, omitting both R_2's, and applying no permanent grid bias. In some circumstances, however, it is advantageous to use arrangement 1 of reference 5, particularly when it is desirable to vary the length of interval $t_1 \rightarrow t_2$ without altering the period of the entire cycle. In this case the synchronizing connection from the plate of V_{11} (Fig. 2) is removed and an external triggering pulse is introduced at A_1 or A_2 as determined by the polarity of the pulse and by the type of delay desired.

The sweep circuit can be made to give a quite linear (with time) trace displacement but since the time intervals are indicated directly on the pictures and since there is no question of trace distortion in this type of record, great linearity is not necessary.

Deuteron beam control

The square pulses controlling the incidence of the deuteron beam on the target are generated by the circuit comprising tubes V_7 and V_8. The connections given provide for the initiation of this action at time t_2 in Fig. 3.

When the triggering action of V_1 and V_2 suddenly renders V_1 conducting, initiating the

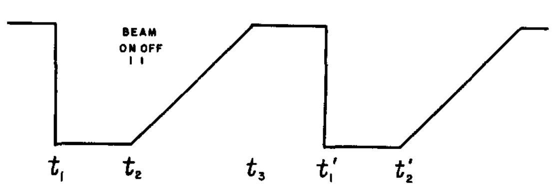


FIG. 3. Oscilloscope sweep voltage.

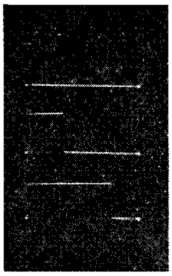


FIG. 4. Oscillograms of "beam pulses" of various lengths. The longest extends over 750 μsec.

oscilloscope sweep, a square negative pulse is generated in the plate circuit of V_1 which persists until t_1'. The grid of V_7 receives through C_3 an abrupt negative impulse which is much larger than necessary for cut-off of this tube. V_7 remains non-conducting until the exponential decay in its grid circuit has reached the cut-off point again, following which the plate current rises to saturation, thus producing a moderately square pulse of which the rise is extremely steep, but the fall "tails" off somewhat after a steep beginning. This pulse is fed to the grid of the beam power pentode V_8, which is normally biased at or near cut-off, and is much more than sufficient to lift this grid to the point where it draws current, saturating the tube and producing practically a short circuit across the deuteron deflecting plates. Since the time constant C_4R_{11} is great, the grid of V_8 remains at saturation point until V_7 has become conducting again after which only a small, and hence steep, part of the recovery of the plate of V_7 is necessary to return the grid of V_8 to cut-off. The "overshoots" of the impulses delivered to the grid of V_8 accentuate the steepness so that an extremely square pulse is delivered to the deflecting plates. (See Fig. 4.) Exact reduction to ground potential, resulting in a centered deuteron beam, is secured by adjustment of point Y. For viewing purposes the reduced pulse taken from point Z is applied to the scope through C_{14}. When making a neutron pulse record this same pulse is applied through the short time constant circuit $C_{13}R_{22}$, producing sharp pulses on the scope when the beam pulse goes on and off. (See Fig. 5.)

The length of the beam pulse is controllable from a few microseconds to several milliseconds by controlling the grid resistor of V_7, thus determining the time during which this tube remains cut off. Pulses of various lengths are illustrated in the oscillograms of Fig. 4.

The neutron pulses

The neutron pulses received from the detector amplifier are sharpened by thyratron V_{14} together with the low value of $R_{34}C_8$. A square brightening pulse is generated across the cathode resistor R_{29} of the thyratron as in the case of the time scale circuit. However, more brightening is necessary for these instantaneous pulses than can be provided by the voltage across R_{29} unless the latter is made so large as to slow down the action. Amplification and additional squareness are therefore provided by V_{15}, V_{16} being added as a phase inverter.

If the pulses delivered by the amplifier following the detector are positive they are fed directly to V_{14}, if negative, V_{13} serves to invert them. In cases, however, when the amplifier has a thyratron or trigger circuit output as, for example, the discriminator circuit of a linear amplifier, V_{14} is not necessary for sharpening and the pulses are fed directly to the scope through C_8'. The same pulses, fed to V_{10}, are given squareness by virtue of its grid being carried to cut-off. The short time constant of its input circuit enables it to recover quickly after the initial surge of the input pulse, thus imparting a moderately square pulse to V_{15} for brightening purposes.*

When introduced into the circuit through the dotted plate connection V_9 serves, in conjunction with V_{13}, to provide a coincidence circuit. In addition to being available for ordinary gamma-

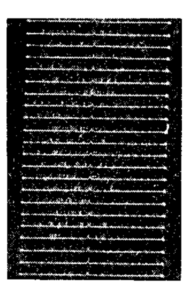


FIG. 5. Typical neutron pulse record with boron counter close to a paraffin block. Note pulse after 9th time interval, indicating end of irradiation, and the rise and fall of neutron intensity during and after irradiation. Time scale marks only are shown on the last two traces, the intervals being 50 μsec. For purposes of reproduction this oscillogram was purposely made somewhat denser than those allowing best pulse resolution when counting.

* Considerably better focusing of the neutron pulses was obtained by applying negative, rather than positive, pulses to the oscilloscope, presumably because the defocusing produced by the deflecting plate change, and that produced by the modulator grid swing then tended to cancel each other.

gamma, etc., coincidence work, this circuit has proved valuable in the following way. By impressing the proper square wave on V_9 the circuit may be made to respond only during some desired time interval. For example, by biasing V_9 to cut-off and impressing the square positive pulse from point X all counts are suppressed during the time that the deuteron pulse is on the target. Pulses passed on by V_{13} (or V_{14}) to, say, a scaling circuit will, therefore, be free of fast neutron pulses since none of the latter will be present for any appreciable time after the removal of the deuteron beam from the target. A switching arrangement (not shown) provides for increase of C_{17} and substitution of a mechanical counter for R_{28} in cases where the intensity does not warrant the use of a scaling circuit.

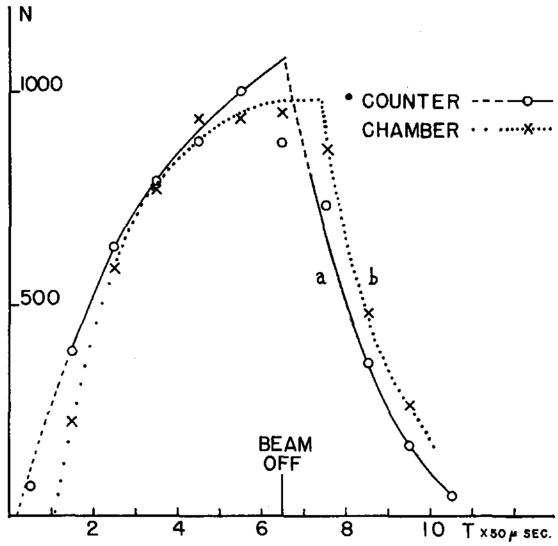


FIG. 6. Rise and fall of slow neutron intensity outside surface of paraffin blocks. (a) BF_3 counter, used as detector, placed against surface of 5-inch cube with target at center; (b) near half of cube removed and BF_3 ionization chamber substituted for counter.

Incidental equipment

The oscilloscope is a Western Electric type 326C, having a very fast blue screen seven inches in diameter. The photographic records are made on 35-mm Eastman Super XX film using an f:2 lens of 45 mm focal length, set at f:2.8. As the height of the pulse traces is kept small for intensity's sake, only about 1.5 mm of film are needed for one exposure. The camera utilizes the film holder and sprockets from a commercial projector. A spring-driven pawl, acting on a toothed wheel, provides sufficiently rapid motion of the film between exposures so that shuttering is not necessary.

The relays shown in Fig. 2 permit photographing of the beam pulse and suppression of the neutron pulses and/or the time scale. Identification marks to set off different parts of the record may be made in this manner.

A small 35-mm still projector is utilized during the counting process. A mirror arrangement permits projection on a screen placed on a slightly sloping table top. About 20 traces are viewed at one time on an 18×12 inch screen. Counting is usually done vertically, that is, a given time interval is counted over the whole frame, thus requiring a minimum of written records.

DISCUSSION

Various experiments have been conducted to test the rapidity of response of the apparatus. With the target grounded through a fairly high resistance the pulse produced on it by the ion beam was passed through one of the neutron pulse amplifiers, but not the thyratron, and applied to the oscilloscope. Within the limits of error ($\sim$2 μsec.) coincidence was observed, as is to be expected, between attainment of complete neutralization of the deuteron deflecting field and incidence of the beam on the target. There exists, however, a delay of approximately 8 μsec.* between triggering of the oscilloscope sweep circuit, initiating the sweep and the first time interval, and the beginning of the deuteron current, a delay easily measured and corrected for. It should be noted that the result of the first-mentioned test precludes any appreciable delay in the pulse amplifier.

To determine the over-all delay, including any effects due to the neutron detector response and to the processes of slowing down and diffusion in the paraffin block, a detector was placed in contact with the block and a time distribution of pulses obtained while using a rather long beam pulse. Results of such an experiment in which a small BF_3 proportional counter was employed as

* In the most recent work this delay has been reduced by converting V_7, V_8 into a regenerative trigger circuit by means of a condenser from the plate of V_8 to the grid of V_7.

a detector are shown in Fig. 6, curve a. The paraffin block was a five-inch cube. The exponential rise and fall are the result of the finite lifetimes of the diffusion and capture processes inside the paraffin.

In order to determine the total delay from extrapolation of this curve some calculation is necessary if the count in the first time interval is to be used. If any delay, including that of the fast neutron burst, is present it is obvious that the curve should not pass through this point. For example, if the delay covers more than half of the interval, the point would be plotted at a time before the counting actually began! Since the extrapolation is difficult without the use of this interval, the following method was adopted. From the shape of the curve, excluding the first interval, the mean life corresponding to the exponential rise, and the saturation value N_0 were calculated, thus giving the constants in the equation

$$I=\frac{N_0}{\Delta t}(1-e^{-t/T})$$

where $\Delta t=$ the length of a time interval (50 μsec. in this case). To determine t_0 the time at which counting actually started it is only necessary to set

$$N_1=\int_{t_0}^{\Delta t}\frac{N_0}{\Delta t}(1-e^{-t/T})dt$$

to determine t_0.

Applying this method to the data of Fig. 6, a value $t_0=6$ μsec. was obtained indicating that no delay whatever was present except for that involved in the production of the fast neutron burst and the gradual diffusion from the interior of the block. A similar result was obtained when the counter was placed in the center of a 25-gallon tank of distilled water.* In both cases decay started immediately when the beam was redeflected. Indeed, considerable decrease occurs during the first half-interval after the deflection as seen by the low value of the count for the interval centering about the time at which the beam was turned off.

Results of a similar experiment using a double parallel plate ionization chamber (20-cm diameter, 2-cm depth in each half), and a somewhat smaller paraffin block (hence a shorter mean life) are shown in curve b of Fig. 6. Calculations are more difficult in this case but as well as can be determined the total delay seems to be slightly in excess of 50 μsec. Part of this delay, in addition to that of the fast neutron burst, can be directly accounted for. A few microseconds are required for the neutrons to pass from the paraffin block into the active part of the chamber. In addition an oscillographic study made by superposing the discriminator pulses on those delivered by the amplifier indicated that on the average about 20 μsec. elapsed between the beginning of the latter and their obtaining of sufficient intensity to trip the biased (above background) discriminator. The apparently remaining unresolved delay of 10 to 15 μsec. may be the result of uncertainties in the analysis of the causes or may be due to some additional lag within the chamber. Whatever the cause, it is felt that a value of 50 μsec. for the total is sufficiently accurate for practical purposes.

As a final check fast neutron recoils in the chamber were studied in the absence of paraffin. The distribution was essentially square, slight departures being doubtless due to the presence of a few stray slow neutrons. A few counts were observed in the first time interval, indicating a delay shorter than that above by just about the time required for the slow neutrons to penetrate the chamber.

The resolution of the apparatus is determined almost entirely by the length of the time intervals covered in counting and by the time distribution of the burst of slow neutrons. Both must in turn be chosen in accordance with the available slow neutron intensity. The curves of Fig. 6 illustrate that the burst of slow neutrons escaping from the paraffin is much more extended than is that of the fast neutrons. Unfortunately, reductions in amount of paraffin and therefore in mean life are accompanied by corresponding reductions in slow neutron intensity, so that one is forced to compromise between two evils.

It should be pointed out that the relative velocity distribution within the slow neutron burst is not constant as a function of time. For example, very few neutrons of much greater than thermal energies will be present for any

* The mean life for this case was, of course, much longer.

appreciable time after the fast neutron burst is over. Indeed, the time distribution of the escape of such neutrons is undoubtedly much more nearly like that of the fast neutrons than are the distributions of Fig. 6.

The apparatus has both advantages and disadvantages compared to those of other investigators. It is more precise than most in the matter of time delays, all of which are small and easily corrected for. The actual recording is superior to that of FGMTW[4] to judge by their published oscillograms. The pulses are much sharper; the length of trace per cycle is much greater; and the presence of the time scale eliminates the necessity of measurements on the film. Compared to the direct counting method of Alvarez,[2] and Baker and Bacher[3] it has the advantage of obtaining the entire distribution record at once, thus reducing the time of using the apparatus and simplifying the problem of monitoring. The chief disadvantage is that considerable time is required to count the pulses recorded on the photographic film.

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A Photoelectric Star Counter

S. W. McCuskey and R. M. Scott

Warner and Swasey Observatory of the Case School of Applied Science, East Cleveland, Ohio

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A new device which performs the photometry of stellar images on a photographic plate and which segregates the images according to size is described. The star images to be photometered are manually shifted into the optical focus of the device. The results of tests indicate greater accuracy in counting than is attainable by visual means. No systematic deviations of the counts so obtained from catalog compilations or from the results deduced visually were found.

Introduction

In modern astronomy the stellar statistical problem of determining the number of stars per unit volume of space is of considerable importance. It leads directly to a knowledge of the structure of the galaxy, particularly in the neighborhood of the sun. In order to provide the data for such a study it is necessary to count the stars in given intervals of magnitude.[1] If individual stellar images are measured on a photographic plate as a necessary preliminary to the segregation of the stars into magnitude intervals, the photometric problem obviously becomes long and tedious. The number of stars involved in a complete census of a plate to a moderately faint magnitude limit may easily exceed 50,000.

The usual counting process consists of placing against the film of the photographic plate containing stellar images, a small graduated scale of similar images, and simply counting the number of images on the plate which are larger than successive scale images. It is essential, of course, that the scale contain images comparable in density and shape to those on the star photograph. From a sequence of stars of known magnitude the artificial scale is calibrated so that the stellar magnitude corresponding to a given scale image is determined. The resulting counts thus represent the numbers of stars brighter than a specified magnitude. These may be converted into the numbers brighter than any whole or half magnitude by a graphical process. The data are expressed in terms of $\log N(m)$, where $N(m)$ is the number of stars brighter than magnitude m. The actual number in any interval obviously may be found by subtraction.

[1] An interval of one stellar magnitude corresponds to a change of 2.512 times in the light of a star.