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ABSORPTION-LINE REDSHIFTS OF GALAXIES IN REMOTE CLUSTERS OBTAINED WITH A SKY-SUBTRACTION SPECTROGRAPH USING AN SIT TELEVISION DETECTOR

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ABSTRACT

A prism spectrograph with an associated SIT television camera, operating as a two-dimensional detector with digital readout, has been used at the 5-m Hale telescope. The system was tested for its ability to subtract the sky spectrum, and was found to produce difference spectra that are essentially photon noise limited.

Redshifts of 14 galaxies in clusters with $0.01 \leq z \leq 0.4$ were obtained, each with exposure times of 90 minutes or less. Nine of the redshifts are new. Redshifts for the remaining five agree with previous values to within the measuring errors.

The speed and sky-subtraction capabilities of the instrument are sufficient to begin routine measurement of absorption-line redshifts for remote cluster galaxies in an effort to extend the Hubble diagram.

Subject headings: galaxies, clusters of — redshifts

I. INTRODUCTION

Spectra for very faint objects cannot be obtained on photographic plates because the nightsky airglow saturates the emulsion before an acceptable signal-to-noise level is reached. For example, Humason (1957) was stopped in his program to measure redshifts of cluster galaxies at $z \equiv \Delta\lambda/\lambda_0 \approx 0.2$. Plate III-8 of Humason, Mayall, and Sandage (1956) shows the severity of the problem, near sunspot maximum, for the Hydra cluster. The widespread use of image tubes during the 1960s, thanks in large part to the very successful efforts of the Carnegie Committee on Image Tubes for Telescopes (Carnegie Institution of Washington Yearbooks, 1953–1969), greatly increased the speed of obtaining spectra, but did not change the faintness limit, because the image tubes also used photographic methods to record the spectra.

In more recent years, the replacement of photographic emulsions by linear detectors with large dynamic range has made it possible in principle to obtain spectra for arbitrarily faint sources, limited in practice only by the time one is willing to devote to the observations, which is determined by the telescope aperture, the quantum efficiency of the detector, and the ultimate limit of the noise due to the random arrival of incoming photons. With a linear detector, the sky background can be subtracted, and exposures added together to increase signal-to-noise ad lib. A wide variety of detectors have been built or proposed, including the Robinson-Wampler (1972) image-dissector scanner and a similar device developed independently by W. K. Ford, the Boksenberg-Burgess (1973, quoted in Glaspey and Walker 1973) device, the Princeton SEC system (Lowrance and Zucchino 1969; Zucchino and Lowrance 1971), the Digicon (Beaver and McIlwain 1971), and others (cf. the proceedings of a conference on television-type sensors edited by Glaspey and Walker 1973).

The present paper gives the first results from a new system which uses an SIT (*S*ilicon *I*ntensifier *T*arget) television camera tube as a detector.

II. THE DIGITAL PRISM SPECTROGRAPH WITH SIT DETECTOR

To measure redshifts of faint galaxies, we have built a system that consists of a prism spectrograph and an SIT television detector with digital output. A prism system was chosen to maximize the throughput for faint objects. The spectrograph design parameters were matched to the detector and optimized for the galaxy redshift problem. The projected slit width is about 60 μ for a 1″ slit opening, while the resolution element of the detector is 40 μ. One, two, or three prisms can be used to provide a range of dispersions. The two-prism configuration used for the measurements reported here gives a spectral resolution (including the detector) of 7 Å, with a dispersion of 125 Å mm^{-1}, at Hγ.

The detector system was developed and is being used as an area photometer. A detailed description is given elsewhere (Westphal 1973, quoted in Glaspey and Walker 1973; Kristian and Westphal 1975). It uses a commercial 16-mm SIT television camera tube (RCA 4804) operated in an integrating mode. The front of the tube is a fiber-optic plate, with a S20 photocathode deposited on its inner surface. Photoelectrons liberated at the photocathode are accelerated through a 10-kV field and electrostatically focused on a silicon wafer target. It is this target which gives the tube its unique properties: the electron acceleration section is similar to other image intensifiers.

The target contains about a million individual silicon diodes, on a rectangular grid with 10-μ spacing. The target is back biased, and the diodes act as individual storage capacitors. The target is fully charged ($\sim 10^5$ electrons per diode) before an exposure. Each accelerated photoelectron creates about 1000 electron-hole carrier pairs when it strikes the target. The holes then migrate to the diodes and partially discharge them.

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After an exposure is made, the tube is read out by re-charging the target in a raster pattern. The charging current at any place on the target is proportional to the number of photons incident at the corresponding place on the input face plate. The read beam is de-focused so that the landing spot is about 40 μ in diam-eter, which sets the basic resolution of the detector. The read beam current is amplified and A/D converted. The resulting 12-bit binary numbers, which are a linear representation of the two-dimensional intensity distri-bution of the spectrograph output, are recorded on digital magnetic tape for later reduction.

The readout noise is about 500 carriers rms per pixel ("pixel" is an acronym for picture element: i.e., resolu-tion element). Because *each* photoelectron produces about 1000 carriers, it follows that individual photo-electrons can be detectable, and the system should be nearly photon-noise limited. This expectation is ob-served to be the case. The target saturates at a level of 1000 photoelectrons per pixel (10^6 carriers), so that the dynamic range is about 10^3. The output is very nearly proportional to the input, except for small devi-ations which are well-behaved and easily calibrated (Kristian and Westphal 1975).

It should be noted that the output is fully two-dimensional, which has two major advantages for spec-troscopy over a one-dimensional format: (1) The relative sensitivity of the tube can be calibrated transverse to the dispersion, so that the calibrated output does not depend upon the details of the light distribution along the slit, which will vary in an uncontrolled way due to seeing and tracking changes. (2) If a long slit is used, a large sample of sky can be measured simultaneously with the star or galaxy spectrum with high accuracy, by adding the large number of available sky pixels. This means that no extra telescope time is spent on sky measurements, and that sky subtraction can be done even with rapidly changing sky conditions.

III. FIRST OBSERVATIONS

The spectrograph and detector were first used at the Cassegrain focus of the Hale reflector in 1974 October and December. The aim of the observations was to test (1) the speed of the system, (2) the sky-subtraction capability, and (3) the suitability of the system for measuring absorption-line redshifts of faint galaxies. The October observations were marred by continuous variable cirrus cloud cover, heavy enough to prevent observations most of the time. These made the results of the speed tests only impressionistic, but provided an especially severe test for sky-subtraction. The Decem-ber observations were made through thin clouds, with good seeing. Spectra and redshifts were obtained for galaxies in 14 clusters, with redshifts ranging from 0.013 to 0.392.

Sky subtraction was done for each frame, using the data for that frame only. A long slit was used, and the sky spectrum determined by averaging over the parts of the slit away from the galaxy. The mean sky spec-trum was then subtracted from the galaxy spectrum, point-by-point. Figure 1 shows the results of the sky-subtraction for the cluster 0024+1654.

The subtraction appears to work well on all the avail-able data. In all cases, the bright emission lines from the airglow and from the city lights of San Diego were reduced to the photon noise level. In several cases, lines in the galaxy spectra were recovered at the same wave-length as a subtracted nightsky line. One example is the G-band in NGC 7619 (fig. 2), which was recovered from directly under the very bright λ4358 mercury line. Sky-subtracted spectra for two additional galaxies are shown in figure 2.

The three clusters shown in the diagrams are repre-sentative of the other data we obtained. They cover the range of redshifts ($z = 0.01$ to 0.4) measured here in these tests, and are also of historical interest. NGC 7619 was the prime test object used by Humason (1929) to prove his techniques before embarking on the long-term program of redshift measurements to extend Hub-ble's (1929) original velocity-distance relation. The red-shift was twice as large as any obtained previously, and was measured from two spectra taken with the Mount Wilson 100-inch (2.5 m), with exposure times of 33 and 45 hours. For comparison, the spectrum shown in figure 2 was obtained in 30 minutes through several magni-tudes of cloud cover. Abell 520, at $z = 0.2$, is near the limit for absorption-line redshifts using photographic techniques. The cluster 0024+1654 ($V \approx 20$ mag) was beyond Humason's reach with the 200-inch (5 m) prime-focus spectrograph (Humason 1957). It was one of the first objects measured by Baum (1962), using the tech-nique of measuring redshifts from the shift of the galaxy continuum, and by Oke (1971), using the same technique with the 200-inch multichannel scanner.

The error bars in figures 1 and 2 show the *expected* rms fluctuations due to photoelectron counting statistics. These are comparable with the *observed* noise in the spectrum itself, indicating that the system is limited primarily by photon statistics rather than by internal instrumental noise.

The first redshifts measured with the SIT system are given in table 1. The procedure for calibrating the wave-length scale is analogous to that used with photographic plates. Comparison spectra were recorded with each galaxy spectrum and used to determine wavelength as a function of position on the tube. Approximate red-shifts ($\Delta z \sim 0.01$) were first determined by direct visual inspection of the absorption-line wavelengths. More ac-curate values were then determined by cross-correlating the spectra against a high-resolution scan of the center of M31 (kindly supplied by Hyron Spinrad), numeri-cally redshifted over an appropriate range, and degraded to our present spectral resolution. The final accuracy of the redshifts appears to be $z \leq 0.001$ in all cases. Of the 14 redshifts given in table 1, five had been measured earlier by others using conventional techniques. Our results agree with the earlier values to within the com-bined errors.

The speed of the spectrograph appears to be satis-factory. Spectra with more than adequate signal-to-noise were obtained in 30 minutes for galaxies at $z = 0.2$ and in 90 minutes for galaxies at $z = 0.4$. Although it is difficult to make a quantitative statement without a direct measurement of the throughput, this seems to
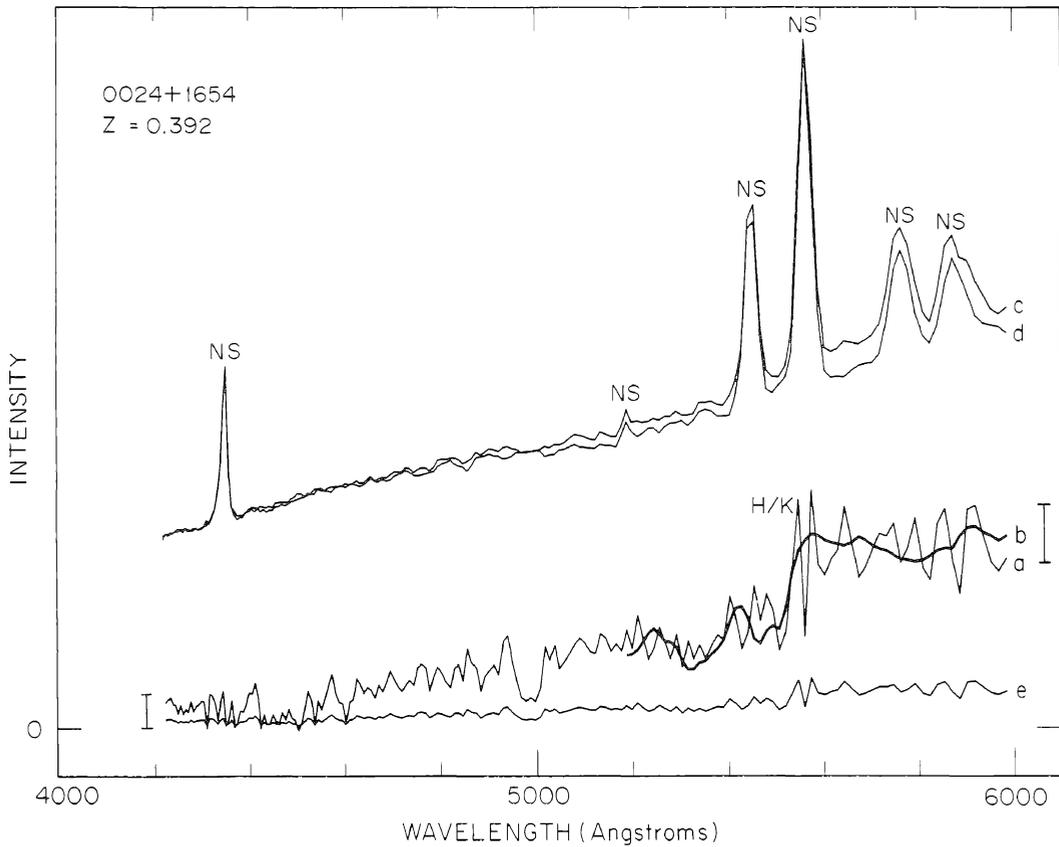
FIG. 1.—Digital prism spectrograph data for the cluster 0024+1654, showing the sky subtraction capability of the instrument. Curve *c* is the raw data for the galaxy spectrum, 90% or more of which is due to contamination from the night sky. The emission lines labeled"NS" are nightsky airglow and mercury lines from San Diego. Curve *d* is the spectrum of the night sky alone, averaged over those parts of the spectrograph entrance slit away from the galaxy. Curve *e* is the difference, $c - d$ which represents the uncontaminated galaxy spectrum. Curves *c*, *d*, and *e* are on the same vertical intensity scale, with zero marked, while curve *a* is the same as *e*, with a factor 5 increase in vertical scale. The error bars to the left and right of *a* show the expected fluctuations due to photoelectron counting statistics. It may be seen that the observed fluctuations are very closely the same. The increased noise at the continuum break, just longward of H and K, is likely due to increased counting noise in the very bright [O I] nightsky line at λ5577. The heavy curve *b* is Spinrad's spectrum of the center of M31 redshifted and degraded in spectral resolution to match our galaxy spectrum. The dip near λ5000 is due to a fleck of dirt on the face of the tube.
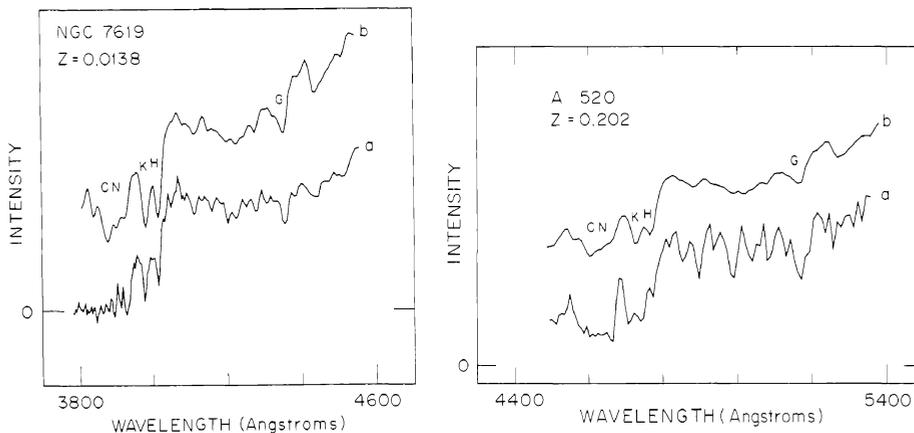

FIG. 2.—Sky subtracted spectra for galaxy clusters A520 and Peg I (NGC 7619). In each case, *a* is the galaxy spectrum, after subtraction of the sky, and *b* is Spinrad's spectrum for the center of M31, redshifted and degraded as in fig. 1.

TABLE 1

New Redshifts of Faint Galaxy Clusters

Cluster	Position*		Redshift,† $z = \Delta\lambda/\lambda_0$	Other Redshifts, Notes, and References
	α(1950)	δ(1950)		
0024+1654..........	$00^h24^m00^s$	$+16°53' 24''$	0.392	0.38 ± 0.01(A)
A98.................	00 43 51	+20 11 53	0.1042	0.1034 (B)
A222...............	01 35 06	−13 15 16	0.216	
A223...............	01 35 34	−13 00 34	0.205	
A278...............	01 54 22	+32 00 15	0.0891	0.0904 (C)
0221−0849..........	02 21 31	−08 49 08	0.273	
A376...............	02 42 59	+36 41 50	0.0490	0.0487 (C)
A520...............	04 51 27	+02 48 40	0.203	
A593...............	07 46 02	+72 54 36	0.226	
A795...............	09 21 21	+14 23 28	0.1357	
0939+0912..........	09 39 21	+09 12 00	0.206	
A963...............	10 14 06	+39 17 39	0.206	
A1146..............	10 58 47	−22 27 34	0.137	0.142 ± 0.007(D)
Peg I (NGC 7619)....	23 17 42	+07 55 53	0.0133	0.0132 (E)

* Positions measured by us for the galaxy whose redshift is given: this is the brightest cluster galaxy in all cases. Positions should be accurate to better than 15″ in each coordinate.

† Redshifts corrected for galactic rotation: $\Delta z = \sin l^{II} \cos b^{II}/1000$. When three decimal places are given, the accuracy of z is better than 0.001: when four decimal places are given, the accuracy is better than 0.0005.

Notes and References.—(A) Baum 1962, Oke 1971; (B) Sargent 1973; (C) Peterson 1970; (D) unpublished continuum redshift by Kristian, using the 200-inch multichannel scanner; (E) Humason et al. 1956.

compare favorably with our experience using the regular 200-inch Cassegrain image-tube spectrograph. We would expect that the quantum efficiencies of the photocathodes are comparable, but that the prism spectrograph has a throughput advantage of some tens of percent over a grating instrument. The data on exposure times are consistent with this expectation.

The major advantage of the SIT system over the image-tube spectrograph, however, is not speed, but storage capacity, reproducibility of the transfer function, and therefore the sky subtractive capability which permits fainter objects to be measured. The measurements at $z = 0.4$ have given no more problems than those at $z = 0$, except for the longer exposure times, and we anticipate no difficulty in going appreciably fainter.

In summary, it appears from these tests that a commercial SIT tube can be used in a straightforward way to obtain two-dimensional spectra with digitized, linear output. The data are nearly photon-noise limited. The sky can be obtained on the same exposure as the object, and can be subtracted to the photon noise level. Redshifts for faint galaxies were measured, and agree with conventional photographic values.

We plan to use the digital prism spectrograph described here to measure line redshifts for the faintest possible cluster galaxies in an effort to extend the Hubble diagram.

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