YZ CAS ± 0.5%

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I will discuss one of the results of a continuing program to determine accurate masses and radii of stars in eclipsing binaries. This program actually began in 1976 with my work on the faint M-dwarf system CM Dra (Lacy 1977). By faint I mean $B = 14^{m}.5$. I needed high-dispersion spectra to get radial velocities, and an intensified solid state array detector called the Digicon, which had recently been installed on the coude spectrometer of the 2.7m reflector at McDonald Observatory, turned out to be the answer. 30 minute integrations were sufficient to get accurate radial velocities from the Hγ emission lines. The Digicon is very good at getting crumby spectra of faint objects fast. By crumby, I mean signal-to-noise ratio of less than 100.

My Reticon, solid state array studies began in 1978 in collaboration with David Evans. Regular observations of YZ Cas and about two dozen other systems have been made since then on the 2.7m and 2.1m reflectors at McDonald Observatory. The Reticon is a high signal-to-noise ratio detector and is therefore complimentary to the Digicon. The Reticon is very good at getting really marvelous spectra of bright stars fast.

The Reticon and Digicon are both mounted on a sliding table at the camera focus. Changing detectors is a matter of only a few minutes now. Both Reticon and Digicon use a solid state array, but in the Digicon the array is at the back end of an image tube and detects photoelectrons rather than photons. A coude Reticon system has also been installed at the 2.1m Struve reflector. This system was used for a few of my observations of YZ Cas, but most of the observations were taken with the 2.7m Reticon system.

The only photoelectric light curves for YZ Cas were taken by Gerald Kron in the late 1930's. Kron normalized the light just preceeding or following eclipse to eliminate differences in the optical path of his photo-comparator, but was unable to do so between eclipses.

Kron's 1939 and 1942 light curves of YZ Cas have been re-analyzed in at least 8 other studies. All studies are in good agreement.

I have adopted a weighted average of the 8 photometric orbits for the purposes of this study. I estimate the average relative radii to be uncertain by about 1% and the inclination by $0^{\circ}.2$.

Single-lined spectroscopic orbits for YZ Cas have been done by Plaskett (1926) and Perry and Stone (1966). Since the light ratio is roughly 10 to 1 for YZ Cas, features due to the secondary

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will be at most 2% deep except for the hydrogen lines which are always blended. Normal photographic spectrograms are not capable of detecting lines this faint. Popper failed in a concerted effort to detect lines of the secondary using photographic plates. Because YZ Cas is fairly bright ($V = 5^m.6$) the Reticon can achieve a signal-to-noise ratio of 500 to 1 in about 30^m, good enough to detect moderately strong lines of the secondary.

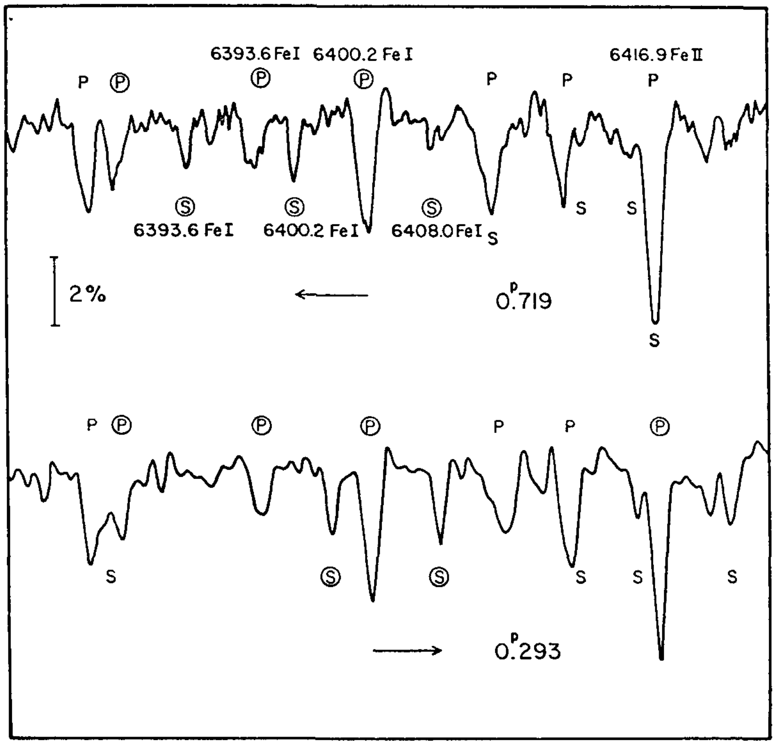

Fig. 1. Reticon scans of YZ Cas at opposite quadrature phases. Features due to the primary (P) component are labelled and identified above each scan and those of the secondary (S) are shown below each scan. The circled features are those actually used in the cross-correlation analyses for radial velocities. The secondary's features are shifted relative to the primary's as indicated by the arrows. The bar shows the flux corresponding to 2% of the continuum. Figure 1 shows a small part of two reticon scans in the region near 6400 Å at opposite quadrature phases. Unblended lines of the primary and secondary are marked. In all 29 such scans have been obtained.

Radial velocities have been extracted using a differential cross-correlation technique. Unblended lines are cross-correlated with lines in scans of a suitable radial velocity standard star.

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The shift in position of the cross-correlation maximum then gives the difference in velocity between the standard and variable star. The absolute radial velocity is then just the sum of this difference and the standard star's absolute radial velocity corrected for the orbital and rotational motion of the observer. The radial velocities of the primary were obtained relative to ο Peg, and the secondary relative to ι Psc. The resulting radial velocities are shown in Figure 2.

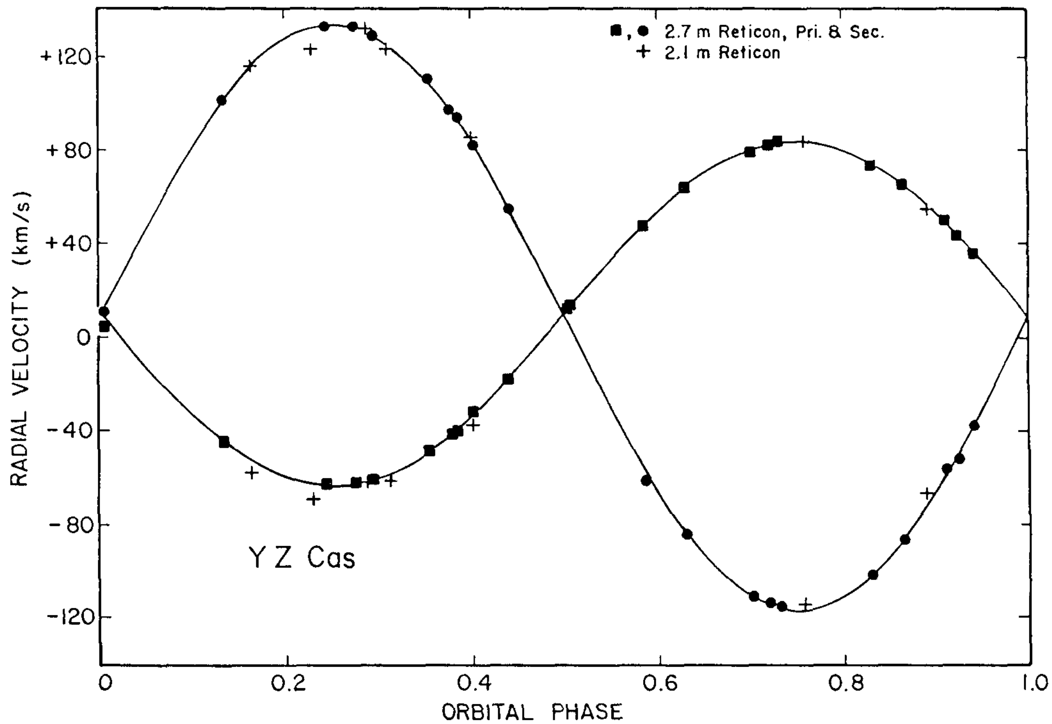

Fig. 2. Radial velocity observations and the fitted spectroscopic orbit.

The final adopted circular orbit is also shown. Residuals from this orbit are 0.7 km/s for the 2.7m data. The orbit is consistent with those of previous investigations of the primary but considerably more accurate. The observed line profiles were analyzed to give the rotational velocities. The secondary is rotating synchronously with the orbital period, but the primary is rotating 20% faster than synchronously.

Unpublished uvbyβ observations by Ed Weis taken inside and outside of primary eclipse have been used to estimate the absolute magnitudes of both stars based on the derived radii. The resulting masses, radii, and luminosities of the stars have been compared to predictions of the evolutionary models of Hejlesen and Mengal et.al. A summary of the results of this investigation is presented in Table 1.

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Table 1. Physical Properties and Standard Errors of YZ Cas

	Primary	Secondary
Mass (solar)	2.31±0.01	1.35±0.01
Radius (solar)	2.53±0.03	1.35±0.02
log g (cgs)	3.995±0.010	4.307±0.013
Rotational velocity (km/s)	34±1	16±2
Synchronons velocity (km/s)	28.7	15.3
Absolute bolometric magnitude (from color)	+0.4±0.2	+3.3±0.2
Distance (pc)	107±11	
Composition (from models): X	0.67±0.04	
Y	0.30±0.03	
Z	0.03±0.01	
Age (years)	$(3.8\pm0.3)\times10^8$	

The masses are known to about 0.5% and the radii to about 1% accuracy. The theoretical models indicate an age of about 4×10^8 yr. and a helium abundance of 30% by mass, a heavy element abundance of 3% by mass.

I believe that from a spectroscopic point of view this investigation is probably the most accurate one that has been done on an eclipsing binary. How much better could this work be done with existing equipment? I think that with somewhat more care in the observations and reductions one could achieve 0.5 km/s accuracy with the Reticon, but I doubt that 0.1 km/s could be reached without extensive modifications to the equipment. I have heard it said that a radial velocity meter such as Griffin's or CORAVEL is the answer to all these problems. Indeed, Griffin has used his device on several double-lined binaries already with high stated accuracy. I believe that the stated accuracy in these cases is probably illusory. As Dan Popper pointed out to me several years ago, the radial velocity mask is a dumb device, by which I mean that it is not smart enough to reject blended lines. It is my experience that at any given phase a goodly fraction of all lines of one component of a double-lined binary will be blended with oppositely displaced lines of the other component. If one indiscriminately used all lines, whether blended or not, to get the radial velocity, one would find not only an increase in the scatter of the radial velocity determinations but, more importantly, a phase dependent systematic error which would probably not show up in the residuals from a fitted orbit in any obvious way. If the lines of both components were narrow the error would mimic random noise with high frequency in phase. In general, the amplitude of this noise would decrease as the number of lines passed by the mask increased. The modulation frequency would decrease as the line widths increase. This must lead, in some cases, to systematic errors in the derived orbital elements, especially the eccentricity and semi-amplitudes. The sizes of these errors depend on the specific parameters of each component (line widths and strengths), on the orbital elements of the system, and on the specific lines passed by the mask. In order to evaluate the

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significance of this effect one could do computer simulation studies, but to my knowledge this has never been done. If I am ever asked to referee a paper using a radial velocity meter on a double-lined binary, I will have to reject the paper unless such a simulation study has been done either to correct for this effect or to show that it is negligible in that specific case.

I would like to finish this talk by summarizing the status of my current eclipsing binary program. Reticon observations are essentially complete now, for EE Peg, which is spectroscopically similar to YZ Cas but with a better light ratio, and the final orbit should be available in a couple of months. Observations of CW CMa are also completed. This is an early A system with nearly equal components, the first system I worked on in the 4500 Å region. Line blending there is much more of a problem than it is in the red, but early A stars don't have many lines in the red and I only get 100 Å at a whack with my detectors. Work is nearing completion on V442 Cyg and FL Lyr which are faint, late type systems I do with the Reticon in the 6400 Å region. Light curves for these two need to be done or re-done properly. Work is continuing on IQ Per, V906 Sco, BW Boo, TX UMa, and HU Tau with the Reticon. Since about a year ago a dual-array Digicon has been available on the 2.7m coude system. I have been using it on systems too faint to be profitably done by the Reticon. This only works if the light ratio is less than about 4 since the Digicon is a low signal-to-noise device. The systems I have used it on so far are KP Aql, QX Cas, and AY Cam although I did use it a few times on CW CMa. QX Cas stubbornly refuses to show double lines and I have become disgusted with it. KP Aql and AY Cam are fine though. I will do a literature search this summer to try to find many more faint candidates for the Digicon. If you know of a worthy system that I don't, I would be grateful if you would tell me about it.

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DISCUSSION

FLETCHER: A radial velocity scanner is only as dumb as the operator.

LACY: No, it is as dumb as the radial velocity mask, which is very dumb.

FLETCHER: No, because when you talk about blending, with radial velocity scanners you can see how much blending is there immediately and not be taken in.

LACY: I think the operator does not explicitly realize what is going on, but it is always there. You only explicitly realize it when the phases get close to what would be eclipse in an eclipsing binary, and then the two radial velocity dips really do begin to blend, but at any phase a large fraction of the lines will be blended with oppositely displaced lines of the other component. The argument is that with a large enough number of lines the blending one way or the other will average out, but this has never been shown. In order to really show it, you must do a computer simulation.

BATTEN: This is a beautiful velocity curve - I wish I had done it.

LACY: Thank you, I'm glad I did.

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