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Advances in Detectors for Astronomical Spectroscopy

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Advances in detectors for astronomical spectroscopy

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Image-reproducing detectors for ultraviolet, optical and near infrared spectroscopic applications in astronomy are described. Emphasis is placed on detectors of the image photon-counting type and on charge-coupled devices.

1. Introduction

Spectroscopy is the most important investigative technique applied in astronomy; it accounts for the use of about 80% of the time on the world's major telescopes. In many respects it is far more challenging to find appropriate image-reproducing detectors for astronomical spectroscopy than for direct-imaging applications: the faint image of a distant object merely requiring detection when found photographically is made even fainter when dispersed into a spectrum, which additionally requires precise quantitative study. Several forms of detector or detector-combination suitable for this application now exist and some have been in constant use for many years. The functional tree given in figure 1 indicates the operation of various practical imaging detectors in current or planned use. The diagram is constructed to show both how single devices are assembled and how two or more devices are coupled to form systems commonly used in astronomy. For example, direct interaction of photons with the recording medium occurs in photographic emulsion, in electronically scanned silicon devices such as the charge-coupled device (c.c.d.), and in electron-beam scanned television camera tubes of the simple vidicon type of which the lead oxide vidicon is a high-quality example used widely for broadcasting. In all other devices mentioned or implied in figure 1 a photocathode is used to produce an intermediate electron image, which then is accelerated to relatively high energy to enable the signal to be enhanced by some gain process before, or in the act of, recording. Photocathodes also are used in this way in the secondary electron conduction (s.e.c.) vidicon, the silicon intensified target (s.i.t.) vidicon and the image dissector tube, which are grouped as shown for ease of presentation.

Most detector devices produced commercially are developed for broadcast or military markets, and for reasons of cost and availability it has been advantageous to employ the more appropriate of these in astronomy. Many of the detectors described here are in this category but there are several important exceptions. Because of the great development effort required to make available any new device in this difficult field, it is unlikely that anything fundamentally new will appear in more than basic prototype form for many years to come.

A clear trend in the use of detectors in astronomy in recent years has been the increased application of electronic data processing and computer techniques. This applies both to the 'modern' detector systems with their sophisticated processing and recording techniques applied on-line while at the telescope, and to the highly versatile measuring machines used for the reduction of photographic or electronographic recordings. Indeed, the apparent

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simplicity of the latter detecting methods is illusory when it is realized that the use of such measuring machines is an essential part of their technique.

At very low light levels, the normal situation in astronomy, the ultimate limit to the accuracy of image recording set by the quasi-poissonian statistics of the incident photons soon becomes evident. An ideal detector would unambiguously register the arrival of each photon in its

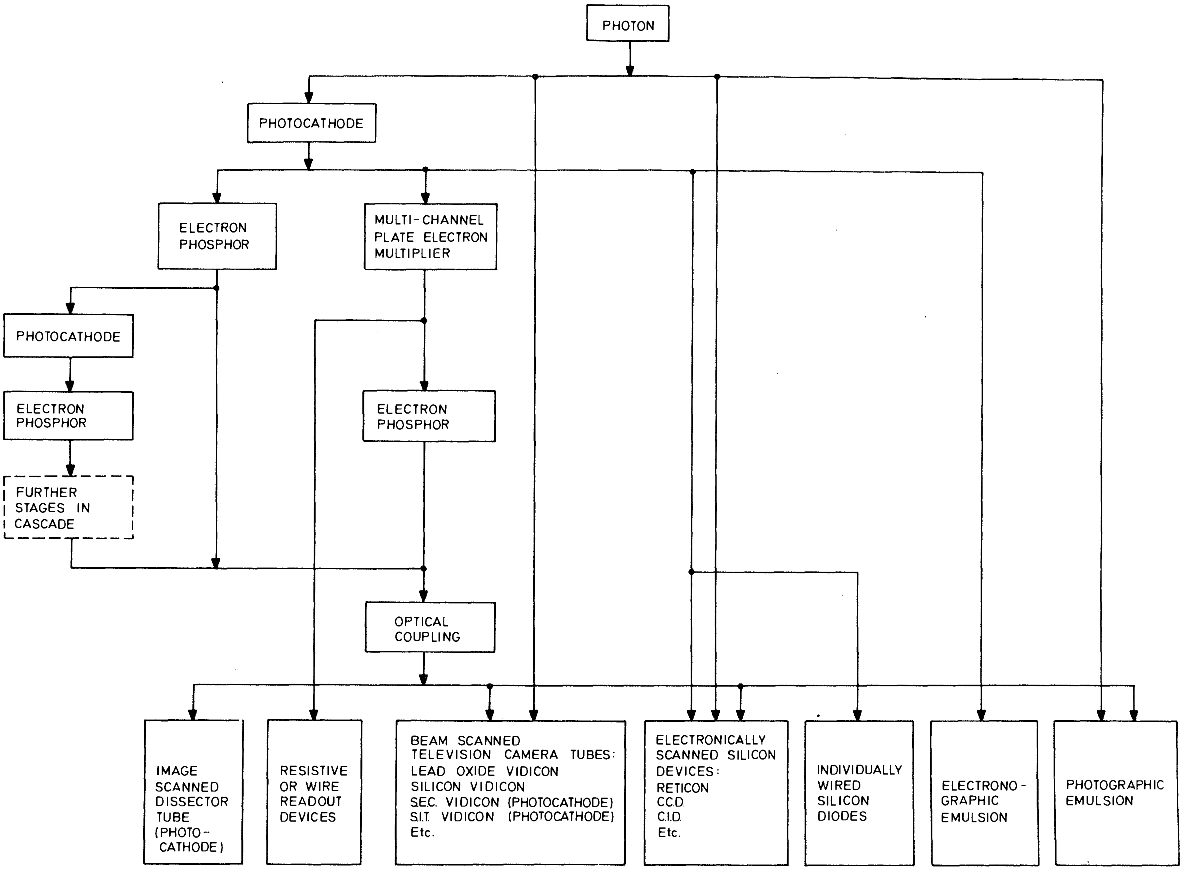

FIGURE 1. Diagram showing how available detector components are used in current or planned applications in astronomy.

correct image position, and a signal of N_I photons per unit area would be measured with the maximum possible signal:noise ratio of $N_I/N_I^{\frac{1}{2}} = N_I^{\frac{1}{2}}$. Practical detectors invariably contribute additional noise, principally because a fraction of the photons goes completely undetected, but also due to uneven gain processes that accord detected photons unequal statistical weighting, and to the addition of background noise. Additional information losses arise in real detectors because of image spreading and halation effects, resulting in a loss of resolution and contrast. A frequently used figure of merit is the detective quantum efficiency (d.q.e.), which may be defined as the ratio of the number of quanta (N_I) required by an ideal detector to the number (N) required by the actual detector for identical output signal:noise ratio, i.e. d.q.e. $= N_I/N$.

In the following sections I shall give an account of some of the techniques implied in figure 1, but shall avoid detailed descriptions of individual devices, which in the most part are adequately covered in the literature. I shall confine my account to detectors suitable for astronomical applications in the ultraviolet, optical and near infrared (to about 1 μm) spectral ranges.

2. Photographic emulsion

It is now more than a century since the invention of the gelatin photographic emulsion, but this is still the most frequently used medium for recording astronomical images. Progressively, there has been much improvement in sensitivity and other characteristics of emulsions, and the introduction of special sensitizing techniques has resulted in further large gains in sensitivity (Sim 1977; Latham 1974). However, the photographic process has many deficiencies, including nonlinear response, restricted dynamic range, reciprocity failure, adjacency effects, and even for the best available hydrogen-baked Eastman Kodak IIIaJ plates the d.q.e. is no higher than 4% and even then over a very limited dynamic range (Coleman 1977).

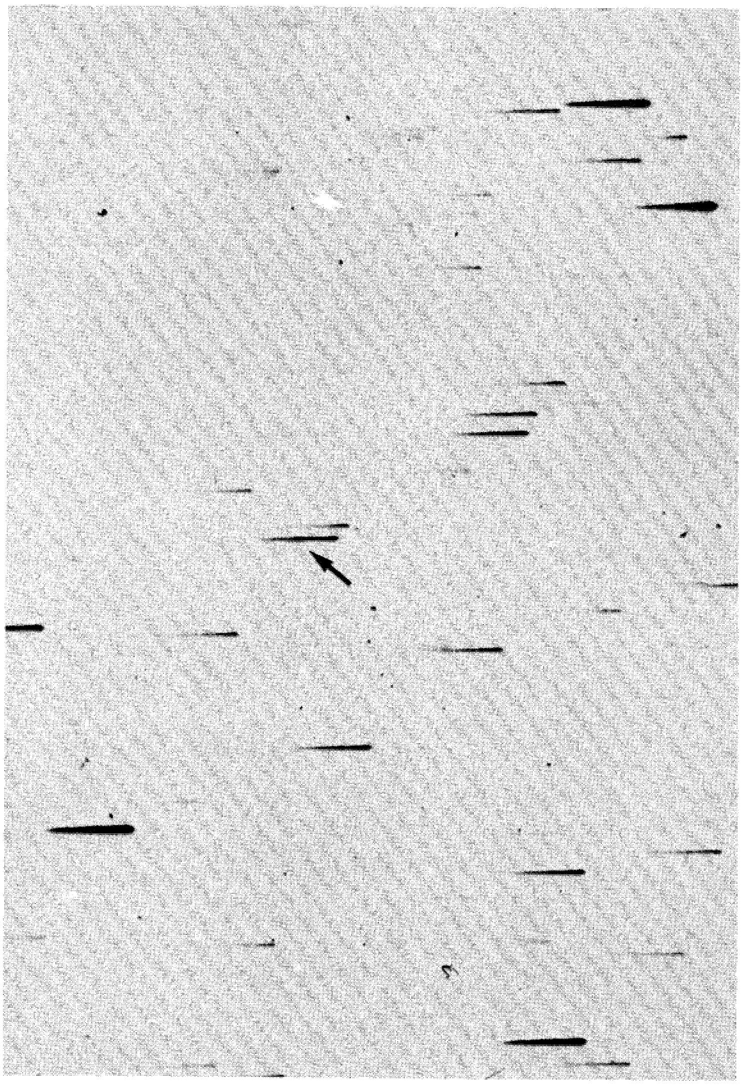

Figure 2. A small portion of a Schmidt telescope objective prism survey plate recorded photographically. Most of the spectrally dispersed images are of stars in our Galaxy. The arrowed image is of a quasar whose highly red-shifted Ly α emission line is clearly evident. Blue is to the left in all images.

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Photographic emulsion, however, has an overwhelming advantage over all over detection media when a huge number of picture elements is required: the Schmidt sky surveys, of which the high-quality IIIaJ southern sky direct and objective prism surveys by the U.K. 1.2 m Schmidt telescope (Cannon 1976) are outstanding examples, use photographic plates up to 35 cm across. The objective prism technique, although providing spectra of very low dispersion, is particularly advantageous as a means of searching over a large field simultaneously for particular classes of object having a clear spectroscopic signature (see figure 2); conventional spectroscopy, using a telescope with spectrographic instrumentation pointed individually to known objects of interest, is not suited to such large-scale surveying but takes over for the detailed studies that follow discovery by survey. Such survey plates contain a remarkably high quantity of information and have a picture element capacity many orders of magnitude greater than any photoelectronic devices yet available. For such applications this advantage of the photographic plate far outweighs its disadvantages and there is little doubt that its superiority in this field will be maintained for the forseeable future. Probably there will be continuing but gradual improvements in emulsion characteristics, but the main advances in the technique undoubtedly will be in the automatic extraction and processing of the vast amount of recorded information by use of 'intelligent' measuring machines with programming and pattern-recognition facilities.

3. Electronography

In 1934 Kiepenheuer (1934) proposed that an efficient detector could be made by accelerating and focusing electrons from a photocathode onto a photographic emulsion. That there should be a considerable gain in sensitivity over pure photography was evident, because it was known that every high-energy electron entering the emulsion produces developable grains and there is no reciprocity failure. The overall efficiency should therefore depend mainly on the efficiency of the photocathode. Lallemand in 1936 independently conceived the same idea and started work on what he later called the caméra électronique. He published his first astronomical results in 1952, and reported a tenfold gain in speed over a photographic plate used directly (Lallemand 1952). Ever since, Lallemand and his collaborators have continued with the development and astronomical use of the caméra électronique (Lallemand *et al.* 1976) but because of technical difficulties in its operation, few observatories outside France have adopted it for general use. Modifications to the technique by Kron (1969) and particularly by McGee (McGee *et al.* 1966) who in his 'spectracon' used a mica barrier membrane to protect the photocathode and also to allow the emulsion to be used in air, have resulted in more convenient operation and consequently wider use. A recent version of electronographic camera, developed by McMullan (McMullan & Wehinger 1977), combines the advantages of previous devices and also is automated for greater ease of operation.

Electronographic cameras now use nuclear not photographic emulsions (Coleman 1975); these are particularly fine-grained, have a very low background fog level, and their silver-halide: gelatin ratio is high to provide good electron-stopping power. An important characteristic, greatly simplifying data reduction, is that the measured optical density (D) is proportional to exposure up to $D = 6$. Taken together with the fine grain and low noise, this results in very high storage capacity, and, although an electronograph may appear visually less dense and of lower contrast than a photograph, efficient microdensitometric analysis reveals the higher information content of the electronographic record (McMullan & Wehinger 1977).

Of course, the performance of an electronographic camera, as with all the photoelectric devices to be discussed here, depends critically on the responsive quantum efficiency of the photocathode. The most commonly used photocathode in optical astronomy, trialkali, has an efficiency of about 20% in the blue falling to about 1% at 8000 Å.† Many other photoemitters are known; a good description of a wide range of materials, and the theory of photoemission, is given by Sommer (1968). Recent advances in solid-state technology have led to the discovery of a new class of 'negative electron affinity' photoemitting materials such as GaAs(Cs) (Sommer 1973*a*, *b*) with a high efficiency in the red and near infrared.

In recent years, electronography has been overtaken by more convenient techniques and in future is unlikely to have application in astronomical spectroscopy. However, for completeness, I have given it space in this article because the technique does represent the intellectual and pioneering work on which all modern image-detecting equipment is based.

4. Image intensifiers

As for electronography, all image intensifiers‡ used in astronomy (Coleman & Boksenberg 1976) depend on the initial conversion of photons into an electron image by photoemission. In one commonly used technique the electrons are then accelerated onto a cathodoluminescent phosphor screen to produce an enhanced optical image, which is recorded by conventional photographic means. A blue-light gain of 50 is typical for a simple device of this kind and, as indicated in figure 1, several such stages can be arranged in cascade to give a very high overall gain. Means of focusing the electron image are shown schematically in figure 3. The simplest is proximity focusing, in which the electrons are merely accelerated between the plane-parallel photocathode and output screen, which are narrowly separated by 0.5–1 mm to reduce the lateral spreading of electrons during transfer. The practical gain and resolution performance of proximity-focused intensifiers is limited by mechanical and electrical breakdown considerations and is lower than for types with electrostatic-lens or magnetic focusing. For highest gain and resolution the magnetic type is generally used. Cascaded stages are most simply produced by coating the phosphor of one stage on one side of a thin transparent membrane (usually mica) and the photocathode of the next stage on the other side, and containing all stages in one vacuum envelope. A four-stage intensifier of this kind produced by E.M.I. has a blue-light gain of *ca.* 10^7. However, electrostatic-lens focusing produces a more compact intensifier. Then, for the best electron-optical performance over the whole image area, both the photocathode and screen surfaces must be curved; this can present difficulties in matching optically, but the problem is usually overcome by using plano-concave fibre-optic faceplates to transfer light between outer plane optical surfaces and inner concave surfaces. Until recently, fibre-optic faceplates had rapidly falling transmission below 3800 Å, but versions transmitting further into the ultraviolet (3200 Å) are now available. Owing to the curvature of the input and output fibre-optics, several effects combine to give a radial decrease in light gain for such an intensifier, reaching about a factor of 2 in multistage devices. Near the transmission limit, higher absorption in the thicker parts of the faceplate further aggravates the problem. In commercial devices a compromise is often struck in reducing the loss in centre-to-edge gain

† 1 Å = 10^{-10} m = 10^{-1} nm.

‡ The term intensifier is used rather loosely: it implies a device with a net *photon* gain but with arbitrary input and output spectral characteristics; e.g. a device may accept an ultraviolet image but convert it to an enhanced optical image.

at the expense of off-axis resolution and the introduction of pin-cushion type distortion. Magnetically focused intensifiers, on the other hand, have the advantage of plane electron-optical surfaces, not requiring fibre-optics, and so can be made with an input window fully transparent in the ultraviolet.

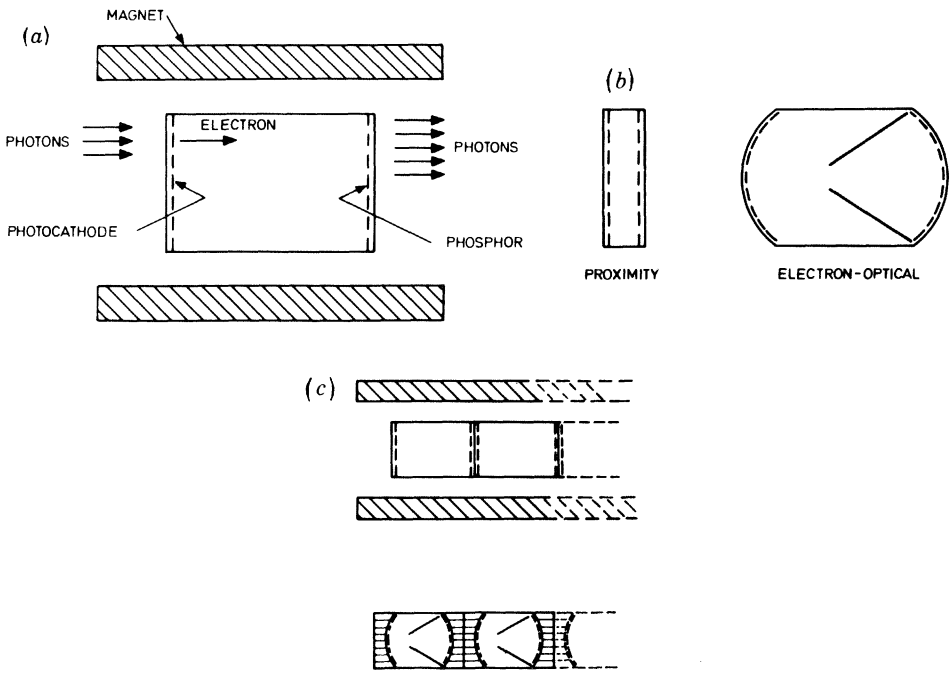

FIGURE 3. Focusing methods and cascading of photocathode–phosphor image intensifiers: (*a*) magnetic focusing; (*b*) electrostatic focusing; (*c*) multistage.

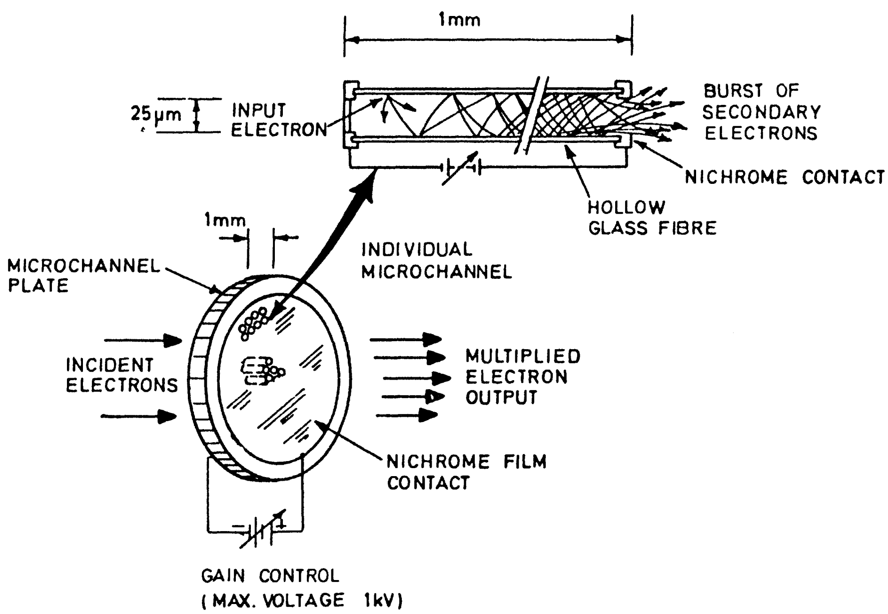

FIGURE 4. The operation of a microchannel-plate imaging electron-multiplier.

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The microchannel plate (m.c.p.) is a different kind of imaging electron multiplier capable of extremely high gain. It consists of a close-packed array of fine, slightly conducting glass tubes with a secondary emission coefficient greater than unity. An accelerated electron entering one of the channels and striking the wall produces secondaries, which in turn are accelerated by an internal electric field to strike the wall again; the process continues until an avalanche of electrons emerges from the output of the channel (figure 4). The m.c.p. can be built into a very

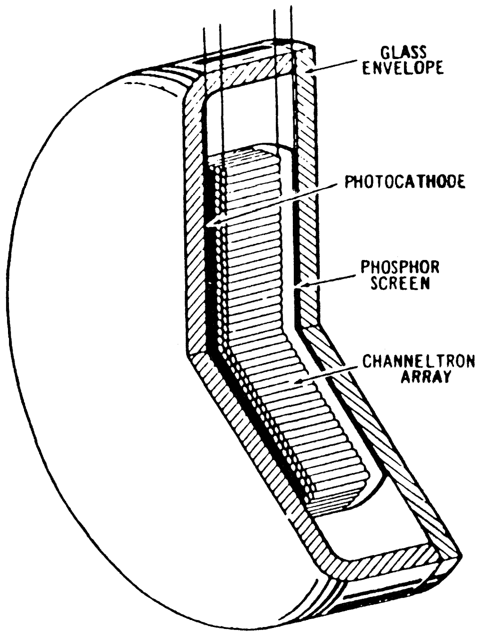

Figure 5. A wafer intensifier (seen in section) incorporating a microchannel-plate imaging electron-multiplier.

compact double proximity-focused structure by using a conventional photocathode on its input window to give a 'wafer' intensifier with high gain and no distortion (figure 5). Alternatively, with the omission of the input window and a suitable dielectric photocathode (e.g. CsI) deposited directly onto the channel walls, the device can be made sensitive from the far ultraviolet to the soft X-ray region. The electron gain of a typical m.c.p. with straight channels is 10^4 at 1 kV applied (Riggieri 1972; Manley *et al.* 1969), normally limited by the onset of positive-ion feedback, and the output pulse sizes exhibit a broad distribution, which results in a noisy image and leads to a reduced d.q.e. for the device. Recently, several techniques have been introduced to suppress ion feedback, the most promising method being to curve the channels (Bontot *et al.* 1976), and then an electron gain of more than 10^7 is achieved without difficulty. Additionally, the output pulse sizes at such high gains are confined to a sharply peaked distribution that substantially decreases the noise in the image compared with the low gain performance.

The output of an image intensifier may be recorded photographically, as already mentioned, by using fibre-optic or lens coupling from the output phosphor to the emulsion. This combination then has a much higher d.q.e. than direct photography but obviously still suffers from nonlinearity and small dynamic range. Coupling to a photoelectronic detector is described below.

5. Integrating television camera tubes

The performance of general-purpose industrial or broadcast television cameras is adequate for normal lighting conditions, but is severely limited by noise (from the video preamplifier and other sources) at low light levels. Under such conditions, it is convenient to use a camera tube with high internal gain and the capability to integrate a weak signal over a long period before readout. Two tubes having these properties are the s.e.c. and s.i.t. vidicons which, apart from the target, are identical in construction (figure 6). An image incident on the photocathode generates photoelectrons, which are accelerated to a few kiloelectronvolts in

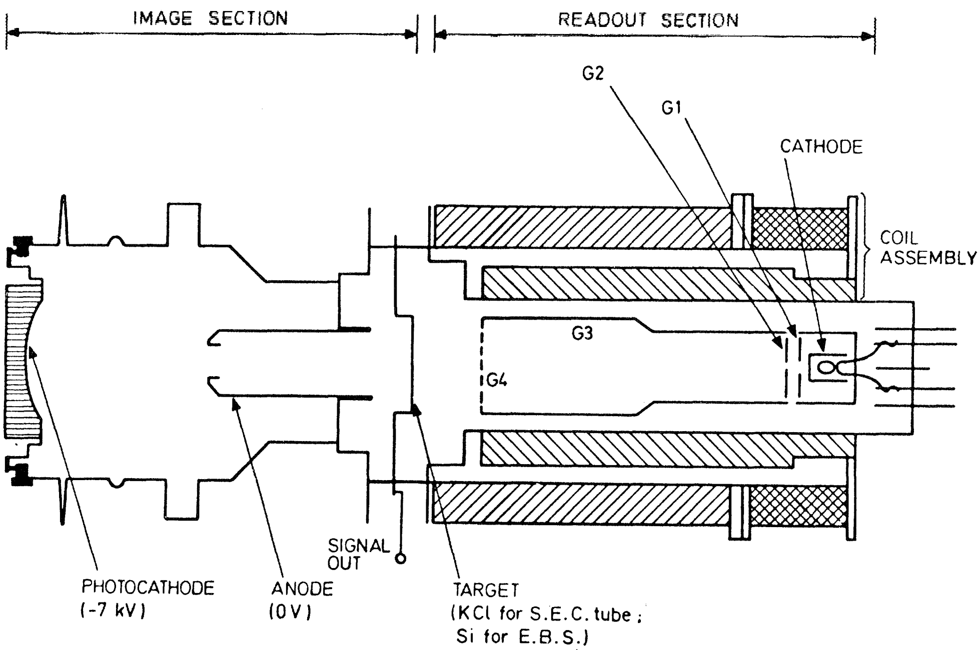

Figure 6. Schematic diagram of the high-gain s.e.c. and s.i.t. (also called e.b.s. for 'electron bombarded silicon') camera tubes. This configuration has an electrostatically focused image stage but magnetically focused versions are also available.

the image section and focused at the target. Electron multiplication takes place in the target and, at the end of the exposure, the amplified electron image is read by a scanning electron beam in the readout section. The s.i.t. target has an electron gain of *ca.* 2000 and requires strong cooling (e.g. to -60 °C) to reduce the dark current sufficiently to permit long integration times. The s.e.c. target has lower gain (*ca.* 100) but can integrate and store charge images indefinitely at room temperature without degradation, which makes this tube more convenient to use than the s.i.t., but it has the disadvantage of lower storage capacity.

Several observatories have used these tubes in optical astronomy programmes (Westphal & Kristian 1976; Ingerson *et al.* 1976; Lowrance *et al.* 1972). S.e.c. vidicons also have been used for ultraviolet astronomy; for example, as the spectroscopic image detectors in the *International Ultraviolet Explorer* (*IUE*) astronomical satellite (Boksenberg 1975). In this case the visible-light sensitive s.e.c. tube is preceded by a proximity-focused ultraviolet–visible converter (with MgF_2 faceplate and Cs–Te photocathode) to render the combination sensitive in the region 1150–3200 Å (figure 7).

6. Image photon-counting systems

As was mentioned in the introduction, there has been a clear trend to employ electronic data processing and computer techniques to augment and enhance the use of detectors in astronomy. A good example of this is the technique of 'image photon counting' (figure 8). The basic approach of the technique is to amplify the photoelectron image to a level where all the scintillations from single detected photons can be discerned above the readout noise of a television camera used to view the output screen of the intensifier. In the image photon-counting system (i.p.c.s.) developed at University College London (Boksenberg 1970, 1972, 1976) a lead oxide vidicon is lens-coupled to a four-stage magnetically focused intensifier and a signal of several hundred thousand electrons is generated in the camera tube target for each detected photon. The video output contains, in addition to the photoelectron scintillation

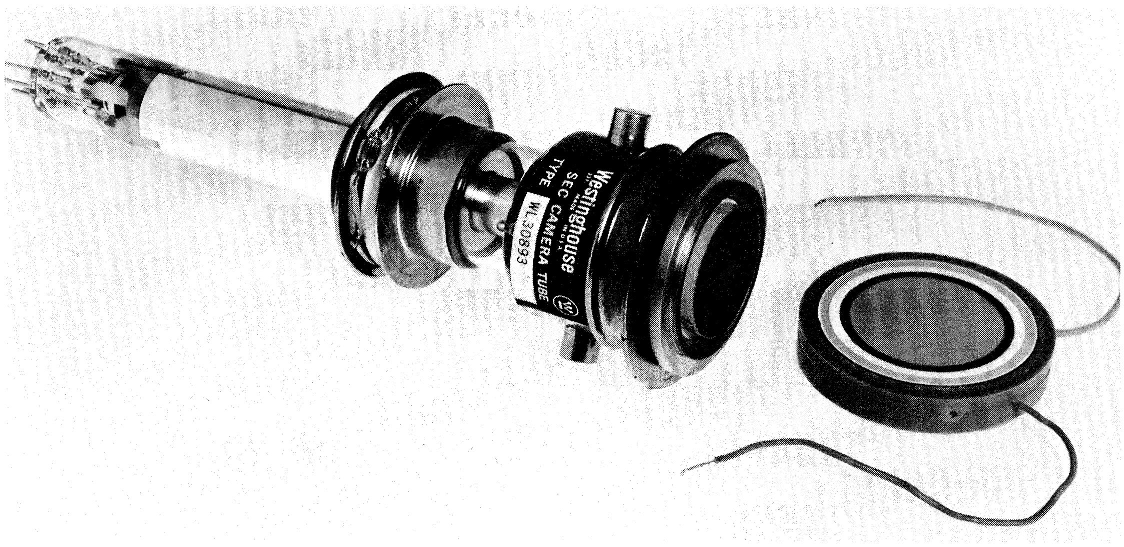

Figure 7. Detector components (s.e.c. camera tube and proximity-focused ultraviolet–visible converter–intensifier) for the spectroscopic instrumentation on the *International Ultraviolet Explorer* satellite. The components are normally bonded face-to-face but are here shown separated for clarity.

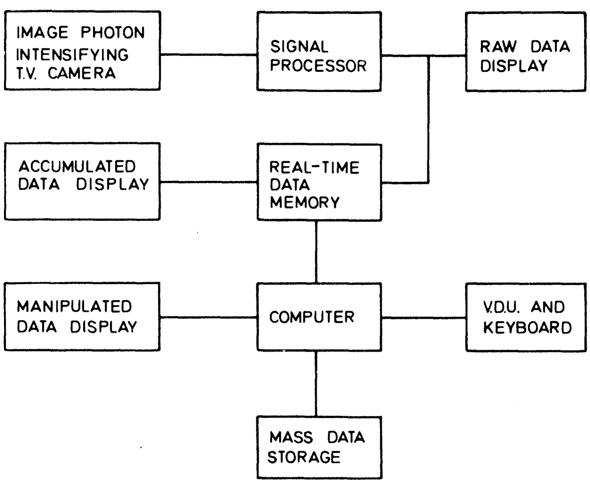

Figure 8. Block diagram indicating the method of image photon counting.

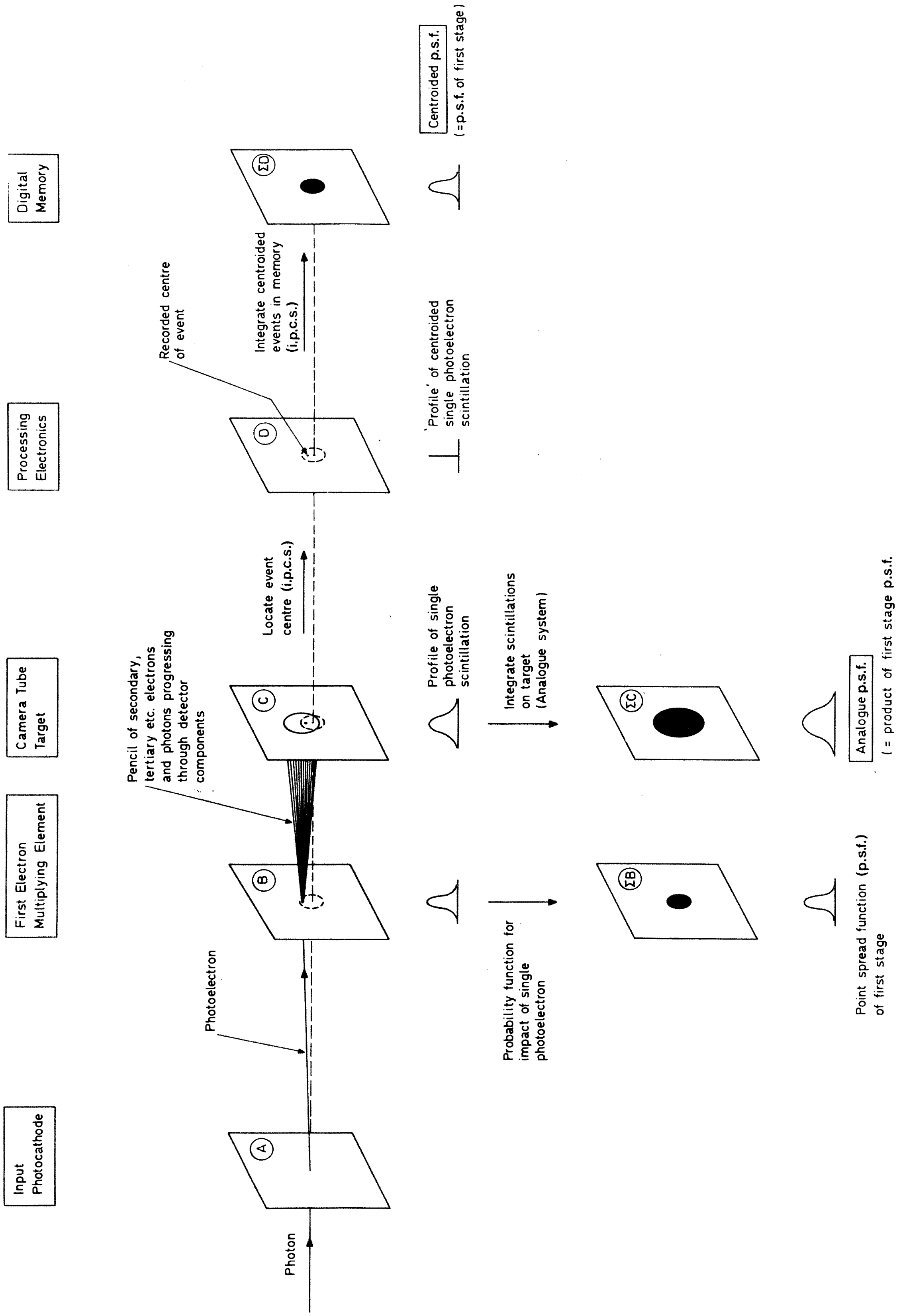

FIGURE 9. Comparison of the resolution of a centroiding image photon counting system with that of an analogue detector.

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information, high-frequency noise and low-frequency level changes. A pulse amplifier with optimized integration and differentiation time constants is used to reject much of the noise. The pulses are fed to a hard-wired digital signal processor, and thence to a computer. The special processor is essential to a true photon counting system; its principal functions are as follows.

(*a*) Location of the geometric centre of each event ('centroiding'), and elimination of multiple counting of a single event. This latter is necessary because the finite size of a scintillation means that it can be detected on perhaps two or three adjacent television scan lines. Centroiding thus ensures maximum d.q.e. by according equal statistical weight to each counted event. The other important advantage, compared with analogue image detection, is that recording the position of the centre of each scintillation results in markedly improved spatial resolution. This is illustrated in figure 9, the upper half of which represents the progression of the signal from an individual detected photon through the i.p.c.s. The photoelectron released from the input photocathode (A) deviates slightly from the axis according to the magnitude of its emission velocity components, which are statistically distributed. The primary photoelectron therefore lands on the first electron-multiplying element (B) (e.g. a phosphor–photocathode dynode) at a position determined by a two-dimensional probability function; the size and shape of this function are identical to the large-signal 'point-spread function' (p.s.f.)†, which is generated by the statistical accumulation of individual electrons (ΣB). The slightly divergent beam of secondary electrons from the point of impact of the primary on (B) passes through the rest of the system and gives rise to a scintillation of finite diameter on the camera tube target (C). The centroiding logic determines the geometric centre of the scintillation and this is recorded at the appropriate memory address in the computer (D) corresponding to the point at (B) on which the primary photoelectron was incident. For a large number of electrons originating from a point image at (A), integration in the external memory (ΣD) results in a p.s.f. similar in size and shape to the probability function at (B). In an analogue system, by contrast, the signal from each photoevent is not processed independently; the p.s.f. of the first stage (ΣB) is further broadened (by convolution with the scintillation profile) to give a larger output p.s.f. at the camera tube target (ΣC). Thus the resolution loss in an analogue system is considerably worse than in a centroiding i.p.c.s.

(*b*) Rejection of low-amplitude noise pulses, and of high-amplitude pulses due to ion noise scintillations in the intensifier. For efficient discrimination, it is only necessary to have adequate gain and for the scintillations to have a favourably peaked brightness distribution, as is obtained with photocathode–phosphor intensifiers or with m.c.p. intensifiers operating in the pulse-saturated mode.

(*c*) Encoding the positions of the centroided photon events and passing the data to the computer, where the appropriate memory addresses are incremented.

Because of the digital (photoevent/no photoevent) mode of operation, the system performance is far less sensitive than in an analogue system to detailed aspects of the detector's construction; the performance of an i.p.c.s. is generally limited only by the efficiency of the primary photocathode and by the resolution of the first intensifier stage. The separation of the detection and storage functions of an i.p.c.s. results in several additional advantages.

(i) Storage capacity is effectively unlimited, being completely independent of the detector and depending only upon the size of the computer memory.

† The p.s.f. is the shape of the output image resulting from a delta function (point) input; its diameter at half maximum height may be regarded as a measure of the loss of resolution in the imaging system.

(ii) Rapid time-varying effects can be accommodated.

(iii) There is no low-level threshold for very weak exposures of only a few photoelectrons per pixel, so that very faint images can be recorded.

(iv) Real-time display of the accumulating image on a monitor results in high operating efficiency; for instance, in astronomical observations, considerable time may be saved by terminating exposures as soon as the required image signal:noise ratio has been achieved.

(v) The exposure linearity and system stability allow accurate photometric calibration and

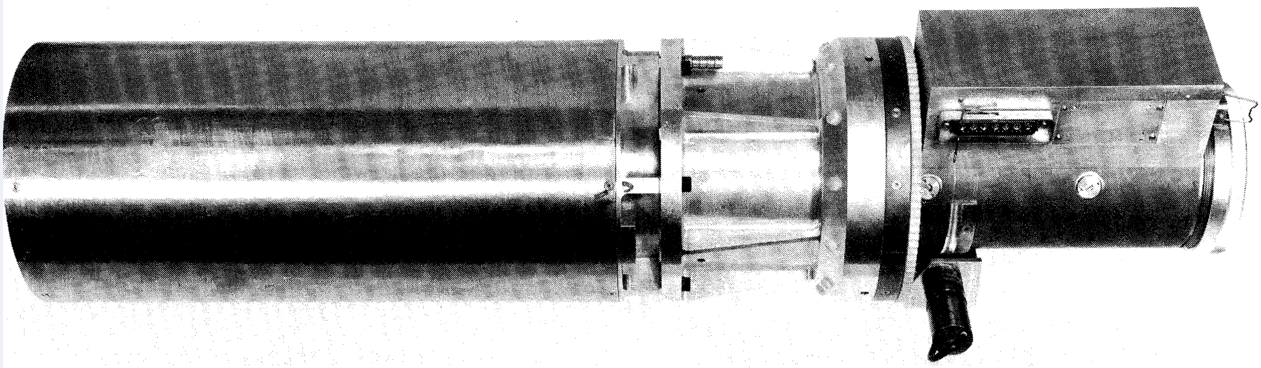

FIGURE 10. The U.C.L. i.p.c.s. detector head unit, containing image intensifier, coupling lens and television camera.

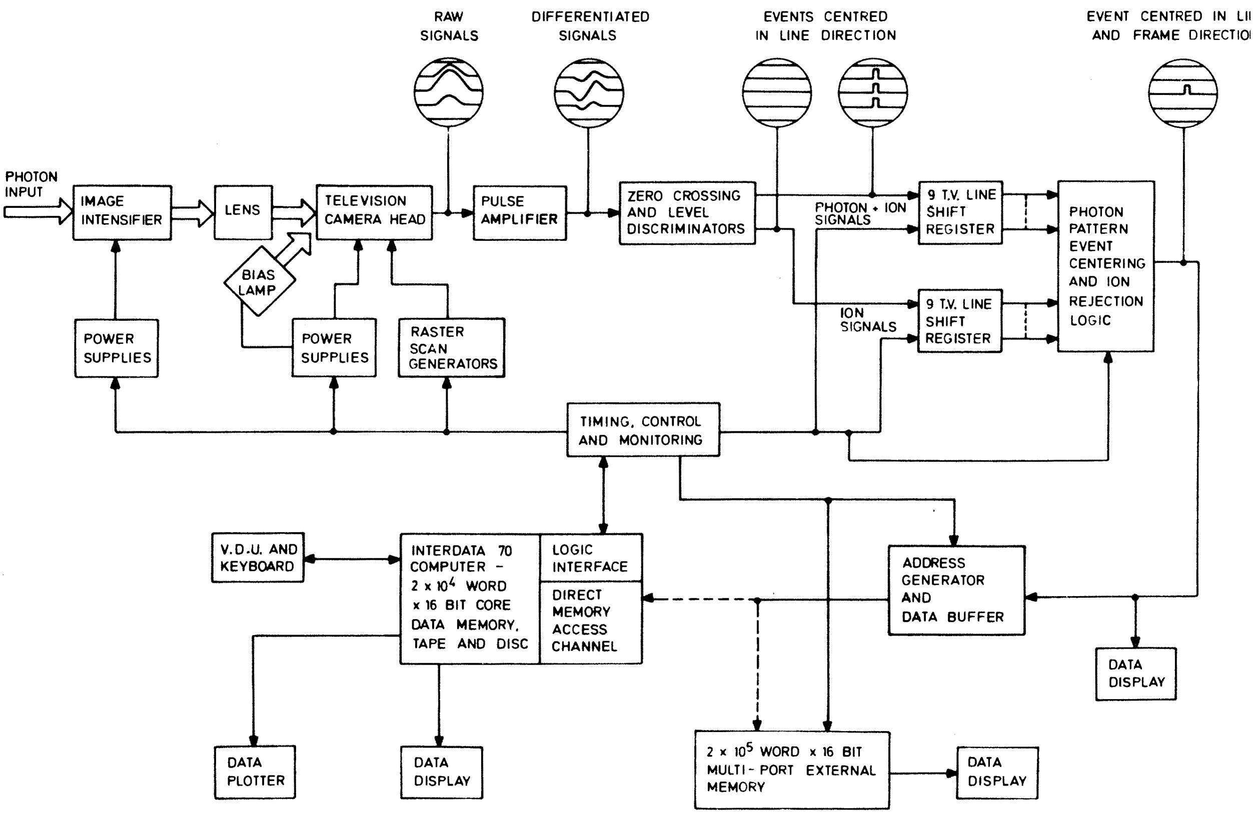

FIGURE 11. Block diagram showing the electronic processing functions of the U.C.L. i.p.c.s.

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background subtraction. The latter is particularly useful in astronomical spectroscopy of faint objects, where the signal can be extracted from a background containing bright night-sky emission lines; subtraction and calibration may also be carried out in real-time.

(vi) Within the limit of about 10^6 available pixels the data acceptance format is completely flexible; the system may be pre-programmed to accept image information from selected areas, or to sum over adjacent groups of pixels.

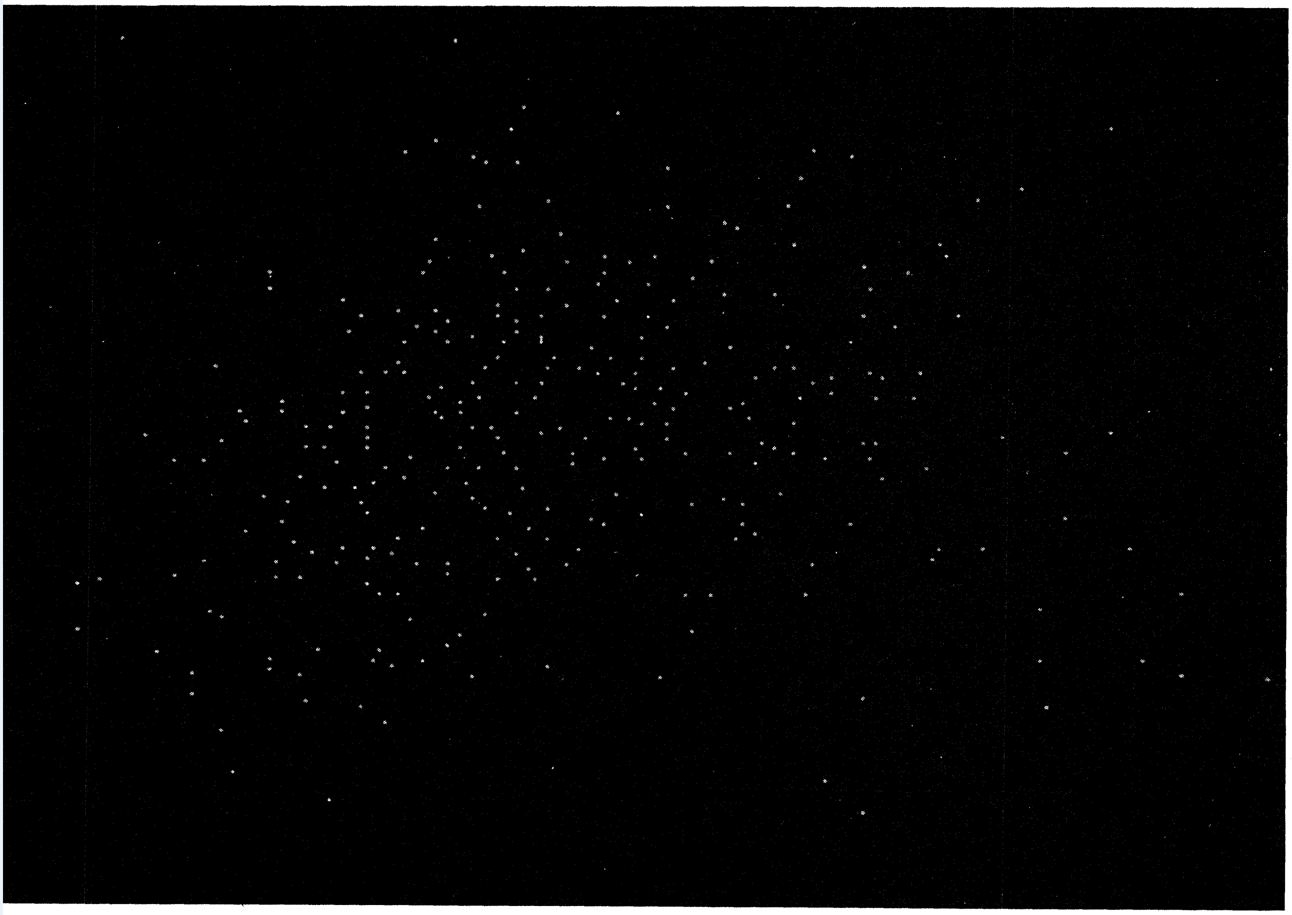

FIGURE 12. Single-photon events, fully processed and centroided, in a field of 2×10^5 image elements: exposure to a faint image of a nebula.

A picture of the U.C.L. i.p.c.s. detector head unit is shown in figure 10, and an electronic block diagram with representation of the signal processing functions in figure 11. A digital display of fully processed instantaneous photon events in a faint image is shown in figure 12. An indication of the gain in spatial resolution achieved when using the electronic centroiding technique as shown by the widths of comparison arc lines obtained during spectrographic recording is given in figure 13.

The i.p.c.s. has been in routine observing use at several observatories since 1973. An example of a two-dimensional spectrum obtained with the system is given in figure 14. A system similar in configuration to the U.C.L. i.p.c.s. is to be used on the Space Telescope.

Several other image photon-counting (or quasi-counting) detectors have been or are being developed using various forms of readout including solid-state, resistive and other position-

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sensitive layers (Cenalmor 1976; Currie 1976; Tull 1976; McNall & Nordsieck 1976; Timothy 1976; Broadfoot & Sandel 1976; Lampton 1976). Two other systems that have been in routine use for many years are the image-dissector scanner (Robinson & Wampler 1972) and the intensified Reticon scanner (Shectman & Hiltner 1976). These have more restricted channel

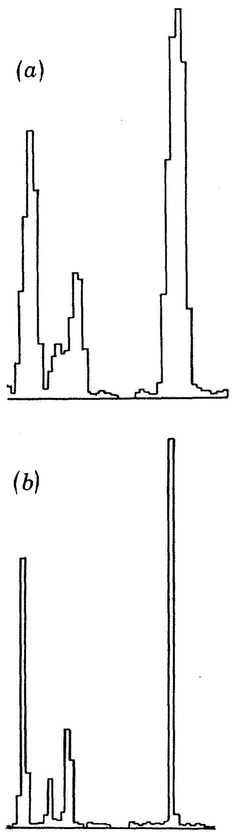

FIGURE 13. Small region of a comparison arc spectrum recorded with the U.C.L. i.p.c.s. The centroided line-spread function (*b*) is clearly less than one channel width (25 μm in this case), while the non-centroided case (*a*) extends over many channels.

capacity than the i.p.c.s. but are excellent for many one-dimensional spectroscopic applications. Another one-dimensional device, the Digicon (Beaver & McIlwain 1971), which found initial use for ground-based optical astronomy is soon, in further developed form, to be used for spectroscopic applications on the Space Telescope.

Further developments in the image photon-counting technique involve the use of c.c.ds for readout of the photon information. One such system has been developed at Mount Stromlo and Siding Spring observatories, using a c.c.d. optically coupled to an m.c.p. intensifier (Stapinski *et al.* 1981). A similar system, using a reducing fibre optic feed from the m.c.p. to the c.c.d., is under development jointly at University College London and the Royal Greenwich Observatory; an additional feature of this system is electronic interpolative centroiding, which effectively increases the number of available image elements by at least a factor of 25. It is also possible to detect photon events by direct bombardment of thinned c.c.ds (Hier *et al.* 1979) and devices using this technique are in active development.

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7. Solid-state detectors

Several types of solid-state imaging detectors have become available for astronomy in the past few years, all based on silicon as the photon-detecting medium. Silicon is particularly efficient in the red and near infrared compared with photoemissive surfaces, reaching about 80% between 5000 and 7000 Å and extending beyond 11000 Å. When cooled, which is necessary for applications in astronomy, the infrared limit shifts towards the blue (Geary 1976). The various devices are distinguished by the method of reading out the stored image:

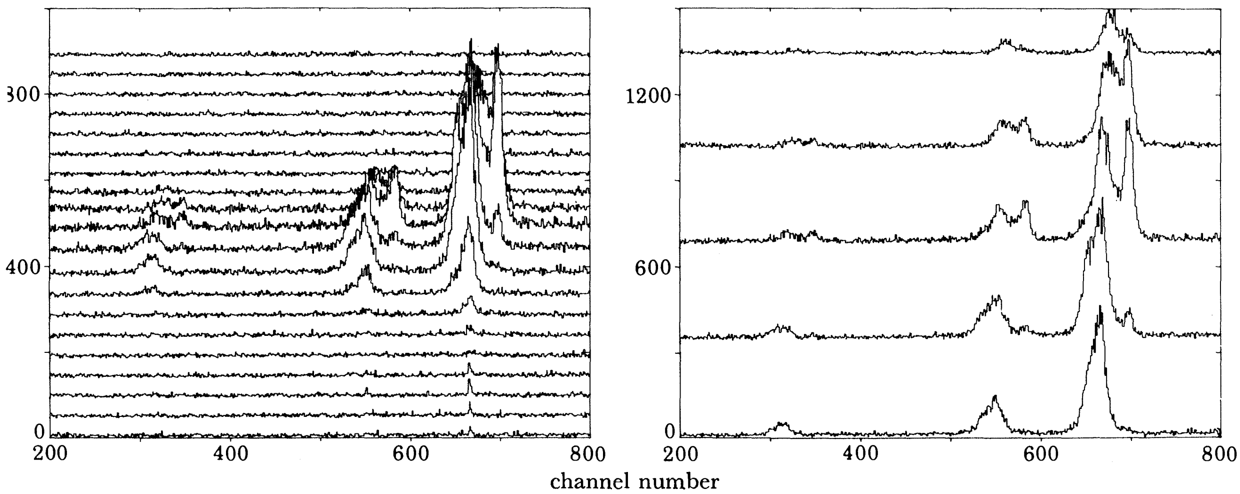

Figure 14. Small region of a two-dimensional high-resolution spectrum of the Seyfert galaxy Mkn 78 near the nucleus showing the [O III] 4959, 5007 and Hβ emission lines indicating violent internal motion (obtained with the U.C.L. i.p.c.s. on the Palomar 5 m telescope by A. Boksenberg and W. L. W. Sargent). The ordinate indicates the relative scale of counts only; the zero point of each spectrum is successively displaced vertically for display, representing position along the spectograph entrance slit. On the right is a selected and vertically more separated region from that shown on the left.

self-scanned or integrated diode arrays, c.c.ds and charge-injection devices. The d.q.e. is more or less limited by readout noise and build-up of charge background, and is highest for the c.c.d. Towards the red, silicon becomes increasingly transparent, and interference effects in the layer sometimes give severe spurious image modulation; however, processing techniques are now available to deal with this (Jorden *et al.* 1982). The c.c.d. is now finding increasing use in astronomy (see, for example, Storey *et al.* 1982), and if any trend can be recognized in the development of detector components it is that solid-state devices of this kind will eventually supplant all vacuum-tube imaging devices.

C.c.ds are now available from several manufacturers. The efficiencies of several commercial c.c.ds compared with an S-20 photoemissive cathode are shown in figure 15. These devices contain a two-dimensional array of sensitive elements typically of dimension 15–30 μm, with several hundred on a side. Arrays of up to 1500 × 1500 elements are in development (General Electric Company). The device is essentially a silicon integrated circuit of m.o.s. type and comprises an oxide-covered silicon substrate upon which is formed an array of closely spaced electrodes. Each electrode is equivalent to the 'gate' of an m.o.s. transistor. Signal information is carried in the form of a quantity of electric charge (localized beneath the electrodes with the highest applied potentials). Charge accumulates in these potential wells when released for conduction in the silicon by the action of the incident photons that the device is constructed to detect. 'Charge-coupling' is the technique by which this signal charge can be transferred from under one electrode to the next, and is achieved by sequentially pulsing the voltages on the electrodes between high and low levels; thus charge can be made to pass down an array of very many electrodes with hardly any loss and very little addition of noise. By this means the entire

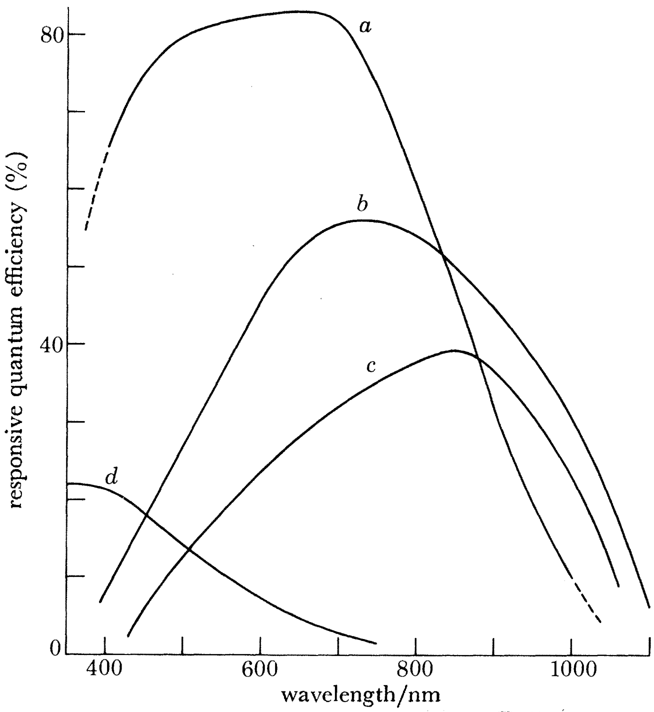

FIGURE 15. Efficiencies for photon detection of several commercial c.c.ds compared with a good S-20 photoemissive cathode. (*a*) R.C.A. thinned c.c.d. SID 53612-XO; (*b*) Texas Instruments thinned c.c.d.; (*c*) G.E.C. c.c.d. MA 357; (*d*) S-20 photoemissive cathode.

charge image can be shifted out bodily and then caused to enter a further line-readout section, which delivers the now sequentially arranged signals to an on-chip video amplifier. The noise in this amplifier represents a limit to the minimum detectable signal but in current devices can be as low as six electrons r.m.s. per image element. Cosmic ray events represent another limitation as silicon is an efficient detector of high-energy charged particles.

For use in astronomy, inevitably for the detection of faint images, the devices must be cooled to avoid the build-up of thermally induced charge, which otherwise would mask the signal. The general method of cooling is by thermal contact in a liquid nitrogen cryostat (figure 16). Exposures of several hours can then be achieved without excessive interference due to dark current.

8. Conclusion

Improvements in image detection are likely to stem at least as much from the application of new electronic processing and data reduction methods as from the development of better devices. The c.c.d. is taking an increasing role in astronomy, and in future all detector devices may be of this type. Means of sensitizing them to operate efficiently in the ultraviolet already

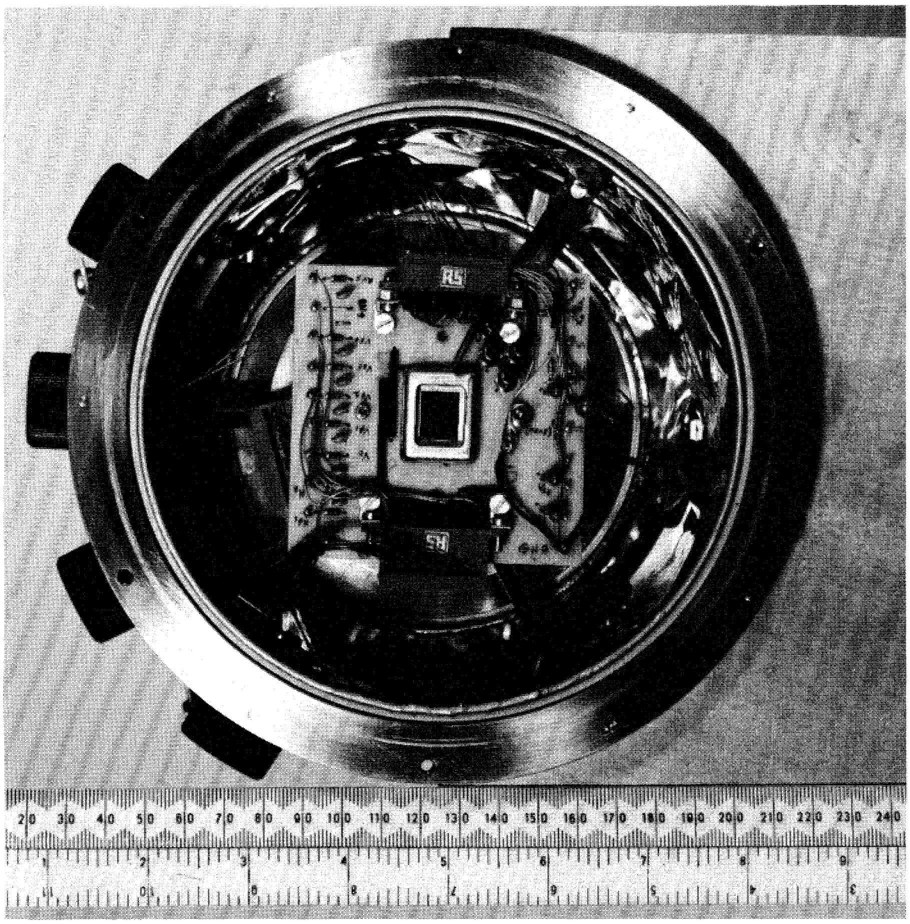

FIGURE 16. Top view of a liquid nitrogen cooled cryostat containing a c.c.d. (centre) and associated electronic circuitry (Royal Greenwich Observatory).

exist, and internal gain might be achieved by avalanche processes already implemented in discrete diode structures. The technique of image-photon counting, with its superior performance at low light levels, may then be achieved entirely in the solid state.

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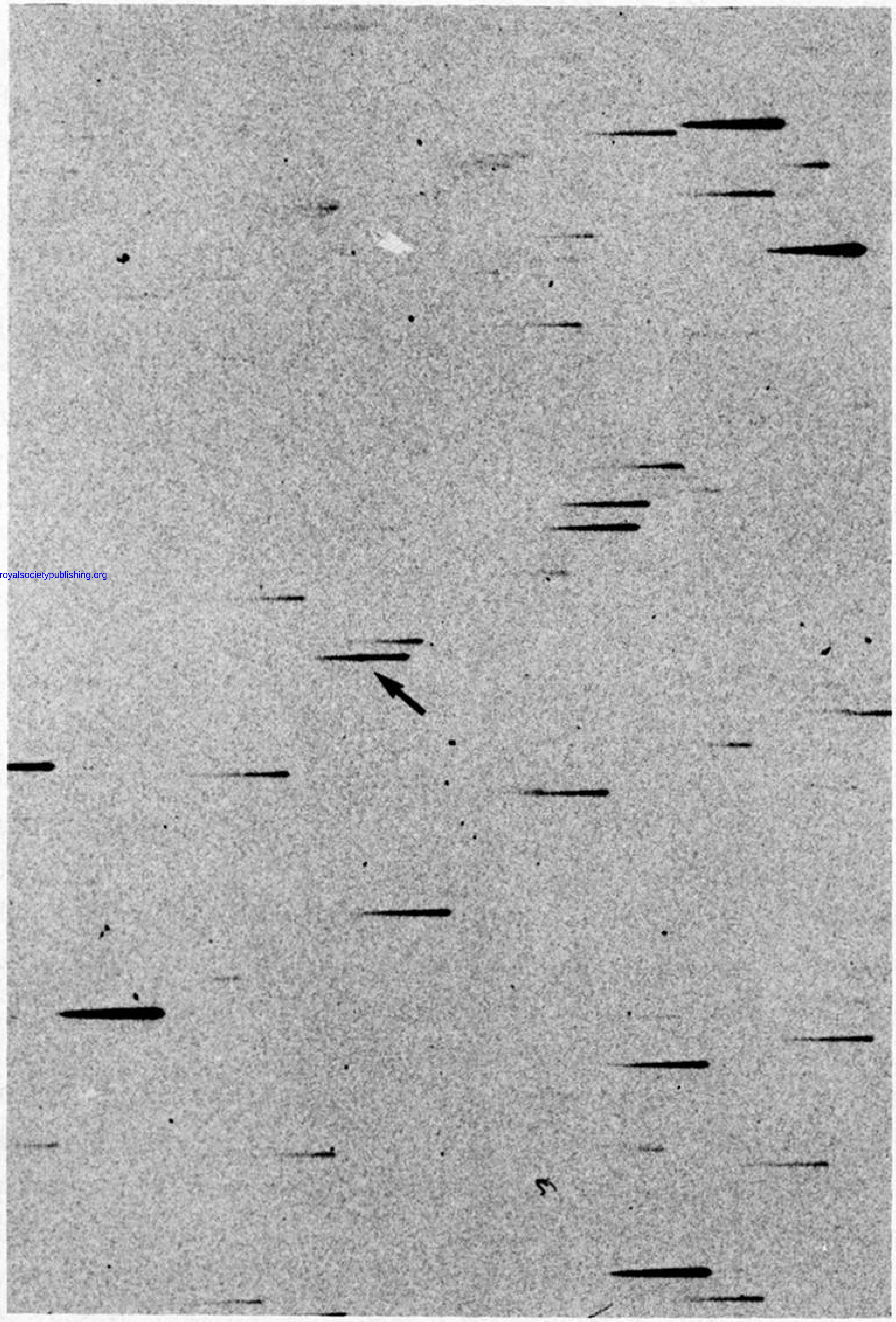

FIGURE 2. A small portion of a Schmidt telescope objective prism survey plate recorded photographically. Most of the spectrally dispersed images are of stars in our Galaxy. The arrowed image is of a quasar whose highly red-shifted Ly α emission line is clearly evident. Blue is to the left in all images.

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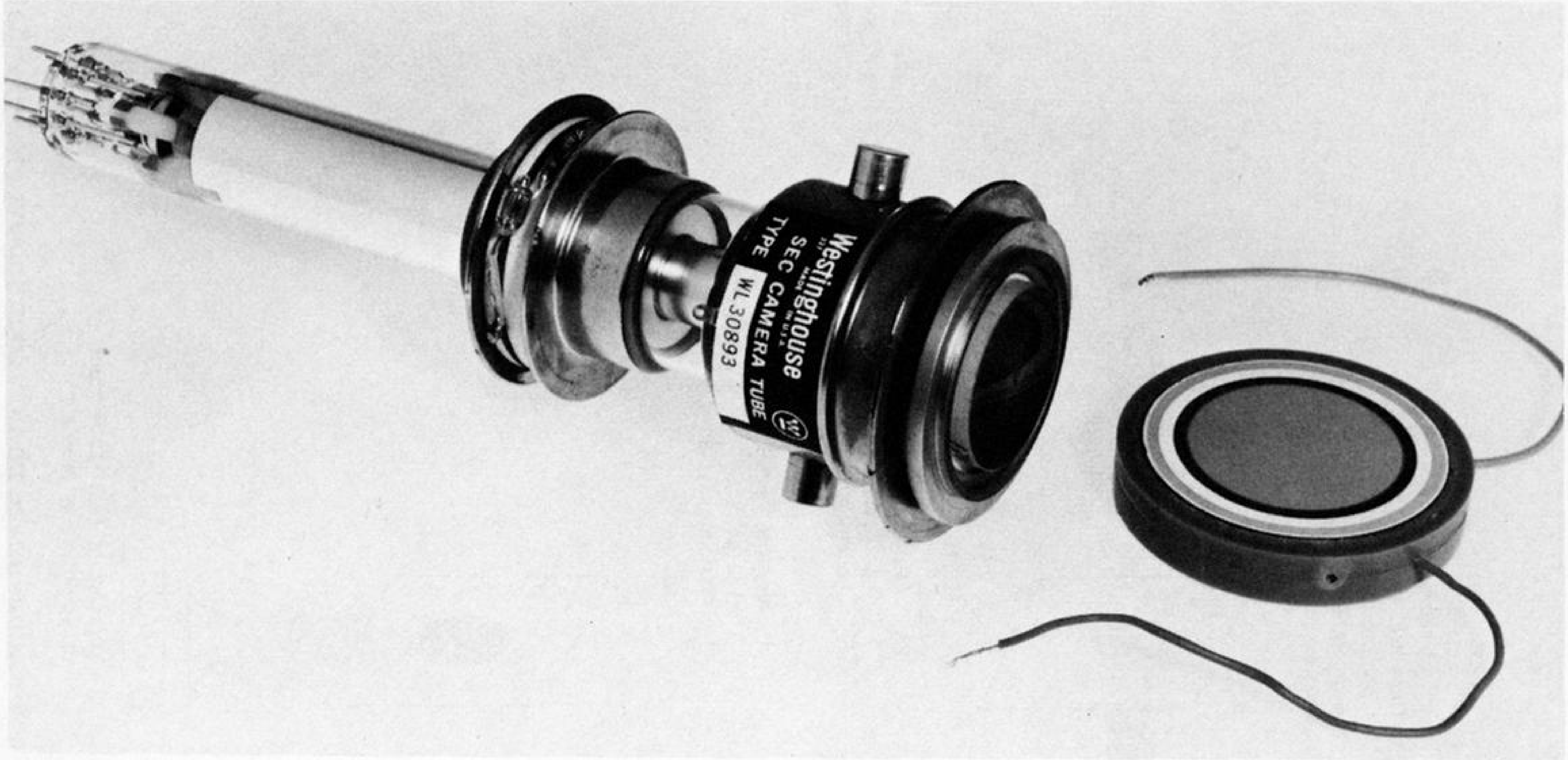

Figure 7. Detector components (s.e.c. camera tube and proximity-focused ultraviolet–visible converter–intensifier) for the spectroscopic instrumentation on the *International Ultraviolet Explorer* satellite. The components are normally bonded face-to-face but are here shown separated for clarity.

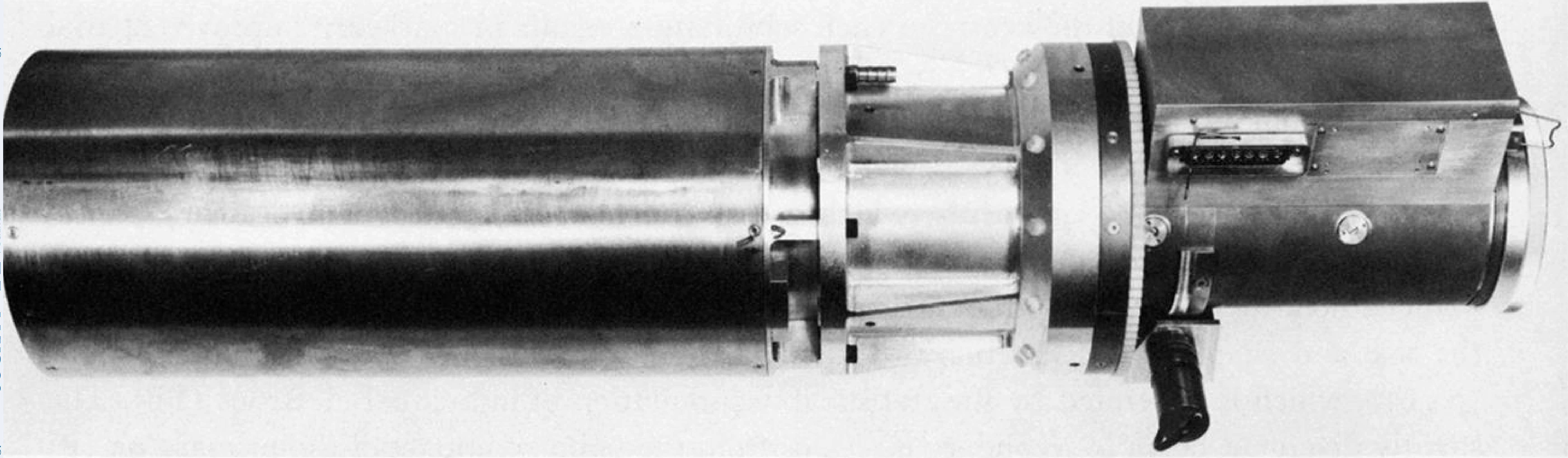

FIGURE 10. The U.C.L. i.p.c.s. detector head unit, containing image intensifier, coupling lens and television camera.

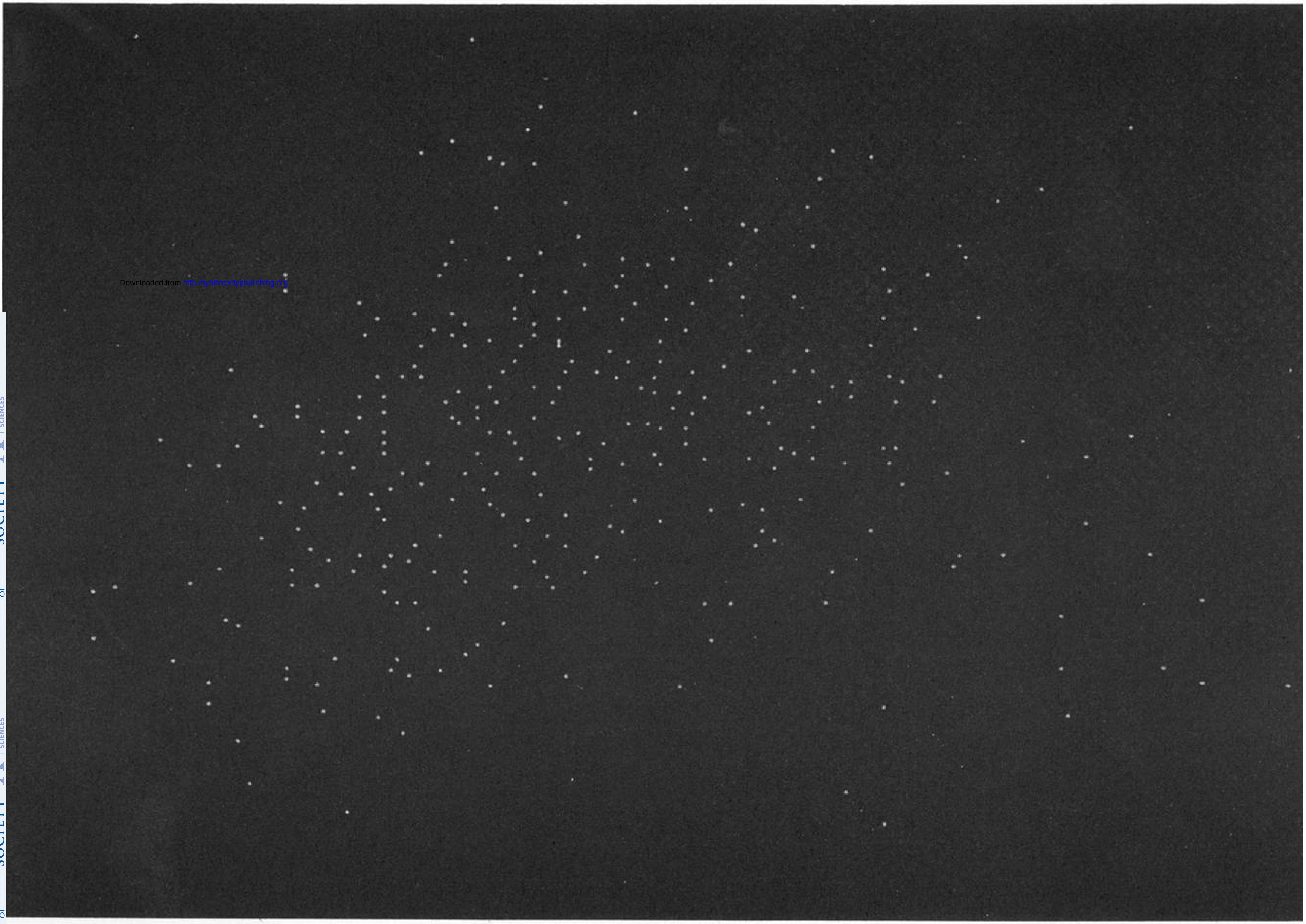

FIGURE 12. Single-photon events, fully processed and centroided, in a field of 2×10^5 image elements: exposure to a faint image of a nebula.

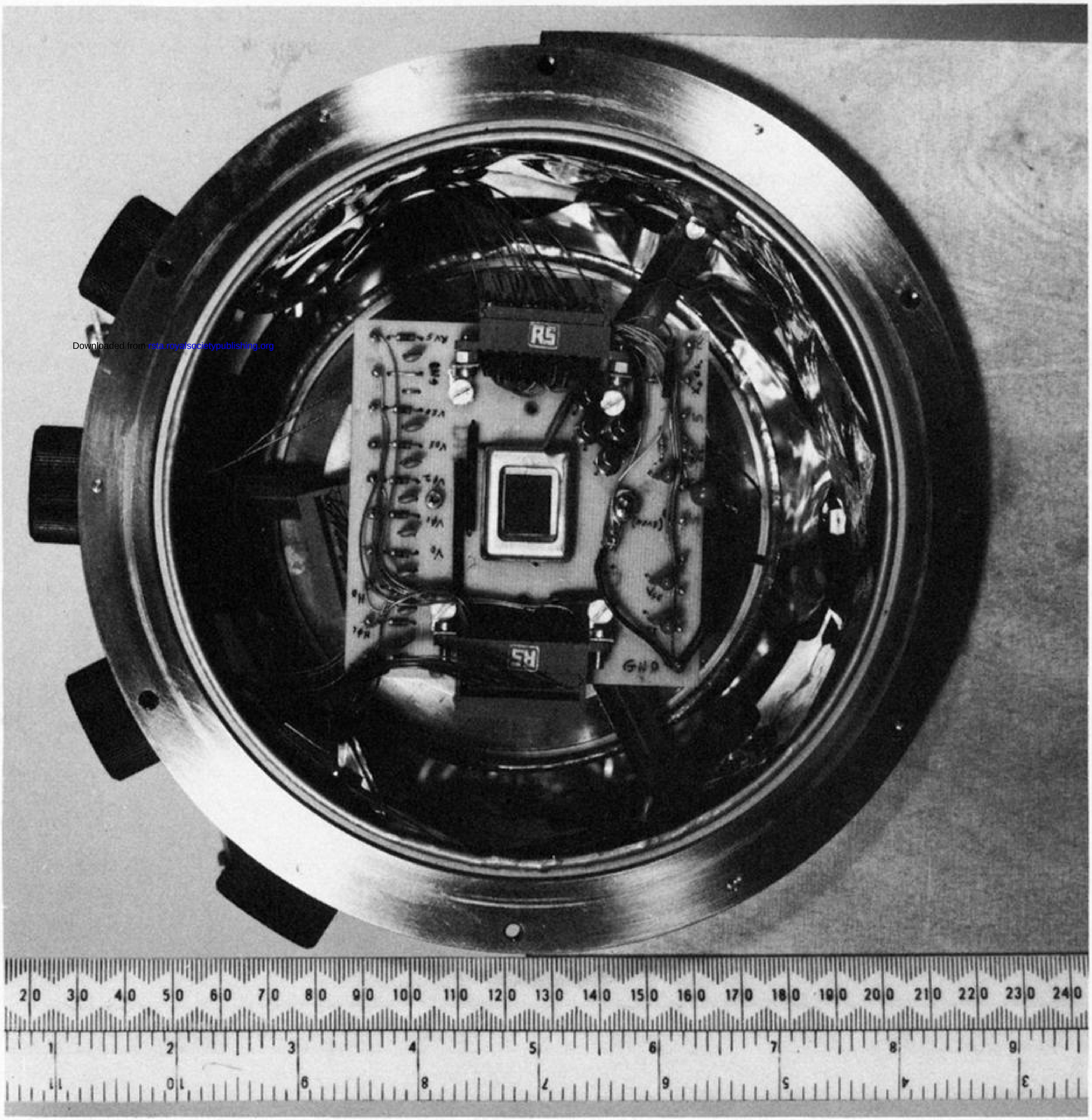

FIGURE 16. Top view of a liquid nitrogen cooled cryostat containing a c.c.d. (centre) and associated electronic circuitry (Royal Greenwich Observatory).