III. SPECTROSCOPIC RESEARCH PROGRAMMES

a) Invited and oral contributed papers

INSTRUMENTATION FOR LOW-RESOLUTION SPECTROSCOPY

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ABSTRACT. Instrumentation presently in use for low resolution, digital spectroscopy on 1 meter class telescopes at three observatories - Lick, Kitt Peak, and Cerro Tololo - is reviewed. A detailed comparison is made between the performance of a typical two-dimensional photon counter, the "2D-Frutti", and currently-available CCDs. Prospects for further detector advances center on large-format, low-noise, uv-sensitive CCDs.

1. INTRODUCTION

Two articles which are still the standard references on optical band K-corrections for giant elliptical galaxies appeared back-to-back in the 1971 October 15 issue of the Astrophysical Journal. These papers, by Schild and Oke (1971) and Whitford (1971), are especially relevant to the subject matter of this Symposium since they were based entirely on low-resolution spectrophotometry carried out with "small" telescopes. In fact, the spectra published by Oke and Schild were made with a 4-inch telescope, which even for this meeting must be considered extreme! Those of Whitford were obtained with the 36-inch Crossley telescope at Lick Observatory.

In drawing attention to these papers, there are at least two points to be made. First of all, it is clear that there are many important contributions to be made in modern astronomy with spectroscopic observations obtained on 1 meter class telescopes or smaller. This is especially true in the case of projects requiring frequent monitoring over several weeks or months, which are virtually impossible to carry out on larger, more oversubscribed telescopes. Equally relevant, but perhaps not so obvious, is the realization that there exists a certain class of problems which must almost by necessity be tackled with small telescopes. The problem facing Oke and Schild and Whitford was to calibrate the magnitudes of distant galaxies from the energy distributions of nearby, bright giant ellipticals. Since a large fraction of the total light of distant ellipticals is usually observed in photometric studies, and the colors of giant ellipticals are known to be a function of radius, it was imperative that very large apertures be used for the

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nearby galaxies. Satisfying this requirement while maintaining adequate (≲100 Å) wavelength resolution ruled out all but the shortest telescope focal lengths, thereby effectively restricting the problem to small telescopes only. Instrumentation for low-resolution spectroscopy on small telescopes has changed considerably since 1971, but the lesson offorded by this example is still very much a valid one.

In this talk, I will purposefully avoid giving an all-encompassing review of modern instrumentation employed for low-resolution spectroscopy. Rather, I wish to concentrate attention on three observatories - Lick, Kitt Peak, and Cerro Tololo - where spectroscopic facilities for 1 meter class telescopes have been developed which are illustrative of the current "state of the art" with conventional Cassegrain spectrographs and digital detectors. I shall attempt to provide both a brief summary of the instrumental configurations employed at each site, and to mention a few of the research programs carried out recently with the same facilities as a way of underscoring the scientific potential of such instrumentation on small telescopes. The relative merits of two-dimensional photon counters and CCDs shall be examined in somewhat more detail, and brief consideration will be made of detector and spectrograph options for the near future.

2. LICK 1 METER NICKEL TELESCOPE

The 1 meter Anna L. Nickel Telescope went into operation at Lick Observatory in early-1980. This instrument was dedicated exclusively for the first few years to low-resolution spectroscopy, but is now also employed for digital imaging. The standard spectroscopic configuration consists of a copy of the image dissector scanner (IDS), developed by Robinson and Wampler (1972, 1973; see also Miller, Robinson, and Wampler, 1976), mounted on a conventional Cassegrain spectrograph. This combination is soon to be augmented by a new spectrograph designed especially for use with CCD detectors. In this talk, however, I shall concentrate on the older, dual-channel IDS spectrometer.

The IDS detector was designed at Lick over 15 years ago for the specific application of low- and moderate-resolution spectroscopy. The "front end" consists of a chain of three 40 mm, S-20 photocathode, electrostatically-focussed image tubes, coupled with fiber optics bundles. The phosphor of the third tube is repeatedly scanned by an image dissector at a rate roughly comparable to the characteristic decay time of the phosphor. The phosphor screen effectively serves as a short-term storage element, thereby enabling the system to approach true photon-counting performance. The spectrograph is equipped with dual entrance apertures so that separate spectra of object and sky are simultaneously imaged on the photocathode of the first image tube. The image dissector sweeps are preset so that the object and sky spectra are scanned alternately, with the data recorded as two 2048-pixel, one-dimensional arrays. During observations, the object is normally switched back and forth every 4 or 8 minutes between the two spectrograph apertures in order to optimize sky subtraction.

The general properties of the IDS spectrometer on the Nickel

Telescope are summarized in Table I. The IDS may be considered by some a relatively old-fashioned detector, but as shown in Table I, it is still quite competitive in many ways. Perhaps its chief disadvantage is the one-dimensional format. Another limitation results from the persistence of the phosphor screen which, while vital to the functioning of the instrument, can produce an annoying residual glow that lasts for several minutes, or even hours, after exposure to a very bright object. Hence, the observing program must be carefully planned to avoid scheduling faint objects immediately after bright standards.

In the more than 5 years that the IDS spectrometer has been available on the Nickel Telescope, several noteworthy papers have appeared based on data obtained with this facility. Antonucci and Cohen (1983) were able to monitor optical spectral variations of the nucleus of the Seyfert galaxy NGC 4151 over a 12-month period with a time resolution and accuracy rarely before achieved in such studies. Stauffer (1982) and Keel (1983a,b) both completed large spectroscopic surveys examining the nature of the ionized gas in spiral galaxy nuclei. In the area of stellar astronomy, Clarke, Capel, and Bowyer

TABLE I

	Lick 1 m	KPNO 0.9 m	CTIO 1 m		
	IDS	IRS	2D-Frutti	GEC CCD	RCA CCD
Detector Dimensions	40 mm (diam)	25 mm (diam)	40 mm (diam)	8.5 x 12.7 mm	9.6 x 15.4 mm
Peak Quantum Efficiency	~20%	~20%	~20%	~40%	~80%
Number of Independent Resolution Elements	~350	~300	~1000	288	256
Useful Wavelength Sensitivity	3800-7500 Å	3200-7500 Å	3200-7500 Å	5000-10000 Å	3700-10000 Å
Range of Wavelength Resolutions	3.5-20 Å	2.6-12.4 Å	1.4-7.5 Å	2.1-17 Å	2.9-23 Å

(1984) carried out a unique spectrophotometric study, covering one full outburst cycle of the dwarf nova SS Cygni, and chronicling for the first time ever the full sequence of changes in the hydrogen and helium emission lines with respect to the continuum variations. And, lest it be forgotten, the key spectroscopic observations that revealed the truly bizarre nature of SS433 were obtained with the same IDS and spectrograph when it was dedicated to the Lick 0.6 meter telescope (Margon _et al_. 1979).

3. KITT PEAK 0.9 METER TELESCOPE

Since early-1980, one of the Kitt Peak National Observatory (KPNO) 0.9 meter telescopes has been equipped with the so-called "Intensified Reticon Scanner" (IRS) dual-beam spectrometer. Like the Lick IDS system, the IRS records one-dimensional spectra produced from separate object and sky apertures. The detector chain consists of an S-20 photocathode, ITT proximity-focussed image intensifier followed by a Varo microchannel-inverter image intensifier and a Reticon dual 936-element array with fiber optic faceplate. Only 820 elements in each Reticon array are useable. The pixels are 30 microns wide (i.e., along the dispersion), and are long enough to allow the use of large (45 arcsec) apertures.

The dual Reticon array is normally read every 10 seconds. Electronic noise equivalent to ~4 photons per read per pixel is generated with each frame, so that readout noise is a problem only for faint objects. The Reticon also suffers from non-negligible dark current, fixed pattern noise, and pixel-to-pixel base line and sensitivity variations, all of which must be carefully calibrated via bias and quartz lamp scans. The same beam-switching observing technique described for the IDS is normally employed at the telescope.

The general properties of the IRS may be compared in Table I. This instrument is well suited for spectrophotometric investigations, with a precision of 3-4% achievable under favorable observing conditions (e.g., see Massey 1984). The system is stable enough to allow reasonably accurate (3-5 km sec^{-1}) radial velocity work as well. The disadvantages of the IRS are the same mentioned for the IDS, namely the one-dimensional character of the data and problems introduced by the persistence of the phosphor glow.

In a paper to be given at this symposium, George Jacoby will review in more detail the important scientific contributions which have come from instrumentation on small telescopes at KPNO, including the IRS. Certainly among the most prominent would figure the study by Hunter, Gallagher, and Rautenkranz (1982) of star formation rates in irregular galaxies, Barker's combined optical and ultraviolet observations of planetary nebulae (1985; and references therein), and Massey's spectrophotometry of northern Wolf-Rayet stars (1984). Special mention should also be made of the comprehensive spectral atlas based on IRS data put together by Jacoby, Hunter, and Christian (1984).

4. CERRO TOLOLO 1 METER YALE TELESCOPE

4.1 2D-Frutti

A copy of Steve Shectman's (1984) "2D-Frutti" two-dimensional photon counting detector is now in the final stages of commissioning on the Boller & Chivens spectrograph of the 1 meter Yale telescope at Cerro Tololo Inter-American Observatory (CTIO). This is the second copy of the 2D-Frutti to be built by CTIO, the first having been in regular service on the 4 meter telescope spectrographs for nearly a year. Unlike any of the other detectors mentioned in this talk, the 2D-Frutti is a genuine photon counting system. The front end of the detector is a 40 mm, S-20 photocathode, two-stage RCA "Advanced Carnegie" image tube. The output phosphor of this tube is reimaged with a transfer lens onto the photocathode of a 40 mm Varo electrostatically-focussed image tube, which is itself fiber optically coupled to 50/40 mm Varo microchannel-inverter image intensifier. To complete the chain, the output phosphor of the second Varo tube is imaged via a fiber optic minifier onto a 380 x 244 pixel Fairchild CCD with special fiber optic faceplate.

The size of the CCD is 11.3 x 8.8 mm, onto which is projected an area of approximately 35 x 28 mm from the spectrograph focal plane. The CCD is clocked at 15 MHz (2x standard TV rate), with full read out requiring about 7 msec. However, it is possible to read out only 1/2, 1/4, 1/8, or even 1/16 of the full verticle format, depending on the application. For the f/10 focal ratio of the 1 meter telescope, the full spectrograph slit length of 6.2 arcmin fits entirely within the 1/8th format (i.e., 32 horizontal lines of the CCD).

As the Fairchild chip is read out, individual photon events are identified and their locations tagged to a precision of 1/8th of a pixel through a digital centroiding technique. Double counts of photon events due to phosphor persistence are eliminated by subtraction of the previous frame before centroiding is carried out. In 32-line mode with 1/8th of a pixel centering both horizontally and vertically, the 2D-Frutti data format translates to 3040 x 256 pixels, with a resolution of 3 such pixels in either direction.

Representative performance figures for the 2D-Frutti on the 1 meter telescope are given in the third column of Table I. Dark current for the 2D-Frutti is so low that the detector performance is truly that of a photon counting system, even at very faint light levels. The wavelength stability of the 2D-Frutti is also quite good. However, as with any serial-readout photon-counting detector, coincidence losses set in and the detector becomes nonlinear at high count rates. Not surprisingly, the maximum permissible count rates for stellar objects are higher than those for pure continuum sources. The saturation limit for stars works out to be about 9 counts/resolution element/sec. On the 1 meter telescope spectrograph, this bright limit translates in the blue to $B \approx 12$ for a wavelength resolution of 4 Å. Another somewhat bothersome property of the 2D-Frutti detector is the image distortion produced by the combination of image tubes, but this can be dealt with successfully (albeit somewhat painfully!)

through software at the reduction stage. Examples of a spectra taken with the 2D-Frutti on the 1 meter telescope are shown in Figure 1. These data were obtained at a resolution of ~2 Å.

4.2 CCDs

In November 1983, a CCD detector was used for the first time on the CTIO 1 meter telescope. The particular device was a GEC P8603 epitaxial chip, which has a 385 x 576 format with 22 micron square pixels. The rms readout noise of this first chip was ~20 electrons, but during 1984 a newer GEC CCD was commissioned having only 6-7 electrons noise. These chips are not thinned, but rather are front-illuminated, and thus have little response below 4000 Å. They have about 30-40% quantum efficiency from 5500-9000 Å, falling close to zero beyond 1 micron.

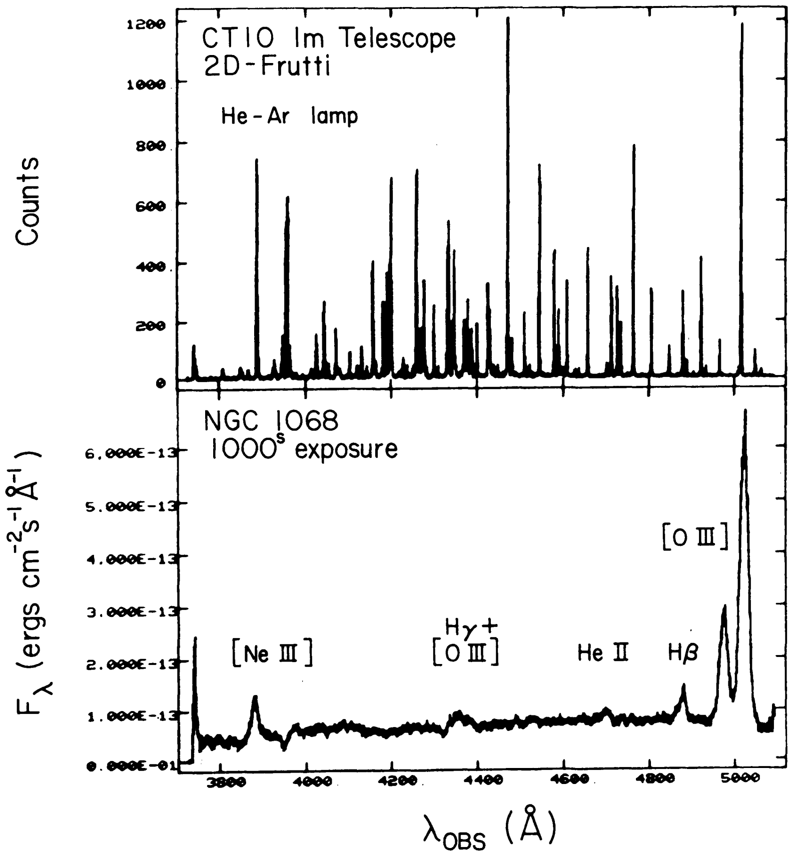

Figure 1. Examples of 2D-Frutti spectra taken on the CTIO 1 meter telescope.

The GEC CCDs suffer from several problems. Radiation events (including cosmic rays) are detected at a rate of about 2 per minute over the whole chip, and can be a considerable nuisance for long exposures. Some columns also show "traps" which are dead at low light levels. Even more bothersome are charge transfer problems which can lead to poor sky subtraction of the OH emission lines redward of 7000 Å. This problem is minimized by preflashing the chip - i.e., adding a flat background of roughly 150 photons per pixel to each exposure. Note, however, that this increases the effective readout noise to approximately 14 electrons.

An RCA SID501 thinned 320 x 512 pixel CCD with 30 micron square pixels was recently tested on the CTIO 1 meter telescope as a possible alternative to the GEC chips. These detectors offer significantly higher quantum efficiency than the GEC CCDs at most wavelengths, and are useful in the blue down to roughly 3700 Å. Charge transfer is also quite excellent, with no preflashing necessary. Unfortunately, the ~40 electrons readout noise of the RCA severely limits its usefulness on fainter objects (see next section). These devices also produce interference fringes with an amplitude of a few percent which require careful flat field calibration. Finally, the new generation of RCA CCDs suffers a high radiation event rate, amounting to ~6 events per minute over the whole chip for the particular device tested on the 1 meter telescope.

Basic properties of the GEC and RCA CCDs on the CTIO 1 meter telescope spectrograph are included in Table I. A few examples of scientific projects carried out with these detectors deserve mention. Vilas (1985) used the GEC CCD to obtain reflectance spectra of differing terrain on Mercury in search of absorption features due to crystalline Fe^{2+}. Another interesting project begun by Kemper with this detector (and now being continued on the 1.5m telescope) is the calibration of a new abundance parameter for RR Lyrae stars using Hα and the Ca II triplet lines near 8550 Å. The RCA was recently employed by Caldwell in a long-term project to obtain integrated-light spectra of nearby galaxies. Examples of data taken for the latter investigation are given in Figure 2.

5. 2D-FRUTTI VS. CCD

The 2D-Frutti and CCD systems represent different approaches to the problem of providing two-dimensional digital detectors for spectroscopy (on any size telescope). In Table II, I have listed what I feel to be the most relevant properties of a spectroscopic detector and have graded the 2D-Frutti, RCA CCD, and GEC CCD accordingly (+++ = good, ++ = fair, and + = poor). For the purpose of later discussion, I have included in this table similar grades for a Texas Instruments (TI) 800 x 800 pixel 3-phase CCD (with 15 micron square pixels), and a Tektronix 2048 x 2048 pixel CCD (with 27 micron square pixels). The performance of the latter device can only be surmised from preliminary data sheets, since Tektronix has not yet begun to deliver such CCDs. For both the TI and Tektronix CCDs, it is assumed that a uv-flooding technique (e.g., see Hlivak, Henry, and Pilcher 1984) has been used to increase the ultraviolet quantum efficiency to ~50%.

In comparing grades for the 2D-Frutti, RCA CCD, and GEC CCD, it is clear that the detector of choice is a strong function of the specific application. Obviously the 2D-Frutti performs best in the ultraviolet, whereas the GEC and RCA chips are superior at red wavelengths. Similarly, for certain spectrophotometric or radial velocity applications, and for very high signal-to-noise observations, the larger dynamic ranges of the GEC and RCA CCDs are a definite advantage.

A slightly different comparison of the relative performances of the same detectors (including the hypothetical cases of the TI and Tektronix chips) on the CTIO 1 meter telescope is given in Figure 3. At wavelengths of 4000 Å and 5500 Å, respectively, and for a range of stellar brightnesses, I have calculated the maximum signal-to-noise

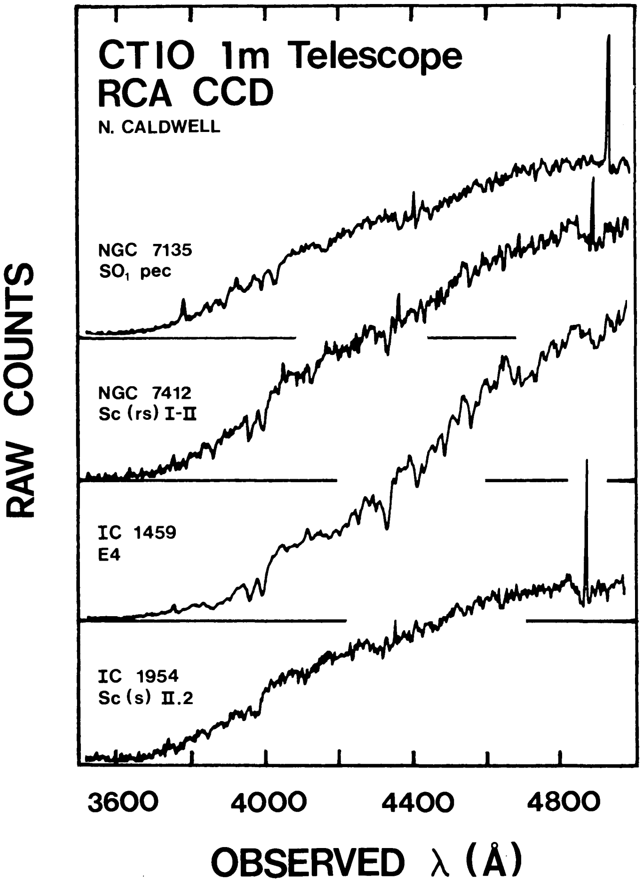

Figure 2. Integrated light spectra of nearby galaxies taken with an RCA CCD on the CTIO 1 meter telescope.

TABLE II

	Detector				
	2D-Frutti	GEC CCD	RCA CCD	TI CCD	Tek CCD
Format:					
Dimensions	+++	+	+	+	+++
Pixel Size	++	++	++	+++	++
Q.E.:					
3500 Å	++	+	+	+++	+++
5000 Å	++	++	+++	+++	+++
8000 Å	+	++	++	++	++
Geometric:					
Flatness	+++	++	++	+	++
Distortion	+	+++	+++	+++	+++
Noise	+++	++	+	++	++
Dynamic Range	+	+++	++	+++	+++
Wavelength Stability	++	+++	+++	+++	+++
Cosmetics	+++	+	++	++	++

ratio per resolution element achieved in a total exposure time of 1 hour. These curves are valid for a wavelength resolution of 6 Å, a slit width of 6 arcsec, and typical Cerro Tololo seeing (~1.5 arcsec). Sky subtraction is assumed to introduce no extra noise, since a long slit and two-dimensional detector allow a virtually error-free determination of the sky spectrum. A far more questionable assumption is that pixel-to-pixel flat fielding is carried out to infinitely high precision. In fact, because of the relatively low maximum count rate limit for the 2D-Frutti, a flat fielding accuracy of 1% is virtually never realized for this device. Hence, I have included in Figure 2 a curve showing the effect on 2D-Frutti data of no flat field correction, in which case the maximum signal-to-noise obtained is limited by the graininess of the front photcathode of the Carnegie image tube (~3% rms). A final assumption made is that the 1 hour integration time must be broken into three separate 20-minute exposures in the case of the CCD observations, so as to be able to eliminate radiation events and bad pixels during reductions.

As may be seen from Figure 3, the TI CCD would hold a clear

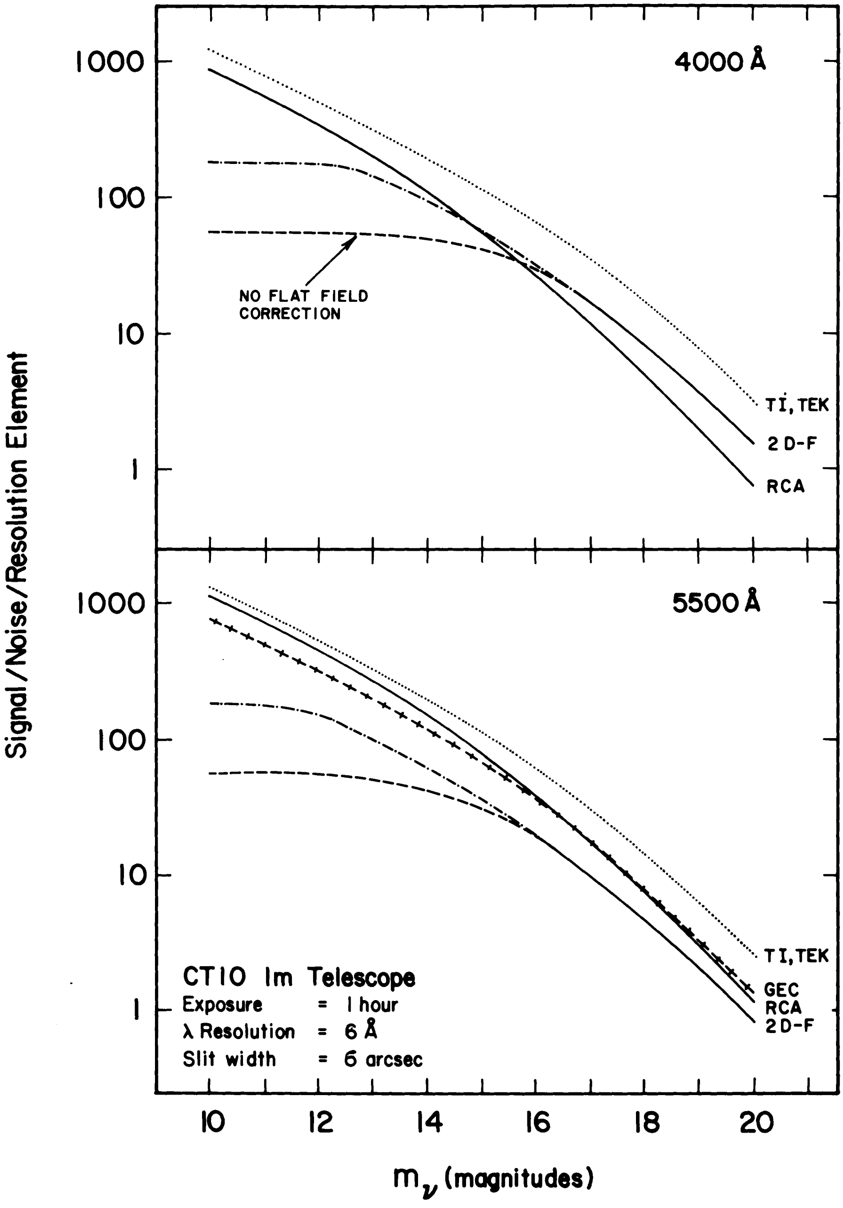

Figure 3. Calculation of the signal-to-noise per resolution element as a function of monochromatic magnitude obtained for various detectors on the CTIO 1 meter telescope. Assumptions behind the numbers are detailed in text. Note that the curves for the TI and Tektronix CCDs are purely hypothetical, as these detectors have never been used for spectroscopy on the 1 meter telescope.

advantage over the other detectors at both wavelengths. This is even more true in the ultraviolet (due to the high quantum efficiency resulting from uv-flooding), while in the red and near-infrared its performance is only rivaled by the GEC chips. Unfortunately, the physical package of the TI chips, and the large deviations from geometric flatness of the sensitive area, make the use of this type of detector with a fast spectrograph camera virtually impossible. Moreover, the small physical dimensions of the device would certainly not suit all projects. Thus, while the performance of each of these detectors is impressive for certain applications, it would seem that as yet no single detector provides all of the characteristics that are ideal for low-resolution spectroscopic applications.

6. FUTURE DEVELOPMENTS

What prospects are there in the near future for further detector improvements in the field of low resolution spectroscopy? Certainly the most promising developments are being made in CCD technology. As shown by the discussion above, currently-available CCDs have already become the detectors of choice for many applications. The recent announcement by the Tektronix Corporation of the development of large-format, low-noise CCDs offers even more promise for such devices. Current specifications call for two chip sizes - 512 x 512 and 2048 x 2048 - each with a 27 micron square pixel size. The format of the 2048 x 2048 chips is truly gargantuan (55 x 55 mm!) by electronic detector standards. The performance of these CCDs is expected to be comparable to that of the TI 800 x 800 devices (see Table II and Figure 3). If so, then the goal of a single optimum detector for both bright and faint object spectroscopy, from the ultraviolet to the near-infrared, may be finally realized. Unfortunately, the announced prices of the 2048 x 2048 devices may restrict there acquisition to larger telescopes, at least initially. Also, the 27 micron pixel size is a factor of ~2 larger than would be ideal for small telescope spectroscopy.

Fortunately, prospects for uv spectroscopy with CCDs do not rest entirely on the Tektronix chips. Over the years, considerable progress has been made with the use of fluorescent coatings on front-illuminated chips such as the GEC epitaxial CCDs. In a recent paper, Cullum *et al*. measured a peak quantum efficiency of more than 25% at a wavelength of 3400 Å for a GEC device with a 3-4 micron thick fluorescent plastic coating. This particular coating causes no significant loss of resolution and is expected to be quite durable. Moreover, the coating seems to even produce a slight enhancement in quantum efficiency in the 4000-6000 Å range.

In this talk, I have restricted myself to low-resolution spectroscopy with conventional Cassegrain spectrographs. However, advances in detector technology can be expected to spark interest in alternative optical configurations. For example, large-format CCDs with high quantum efficiency over a wide spectral range should be ideal for an echelette configuration on a small telescope. The same detectors may also eventually replace photographic plates for much grism and objective prism spectroscopy.

7. CONCLUSIONS

As astronomers, we are certainly witnessing exciting times with the 10 meter Keck Telescope project underway and other large telescopes such as the NNTT being proposed. However, a glance at the curves in Figure 3 shows that tremendous advances have also been made in the area of low-resolution digital spectroscopy on small telescopes. The potential of existing small telescopes for making fundamental contributions to astronomy, particularly for projects requiring frequent access to the telescope, is greater than ever, thanks largely to the development of modern electronic detectors. In the rush to build a new generation of giant telescopes, it is all the more important that we not lose sight of this simple fact.

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DISCUSSION

Garrison: I have a somewhat controversial question. Noting that most of the spectra you showed were emission-line spectra, and considering that I have heard bad things about internal scattering in image tubes, what is your opinion of the use of IDS or Shectograph-type instruments for absorption-line work, especially that involving quantitative line strength or profile work? I'm thinking in particular of the recent work of Burstein et al. using IDS spectra to comment on the so-called "Super-Metal-Rich" stars. My impression is that image tube spectra always have a "washed-out" appearance.

Phillips: Absorption-line work isn't the strong point for a detector with lots of image-tubes in front of it.

Finkenzeller: I would like to draw your attention to how low resolution spectroscopy can help high resolution spectroscopy. If one is interested in calibrated, high resolution line profiles one requires a small entrance slit which is in conflict with spectrophotometric needs. Thus, we have chosen to use a coudé spectrograph concurrently with an IDS at a much smaller telescope. The flux level is established reliably there, and after some work with an image processing system the response of the high resolution spectrograph can be determined easily. In addition, this technique relieves the observer spending valuable time with the large telescope on mostly faint flux standards.

White: Spectrophotometry can be accomplished with extremely small aperture telescopes. Tüg, Lockwood, and myself have completed a spectrophotometric comparison of Vega and the Sun using a two inch and 20 micron aperture telescopes respectively.