SPECTROSCOPY WITH PHOTON-COUNTING RETICONS

David W. Latham
Smithsonian Astrophysical Observatory

Since 1978 we have been using photon-counting Reticons for spectroscopy at Mt. Hopkins. With these detectors we have accumulated approximately 50,000 exposures, resulting in nearly 10,000 reduced astronomical spectra. This paper describes the performance of the detectors, discusses some of the procedures we use for remote observing, outlines the magnitude of the data-handling problem, and gives a few examples of recent results.

1. INTRODUCTION

At Mt. Hopkins we are using photon-counting Reticon detectors for a variety of spectroscopic programs, both on the 1.5-m telescope operated by the Smithsonian Astrophysical Observatory (SAO) and on the 4.5-m Multiple-Mirror Telescope (MMT) operated jointly by SAO and the University of Arizona (UA). During dark of moon the detectors are used at moderate dispersion (30 to 120 A/mm) for faint objects, and during bright time the same detectors are shifted over to Cassegrain echelle spectrographs for high resolution studies of brighter objects at high dispersion (1.5 to 4 A/mm).

The 1.5-m system has been in operation since 1978, and the observing time has been divided between a large-scale redshift survey and a variety of smaller research projects. The requirements for the redshift survey set the performance goals for the detectors and provided the motivation for the ongoing process of improving the systems. The smaller projects have mostly taken advantage of the new capabilities as they became available, but have played the important role of opening up new lines of research and providing several scientific problems that could be solved and published in a time scale short compared to the survey. Needless to say, only some of these smaller projects have paid off.

At the MMT a second photon-counting Reticon system has been in use since mid 1980. It has proven to be the most requested instrument

C. M. Humphries (ed.), Instrumentation for Astronomy with Large Optical Telescopes, 259–270.

by far, servicing a large community of users at SAO, UA, and visitors. In the first year of operation 6000 exposures were accumulated with this detector, leading to nearly 1000 reduced spectra with approximately 40 astronomers involved.

In this paper I document the present performance of our detectors, which has been improved dramatically since our early efforts (Davis and Latham, 1979), with an attempt to point out both the strengths and weaknesses. Because of the large geographical separation between most of the SAO scientists in Cambridge and the Mt. Hopkins observatory in Arizona, we have developed protocols for remote observing of about half of the programs on the 1.5-m telescope. Since other observatories may be forced to consider this type of operation, I discuss some of our experiences. We have chosen to invest a large fraction of our resources into computer control of the detectors, into semi-automatic reduction of the spectra to intensity vs. wavelength, and into complete analysis of the radial velocities with sophisticated correlation techniques for the redshift survey. In this paper the data-handling efforts are outlined but not described in detail. Finally, I present two examples of recent results; an MMT spectrum of the quasar 1548 + 115A, and an accurate radial velocity for an faint Hyades member, just one example of the several hundred stellar radial velocities measured in the past year with the 1.5-m telescope.

2. DETECTOR PERFORMANCE

Both of the detector systems now in operation use high-gain image intensifier packages coupled with fiber optics to Reticon diode arrays, with one channel for object and a second channel for sky. The frame time is 1 ms, marginally longer than the decay time of the P-20 phosphors, so frame subtraction is employed before individual events are centroided. The basic philosophy of the detector was pioneered by Shectman (Shectman and Hiltner, 1976), but many of the details have continued to evolve on a time-scale of 6 to 12 months. Thus we have taken a modular approach, so that improved components, such as better image intensifiers, could be installed at minimum expense.

Both of the present systems use two Varo 8605 40-mm electrostatic diode inverters and for the final stage a Varo 3603 25-mm MCP inverter, procured without the normal long decay phosphor component. Our earlier systems had the MCP tube in the middle, but this degraded the DQE by about a factor of two because not enough electrons were created per event at the cathode of the MCP tube to overcome its quasi-exponential pulse-height distribution. We have now learned how to clean and encapsulate these intensifiers so that the front tubes can be run with voltages as high as 30 kv each, twice the rated voltage, even at -29°C. In practice we use them at the more conservative level of 20 kv each, with 10 kv dropped across the fiber-optic faceplate between them. To power the front two tubes we use the standard Varo three-stage high-voltage supply encapsulated with the tubes, with the leads normally used for the middle tube interchanged to get the voltage drop across our tube interface. The Varo supply provides protection against over-illumination, a feature that has been tested an embarrassing number of times. A 1.5-inch fiber-optic boule made by Galileo is used to isolate the front two stages from the MCP tube, and we have dropped as much as 48 kv across these boules without permanent damage. One can get interesting effects, however, at these voltages.

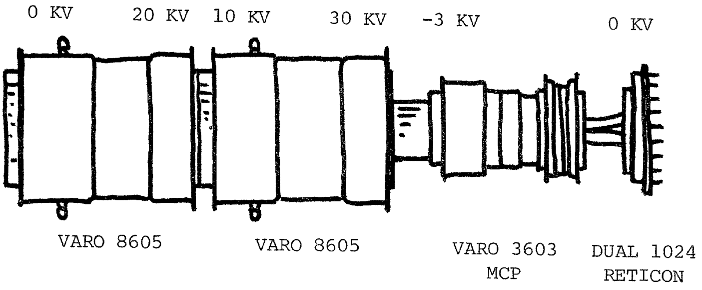

Figure 1. Schematic of the image intensifier package

All of the optical coupling in our packages involves fiber optics. For the critical front stages we use optical cement, but for the expensive elements in the back we use immersion oil. In particular, we have noticed a moderate amount of fatigue on the area of the MCP tube that is most heavily used. Although we still have extra gain available, the lifetimes of these tubes are clearly limited, as expected.

On the MMT detector we have used special fiber optics to split apart the object and sky spectra, which lie very close together at the final phosphor, so that the spectra can be mapped onto two separate Reticon arrays. This appears to be a technique that can be used rather generally to map crowded images onto diode arrays with more open geometries.

2.1. Cathode sensitivity

The sensitivity vs. wavelength of image intensifiers varies so much from one manufacturer to the next and from one tube to the next that it is essential to be able to measure all candidate tubes on a standard relative basis. Absolute sensitivities are less critical, but still of importance when it comes to comparing results with other observatories or other devices, such as CCD's. At SAO we have a simple setup for measuring cathode sensitivities which nevertheless cost nearly $10,000. The fundamental calibration is set by a 1 cm^2 silicon diode calibrated by EG&G. This has been compared carefully to the system developed by Cromwell at UA, and gives agreement within a few percent of Cromwell's latest calibration. In figure 2 we show the dc sensitivity vs. wavelength for three of the best tubes out of literally dozens measured. Red Hot is a standard extended red S-20 Varo 8605, where the ultimate drop in the near ultraviolet is due to the input fiber-optic faceplate. Old Blue is a similar tube, but specially processed to have a thinner cathode, and therefore somewhat better blue response at the expense of the red. Big Blue is the 40-mm ITT (Fort Wayne) F4089 magnetic tube which will become the first stage of a package being assembled by Cromwell at UA. This has the best blue-near ultraviolet response of any tube tested at UA or SAO in the past five years.

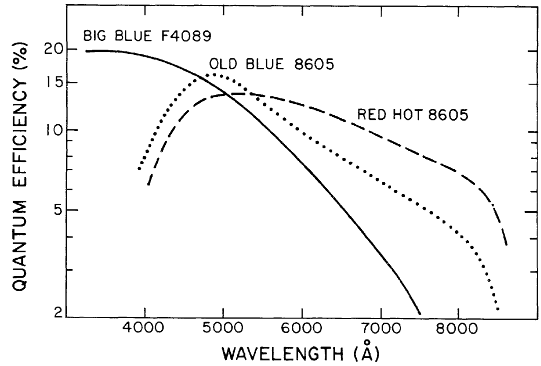

Figure 2. Measured cathode sensitivities

2.2. Integrated pulse-height distribution

In figure 3 we show the integrated pulse-height distribution for two versions of our photon-counting electronics, as measured in the laboratory. These curves do not flatten out into well-defined plateaus, and it is necessary to pick a compromise threshold setting that gives away some counting efficiency in order to discriminate out spurious low-amplitude noise events. However, the loss in DQE is not large. Measurements of the absolute counting rate using the same standard lamp as for the dc cathode sensitivity measurements suggest a counting efficiency of about 80%. Since the lamp must be attenuated by about 10^4 for this measurement, this result is no better than the calibration for the attenuation, estimated to be good to about 10 or 15 percent. Thus we have direct measurements that the degradation of the DQE of the first cathode by the entire system is significant but hardly overwhelming.

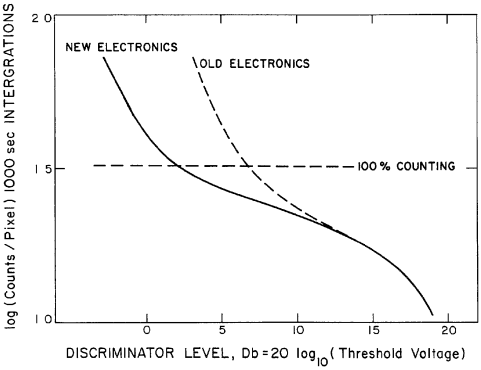

Figure 3. Integrated pulse-height distributions

2.3. Cooled dark rate

Perhaps the most difficult aspect of the image-intensifier package has been how to achieve cooled operation in the tight quarters dictated by our fast spectrograph cameras and with the large internal voltage drops dictated by our need to have both the front and back ends at ground. We circulate chilled methanol at about -30°C reservoir temperature from a commercial cooler through silicone rubber tubing that is encapsulated directly with the image intensifiers in a spiral, and flows through a copper nose piece that enshrouds the first stage. The intensifier package itself is insulated with several layers of foam sheeting, and the cooling lines are insulated with standard plumbing foam jackets. We find a temperature rise of about 4°C over 15 feet of cooling line, and this inexpensive approach can not be used for long lines. They do remain flexible at our lowest temperatures and have proven durable to considerable astronomer abuse.

At -26°C cathode temperature we achieve typically 5 counts/cm^2/sec, with virtually no ion events, for all the recent Varo packages. For the dual 936 Reticon in use at the 1.5-m telescope this gives about 1.2 counts/pixel/hour (limiting detector resolution is about 2 or 3 pixels FWHM). It is this low dark rate which makes possible high resolution spectroscopy of rather faint objects. For example, figure 4 shows a six-hour cooled dark integration with Red Hot. Note that there are no hot spots or wildly non-statistical areas in this dark spectrum.

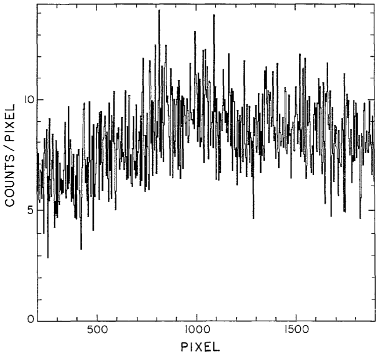

Figure 4. Cooled 6-hour dark integration, Red Hot

At -30°C frost can be a problem. With our echelle spectrographs we use adaptors that have a clear window and a small enclosed volume which is purged at a slow leak rate with bottled dry nitrogen. This has worked flawlessly. With the MMT spectrograph there is no window, and the entire inside of the spectrograph must be kept dry to avoid frosting. This has proven to be more difficult than originally anticipated, and agressive purging is needed after every time the detector is removed and moisture has entered the spectrograph en masse. Frost has been the single largest cause for lost observing time at the MMT.

2.4. Resolution

All the electronics in use since 1978 have centroided to the level of 2 pixels per Reticon diode, giving pixel widths of 19 and 16 microns for Red Hot and Old Blue, respectively (originally there was a 1:1.6 fiber-optic reducer in Old Blue, but this was removed in February 1981 to give better resolution). These systems can give routinely a FWHM resolution of better than 3 pixels for comparison lines in all the spectrographs, corresponding to a limiting resolution of the detectors themselves of no worse than 45 microns FWHM at the cathodes. Recently we have completed laboratory tests of new electronics developed jointly by SAO and UA. They bin 4 pixels per diode and provide 50% better limiting resolution, no worse than 30 microns FWHM at the cathode. Since the new interface boards can be used at either 2 or 4 pixels per diode from software, we have been able to demonstrate that the improved resolution is due entirely to the finer sampling.

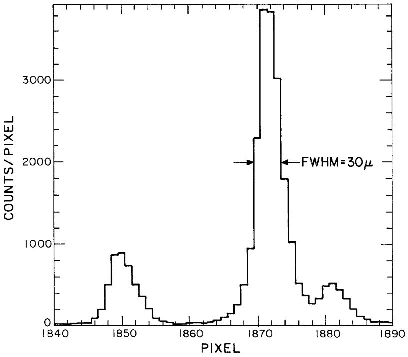

Figure 5. Typical echelle Th-Ar lines at 4 pixels per diode.

2.5 Persistence

Because of the frame subtraction, there are no false counts due to residual phosphor glow except in the first few seconds after a source is removed. This makes it possible to apply very intense comparison exposures immediately before and after an exposure of a very faint object. This turns out to be crucially important for programs of accurate radial velocities using cassegrain spectrographs. In just 60 seconds of comparison exposure it is possible to get a full complement of lines so that accurate wavelength fits to several dozen lines across the spectrum are possible. Thus it is possible to map out the total flexure of the spectrograph and detector over the object exposure time. On the 1.5-m telescopes, exposures are normally limited to half an hour or less to keep flexures under control. At the MMT much longer exposures are possible (but rarely used) because of the alt-az mount and correspondingly less flexure in the spectrographs.

2.6 Coincidence

At count rates of about 1 count/pixel/sec or 2000 counts/spectrum/sec there is roughly 1% coincidence. The exact amount depends on the nature of the spectrum, and for isolated emission lines much higher local rates can be tolerated. This sets a rather severe limit on observing very bright objects such as spectrophotometric standards. The coincidence rate is lower when the MMT echelle image stacker is used because the spectrum is spread over six times more cathode area.

2.7. Flatfielding and spectophotometry

These detectors have not yet been used for accurate spectrophotometry. Accuracies of 5 or 10% seem relatively easy to achieve, but for more precise work there are several problems. The Reticon readout system itself has patterns, typically in every 2, 4, and 8 pixel frequencies, but these can be corrected with remarkable accuracy under controlled conditions. Signal-to-noise of 200 has been achieved in the laboratory over a few hours, and here the limit was set by the 32000 maximum count per pixel due to the 16-bit word size of the interface-board integration memory. In real life the flat-field corrections appear to be limited at the 2 to 5% level, ultimately by nonuniformities in the response of the cathode. The problem is that the exact area of the cathode that is mapped onto the Reticon depends on the stability of the electrostatic image intensifiers and does not reproduce exactly for different pointing directions or over long periods of time. We have also seen the Reticon patterns change from time to time in ways that we do not understand. Another practical complication is especially prevalent at the MMT, where it is common practice to change the spectrograph settings several times during the night. This makes it difficult to reproduce the way the cathode was illuminated for all the exposures, and the validity of the flatfield exposures are inevitably compromised.

2.8. Reliability

Red hot has been scheduled for every night of the past year on the 1.5-m telescope. The total down time due to detector problems has been about a dozen hours over that period. At the 1.5-m we have the advantage of a limited number of experienced users. The reliability of Old Blue at the MMT has not been so impressive. The few experienced users have lost very little time to hardware failures, but the various newer users have had more trouble. The problem has been exacerbated by the rather chaotic environment of a big new complicated telescope that is in the throes of conversion from engineering development to routine astronomical observations. However, the multi-user environment will continue at the MMT, clearly requiring a level of design for useability and maintainability that is beyond the normal laboratory style of instrumentation. We are accepting this as a challenge to our ingenuity.

3. REMOTE OBSERVING

Approximately half of the observations with the 1.5-m telescope leading to 3000 reduced spectra for the redshift survey were carried out by a staff of two remote observers, each working alone. The other half were done by a few astronomers travelling from Cambridge. The learning curve for the remote observers was characterized by a time constant of 6 to 12 months, and their productivity was never quite up to the level of the most efficient of the astronomers. In this case, where the protocols were well defined and did not change from night to night, the degradation of throughput because of remote observing was perhaps 25% compared to the best astronomer. We have had similar experiences with other survey programs using the echelle spectrograph on the 1.5-m telescope, although here the degradation has been somewhat worse because of more difficult protocols.

We have experimented with remote observing for the various smaller, less well-defined observing projects, with mixed success. The basic concept is to provide enough real-time communications between Mt. Hopkins and Cambridge so that the astronomer does not need to travel but can carry out his program from a computer console in Cambridge. At present we provide a 1200-baud link between the telescope computer and a similar system in Cambridge, which is normally used to reduce data during the day. The link uses standard voice-grade telephone lines, and can transmit a raw spectrum in about 90 seconds. A few astronomers have been able to direct special observations with this setup, but the system has not met with much use. The problem seems to be mostly psychological. The astronomers do not seem to feel the same committment to observing from a console as they do to being there. Nevertheless, to help convince astronomers that remote observing can work for them, we are adding a video link to allow viewing of the TV guider (and CCD image displays too). This will use an inexpensive converter designed for the amateur-radio market, that freezes a TV monitor frame digitally, converts the 128 x 128 by 4 bit digital image to an audio signal that can be transmitted by normal voice-grade telephone in 8 sec, and then converts the transmitted picture back to a video signal at the receiving end using an identical converter. It remains to be seen whether remote observing can ever be fully satisfactory for non-routine projects. As travel costs mount, pressure towards this mode of operation will rise.

At the MMT we are not yet close to remote observing. The time on this telescope is so valuable and contested for so hotly that our present policy is to have most of the observations made by a handful of experienced astronomers for the community of users at the Center for Astrophysics.

4. DATA HANDLING

The real power of our spectroscopic detectors lies in the computer systems that we have developed, both for the real-time operations at the telescopes and for the subsequent reduction, display, analysis, and interpretation of the data. The real-time systems are based on Data General Novas, enhanced by extensive peripherals: Lexiscope 4000 boards for fast vector graphics, a Versatek printer/ plotter for high quality hard copy, and a tape drive for data archiving and data transport. For three years we operated the real-time systems with a dual floppy disk drive, but recently we have added 50-megabyte Trident hard disks. This alleviates the disk thrashing experienced with the floppies, which had been getting worse as the operating systems evolved to higher levels of sophistication. A pair of similar installations are located in Cambridge, where the raw data are "automatically" converted to "reduced files" in the form of intensities vs. wavelength. The reduced files, together with the various observing and reduction parameters, are stored chronologically on disk packs so that a user can access any one of the reduced spectra almost instantaneously. In addition the radial-velocity and line-strength analyses are also carried out "automatically" on the Novas.

The operating systems are based on a version of FORTH which was developed at SAO and has gradually evolved over the past several years. SAO FORTH has virtual data management, powerful overlay schemes, and efficient math packages. Altogether several man years have been invested in the software development, counting the basic FORTH systems, real-time operating systems, and data analysis systems.

5. SAMPLE RESULTS

On the following pages I show two samples of results using the SAO photon-counting Reticons. Figure 6 is the spectrum of the QSO 1548+115A showing a rich spectrum of narrow emission lines at a redshift of 0.4356. This MMT spectrum required 80 min of integration through thin clouds. The slit was 1 x 3 arc-sec and FWHM resolution is somewhat better than 10 A. The interesting thing about this QSO is the companion QSO 5 arc-sec away and with a redshift of 1.905. CIV is quite strong in the V = 19.1 companion QSO, and falls exactly at the wavelength of the weak, slightly broadened feature at 4500 A in the V = 18.1 primary QSO. Is this evidence of gravitational lensing or is the 4500 A feature a Bowen fluorescence line from 3133 A? This question, first raised by Wampler et al. (1973), is not settled even by this high signal-to-noise high-resolution spectrum. Further spectra near 3500 and 8500 A are needed to check for lensed Lyman alpha and Mg II.

The second sample result is shown in figure 7. The spectrum on the left is a 4 min echelle exposure from the 1.5-m telescope of a K2 IAU radial velocity standard, one of several templates that we use in our correlation analysis for stellar radial velocities. The strong feature at 5183 is one of the Mg B triplets, and several strong iron lines are sprinkled through this order. The spectrum on the right is a 20 min exposure of a V = 14.2 Hyades proper-motion candidate, L-73. Although the individual spectral features are hard to recognize because of the very low signal to noise in this exposure, nevertheless the correlation analysis gives a radial velocity good to about ± 1 km/sec. A plot of the correlation for L-73 against the K2 template is shown in figure 8.

6. ACKNOWLEDGEMENTS

Many people at CfA have contributed to the success of the photon-counting Reticons. Marc Davis played an instrumental role, especially in the early stages of the project. Tom Stephenson was responsible for much of the computer systems development, and John Tonry wrote most of the analysis software. Bill Wyatt has made major contributions to the development of the real-time operating systems. John Geary has been in charge of the newer electronics, and Charlie Hughes has carried out all the tricky work with the image intensifier packages. At Mt. Hopkins, Fred Chaffee and his

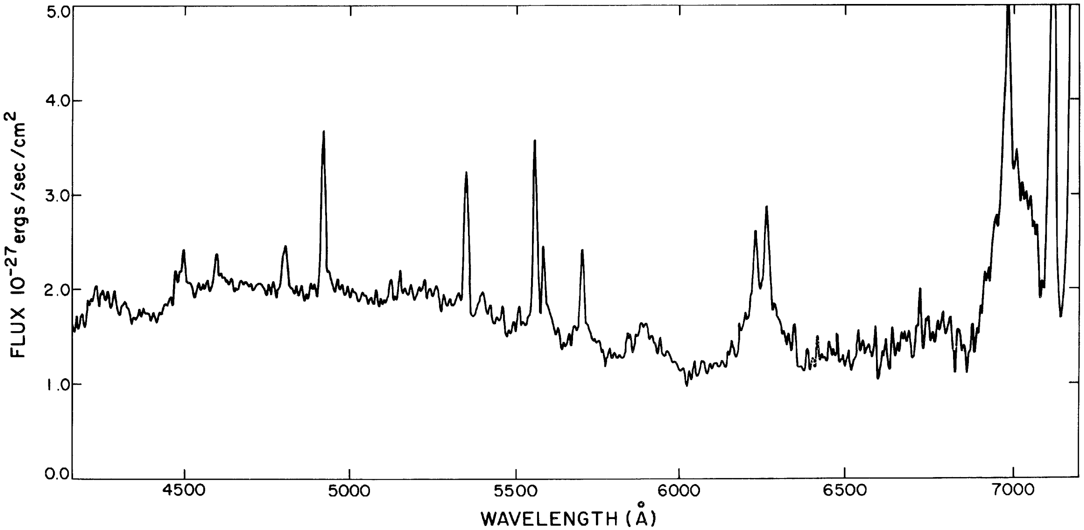

Figure 6. An 80-min MMT exposure of 1548+115 A

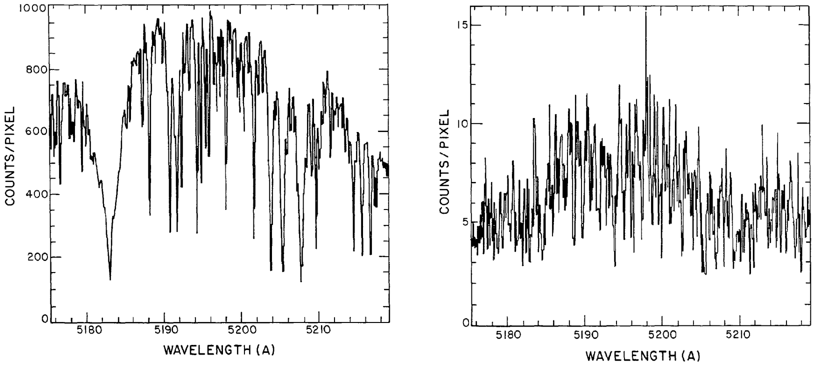

Figure 7. Echelle spectra of a K2 template (left) and V = 14.2 Hyades member (right)

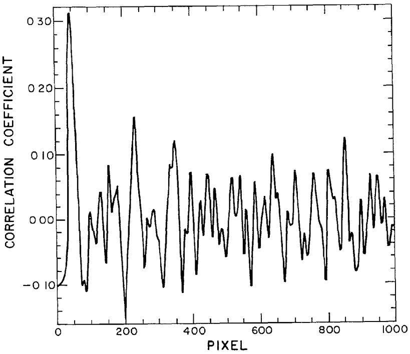

Figure 8. Correlation of the faint spectrum in figure 7 against the template

technical and observing staff have kept the systems going, and in Cambridge Neal Burnham has reduced and analysed most of the data. Finally, the users, especially John Huchra, have kept us honest and motivated.

7. REFERENCES

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