PHOTON-COUNTING RETICON™ DETECTOR

Marc Davis and David W. Latham
Harvard-Smithsonian Center for Astrophysics
Cambridge, Massachusetts 02138

Abstract

For applications in faint-object spectroscopy at the Mt. Hopkins Observatory, a photon-counting detector has been built using a dual 936 Reticon diode array fibre-optically coupled to a high-gain image intensifier package. The electronic signal processing follows closely the design of Shectman; the diode array is scanned every millisecond, each frame is subtracted from the previous to minimize multiple counts from the tails of the P-20 phosphor decays, and the centroid of each photon event is located to recover much of the resolution of the first image intensifier. For each detected event, the corresponding address in a Nova computer is updated by a direct memory access, thus allowing simultaneous data collection, analysis, and display. Two different intensifier packages have been used, both sandwiching a 25-mm Gen II microchannel-plate tube fibre-optically between 40-mm Gen I tubes for the first and third stages. This has made possible a compact intensifier package at the expense of a poor pulse-height distribution. Our first version of the detector has been in use with the 60-inch telescope at Mt. Hopkins since February 1978. A new version using a custom dual RL1024SF Reticon is now under construction for use on the Multiple-Mirror Telescope.

Introduction

In the spring of 1977 we undertook a project to build a spectroscopic detector suitable for observing faint objects with the 60-inch telescope and spectrographs at the Mt. Hopkins Observatory of the Smithsonian Astrophysical Observatory. The original scientific motivation behind this project was a red-shift survey of all the northern galaxies brighter than magnitude 14.5, nearly two thousand in number. Most of these galaxies have a surface brightness similar to the night sky, so we wanted a low-light level detector with at least two channels of spectrum in order to measure the galaxy plus sky and nearby sky simultaneously. At the same time we wanted good dimensional stability along the spectrum in order to achieve accurate redshifts. We also wanted to start with a proven design so that we could get on with the scientific programs and not get bogged down in another major instrumentation development. These are some of the main reasons that we chose to build an intensified pulse-counting Reticon system, copying many of the ideas and designs pioneered by Shectman.(1) Since this detector continuously updates the spectrum accumulated since the beginning of the exposure, we incorporated a Data General Nova computer, not only for control of the instrument, but also for display and analysis of the data during an exposure. The intention was to maximize the real-time feed back to the observer in order to use precious telescope time as effectively as possible.

Our philosophy has been that the system should evolve. We rushed the first version to the mountain so that we could get going on the scientific programs and could get feedback on the detector's strengths and weaknesses. In the meantime we started work on the first round of improvements that we had seen were needed to correct important shortcomings already identified in the laboratory evaluations. Almost every month we have made some kind of change to the system, several of them major improvements. In our view, this kind of interaction between the users on the mountain, trying to accomplish difficult observations, and the laboratory scientists back in Cambridge (often users themselves) trying to prepare a field retrofit in order to improve the performance, has been essential to the success of the detector. Not only are the most important weaknesses clearly identified for more work, but at the same time scientific results coming out of the instrument inspire the further developments and help convince management and funding agencies that the work is worth supporting. Indeed, the detector has been successful in the sense that it has been in heavy demand. In the fall of 1978, for example, it was scheduled for more than 90 percent of the time on either the 60-inch or 24-inch telescopes for a variety of programs in extragalactic, stellar, interstellar, and planetary astronomy.

In this paper we describe the detector system and its performance, pointing out both its strengths and its weaknesses. Although a two-dimensional photon-counting spectroscopic detector should ultimately outperform two-line detectors, we feel there is a place for intensified Reticons in astronomy until the two-dimensional devices become less expensive and more practical.

Instrument Description

To achieve a high counting rate, a photon-counting detector must be read out at a correspondingly high frame rate. In the case of our dual 936 Reticon self-scanned diode array, the maximum rate with which the array can be scanned using the manufacturer's driver electronics is 2 megahertz on each of two parallel video lines. At present we scan the array at half this speed, because of the difficulty in making a high-speed low-noise preamplifier circuit. Even at 2 μsec per diode, the preamplifier noise in our original electronics was about 20,000 electrons. It was this noise that set the requirement for very high gain in the intensifier package, namely we needed many times 20,000 photons per diode during the first 1 msec or so of the light flash at the last phosphor resulting from a photoelectron from the first cathode. High-gain multi-stage image intensifiers give away resolution in the sense that the light flashes get spread out by the successive stages, and can end up several times larger than the resolution of the first stage. However, if the centers of the final flashes are highly reproducible compared to the flash diameter, then a centroiding scheme should be able to recover much of the resolution of the first tube.

There would be no need to compare one frame with the next if the net decay curve of a light flash at the final phosphor was much faster than the 1 msec frame time. However, the P-11 and P-20 phosphors most often used in production intensifiers have long tails in their decay curves. With no frame comparison, multiple counting of single events would cause a degradation of the detective quantum efficiency, because the broad distribution of flash heights in our image intensifiers would result in unequal weighting of photoelectrons. To minimize this effect, we compare successive frames and in effect trigger on the fast rising edge of a new light flash and ignore the slowly decaying tail of an old flash. Finally, if a light flash starts rising just a fraction of a frame time before its diode is scanned, the light falling on the diode might exceed the discriminator threshold on two successive frames. To eliminate this possible source of double counting, consecutive events from a diode and its immediate neighbors are vetoed electronically.

Reticon and Scanning Electronics

The dual 936 linear photodiode array is a custom modification of the standard RL1872F single-line array. The diodes are arranged in two adjacent rows 28.08 mm long, together 0.750 mm tall, with 0.022 mm wide diodes spaced on 0.030 mm centers. In our first version we used the manufacturer's standard mother boards to supply the clocking, and slightly modified versions of the standard driver/amplifier boards to generate the output video signals. For each clock pulse the charges from two successive diodes in a row are switched and amplified simultaneously onto two parallel output video lines. The boards used to match, trim, and multiplex these lines together were borrowed directly from Shectman's latest design.(2)

For our second version of these electronics we designed new driver/amplifier circuits, incorporating a correlated double-sampling technique on the charge preamplifier and changing the clock drivers to give crisper wave forms. At the same time, some superfluous reset circuitry was eliminated from the mother board. These changes improved the noise to about 10,000 electrons per diode per readout at the present 1 msec frame time, compared to 20,000 at the previous 2 msec frame time. We feel that we have not pushed very hard on the design of fast low-noise preamplifiers, and there is room for considerable improvement in this area of our electronics. The next paper describes a new preamplifier design now under construction for the MMT version of the detector.

Pulse Processing Electronics

The multiplexed video signal is fed into a frame differencer, which uses a digital delay line to store the previous frame. This circuit is the key to Shectman's approach, because in one step it eliminates much of the fixed pattern in the Reticon response and avoids most of the multiple counting from the phosphor decay tails. The output of the frame differencer is then converted back to an analog signal and filtered with a minimum-phase filter to produce symmetrical, smooth pulse shapes. If the peak of the differenced video signal is larger than the discriminator threshold, the zero crossing of the derivative is used to clock the position in the array. The corresponding location in the computer memory is immediately incremented using a direct memory access that steals only one computer cycle time. The pulse-processing electronics can sit with the computer in a warm room many feet from the telescope, with only two coaxial cables running to the Reticon electronics — one for the master clock signal and the other for the multiplexed video.

Computer System

Our Data General Nova 2 computer is programmed in SAO FORTH using a foreground/background technique. In the foreground mode the status of the detector is displayed continuously on the top portion of a TV monitor. Various commands to the instrument can be entered at the computer keyboard or from a handheld terminal at the telescope. This terminal has 20 buttons, multiplexed to full ASCII, and a 12-digit LED readout for displaying the status of various aspects of the system, such as the present count rate or object identification. The most common system commands are assigned to the terminal buttons so that the operator can run the instrument from the darkened observing floor using single buttons plus a confirming execute when the desired prompt is returned on the LED display.

In the background mode the computer can be used for running any program that fits, even while the detector is integrating. Since the operating system features virtual memory for data management and will soon implement an overlay facility for program management, a wide variety of data analysis or even development of new code can go on while data is being accumulated. A Tektronix graphics terminal and associated hard-copy unit have proven especially popular and useful for real-time data assessment and analysis. Normally the accumulated counts for each exposure are recorded on floppy disc and sent back to Cambridge for final analysis on a similar Nova system and archival storage on magnetic tape. Most of the "permanent" software is developed and tested in Cambridge before use on the mountain, although there is always a certain amount of new code that gets written for specific situations as they arise.

Image Intensifier Package

Because the readout noise of the dual 936 Reticon is so large, about 10,000 electrons per diode per readout, a high-gain image intensifier is required for photon counting. For a light flash from the final phosphor that covers several diodes, a signal-to-noise of about 10 per diode will be required for centroiding to an accuracy of half a diode. Thus a net light gain of at least 10^6 photons per first-cathode event is required (in the first half frame time of the event, since the average event occurs half way between readouts). Shectman's early versions of the detector used two Varo 40-mm diameter three-stage Gen I image intensifier packages fibre-optically coupled together and lens coupled to the Reticon. Although such a package has more than enough gain, it suffers from large center-to-edge variations in gain, an uncomfortably long net decay time resulting from the convolution of six phosphor decay curves, a bulky mechanical package susceptable to flexure, high voltages, and substantial distortion.

Configuration. In the hope of improvements in the above areas, we decided to use a Varo Gen II microchannel-plate (MCP) intensifier in place of the four middle tubes and to use fibre-optic coupling onto the Reticon as well as between the intensifiers. Although the first- and third-stage Gen I tubes in our package have 40-mm diameter cathodes, the Gen II tube is only 25 mm in diameter. A ring of bright background around the edge of the Gen II tube further reduces the useful length of the 28 mm Reticon to about 23 mm.

The center-to-edge gain ratio is about 3:2 on our package, substantially better than the six-stage packages. The electronics incorporate a circuit that compensates for this gain change so that a single discriminator voltage can be used for the whole array without causing large changes in the counting efficiency as a function of position in the array. The Gen II tubes all have a spot of lower gain, located near the edge of the field. Although we have been locating this spot at right angles to the array length, as far away as possible from the Reticon, we now wonder if the sideways distortion might be better if the dark spot were positioned just off an end of the array.

Our entire detector package is only 16 inches long, and both the input focal plane and the last phosphor are at ground potential. The grounding of the input is important because there is very little clearance between the semi-solid Schmidt camera of the low dispersion spectrograph and its focal plane, especially when the requirement of cooling the image-intensifier cathodes is included. The grounding of the output phosphor of the intensifier package simplified our concerns about the Reticon electronics, especially the questions of noise pickup and safety for the Reticon chip itself (not to mention people). With our configuration of tubes, approximately 18 KV is dropped from the first phosphor to the cathode of the Gen II tube, and 24 KV from its phosphor to the third cathode. To avoid dropping these full voltages across the standard fibre optics of the tubes, we incorporated additional 3/4-inch long fibre-optic boules on the input and output of the Gen II tube.

Phosphor Decay Characteristics. One of the first things that we learned with our initial intensifier package was that the phosphor of the military Gen II tubes in general and of our Varo 3603 in particular is not a simple P-20. Apparently these tubes are normally made with a P-1/P-39 mixture in order to smear out the "noisy" visual appearance of the P-20 phosphors on the early versions. Indeed, less than 10% of the total light gain was concentrated in the first msec with a standard Varo 3603 in our package. Fortunately Varo was happy to process a special tube with a fast, single-component phosphor, although they would not tell us what exactly the phosphor was. The P-20 phosphors on the Gen I tubes have principal decay times of about 150 μsec and long tails. The principal decay time of the entire package is about 250 μsec, while the rise time is at least 25 times faster.

Pulse-Height Distribution. The next major disappointment with the Gen II tube was the poor effective gain of the first two intensifiers when operated in series. Alone, the Gen I tubes gave a dc gain of 370 photons per cathode electron. For a cathode quantum efficiency of about 10% near 560 nm, where these green phosphors emit, each event should have caused about 37 electrons at the cathode of the Gen II tube. Instead we found an effective gain of only 6 or 7 electrons per event at the Gen II cathode. This was first noticed when the gain of a Gen I into Gen II combination gave about 6 times less gain than the individually measured gains multiplied together. It was confirmed by demonstrating that a Gen II into Gen I combination did indeed give the expected multiplicative gain. Since the phosphor decay times are much longer than the transit times of electrons through a tube, an event at the phosphor of the first tube gives a burst of roughly 37 photoelectrons, originating sequentially from a spot roughly 0.02 or 0.03 mm in diameter. These electrons are then focussed onto a few channels of the MCP. It may be that the first few electrons collect most of the available charge on the walls of their channels, and subsequent charges arriving over the next msec or so do not get full multiplication in the MCP. We have procured a Varo 3603 with a fast phosphor and an MCP selected for low resistance (50 MΩ as opposed to 200 MΩ) in order to test this speculation.

The low effective gain of the first stage has seriously degraded the pulse-height distribution of the package. The problem is that our single-MCP tubes have a particularly broad pulse-height distribution. There is a long tail of second-cathode single-electron events which can be stronger than first-cathode events, even though the latter have an extra gain of about 6 from the first stage. When we designed the intensifier package, we were counting on a gain of at least 30 from the first stage, so that we could discriminate against nearly all the second-cathode dark events using a high threshold. For this reason we thermoelectrically cooled just the first cathode in our first package. With the first cathode at -10° C, the limiting dark rate was about 750 counts/sec/cm^2, with at least half of the events arising from the second tube. Our most recent package incorporates cooling of all three tubes to about -25° C, and we have achieved about 15 counts/sec/cm^2 with this approach.

A second consequence of the low effective gain of the first stage is that the discriminator threshold has to be set fairly high to avoid the twin evils of multiple counting and persistance. This means that we are giving away some counting efficiency. Once again the culprit is the very broad distribution of pulse gains from the MCP tube. If the threshold is set low enough to count honest first cathode events (which correspond to 6 electrons from the Gen II cathode) then a few events that arise from only one or two electrons at the Gen II cathode but get unusually high multiplication in the MCP can also be counted. Such one- or two-electron events can occur in the decay tail of the first-tube phosphor despite the frame subtraction, just because of statistical fluctuations in the photon emission from the phosphor. This problem gets much worse at high counting rates, for example at the centers of strong emission lines, because of the general glow of the first phosphor from many overlapping decay tails and the larger statistical fluctuations that result.

It is possible to test for multiple counting by looking at the fluctuations in the observed counts for successive exposures to uniform light. The number of effectively registered events is given by the square of the observed signal-to-noise in the successive counts. The effect of multiple counting at low discriminator thresholds is shown in figure 1, where we have plotted the log of the total counts above threshold, in counts/pixel/sec vs. the threshold setting, in dB. At the lowest discriminator threshold, the raw observed counts, shown by the dashed curve, rise 35% above the statistically effective counts, shown by the solid curve, while at higher thresholds the two are indistinguishable.

The phenomenon of persistence is closely related to multiple counting, and relies on the same mechanism of fluctuations in the decay of the phosphor of the first tube to circumvent the frame subtraction. Our observational protocols for the red-shift survey demand especially low persistence, because we routinely bracket long exposures of faint-object galaxy spectra with short exposures of bright emission line comparison spectra for wavelength standardization. In the centers of the brightest lines, the count rate can

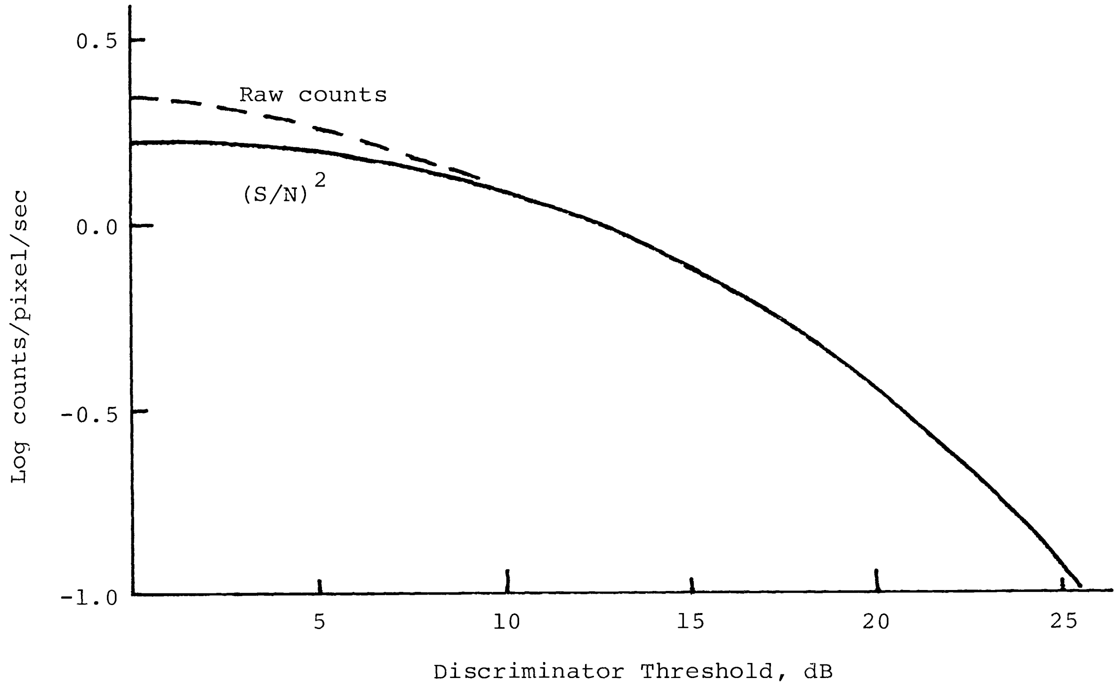

Fig. 1. Integrated pulse-height distributions. The dashed curve shows the raw counts, the solid curve shows the statistically effective counts.

be more than 1000 times higher than for the faint-object spectra, and a persistence of 10^{-5} of the peak comparison-line rate can make a small but significant contribution to the faint-object spectrum. For the case shown in figure 1, the threshold had to be set above 22 dB in order to push the persistence below 10^{-5}. Clearly this high a threshold setting gives unacceptably low counting efficiency, only 15 percent for the example in figure 1. However, this figure refers to the special case where the first tube was run at slightly less than half its maximum voltage, and the situation is improved dramatically for the normal case where the gain of the first tube is set to its maximum. In this case the persistence limits the counting efficiency to about 70 percent. The efficiencies quoted here depend on our estimates of the assymptotic value of the integrated pulse-height curves, which we call 100 percent, and should be treated with some caution. We intend to confirm these results using a continuum lamp with a well-calibrated scale of absolute photon flux. We will compare the observed count rates with the quantum efficiencies already measured in the form of dc cathode sensitivities with the tubes used as simple diodes looking at the same calibrated lamp, only at a much higher light level.

Cathode Evaluation. The detective quantum efficiency of an intensified photon-counting detector can never be better than the quantum yield of the first cathode, and the resolution of a centroiding system can never exceed the performance of the first stage. Selection of the first-stage tube for optimum spectral sensitivity of the cathode is especially important, because differences of a factor of two or more from one tube to the next are not uncommon. At the Center for Astrophysics we have set up a laboratory for the evaluation of image tubes, primarily because we did not feel we could rely on the manufacturers for the measurements of cathode sensitivities needed for careful selection of first-stage tubes. For one thing, the people who make vast production runs of tubes for military night-vision applications seem reluctant to measure cathode sensitivities anywhere except at the reddest wavelengths, while astronomers are greedy for the near ultraviolet and blue as well as the red and near infrared. For another thing, each manufacturer seems to have his own absolute scale of sensitivity, "traceable to NBS", but with some scales more optimistic than others by 20 percent and more. One way to translate different tube types to a common sensitivity scale is to measure them all on the same system, and the one way to hold a manufacturer to an agreed performance specification is to have independent, legitimate measurements of our own.

Our attempts to set up a light source with an accurate absolute spectral calibration between 350 and 1000 nm illustrate the level of uncertainties to expect in this business. Our primary light source is an Optronics Laboratories model 310, which uses a tungsten-iodide lamp and ten well-blocked interference filters about 10 nm wide to define a set of "monochromatic" beams, each calibrated to a nominal accuracy of 5 percent. We chose the model 310 because it incorporates apertures and neutral-density filters that give a range of 10^5 in the overall level of the light output. At the brightest level there is enough light to measure the cathode currents directly, while the faintest levels are useful for testing the detectors in the photon-counting mode.

We have compared the absolute calibration of the brightest level of the 310 against two other calibrations. Direct measurements with two UV444A photovoltaic diodes calibrated by EG&G implied that the model 310 was giving out 9 percent more light than claimed by Optronics, while a transfer to the system run by Rich Cromwell at Steward Observatory implied that the Optronics calibration was too faint by about 25 percent. There was no obvious color dependence in the EG&G vs. Optronics comparison, but a fairly substantial increase in the disagreement towards the red for the Cromwell vs. Optronics results. The important point is not whether Optronics, or EG&G, or Cromwell is "right," but rather that we can accurately compare one manufacturer's tubes to another, or the results of our evaluations with those done at Steward Observatory.

Wampler[3] has written a nice summary of the status of phosphor-output image tubes in astronomy and Cromwell and Dyvig[4] have published an impressive amount of practical information for several of the popular tubes. However, both these sources are getting a little out of date in a field of technology that is evolving fairly rapidly. Therefore we present here some of the more interesting results of our recent image-tube evaluations along with some opinions and comments about what looks promising.

Proximity-focussed MCP tubes with 18-mm III-V cathodes are now being produced by the thousands for the military. Although these particular devices are classified, there is hope that tubes suitable for astronomy will eventually take advantage of this technology. In the meantime, astronomers are limited essentially to bialkali and multialkali cathodes. The night-vision tubes have been optimized for red sensitivity, and thus have thick "S-20" cathodes that absorb red photons well and blue photons too well. All the production night-vision tubes with electrostatic inverting optics also use glass fibre-optic input windows, and the response is cut off sharply below 400 nm for this reason.

For optimum cathode sensitivity longward of about 500 nm, the night-vision tubes can be very good indeed. For example, in figure 2 we have plotted out measurements of the spectral sensitivity (on the EG&G scale) for two selected Varo 8605 40-mm electrostatic

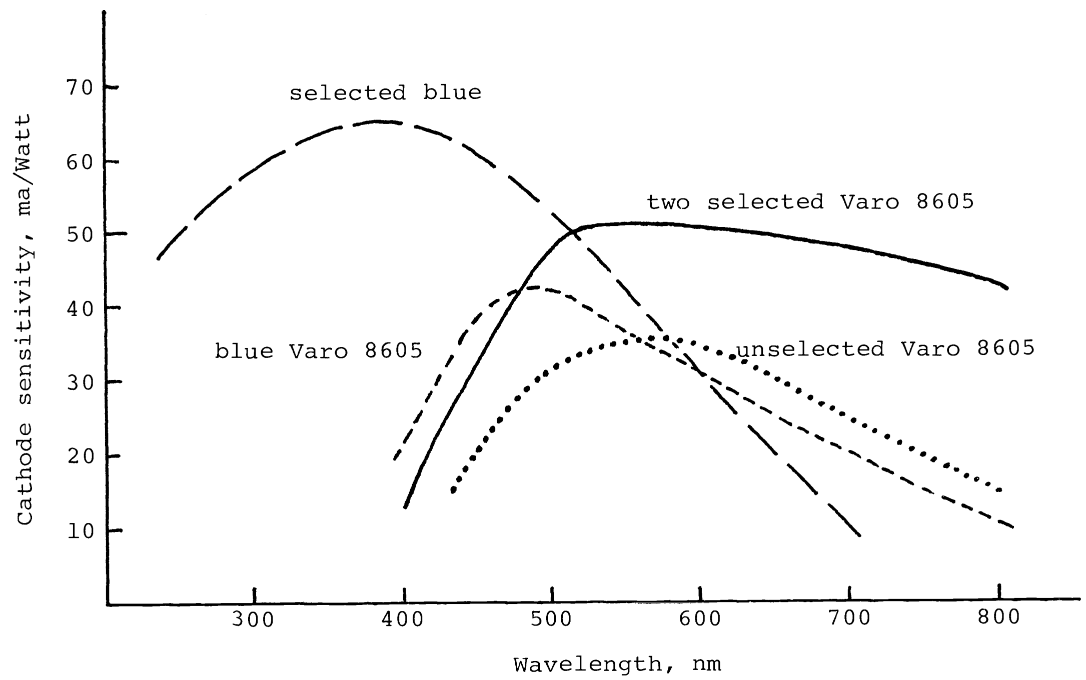

Fig. 2. Cathode spectral sensitivities. The Varo tubes were all measured in Cambridge and are on the EG&G scale. The selected blue is a best guess at what should be attainable for a classical S-20 and ultraviolet transmitting input window.

diode inverter tubes. Even at 800 nm the sensitivity is still 44 ma/watt, or 7 percent quantum yield. However, at Ca II H and K the quantum yield is only 4 percent and dropping fast. In the spring of 1977 Varo supplied a special 8605 to us, processed for optimum blue response. Our measurements of this tube are also plotted in figure 2, and one can see that we gained a modest amount of sensitivity over a small wavelength range near 400 nm at the expense of a substantial loss in sensitivity over a broad range of red wavelengths. For comparison we have also plotted the spectral sensitivity of an unselected Varo 8605 which was procured for the final stage of a package. This tube has substantially lower sensitivity than the selected tubes and would clearly be unacceptable for a first stage.

For optimum cathode sensitivity shortward of 500 nm and extending down to the atmospheric cutoff at 300 nm, one needs a bialkali or thin S-20 plus an ultraviolet-transmitting input window. Several years ago, ITT (Roanoke) produced a handful of electrostatic diode inverters with special untraviolet-transmitting fibre optics. One of these tubes has been used extensively at Lick Observatory.[5] Recent inquiries by Rybski at McDonald Observatory indicate that the cost to produce several more of these tubes would be prohibitively high for a single observatory. The alternatives are tube designs which allow clear input windows, such as magnetically-focussed tubes, proximity-focussed tubes, or flat field electrostatically-focussed tubes.

Suitable flat-field electrostatic tubes are not in production. The main difficulty with the present designs is the lack of good resolution across the full field. There is no obvious fundamental obstacle to future improvements, but it will cost money.

The technology involved in making proximity-focussed tubes has progressed to the point where they are promising for astronomical applications in the blue and near ultraviolet. An ITT (Fort Wayne) tube is in use as the first stage at the image dissector scanner at the Siding Spring observatory.[6] The principle drawback of proximity tubes is that the resolution is degraded towards shorter wavelengths, just in the spectral region where they are of most interest to astronomers. The key parameters are the spacing of the cathode and phosphor, and the field strength accelerating the photoelectrons. Robert Bosch (Darmstadt) has recently begun producing 25 mm proximity tubes that promise to have higher resolution than the ITT versions. These proximity tubes use externally-processed cathodes, and have good sensitivity, uniformity, and distortion. In some versions the signal-induced background is high because of imperfect blocking of optical feedback from the phosphor to the cathode.

When both high resolution and good near ultraviolet sensitivity are needed, the only proven alternative is a magnetically-focussed tube. Several magnetic tubes have been used successfully, including Carnegie tubes made by RCA, and other tubes made by ITT and EMI. The main drawback of these tubes is the requirement for a large heavy magnet, which often generates a lot of waste heat and can make the interface with a fast camera tricky. The signal-induced background can also be high. Although we have not measured the spectral sensitivity of any of these blue-near ultraviolet tubes, we have drawn in a curve on figure 2 for what one ought to be able to get, based on Cromwell's[7] measurements of the Steward Observatory Carnegie tube and various manufacturer's specifications.

Packaging. We have used two different intensifier packages at Mt. Hopkins, both with a Varo 3603 Gen II tube sandwiched between Varo 8605 Gen I tubes. In the first version we simply mounted the tubes as potted by Varo into individual blocks that could be shimmed and adjusted inside a box to get good optical contact between the fibre optics. For the Gen II tube we used the power supplies as potted by Varo, but for the Gen I tubes we potted Varo supplies externally and ran 15 KV leads to the tubes. Initially we had corona discharge problems, especially around the interface between the second and third tubes, where we were dropping 24 KV with only an extra 3/4-inch fibre-optic voltage isolator. We eventually staved off this corona by unpackaging the front and back tubes, repotting them more completely in GE RTV 511, and by controlling the atmosphere inside the package with a flow of dry nitrogen.

This simple scheme for mounting the tubes was possible because we were only cooling the first cathode, using 4 Cambion model 801-3965 thermoelectric modules in parallel. Each module can easily pump 3 watts at a ΔT of 30° C and nearly 100 percent efficiency. This was enough to cool the first cathode to typically -5 or -10° C. The waste heat was dumped directly into the spectrograph case, which would warm up a few degrees above ambient. As explained above, we chose to cool all three tubes in our second package, in order to get a lower dark rate. This led us to encapsulate all three tubes as an assembly in a monolithic pot of RTV 511, allowing us to get a good seal against moisture and corona discharge. Again we used the standard Varo power supplies, this time potted right next to the tubes. We had to unpot the Gen II tube and clean it carefully in order to make it and its power supplies part of the monolithic pot. The heat exchange fluid, usually methanol cooled to -30° C by a Neslab RTE4, is pumped to the package in insulated rubber hoses and then through a rubber tube potted right into the assembly in a spiral around the image tubes. The cooling tube also provides pneumatic relief for the expansion and contraction of the potting compound with temperature. Cromwell and Angel[8] have described their techniques for packaging image tubes, and in many cases we have been guided by their remarks.

Our basic philosophy has been to keep the various optical components modular. Thus the fibre-optic input to the diode array was cemented permanently to the Reticon at the factory, but the coupling to the fibre-optic output from the last phosphor is accomplished with Cargyll immersion oil. This allows us to move the Reticon back and forth between the intensifier packages in the field without a lot of effort.

System Performance

Our photon-counting Reticon is a complex instrument with many optical and electronic components and a complicated set of interactions between the components. The spectral sensitivity and dark rate are characteristics that depend primarily on the intensifier package, and they have been described in the previous section. In this section we report on several other characteristics that depend on the performance of the entire system, such as resolution, coincidence rate, photometric performance, and geometrical stability.

Resolution

We have not measured the resolution of the detector by itself. The only information on resolution that we have comes from the measured widths of emission lines in the helium-neon-argon comparison spectrum of the low-dispersion spectrograph and in the thorium-argon spectrum of the echelle spectrograph. With both spectrographs it is not hard to get lines with full width at half maximum (FWHM) of 0.040 mm. For a Gaussian line profile, FWHM is nearly the reciprocal of the standard "limiting resolution", and 0.040 mm corresponds to 25 line pairs per mm (LP). several sources of broadening contribute to the overall line width, such as the width of the spectrograph slit, the resolution of the spectrograph optics, the resolution of the first-stage image tube, the variation in the electron and photon paths through the image-intensifier package (leading to variations in the centers of events at the diode array), the width of the diode elements, the signal-to-noise in the signal from each diode illuminated by an event, the precision of the centroiding electronics, and the bin size of the final stored image. When the spectrograph slit (typically 0.020 mm FWHM) and optical resolution of the spectrographs (typically 0.015 mm) are taken into account, one can deduce that our detector has a resolution of something like 0.030 mm FWHM. Since the first-stage intensifier has a resolution of 60 or 70 LP, or about 0.015 mm FWHM, and our bin size in the computer is presently 0.015 mm, we conclude that the centroiding electronics together with the second- and third-stage intensifiers can not be degrading the performance much more than 0.020 or 0.025 mm FWHM. For a Gaussian broadening profile this corresponds to a σ of about 0.010 mm. Still, we are degrading the resolution of the first stage by about a factor of two, and there is no obvious fundamental reason why it should not be possible to improve the resolution of the detector until it approaches the performance of the first stage. This is one area of performance which will get our attention as we develop similar detectors for the MMT.

The resolution quoted above is valid for count rates up to about 10 counts/sec/pixel. At higher count rates, the resolution is further degraded by effects which we do not fully understand. However, these are rates for which the coincidence corrections are becoming unmanageably large and for which the detector was not intended.

Coincidence Corrections

In photon-counting instruments, the loss in counting efficiency due to coincidences at high counting rates can be characterized by a deadtime τ and a relation between the observed rate r_o and the "true" rate r_t, in counts/sec/pixel,

$$r_o = r_t e^{-\tau r_t} .$$

We have measured the deadtime of our detector and find that for a sharp emission line it is only 3 msec, while for a continuum source it is more like 10 msec. The data fit the formula up to rates of about 40 counts/sec/pixel. The continuum deadtime is longer because simultaneous events in nearby pixels can not be distinguished, while the emission line concentrates nearly all the centroids into one or two pixels. Indeed, the continuum deadtime of 10 msec is consistent, at least qualitatively, with the observed pulse width of about 0.100 mm FWHM at the Reticon. Two events that occur closer together than this in one frame time can not be distinguished by the pulse-processing electronics and will be counted as only one event. Thus for each 1 msec frame time, at least six pixels are usurped by an event, and the electronics automatically disable the center three pixels on the next frame. Thus it is possible to account for most of the 10 msec deadtime.

In the case of the emission line, there are few events more than a pixel away from the line center, and the main contributor to the deadtime is the 1 msec frame time in which the event occurred plus the 1 msec for the disabled frame immediately following. Again it is possible to account for most of the observed 3 msec deadtime.

Fixed Patterns

All imaging detectors have some degree of nonuniformity in their spatial response, and these patterns must be calibrated and corrected for if one wants to push to the limits of photometric accuracy. In addition to the usual nonuniformities of the cathode response, our detector also has a fixed pattern arising in the readout. For example, figure 3 is a plot of the raw counts accumulated over a 75-pixel region of continuum from a tungsten lamp. It is our belief that the every-four-pixel pattern originates in the diode array

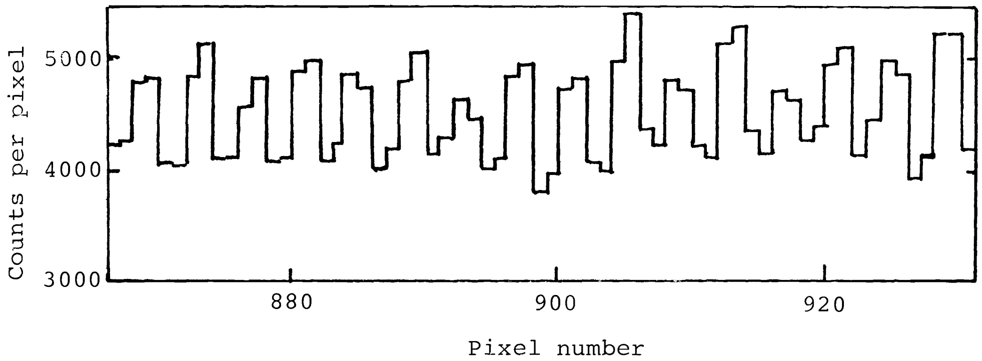

Fig. 3. Fixed pattern. We have plotted the raw total counts per pixel for an 8-hour exposure of an incandescent lamp.

itself, and is cause by asymmetries in the even- and odd-diode video signals (2 pixels = 1 diode here). As far as we know, everyone who has used Reticons with parallel output lines has seen this odd-even pattern, although the amplitude of the modulation depends on the particular chip and the details of the readout electronics.

We have a simple model that can account for the odd-even fixed pattern. Because of the way the odd and even diodes are clocked and then multiplexed into a single video signal, it turns out that the odd line has a substantially longer RC time constant than the even line. Thus some of the signal from an odd diode can be smeared into the next odd diode, while much less smearing occurs for the even diodes. When the multiplexed signal is processed by the low-pass filter of the centroiding circuit, events that occurred in odd diodes can be biased slightly in the scan direction, but events in the even diodes are not biased. John Tonry, a graduate student working with us, has demonstrated with a simulation that approximately 10 percent carryover to the next odd diode can explain the roughly 20 percent full amplitude modulation that we see in our raw data. Other asymmetries in the odd and even video signals can also be important, especially for readout electronics which frame more slowly than our system.

Fortunately, the pattern is reasonably stable over a time scale of a few days, and most of the modulation can be removed by means of "flat-field" exposures. Typically, when we go to bed in the morning after a night of observing, we start a series of continuum exposures using an incandescent lamp. In eight hours of such exposures we can accumulate enough counts to get the photon statistics down to about 1 percent/pixel.

Fortuitously, the odd-even fixed pattern is exactly complementary on the two sides of our dual 936 Reticon, and most of the pattern disappears if we simply add balanced exposures from the two sides. Thus our standard procedure is to take equal exposures, first with the object on one side of the array and then on the other (or alternatively with the object split equally between the two sides). In the reduction procedure we normalize each exposure to an appropriate incandescent exposure and then add the two sides together. With this procedure the fixed pattern can be reduced an order of magnitude, but it still shows up at a signal-to-noise of about 50. The limit seems to be set both by small drifts in the fixed pattern with time and by a weak dependence of the pattern on the level of illumination. It is quite possible that recent modifications to the readout electronics will allow us to reduce this effect further. In the meantime, for faint objects and low signal-to-noise the observed fluctuations in the counts/pixel are only slightly degraded from the expected Poisson noise.

Registration

To achieve accurate redshifts we must know the wavelength scale at the Reticon with an accuracy of a few μm. With both our spectrographs there can be much larger shifts as the telescope is pointed to different directions in the sky. For this reason we have found it necessary to bracket a galaxy exposure with comparison-spectrum exposures immediately before and after. This allows us to calibrate the wavelength scale to an accuracy of better than 0.005 mm at the Reticon.

With the dual 936 Reticon we have had some difficulty ensuring that all the light passing through the slits of the spectrograph falls onto the correct portion of the diode array. The distortion in our second image-intensifier package causes something like 0.150 mm of curvature in the spectrum at the Reticon. When this is combined with the sideways shifts of the spectrum as the telescope is pointed to different parts of the sky, there are times when the spectrum can spill off the 0.375 mm height of one side of the array. So far we have not been able to measure spectral-energy distributions more accurately than about 10 percent because of these registration problems.

MMT Spectroscopic Detector

Although we plan to use the existing spectrographs and photon-counting Reticon detector on the MMT for some of the first astronomical observations, these instruments give away a factor of three in slit efficiency compared to an optimum design. The basic problem is that the combined beam of the MMT has an f/10 envelope that is unfilled, because it is made up of six f/30 beams from the individual 72-inch telescopes. One way to increase the slit efficiency is to arrange the images along the slit and then to redirect the beams so that all six coincide on the collimator. For the same camera focal ratio, this allows three times more demagnification onto the detector, or effectively a slit three times wider on the sky for the same resolution. An immediate consequence of an in-line slit design is that the format at the focal plane of the spectrograph, as well as the height of the entrance slit, must be six times taller. For a two-channel detector the individual diode arrays must be correspondingly taller in order to squeeze all the light onto the array.

We have begun construction of an MMT spectroscopic detector that will utilize a custom dual RL1024SF Reticon. This array consists of two standard RL1024S single-line chips packaged on the same substrate so that there is only 1 mm dead space between the arrays. The individual diodes are 2.5 mm tall spaced on 0.025 mm centers, so there should be plenty of room along the diode height for the in-line slit mode. Although the pulse-processing electronics will be little changed from the present system, the preamplifier design will be substantially different, as outlined in the next paper.

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