Television-electronics study of faint astronomical objects

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Advances in modern television detection techniques have resulted in a new and highly effective method for the study of astronomical objects. Its quantum efficiency approaches that of the instrument's input photocathode, the errors of light-flux measurement are in the tenths of a per cent, and use with on-line computers greatly reduces the time required to process observations. Practical use of the television techniques in the world's leading observatories has demonstrated its promise and produced qualitatively new results in studies of faint variable stars, x-ray sources, galaxies, quasars, and radio sources.

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INTRODUCTION

The television systems the use of which is the subject of the present review belong to the broad class of photoelectronic instruments.[1] The sensors of these systems are television cameras (TC) operating on the basis of the photoemissive or photoconductive effect.[2] The television systems receive and transmit information concerning the optical image projected onto the light-sensitive surface of the TC. Therefore they may also be classified as image-reproducing systems,[3] whose characteristic property is that they convert, reproduce, and record data concerning an optical image. Image-reproducing systems include the human eye, photographic emulsions, and various types of photoelectronic devices that convert optical images to electronic images. They could evidently just as well be called photoelectric image receivers by analogy with the photoelectric radiation receivers. In addition to the television systems, this class includes electro-optical image converter tubes (ICT) and electron-graphic cameras. Various types of ICT and electronic cameras have now been used for two decades for astronomical observations.[4-11] Their designs and operating principles have been described in a number of textbooks and study aids.[12,13]

The distinctive property of a television system is that it converts spatially distributed luminous energy (an optical image) into a time sequence of electrical pulses (a video signal). The stage in which the video signal is converted into an optical image, which is mandatory in broadcast television, may be absent in television apparatus used for scientific research. In the traditional terminology, the section of the apparatus that converts the optical image to the video signal is the transmitting section, while the part that processes the video signal and converts it to an optical image is the receiving section. The corresponding photoelectric and electron-beam instruments are also referred to as transmitting and receiving. The communications channel between these two sections of the apparatus in ground-based astronomical observations is a cable line. Element-by-element conversion of the optical image to an electrical signal and amplification of the signal take place in the transmitting part of the system. The order of readout (commutation) of the elements (image scanning) may be arbitrary as long as it is the same in the transmitting and receiving parts of the apparatus. The video signal is amplified, processed, recorded, and converted to an optical image in the receiving section of the apparatus. The information may be recorded at the output of the television system either by photographing the optical image on the screen of a video monitor (VM) or in the form of an electrical signal. The photographic method has advantages in its high information capacity and convenient long-term storage of the photographs. The latter

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is especially important in astronomy, where every observation is unique. The advantage of recording the electrical signal is the possibility of real-time computer processing of the observations.

Television systems came into use in astronomical research relatively recently. The first television images of faint stars were obtained in the early 1960s,[14-19] and systematic photometric studies of the stars and planets were begun about 10 years ago.[20-24] The pioneering work in this area was done in the USSR. The first book describing experience in the use of television systems for ground-based astronomical observations appeared in 1974.[25] The television observing technique began to develop rapidly at the beginning of the 1970s. The advantages and disadvantages of the method have been analyzed in detail in the reviews of Refs. 26–29 and in the monograph of Ref. 25. Many astronomical studies have been carried out in recent years with the aid of the new transmitting instruments. The experience accumulated enables us to attempt classification of the existing wide variety of astronomical television systems by types of transmitting units and in terms of the astronomical problems that they aid in solving.

1. USE OF IMAGE ORTHICON AND ISOCON TELEVISION CAMERA TUBES TO OBTAIN DIRECT IMAGES OF ASTRONOMICAL OBJECTS AND STAR SPECTRA

Image orthicon and isocon television tubes have semitransparent input photocathodes, and their quantum efficiencies can not exceed that of the photoemissive effect (10–20%). Preamplification of the image in the ICT stage makes it possible to raise the sensitivity of these tubes to $5\cdot 10^6$ lx, which corresponds to a quantum flux of 200 quanta/sec on a 0.1×0.1 mm resolution element. Compared to the image orthicon, the isocon has a better signal/noise ratio, higher sensitivity, and a broader dynamic range. Transmitting tubes developed under the direction of N. D. Galinskiĭ are used for astronomical observations in the USSR (see Ref. 25). Studies made at the Crimean Astrophysical Observatory of the Academy of Sciences of the USSR have shown that lowering the operating temperature of the tubes from +40°C to 0°C increases their threshold sensitivity in recording of point objects by factors of 6–10.[25,30,31] It becomes possible at the same time to store an electrostatic image on the target for several tens of seconds without reciprocity failure. Air cooling is often used in astronomical observing practice.[32,33]

A typical block diagram of television equipment mounted on a telescope to obtain direct photographs of astronomical objects appears in Fig. 1. The television image is usually recorded on a fine-grained, slow emulsion that permits highly accurate measurement of photographic density. Information is accumulated in two steps during observations of faint objects with these systems: on the camera-tube target and on the photographic film. The latter gives rather good averaging of scanning-beam noise. It is also possible to use a storage-type television tube.[34] The Crimean Astrophysical Observatory has obtained the highest light-gathering power with an image orthicon and a multistage image converter.[17,18] Images of 20^m stars were obtained using a 50-cm telescope with a 4-second exposure and a signal/noise ratio of about one. The light flux from these stars during the exposure was approximately 100 photons. The television system proved itself to be nearly as sensitive as a quasi-ideal light detector with a quantum efficiency equal to that of the photocathode.

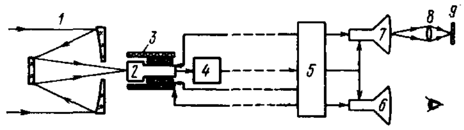

FIG. 1. Block diagram of astronomical television system for direct photography. 1) telescope; 2) television camera tube; 3) focusing and deflecting system (FDS); 4) preamplifier; 5) rack and control panel; 6) video monitor (VM) for visual observations; 7) VM for photographic recording; 8) objective; 9) motion-picture or still camera.

In 1962, the brightness of faint stars was measured in the USSR by a method similar to that in which star brightness is determined from focal photographs.[16,25,35] The $\pm 0^m.10$ error initially obtained in star-brightness measurements from a single photograph was subsequently improved to $\pm 0^m.05$ (±5%). The range of stellar magnitudes in which the calibration curves are linear is $2^m - 3^m$, reaching 4^m when the characteristic curves are rectified.[36,37,38]

The star images obtained with the isocon are in appearance indistinguishable from photographic images (Fig. 2). The calibration curve (Fig. 3) is linear in a range up to 6^m, and the error of a star-brightness measurement is about the same as when an image orthicon is used.[39] Television photographs of extended objects are calibrated against photographs of a stepped wedge obtained with the apparatus operated under the same conditions.[40] The calibration curves are also linear when the characteristic curve rectification procedure is employed. We shall evaluate television-system quantum efficiencies in terms of the detective

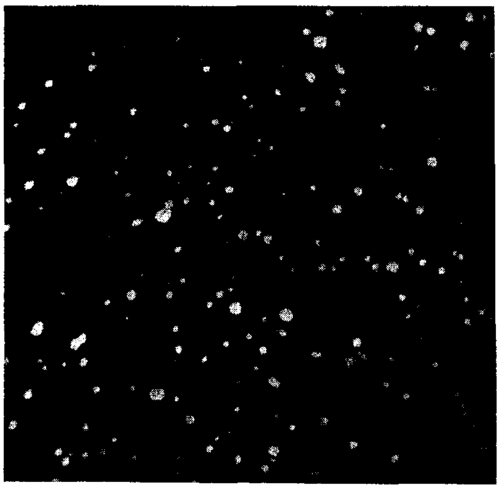

FIG. 2. Photograph of the center of the star cluster NGC 188 obtained with an isocon with a multistage ICT.

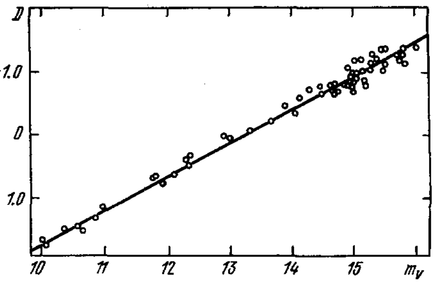

FIG. 3. Calibration curve plotted from photometry data for a photograph of the cluster NGC 188 obtained with an isocon in the "V" color system on the 50-cm telescope; exposure 2 sec. The abscissa is stellar magnitude m_V, and the ordinate $D = \log[(n_b/n_{st})-1]$, where n_{st} and n_b are the readings from a microphotometer with a constant-size diaphragm on the image of the star and on the background near it.

quantum efficiency DQE,[41,42] which is equivalent to the generalized quantum efficiency.[43,25] The DQE does not depend on the nature of light sensitivity of the light receivers and permits quantitative comparison of their efficiencies under actual experimental conditions. By definition

$$\mathrm{DQE} = (S/N)^2_{\mathrm{out}}/(S/N)^2_{\mathrm{in}},$$

where $(S/N)_{\mathrm{in}}$ and $(S/N)_{\mathrm{out}}$ are the signal/noise ratios at the light-detector input and output. The DQE of a real light detector is numerically equal to the transmission coefficient of the neutral filter that would have to be placed in front of the ideal detector to obtain the same result. For direct photography, the signal/noise ratio at the light-detector input is determined from the quantum flux from a star of known brightness.[25] The output signal/noise ratio is estimated from the rms error of measurement of the star brightnesses found on photometric processing of the negatives, which represents the relative error of measurement of the light flux.[36] Table I gives results from determinations of the DQE of a television system with various transmitting tubes under the actual conditions of faint-star ($17^m - 19^m$) observations with the 50-cm telescope. Also included in the last line are the DQE for the television system of Walker *et al.* (see Ref. 44).

The high quantum efficiency of the television technique makes it possible to observe faint stars in telescopes of moderate size and still obtain photographs with high time resolution. As an example, Fig. 4 presents the results of observations made of the same variable star, ES Cep, with telescopes of the same size (D = 50 cm) using the photographic and television methods[45]: 66 photographs were obtained in 40 hours

TABLE I. Detective quantum efficiencies (DQE) of television systems with an image orthicon and an isocon.

Camera	DQE, %	Exposure time
ICT + Li-214	2.0	1 min
Li-217	2.0	16 sec
Li-217	1.0	9 min
ICT + isocon (USSR)	4.0	32 sec
ICT + isocon (Canada)	4.0	—

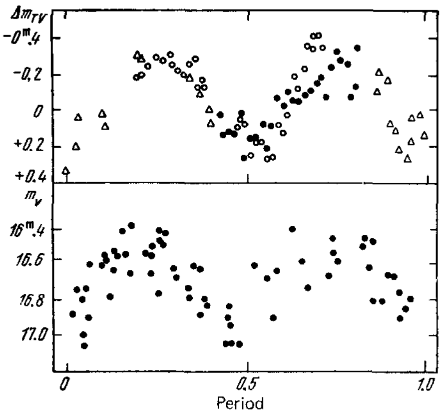

FIG. 4. Brightness data on the eclipsing variable ES Cep from television (top) and photographic (bottom) observations. Each symbol in the upper plot represents the brightness of the star averaged over five television photographs.

of observations and 400 television pictures in 5.5 hours. The exposure times differed by a factor of 40. The large number of television pictures made it possible to detect differences in the brightness curves of the variable from cycle to cycle (see the various sets of symbols on the upper curve). Figure 5 shows the brightness curve of the binary variable 442 Cas during an eclipse of one of its components, as obtained with the television equipment at the Crimean Astrophysical Observatory.[16] The large change in the brightness of the star (by a factor of 10 during one hour) made photographic study of the brightness curve difficult. The same television system was later used to obtain the brightness curves of several faint variables.[47-50] The study of irregular variables is illustrated by investigations of the nature of the optical variability of the x-ray source Cygnus X-2,[51] the brightness curves of supernovae,[52] and by brightness measurements made on objects of the BL Lac type.[53,54] A number of observations of T Tauri variables in narrow spectral bands have produced interesting new conclusions as to their physical nature.[55] It was found that radiative processes in gas-and-dust shells predominate in stars of high luminosity, while processes of the chromospheric-activity type dominate in stars of low luminosity. A television

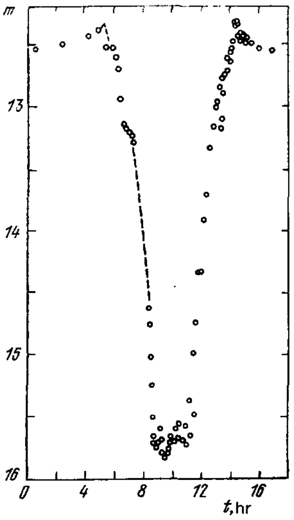

FIG. 5. Brightness curve of the variable star 442 Cas obtained during eclipse of primary component.

search method for supernovae in galaxies has been developed and put to use.[56-59]

The possibilities of controlling the electron image in the television camera tube have made it possible to develop original apparatus for use in the search for pulsars.[25,60-62] Its operating principle is as follows. The image of the object under study can be displaced stepwise in the field of the television system by varying the field of coils set up around the entrance chamber of an image-converter tube. The number of image shifts corresponds to the number of phase intervals into which the period of brightness variation of the observed object is divided. If the shift frequency is the same as or a multiple of the brightness-variation frequency of the pulsar, the image of the object on the television screen will be seen simultaneously in several phase intervals, which represent its brightness curve. As an example, Fig. 6 shows fragments of records of the pulsar NP 0532, which is situated at the center of the Crab Nebula. They were obtained in March 1970 at Simeiz with the 0.8-meter telescope of the Crimean Astrophysical Observatory. There were 16 time-scan intervals, each with a duration of about 2 msec, and luminous energy was accumulated for one minute. Figure 7 shows a photograph of stars with time separation of their images into eight phase intervals. Advantages of the television pulsar-search method are its high quantum efficiency and the possibility of searching simultaneously in a certain patch of sky determined by the size of the input photocathode and the focal length of the telescope.

A television system with an LI-217 camera tube[25] is being used successfully to obtain direct photographs of the major planets through narrow-band optical filters. The high contrast senstivity of the apparatus and the possibility of real-time adjustment to optimum contrast and brightness of the planet's image on the television screen make it possible to record low-contrast images of details of the Venusian cloud cover in the ultraviolet.[63] Figure 8 shows photographs of Venus taken in ultraviolet and blue light in November of 1975, when the unmanned spaceprobes Venera 9 and Venera 10 were in orbit around the planet. The dark spots on its disk are seen clearly in ultraviolet light but are scarcely visible in blue light. The brightness ratio of

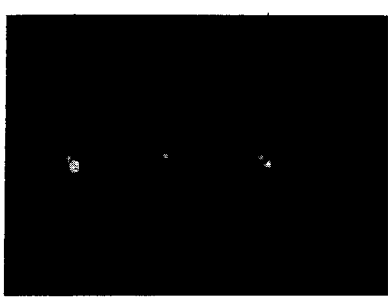

FIG. 6. Fragments of photograph of Crab Nebula pulsar and a star situated about 4″ from it. Taken during brightness maximum of the pulsar (left), brightness minimum (center), and the low secondary maximum (right). The phase duration is about 2 msec on each photograph. They were taken on a 0.8-meter telescope with a 1-minute exposure time.

FIG. 7. Photograph of a star field about 15′ across, illustrating method used to search for pulsating objects. Stars down to the 16th magnitude can be seen on the photograph.

details on the disc was determined accurate to ±3% from a single photograph and to ±1% for each date.

The Crimean Astrophysical Observatory conducted Martian cloud patrols at the times of four oppositions.[64,65] The planet was observed in 10 spectral segments from 377 to 760 nm. Comparison of the television-patrol results with data from visual and photographic observations of Mars showed that the television procedure is nearly as good as the visual method and better than the photographic method with respect to the threshold at which low-contrast cloud formations are recorded. For example, the onset of the 1971 global dust storm on Mars was recorded by the television procedure before it was detected photographically.[66] The large number of observations covering a broad region of the spectrum made it possible to obtain spectrometric data on the reflectances of Martian clouds of various types.[67] It was also possible to explain the puzzling "blue clearing" effect in which the contours of Martian "seas" become visible in blue and ultraviolet

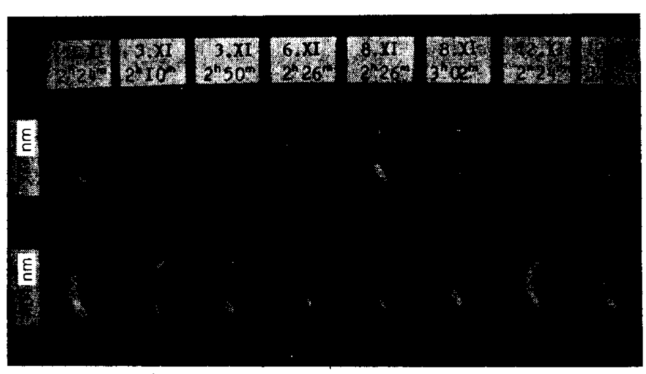

FIG. 8. Television photographs of Venus in two regions of the spectrum (λ_{eff}=377 nm (top row), λ_{eff}=404 nm (bottom row)), obtained on a 50-cm telescope at the Crimean Astrophysical Observatory in November 1975. The observing times are given in UT.

light when the sea-continent contrast increases over the entire spectrum due to the rise of dust from light-colored Martian regions ("continents").[68] The development and decline of the 1971–1972 global dust storm were followed in detail.[69-71] Figure 9 shows photographs of Mars taken during different oppositions with the dust storm in progress and with the Martian atmosphere clear. All photographs show images of the same side of the planet.

The first attempts at using the image orthicon for spectral studies of stars were made in the early 1960s.[16,72] The Main Astronomical Observatory at Pulkovo recently obtained laboratory-spectrum records with an image orthicaon and an isocon.[73] The observatory also uses image orthicons with high signal/noise ratios to record solar spectra,[74] and in 1974 it tested a spectroheliograph-magnetograph with computerized processing of the video signal in analog form.[75] Variations of magnetic fields on the sun with a period of 270 seconds were detected with this system.[75]

An isocon with an ICT is used by the University of British Columbia in Vancouver for spectral studies of astronomical objects.[44,77] The spectrum extends along the frame scan. This sharply lowers the rate of arrival of information and it becomes possible to use standard video-signal encoding apparatus and to computerize all processing of the data. A storage with a capacity of 1800 16-bit words is used to record two spectra. The observing process is monitored on a display. The observer can choose to obtain data on the intensity of one spectrum, the intensity difference between the two spectra, or the difference between the intensities of spectra obtained with the polaroid in different positions in magnetic-field measurements. Spectra of the variable star BW Vul showed changes in the line contours of doubly ionized silicon with a characteristic time of several minutes. Highly accurate profiles of the green line of doubly ionized oxygen in the Seyfert galaxies NGC 4151 and NGC 1068 were obtained, and it was shown that there are four regions that emit this line in each galaxy.[78] Emission lines in the spectrum of the galaxy NGC 1068 were found to be variable with a characteristic time of about a month.[79]

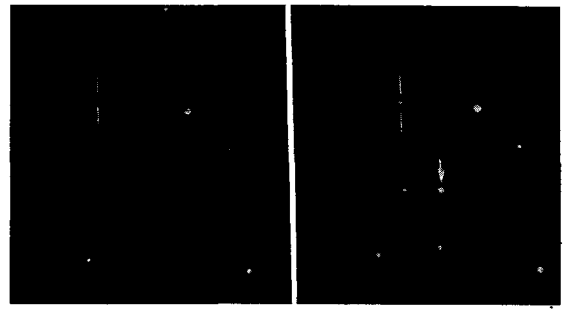

FIG. 10. Photographs of Luna 7 spaceprobe and its booster rocket in the same star field obtained on 50-cm telescope. Because of the wide variation of the spaceprobe's brightness, its image can be seen on only one of the photographs (arrow).

The image orthicon is used successfully in determining the positions of spaceprobes.[80-82] Use of a television system has made it possible to increase the light gathering power of the optical method for artificial-satellite observations by 5^m as compared to pure photography. Observation of deep-space probes (DSP) receding from the earth into interplanetary space to investigate the Moon, Mars, Venus, etc. and determination of their coordinates are important objectives. Figure 10 shows two photographs taken in quick succession of the Luna 7 spaceprobe and its rocket booster.[83] The photographs show displacement of the booster image (indicated by pointers) against the star field. Both television pictures[84] and a procedure in which the coordinate differences between the observed object and comparison stars are read directly [85] are now used to determine the coordinates of spaceprobes.

The television method is also being used successfully to observe minor planets and meteors.[86-93] Photographs of the asteroid Icarus have been obtained using the 2.6-meter telescope of the Crimean Astrophysical Observatory. The photographic method cannot be used near the sun because of the high angular velocity of the

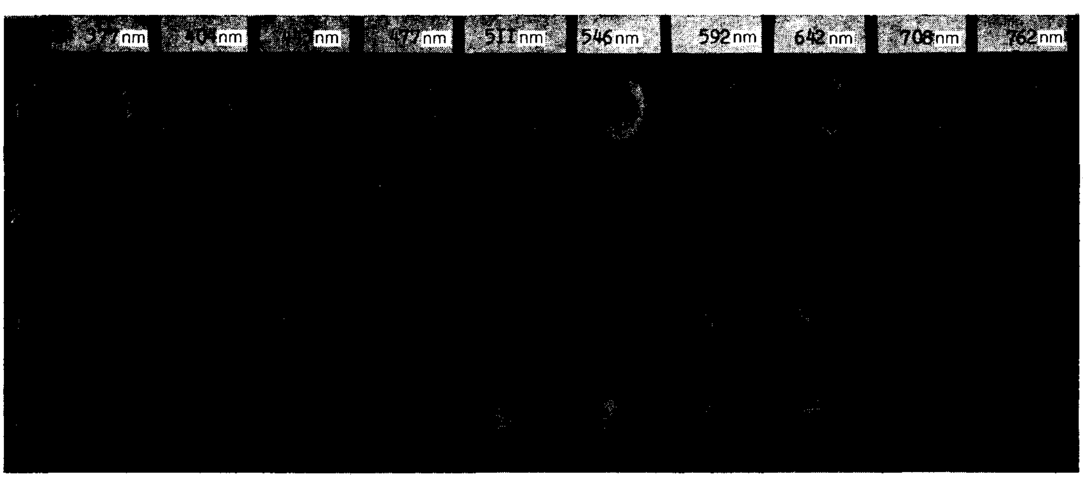

FIG. 9. Television photographs of Mars in various regions of the spectrum (indicated at top). 1) 11 September 1973 (light bluish haze on limb); 2) 22 August 1971 (clear Martian atmosphere); 3) 27 September 1971 (dust storm beginning to develop); 4) 7 November 1971 (global dust storm).

asteroid's motion.[86] Successful television observations of Icarus have also been made using the 50-cm telescope.[87] The television method has been used to study the emission peculiarities of faint meteors in the earth's atmosphere; the spectra have been analyzed quantitatively and features of the emission of individual spectral lines and bands along the paths of the meteors have been detected.[94-98]

Image-orthicon television systems have also been used to study the instability of star images due to turbulence in the earth's atmosphere,[99] and to record the unsteadiness of images of the sun and to analyze their sharpness.[100] A fast shutter that operates on command from a special good-seeing sensor has been devised on the basis of television equipment with a multistage ICT.[101,102] Its use under actual observing conditions has improved the probability of obtaining star photographs of good quality.[103]

2. USE OF THE DIGICON, SILICON DIODE VIDICON AND INTENSIFIED SILICON DIODE VIDICON FOR PRECISION PHOTOMETRY AND SPECTRAL STUDIES

The digicon, silicon diode vidicon, and intensified silicon diode vidicon are instruments of the same class, since they are all vacuum-type signal generating detectors and all of them have silicon diodes as their basic components. The digicon is an image converter tube in which the electronic image is projected onto a system of silicon diodes.[104-107] In it, raster scanning is brought about by using the quadrupole field of deflecting coils positioned around the ICT. The detective quantum efficiency of the digicon is 4% in the blue region. A digicon with about 200 diodes and as many leadouts has been developed and used for astronomical observations. Each diode is 40×300 μm. Self-scanning diode arrays have been recently put to use to reduce the number of leadouts[108-110] (see below). A tube with 2048 diodes was used on the 2.7-meter McDonald Observatory telescope from 1974 through 1976 in a number of astrophysical investigations.[111,112]

The silicon diode vidicon, which has been used widely in astronomy, is a device of the vidicon class in which the photoconductive effect is utilized. The quantum efficiency of the silicon diode vidicon may reach 80–100%, but high noise levels are still an obstacle to its full utilization. Silicon diode vidicons operate at a minimum photocathode illumination of about 10^{-2} lx. Their spectral-sensitivity ranges extend from 300 to 1200 nm. The silicon diode vidicon has a broad dynamic range (10^3–10^5) within which the signal is a linear function of luminous flux. This greatly simplifies photometric calibration and makes it possible to record very low contrasts. The sensitivity of the silicon mosaic is stable in time, and sensitivity nonuniformities of the tube over the field can easily be taken into account in reduction of observations. The possibility of slow readout of information from the target permits the use of inexpensive computers. The disadvantages of the silicon diode vidicon are the need for deep cooling in order to reduce noise and increase the time of accumulation of information on its target. Accumulation over an hour is possible only at the temperature of dry ice (−78°C). The presence of the interference pattern formed between the structure of the field grid and the discrete structure of the target in the thin silicon-oxide film is also very troublesome in operation.[114,115]

McCord and Westphal[116,117] made the first astronomical observations with the aid of a silicon diode vidicon. With the device as a base, they built a two-dimensional photometer with digital recording of the video signal on magnetic tape. The image had 256×256 elements. The authors obtained experimental photographs of Mars in twenty segments of the spectrum. Photometry errors were as low as 1%. The light gathering power obtained with the silicon diode vidicon in star observations was not particularly high: images of 18^m stars were obtained during an accumulation time of 100 sec using the 1.5-meter telescope with the silicon diode vidicon cooled to −65°C. MIT has developed a silicon diode vidicon photometric measurement technique.[118-120] Comparison of measurements made using a telescope with a silicon diode vidicon and an electrophotometer showed differences of no more than 1% between the results.

Television systems based on silicon diode vidicons are now coming into use in astronomical observations.[121-125] Studies made at the University of British Columbia (Canada) have shown that it is advantageous to use a silicon diode vidicon in the red region of the spectrum ($\lambda \geq 650$ nm), where its sensitivity is only slightly lower than that of the isocon.[44]

Thus, the silicon diode vidicon is used to record low-contrast details of extended objects and in precision photometry at rather high light fluxes. It can also be used for observations in the near infrared where the other light detectors have low sensitivity.

Sensitivity was increased appreciably in the intensified silicon diode vidicon.[126,127] These tubes have a multislot input photocathode and an image-transfer section. The electronic image is projected onto a silicon-diode target, and each photoelectron, which has an energy of several kilovolts, forms a set of current carriers in the target. As a result, the tube has an internal gain ranging from a few hundred to 1500–2000, and its sensitivity is considerably higher than that of the conventional silicon diode vidicon. The intensified version works at illuminations down to 10^{-5} lx.

The first tests of the intensified silicon diode vidicon in astronomical observations[128] were successful, and special apparatus was subsequently developed with digital data recording for observations of the spectra of extremely faint objects.[129] It uses a prism spectrograph and a commercial intensified silicon diode vidicon with electrostatic focusing and an input fiber faceplate. The system was mounted at the Cassegrain focus of a 5-meter telescope at the end of 1974. Information was obtained at a rather high rate: the spectra of normal galaxies with a red shift $z = 0.2$ ($m \approx 20^m$) were obtained in 30-minute exposures, while 90 minutes were required for galaxies with $z = 0.39$ (Fig. 11).

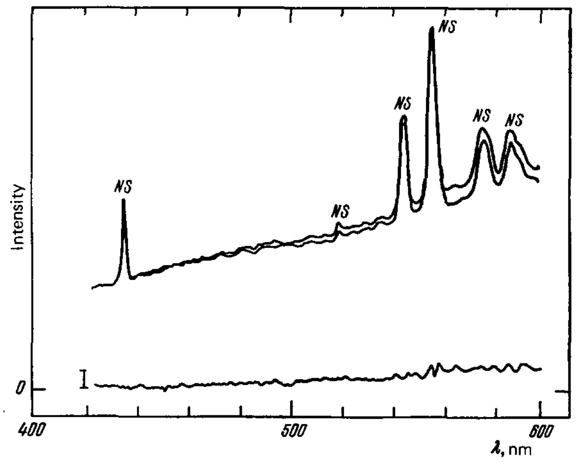

FIG. 11. Data from prism spectrograph with intensified silicon diode vidicon used on 200-inch telescope in spectral observations of a galaxy (~21^m) in the cluster 0024-1654 with a red shift $z = 0.39$. The upper curve corresponds to the observed sum of the spectral intensities of the galaxy and the night sky, the middle curve to the night-sky spectral intensities, and the lower curve to the spectrum obtained for the galaxy by subtracting the intensities of the other two. Night-sky emission lines are marked *NS*.

The new spectrograph was given the task of extending the Hubble diagram in the direction of faint objects. Red shifts were obtained for 37 galaxies, and were larger than 0.2 for 25 of them.[130]

Several observatories are now planning to use intensified silicon diode vidicons for astrophysical research. An automatic supernova-search system is being developed on the basis of a commercial intensified silicon diode vidicon behind a magnetically focused ICT camera.[131] In France, an intensified silicon diode vidicon has been mounted on the spectrograph echelle of the 1.5-meter telescope in Haute-Provence.[132] At Cambridge University in England, development of a computer-controlled system with digital recording of the spectrum has almost been completed.[133] A similar system has been developed at the Kitt Peak Observatory.[134] In Belgium, an intensified silicon diode vidicon is being used to record the images of visual binary stars separated by 1″–5″.[135] A photon-counter system in which a microchannel plate is used in front of an intensified silicon diode vidicon to provide further amplification of the light is being used in France for interferometric star observations.[136] An intensified silicon diode vidicon is being used for stellar spectroscopy on the 1.5-meter telescope of the Cerro-Tololo Observatory in Chile.[137] Spectra of 18^m stars have been obtained on the 1.5-meter telescope at a spectral resolution of 1 nm. Instrumentation for near-infrared observations has been developed by the scientific laboratory at Los Alamos.[138-141] An ICT camera with a cesium-oxygen photocathode was mounted in front of an intensified silicon diode vidicon. Infrared photographs of several sky areas from a scan made in the two-micron range were obtained using the 1-meter telescope at Flagstaff, Arizona. Two infrared stars were discovered and the identifications of seven objects were confirmed.

3. EXTRA-ATMOSPHERIC AND GROUND-BASED STUDIES WITH THE SEC-VIDICON

The SEC-vidicon television transmitting tube was designed more than 10 years ago to meet the need of extra-atomospheric astronomy.[142-147] Development of the tube was based on the then newly discovered secondary electronic conductivity of thin porous dielectric films.[146] The tube came to be known as the SEC-vidicon using the abbreviation SEC for secondary electron conductivity. A modification designed to record ultraviolet radiation is known as the uvicon. The SEC-vidicon has an image-transfer section, and the electronic image is projected onto an SEC target mounted on a signal plate.[25] SEC-Vidicons work with minimum illuminations of about 10^{-2} lx. They have an advantage in the possibility of extended-time accumulation and storage of the information on the target.

With these advantages, the SEC-Vidicon has a number of shortcomings: its target burns out under high illuminations, target gain depends strongly on the level of photocathode illumination, and this dependence is different in different areas of the field.

The OAO-2 orbiting astronomical observatory was launched in December 1968 and carried four uvicon tubes, which were mounted on 32-cm reflecting telescopes with 2°× 2° fields. Two of the uvicons were sensitive at 105–320 nm and two in the range 105–200 nm. The raster had 256 × 256 elements and each frame carried $5 \cdot 10^5$ bits of information, which was transmitted to the ground in digital form via a telemetry channel. The rate of readout from the uvicon target was matched to the rate of data transmission to the ground. The mission was to obtain brightness data on 100,000 stars. However, owing to failure of one of the cameras and a decrease in the sensitivity of the others, with the accompanying departure from photometric calibration, the brightnesses of only 5000 stars were determined.[148] The video data were computer-processed in accordance with a special program. Laboratory measurements of the sensitivity of the tubes in 25 areas of the field at ten different target temperatures and three photocathode illumination levels were put into the computer to interpolate the sensitivity of the instruments to intermediate temperatures, illuminations, and object positions in the field.[149] Painstaking reduction of data made it possible to obtain catalog values of the star brightnesses with errors of $\pm 0^m.1 - 0^m.2$. Despite a number of troubles, the first applications of the SEC-Vidicon for space research indicated that modern camera tubes are not only possible, but also promising tools for these purposes.

An international satellite for ultraviolet research is to use a television system both to identify the sky area under study and to record star spectra at wavelengths of 105 to 320 nm. The identification camera assumes a type of work in which the image of the sky field in the focal plane of the telescope is transmitted to the ground and the operator makes the identification and the fine adjustment of the image position onto the spectrograph slit. The spectra will be recorded with the aid of several identical television cameras. The spectrum produced by the echelle will cover the entire light-sensitive surface, which is 25 mm in diameter. The number of raster elements will be 768 × 768. Use of a production model electrostatic SEC-Vidicon with an input fiber faceplate is proposed (Fig. 12).[150,151] A lensless image transfer converter tube with a photocathode sensitive in the ultraviolet is mounted in front of the SEC-Vidicon. Lowrance at Princeton University has supervised the development of a magnetic-focusing SEC-Vidicon. The tube has a larger useful field and better linear resolution than the electrostatic SEC-Vidicon.

Research is being done at the U. S. Naval Observatory on the use of SEC-Vidicons in a Schmidt camera with electron-optical image amplification.[152] The camera has an ultraviolet photocathode on a solid base and a phosphorescent exit screen (Fig. 13). The SEC-Vidicon, with a fiber faceplate at its input, is mounted flush against the screen. Among the advantages of this design are the use of an opaque photocathode with high quantum efficiency and replaceability of the SEC-Vidicon without disturbing the performance of the entire instrument. The camera has a set of interchangeable correcting plates made from various materials to permit isolation of the desired segment of the spectrum. A plane mirror with a plane diffraction grating on its back is mounted in front of the camera. The switch from observation of star fields to observation of spectra can be made by turning this mirror. In addition to star photographs in several spectral bands, the camera can be used to obtain objective-grating star spectra.

A large space telescope is to carry only television light detectors. Medium- and low-dispersion spectrographs will incorporate Schmidt cameras with SEC-Vidicons and photocathodes 25 mm in diameter. Cameras with high dispersion will require tubes with larger photocathodes. It will be possible to use the tubes developed by Lowrance.

On the ground, SEC-Vidicons are used basically for such auxiliary tasks as identification of faint objects and guiding and focusing of telescopes.[153] Due to the possibility of accumulation on the target, the light gathering power of a SEC-Vidicon guide was found to be $2^m.5$ (10 times) higher than in the case of visual guidance.[154] The Hale Observatories have developed a special SEC-Vidicon television system with brightness preamplification by a single-stage ICT and are using it regularly on the 200-inch telescope.[155] The television has greatly reduced the time required to find a desired object and relieved the observer of the need to stay at the telescope during observations. A SEC-Vidicon television guide is also used at the Cassegrain focus of the 120-inch Lick telescope.[156]

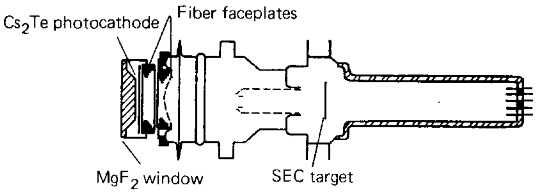

FIG. 12. Electrostatic SEC-Vidicon with a nonfocusing ICT multistage mounted in front of it. This device is used in space to record the ultraviolet emission of stars.

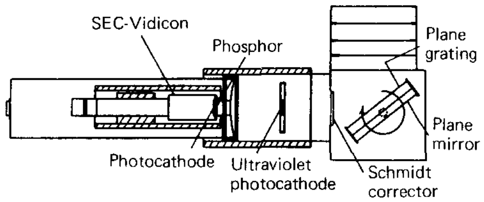

FIG. 13. Schmidt camera with an SEC-Vidicon for sky scanning in the ultraviolet.

A Princeton University laboratory has developed a television system for ground-based observations of the spectra of faint objects, with direct input of the video information into a computer in digital code.[157-160] The unit was designed for measurement of radial velocities, and has been used off and on since 1970 on the 200-inch telescope to obtain quasar and galactic spectra. The spectrum of the quasar PHL 957 ($m = 16^m.5$) was obtained in a 6-hour exposure in Obtober 1970 with a resolution of 0.07 nm in the wavelength range 427–449 nm [161](Fig. 14). Subsequent observations of the same quasar made it possible to obtain radial-velocity values accurate to 0.02 nm. Still later, red shifts were obtained for several other objects.[162-164] It was shown that in some cases the emission lines of quasars are formed in several regions with different radial velocities. The spectra of six galaxies were also obtained with a long slit for study of their internal velocity dispersion.[165-167]

Attempts to use the same instruments for photometry of stars and extended objects produced discouraging

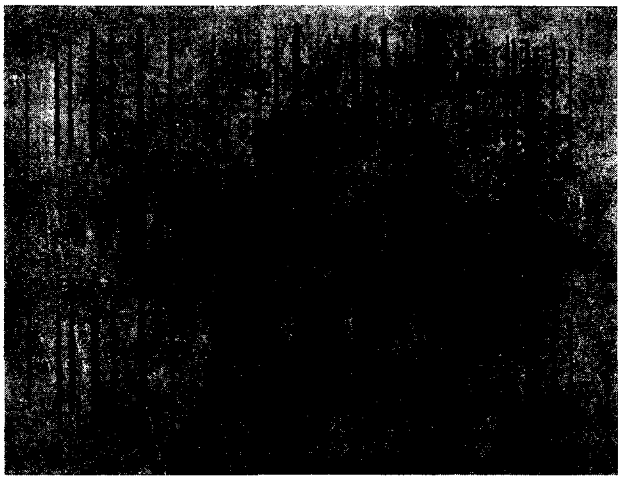

FIG. 14. Digital image of the spectrum of quasar PHL-957 obtained with an SEC-Vidicon on the 200-inch telescope. The small rectangles are elements of the image, and their widths correspond to 1/3 of the resolution (0.075 nm) of the apparatus. The vertical scale has been stretched by a factor of 4.8. The comparison spectrum (top and bottom) is that of an iron arc. The emission line to the left of center is the mercury line at λ 435.83 nm. A few groups of dark rectangles are defects of the SEC-Vidicon target. The record was obtained in the laboratory by modulating the light flux of a lamp by digital data on the intensity of the quasar's spectrum.

results.[168,169] High accuracy can be obtained in brightness measurements only after very careful analysis of each individual SEC-Vidicon and with computer processing of the video data.

4. USE OF PHOTON COUNTING WITH MULTISTAGE IMAGE INTENSIFIERS IN COMBINATION WITH TELEVISION SYSTEMS AND COMPUTERS TO STUDY THE SPECTRA OF FAINT GALAXIES AND QUASARS

The idea embodied in photon-counting television systems that use a multistage ICT is that of counting scintillations on the ICT's output screen with the aid of the television system. The first report indicating the possibility of building such devices with dissectors was published in 1970.[170] The multistage ICT was used as a brightness intensifier and as an intermediate storage element. A number of systems in which the scintillations on the ICT screen were counted with various camera tubes of comparatively low sensitivity (dissector, SEC-Vidicon, plumbicon) that are incorporated into standard apparatus for particle counting have been described in recent years.[171-174] The two systems now used most extensively for astronomical observations are that of the Lick Observatory and the Boksenberg system developed in England.

The Lick Observatory system[175,177] was designed for spectral investigations of faint stars and nebulae. It was mounted at the Cassegrain focus of the 120-inch Lick telescope in August of 1971. All controls are brought together in a warm lighted room manned by an astronomer and an operator during observations. The transmitting camera incorporates a three-stage ICT with electrostatic focusing and fiber faceplates at the entrance and exit, and a magnetic-focusing dissector. The tubes are connected by a long fiberoptic cord. During observations, the ICT (which has a multiple-slit input photocathode) is cooled by circulating cold ether through a tube surrounding it. The spectrograph has two slits: the star image is focused on one, and the other is used to record the spectrum of the night sky. Video information from each spectrum is fed through 2048 channels into a computer with an internal memory capacity of 4096 24-bit words, where it is stored. The signal accumulated from the sky-background spectrum is also subtracted here from the total star-plus-sky spectrum. The computer does preliminary information processing: linearization of the wavelength scale, correction for extinction, etc. The result can then be recorded on a magnetic tape or disk or transmitted by teletype to another computer for further processing. The detective quantum efficiency of the Lick apparatus is 2–3%.[177] This rather low value is explained by the authors as follows: because of the difficulty of matching the glow time of the ICT output screen to the field-scanning time, some scintillations may go uncounted, and some may be counted more than once. The output signal/noise ratio decreases as a result. Attempts to increase the single-count probability produced no significant improvement.[178]

Many astrophysical studies of stars, galaxies, quasars, and radio sources have been made during the last few years with this apparatus mounted on the 120-inch Lick Observatory telescope. The spectra of two faint galaxies near the quasar PKS 2251+11 were obtained and indicated that all three objects have the same red shift.[179] This confirmed the hypothesis that they form a physically connected group. Also obtained were the spectra of a pair of blue objects of magnitudes 17 and 19 that are separated by 4″.8 from one another and are known as a double quasar.[180] It was found that their red shifts are sharply different and that they cannot form a physically bound pair. The red shift of the $18^m.5$ radio galaxy 30 229 was determined[181]; spectrophotometric studies of the galaxies Ton 524 a and b ($16^m.6$ and $18^m.4$) showed that both objects are Seyfert galaxies and have nearly identical red shifts.[182] The red shifts of a bright quasar and five galaxies near the radio source RN8 were found; it developed that the object and three of the galaxies have equal red shifts and apparently form a group.[183] The spectra of five compact members of the Shakhbazyan I group showed that they all have the same red shift.[184] The spectra of several faint type RR Lyrae stars in the cluster M22 were studied with the object of determining the abundances of metals in this cluster.[185]

Spectra obtained at various distances from the nucleus of the quasar Ton 256 (two and four seconds of arc) show that the object consists of a quasar-like nucleus enclosed in a gigantic elliptical galaxy.[186] Emission with a red shift somewhat greater than that of the object was found to the north of 3C 48.[187] On this basis, the authors reject the hypothesis that the red shift of this quasar is of gravitational nature.

Photon-counter television systems similar to the Lick apparatus are also in use elsewhere. A similar system is used at the University of Wisconsin with an echelle spectrograph,[188,189] and another in Australia to obtain star spectra.[190] A two-dimensional photometer is being developed on the same principles at the McDonald Observatory.[191]

The Boksenberg system was developed at the London University College on the basis of a four-stage ICT and a plumbicon television system.[192-196] It is distinctive in that it uses a special processor between the television camera and the computer. It records each photoelectron with equal weight, eliminates multielectron noise scintillations, and raises resolution compared to the analog variant of the same system. Since fiberoptics were not used, the apparatus is highly sensitive in the ultraviolet. The input photocathode of the ICT is cooled. The detective quantum efficiency of the system was found to approach that of the input photocathode.[197] As compared to the Lick system, the Boksenberg system has a higher quantum efficiency, gives better photometric accuracy, and ensures recording of spectra over a broader band (320–800 nm).

The Boksenberg system was designed both to record spectra and for use as a two-dimensional photometer. The authors claim that in the latter application it can provide 10^6 fully independent and simultaneously functioning elements. The information capacity of the system is limited by the specifications of the computer used and could, in principle, be increased. The system provides for determination of the stellar magnitudes of the observed objects in any photometric system from the observed distribution of energy in their spectra. For this purpose, a certain weight is assigned to the flux of recorded photoelectrons at each wavelength, and the result is integrated.

Observations with the Boksenberg apparatus were made early in 1974 on the Isaac Newton telescope in England (mirror diameter 2.5 meters). Spectra of the quasar 3C 273 and the Seyfert galaxy NGC 4151 were obtained with dispersions from 3 to 21 nm/mm. The spectral resolution was brought down to 0.1 nm. Comparison of the results with scans made on the same objects with the 5-meter telescope and a multichannel Oke spectrophotometer showed the Boksenberg system to be quite superior.[198,199]

In October 1973, the same system was used to obtain spectra of the quasar PKS 0237-23 on the 5-meter telescope with a spectral resolution of 0.07 nm in the wavelength range 373-430 nm. The observations showed that the quasar has a complex spectrum and a number of different red-shift values.[200] Later, spectra of normal and peculiar galaxies were obtained and the spatial structure of Seyfert galaxies was investigated.[201]

A similar television system has been built in Italy. It uses standard SEC-Vidicon television apparatus. A system using a 4-stage ICT and a SEC-Vidicon with photon counting has also been developed at the Steward Observatory and installed on the 2.3-meter telescope.[202]

5. USE OF TELEVISION SYSTEMS WITH SOLID-STATE VIDEO-SIGNAL SENSORS AND COMPUTERS FOR ASTROPHYSICAL STUDIES OF THE SUN AND STARS

Advances in integrated circuitry are beginning to play a significant role in the development of television techniques. Solid-state television photoelectric devices (SST PED), which are analogs of vacuum camera tubes, have been developed and put into practical use.[203-208] The 1970 development of a new type of SST PED, which has come to be known as the charge-coupled device (CCD), opened the way to rapid progress in the design of solid-state video-signal sensors. It was possible to make comparatively inexpensive silicon-crystal-based CCD structures that incorporate both light-sensitive elements and shift registers for sequential conversion of stacks of charges into a video signal. Recently developed two-dimensional arrays are successfully replacing low-sensitivity vacuum-type camera tubes.[209-210]

SST PED have a number of properties that render them highly valuable for astrophysical research.[211] Their geometric precision is absolute, and they do not require supplementary adjustment and focusing during use. Their range of spectral sensitivity extends from the visible into the near infrared. They have a photoconductive quantum efficiency of 80% at the spectral sensitivity maximum, which occurs at about 800 nm. It is admittedly not yet possible to realize such high quantum efficiency because of the high noise levels of the devices, which are equivalent to hundreds and thousands of charge carriers. SST PED are easily interfaced with integral circuits and computers. It becomes possible to use modern statistical data-processing methods, to optimize image-scanning parameters, and to design automated television systems. SST PED are strictly linear devices. Their deviations from linearity are within the limits of measurement error. Their dynamic ranges are very wide, sometimes reaching 10^5. As a result, SST PED ensure high accuracy in light-flux measurements.[212]

Three types of SST PED are used for astronomical observations: integrating diode arrays or self-scanned diodes, charge-coupled devices (CCD), and charge-injection arrays. They differ from each other only in the method used to read out the accumulated video information.

Integrating diode arrays (IDA) are often called "reticon" systems after a firm that manufactures them. They have high storage capacities, good linearity, small cross-currents between elements, and high sensitivity in the blue region of the spectrum to 310 nm. They are usually designed as linear devices with photodiode dimensions of $25 \times 600\ \mu m$. Two-dimensional self-scanned photodiode devices have been found less effective than others and are not in practical use.

Linear arrays of self-scanned photodiodes are highly convenient devices for astrophysical studies of the sun, since spectroheliographs and magnetographs require light detectors in the form of a slit that isolates one spectral line or part of a line. Therefore as soon as industrial reticon types appeared they were put to use by several observatories in the development of new magnetograph and spectroheliograph systems.

A reticon magnetograph was developed at the Kitt Peak observatory and is now being used successfully in observations.[213] It uses two linear arrays with 512 diodes in each. The operating temperature of the reticon is held at about +5°C by a special unit during observations. Dry nitrogen is used for drying. A sensitivity comparison between the magnetograph with self-scanned diodes and a magnetograph using forty photomultipliers that had been placed in operation at the same observatory in 1970 showed that the increased number of channels raised the over-all sensitivity of the device by a factor of about 15. The lowest contrast that can be recorded on the new instrument is $\Delta I/I = 3 \cdot 10^{-4}$. Because of the increase in total and contrast sensitivity, the magnetograph is able to record the fine-scale structure of the magnetic field not only in active, but also in quiet regions on the sun (Fig. 15).

The Lockheed Solar Observatory in California has developed a magnetograph around the reticon 512, which operates at a temperature of −40°C.[214] Each scan is digitized in the instrument with twenty-four bits to a word. The signal/noise ratio reaches 2000:1 when the capacitance of the diodes is saturated. A 17-cm reflector and an optical filter with a 0.02 nm passband are used for observations. The time needed to obtain

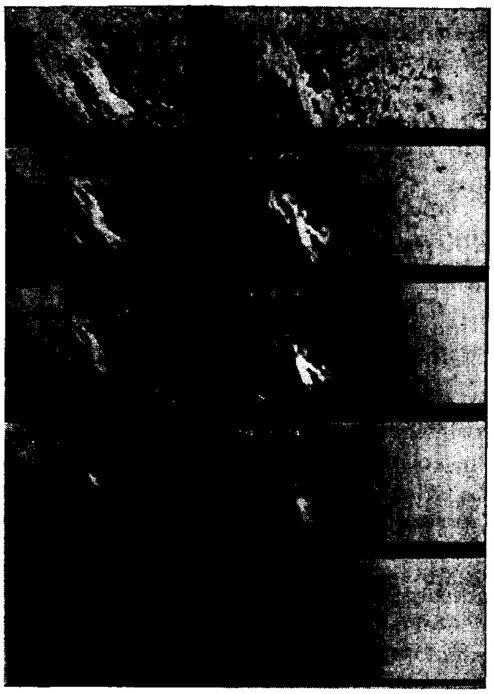

FIG. 15. Magnetograms of two regions on the solar disk obtained on the Kitt Peak Observatory magnetograph in the range 2–2000 Γ. All 4 prints (top) were taken from the same magnetogram with the image reproduced at various gains—1:2:4:16. The photographs at the bottom are of the same regions in visible light.

one magnetogram (683 × 512 elements) is 5 minutes.

Several observatories have conducted experiments in which a reticon was used in stellar spectroscopy. In Canada, a reticon was tested in a spectrograph mounted at the Cassegrain focus of a 2.2-meter telescope.[215,216] A measurement accuracy of 1% was obtained when a reticon was used in a spectrometer.[217] Tests of a reticon 128 for stellar spectroscopy at the University of Arizona showed that it is useful only for observing the spectra of stars of medium brightness.[218]

A spectrograph using a reticon 256 was developed at the McDonald Observatory and tested on the 0.9-meter telescope in observations at 430 to 960 nm.[219] The spectrograph is controlled by a small computer, which also accomplishes preliminary processing of the data obtained. Compared to a PM scanner with a cesium-oxygen photocathode, the reticon spectrograph gives a multichannel advantage of 100. The spectral energy distributions in the spectra of several stars were obtained on the 0.9-meter telescope. Light-gathering power was $12^m.5$ for late spectral class stars at a dispersion of 80 nm/mm, an exposure time of 2 hours, and a measurement error of 1%. The Cerro-Tololo Observatory (Chile) has also used a reticon for infrared spectral observations.[220]

Very few astronomical studies have as yet been made with the reticon. Spectra of ionized-hydrogen regions have been obtained with the object of accurate determination of the line-intensity ratio and detection of faint details.[221] Observations of the H_α hydrogen line of the x-ray source Cygnus X-1 have brought out low-intensity wings.[222]

In all of the above studies, the reticon was used to record rather high light fluxes when high measurement accuracy was required. The reticon is not sensitive enough when the problem is one of recording small light fluxes, and it is necessary to use either a high-gain ICT, as was done at the Max-Planck Institut[223] and the University of Michigan,[224] or microchannel plates[225,226] in front of it to obtain additional intensification of the light.

Solid-state arrays working on the charge-transfer principle are two-dimensional light detectors.[227] They use a combination line-and-frame principle in transferring the accumulated charges from the light-sensitive array to the memory array and a push-pull circuit for delivery of the switching pulses. Their frequency-contrast characteristics differ slightly along the horizontal and vertical. The cross current between elements, which lowers the contrast between details, is a deficiency of these arrays. It has been reported that an array capable of replacing the silicon diode vidicon has been developed.[228] Structurally, the photoarray with its control and primary signal amplifier circuits is built into a ceramic housing with 24 leadins and an optical entrance window. The minimum illumination required to operate it is 10^{-2} lx.

Research on the use charge-transfer arrays in astronomy has been started at several observatories. A CCD has been tested on the 4-meter Kitt Peak Observatory telescope as part of a development program for panoramic light detectors for astronomical use.[229] The Princeton University observatory has developed a camera for observation of faint extended objects in red light. The camera has been tested on the 0.9-meter telescope. It has been used for surface photometry of three galaxies in the wavelength range from 500 to 1000 nm with five optical filters having a half-passband of 100 nm.[230] Lowrance *et al.* used a 100 × 100-element array to record x-radiation at 0.1–2 nm.[231]

The sensitivities of instruments utilizing CCD can be increased by electron optical preamplification of the signal. In a photometer developed at the University of Maryland, an ICT with a multislit photocathode was mounted in front of the array (100 × 100 elements).[232] The authors claim that it records single photons. They have also developed a special procedure by which the dynamic range of the system can be broadened to 10^8.

Charge injection device (CID) arrays have the same sensitivity as CCD, but better transmission of small-detail contrast. Charge-injection devices use cross-over switching-pulse addressing in a corresponding-bus coincidence scheme with direct extraction of the signal current. An advantage of these devices is that they can be read without disturbing the charges, so that the same information can be picked off several times and the data from the various readings summed to raise the signal/noise ratio.

Use of charge-injection arrays for astronomical observations has only just begun. A device whose designers call it an "image spectrometer" has been developed at Cambridge, Massachusetts and tested under astronomical conditions.[233,234] It is intended for use in photography of major planets in narrow spectral bands between 650 and 1100 nm. Its light detector is a 100 × 100-element CID array. A spectral band 1.5 nm wide is selected by an opticoacoustic light filter that makes it possible to shift the passband at will in the segment of the spectrum being used. The transmission of the filter at band maximum is 20%. During observations, the array is cooled by circulating carbon-dioxide-cooled alcohol around it. This reduces the dark current, which can be detected only if the exposures exceed 5 minutes. The storage capacity of the computer used is 10^4 12-bit words. Saturn and Jupiter were observed in January 1975 with the 1.5-meter telescope. The exposure times were 5 and 2 min, respectively. Photographs of Saturn were obtained in 12 segments of the spectrum within the 890-nm methane band. The best signal/noise obtained on these photographs was 40.

Two cameras using charge-injection arrays have been developed for astronomical use at the Kitt Peak Observatory.[235] One of them was designed for use in a Fourier spectrometer, and the other for direct photography and use in solar and stellar spectroscopy. The array has 100 × 100 elements and is mounted inside a liquid-nitrogen-cooled dewar.

Image converters are mounted in front of the array to record extremely weak fluxes, as, for example, in Canada.[216] Use of a 188 × 244-element array is proposed.

CONCLUSION

Television-electronic techniques are now developing rapidly. Many new systems are being developed, but many of them are not viable and are abandoned before they are ever used in practice. These systems were not considered in preparation of the present review, which has concentrated on devices that have been used in astronomical observations. As in any rapidly developing area, it is difficult at this time to predict which of the systems and transmitting devices now being used in television electronics will prove most promising. Theodorou and Pickels' comparison of several types of transmitting tubes, in which they used a consistent laboratory technique, is interesting in this context.[236] These authors used tubes of the highest sensitivity, with electron-optical preamplifier stages. Figure 16 shows two of the plots that they obtained. The results were presented in tabular form with rough tube-quality ratings for various comparison criteria.[236] Table II lists criteria that are important for astrophysical research, and to them we have added data on the quantum efficiencies and photometric properties of the tubes and difficulties encountered in tuning them. Comparison of the results indicates that the isocon is the best tube for ground-based astrophysics. However, it may be more advantageous to use a SEC-Vidicon or a silicon diode vidicon under other sets of conditions.

The current trend in astronomical applications of television electronics is to design a specialized television system for solution of a given observational-astronomy problem. For example, the image orthicon and isocon are most suitable for patrol and search operations in which it is necessary to obtain a large number of photographs of small areas of the sky with maximum time resolution. Silicon diode vidicon television systems have low sensitivities, but they are simple to tune and provide highly accurate light-flux measurements. They can be used for recording low-contrast details of sufficiently bright objects. The SEC-Vidicon is conveniently used in space because information can be accumulated over an extended time on its target. On the ground, it is used for guiding purposes and for identification of astronomical objects, and, in combination with ICT, in determining the radial velocities of galaxies and quasars. Photometry with the SEC-Vidicon is technically difficult. Systems with scintillation counting on the output screens of multistage ICT have been developed for spectral research. They have high quantum efficiencies but are awkward to work with. Systems with solid-state television photoelectric devices occupy a special position. These transmitting devices appeared comparatively recently, and the first attempt to use them in astronomy was successful. Their basic advantages are linear response over a broad range and the absence of geometric distortion. They have a disadvantage in their high noise level, which decreases only on deep cooling. They are still not particularly sensitive, and are used in combination with several ICT stages for observations of faint objects.

Although television techniques in astronomical observations do not replace any of the existing methods,

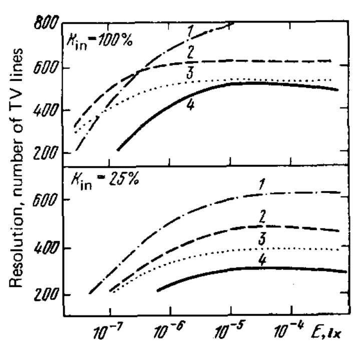

FIG. 16. Resolving powers of isocon (1), silicon diode vidicon with large (2) and small (3) target, and SEC-Vidicon (4) plotted against input photocathode illumination level. The image contrasts at the input were 100% (upper diagram) and 25% (lower diagram).

TABLE II. Comparison of various types of television transmitting tubes with a multistage ICT input stage.

Comparison criteria	Camera tubes with multistage ICT		
	Isocon	Silicon diode vidicon	SEC-Vidicon
Resolution	5	4	2
Contrast sensitivity	5	4	2
Vunerability to damage under strong illumination	5	4	2
Quantum efficiency	5	4	2
Photometry	5	5	3
Loss of definition in bright image	5	4	2
Size, weight, power	2	5	5
Difficulty of tuning	3	5	5

Ratings: 5—excellent, 4—good, 3—fair, 2—poor.

they do place new opportunities in the hands of the investigator. Thorough study of these possibilities will make it possible to solve a number of new problems of modern astrophysics.

Further progress in astronomical, astrophysical, and space research with television-electronics techniques will be determined in large part by progress in the rapidly developing areas of physical electronics. Rapid assimilation of new advances in integrated circuitry and their use in practical astronomical observations should be a priority objective of astronomers.

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