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SYSTEMATIC ERRORS IN RADIAL VELOCITIES MEASURED ON IMAGE-TUBE SPECTRA FROM THE CTIO 1-M TELESCOPE

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RESUMEN

Se investigan los errores sistemáticos de velocidades radiales medidas en espectros obtenidos con el espectrógrafo con tubo de imágenes del telescopio de 1-m (Yale) del Observatorio Interamericano de Cerro Tololo. Los datos de otros autores y los propios nuestros sugieren que estos errores son debidos a la dispersión de la luz estelar en la atmósfera terrestre, fenómeno que ha sido usado para explicar errores similares obtenidos con otros instrumentos.

ABSTRACT

We investigate the systematic errors of radial velocities measured on spectra obtained with the image-tube spectrograph of the 1-m (Yale) telescope at Cerro Tololo Inter-American Observatory. Data from other authors and our own suggest that those errors are caused by the dispersion of the stellar light in the atmosphere of the Earth, which has been invoked to explain similar errors obtained with other instruments.

Key words: RADIAL VELOCITIES

I. INTRODUCTION

Shawl, Hesser and Meyer (1981) found that the errors in radial velocities measured in spectra obtained with the image-tube spectrograph of the 1-m (Yale) telescope of Cerro Tololo Inter-American Observatory correlated well with the stellar declination. Our own results, obtained with the same equipment but using a different dispersion, show the same. Nevertheless, the correlation of our results with the hour angle does not support the idea of Shawl *et al.* (1981) that the proximity of the image tube to the metal mounting might be causing the errors.

On the other hand, different investigators using the spectrograph of Radcliffe Observatory found that their radial velocity errors could be attributed to the atmospheric dispersion of stellar light (Feast and Thackeray 1963; Thackeray and Wood 1978; Catchpole, Evans, Jones, King, and Wallis 1982). In that case, provided that the observations are made not too far from the meridian, one should find a correlation similar to the one of Shawl *et al.* (1981). Since the image tube eyepiece used at CTIO is even more sensitive than the eye to long wavelength light (thus enhancing the atmospheric dispersion effect), we thought it might be convenient to reexamine the evidence on this new light. Besides, the formula used by the Southafrican observers is correct only near the meridian; otherwise, the improved formula that we present should be employed.

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II. OBSERVATIONS

Our interest in the errors of the radial velocities obtained with the image-tube spectrograph of the 1-m telescope at CTIO arose during an investigation of radial velicities of OB stars which is under way at La Plata Observatory. Using a dispersion of 43 A mm^{-1} we measured 110 spectra of three (late-type) *IAU* radial velocity standards (Pearce 1955) and four (early-type) secondary standards recommended by Humphreys (1973) and by Jackson (1976). The former are stars HD 80170, HD 126053 and HD 157457; the latter are stars HD 79186, HD 106343, HD 116119 and HD 142758. We obtained a total of 75 spectra of the *IAU* standards and of 35 spectra of the secondary standards; on the average, about 10 spectra of standard stars were obtained every complete observing night. Qur program stars lie in a few Milky Way fields (Vela, Crux-Centaurus and Circinus-Norma) that cover a small declination range and, consequently, the observations of our standard stars are more adequate to study the influence of the hour

TABLE 1

STANDARD STARS[a]

Star HD	δ (1950)	V_s (km s^{-1})	⟨ΔV⟩ (1979) (km s^{-1})	N	⟨ΔV⟩ (1980) (km s^{-1})	N
80170	− 39° 11′	0.0 ± 0.2	− 5.8 ± 0.8	23	− 7.0 ± 0.9	13
126053	+ 1 28	− 18.5 ± 0.4	− 10.8 ± 1.2	14	...	...
157457	− 50 35	17.4 ± 0.2	− 5.9 ± 1.1	21	− 12.0 ± 2.2	4
79186	− 44 40	31.0 ± 0.3	2.9 ± 2.5	4	− 7.6 ± 3.4	3
106343	− 64 08	− 7.0 ± 1.0	− 6.8 ± 3.6	5	− 13.2 ± 5.6	2
116119	− 61 45	− 22.0 ± 2.0	− 7.5 ± 3.8	4	− 14.5 ± 3.2	5
142758	− 58 35	− 63.0 ± 4.0	− 10.9 ± 2.8	8	− 3.9 ± 4.7	4

a. Where V_s is Standard velocity, $\Delta V = V_{obs} - V_s$

angle, rather than that of the declination, on the radial velocity errors. A combination of our own results with those of Shawl *et al.* (1981), plus the theoretical consideration of how the atmospheric dispersion affects the radial velocities are, however, useful to clarify the picture.

The spectra were taken by one of us (JCM) in April 1979 and April 1980 on Kodak IIa-O plates (baked in forming gas and developed in D-19) and were widened to 1 mm.

The measurements were performed by LPB with the Grant comparator at La Plata Observatory and each spectrogram was measured in both directions in order to minimize errors in setting on the lines. The reduction was done with an HP 1000 computer through a least squares fitting of a third degree polynomial to the wavelength versus measured position data for the comparison lines.

For the *IAU* standards, the rest wavelengths were taken from the list recommended by Batten, Crampton, Fletcher, and Morbey (1971) for the corresponding spectral types and a dispersion of approximately 62 A mm^{-1} an average of 9 lines per spectrogram was measured. The laboratory values from Moore (1945) were adopted for the secondary standards, and weighted means, according to their intensities, were considered for multiple transitions. In this case, 10 lines on the average were measured per spectrogram (all of them are B-type supergiants).

The standard radial velocities were taken from Pearce (1955) for the late-type standards and from Jackson (1976) for the early-type ones. Table 1 presents, for every star, the 1950.0 declination, the adopted standard radial velocity, and the mean residuals for the 1979 and 1980 observations, respectively; the ΔV residuals were computed in the sense of our values minus the standard ones. Table 2 presents, for every star, the Julian Day of the mean exposure time, the mean hour angle and the (heliocentric) radial velocity residual derived from each spectrum.

III. ANALYSIS

Figure 1 presents the mean radial velocity residuals against the stellar declination. Primary and secondary standards are represented with circles and triangles, respectively, and the 1979 and the 1980 observations are distinguished by full and open symbols, respectively; error bars give the square-root of the mean square errors.

We notice there is a correlation similar to the one found by Shawl *et al.* (1981), but that star HD 126053 (the one with slightly positive declination) departs from it. We learned from Hesser (1983) that this star followed very well the correlation in their diagram where it had a slightly positive mean residual. It is the *IAU* standard star for which we have fewer observations, even for 1979, the single year when we observed it. Since

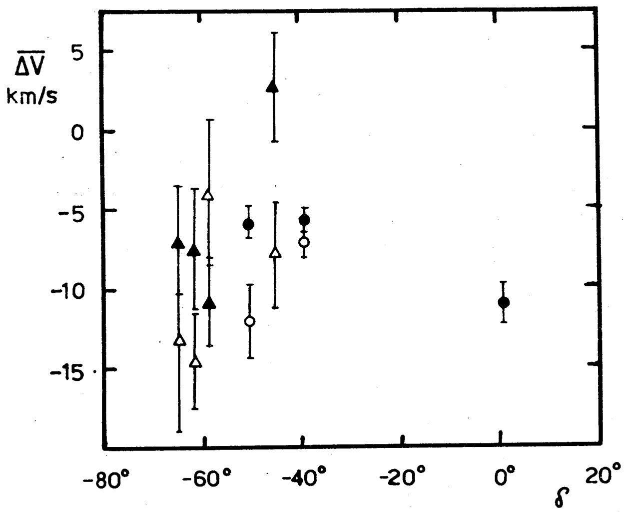

Fig. 1. Mean radial velocity residuals vs. stellar declinations. Circles and triangles represent *IAU* and secondary standard stars, respectively; full and open symbols refer to the 1979 and 1980 observations, respectively. Error-bars give the square root of the corresponding mean square errors.

TABLE 2

MEASURED RADIAL VELOCITIES

	JD (d) 2443000+	t (h)	ΔV (km s⁻¹)
HD 80170			
	974.53	0.00	−14.5
	974.54	−1.37	−11.4
	975.55	0.63	−4.8
	975.64	2.75	−3.8
	975.65	2.87	−7.9
	976.55	0.53	−5.6
	976.66	3.23	−7.6
	976.67	3.37	−0.6
	977.55	1.77	−8.4
	977.64	2.80	−8.7
	977.68	3.80	−1.6
	978.54	0.40	−2.4
	978.54	0.50	−3.5
	978.63	2.73	−3.5
	979.50	−0.27	−5.7
	979.57	1.42	−9.8
	979.63	2.77	−4.1
	980.53	0.43	−9.5
	980.54	0.57	−8.3
	980.65	3.38	−3.6
	980.66	3.52	1.0
	981.53	0.37	−7.6
	981.62	2.70	−2.2
	1332.56	0.30	−5.4
	1332.59	1.03	−6.6
	1332.67	2.77	−7.2
	1333.54	0.30	−6.0
	1335.53	−0.02	−6.6
	1335.58	0.82	−6.2
	1335.58	0.93	−11.2
	1335.67	3.00	−7.4
	1337.50	−0.85	−13.7
	1337.51	−0.75	−7.8
	1337.58	1.07	−6.2
	1337.67	3.07	1.0
	1337.69	3.67	−7.3
HD 126053			
	973.75	0.18	−18.0
	973.80	1.32	−12.4
	974.67	−1.63	−10.6
	974.68	−1.55	−11.6
	974.78	0.87	−10.8
	975.66	−2.98	−14.6
	975.76	0.45	−7.2
	975.76	0.50	−3.9
	976.73	−0.27	−16.1
	976.73	−0.18	−15.6
	978.78	1.20	−13.7
	980.63	−1.40	−7.0
	980.69	−0.87	−6.7
	981.68	−1.13	−3.1
HD 157457			
	973.85	−0.57	−7.9
	973.96	1.07	3.4
	974.79	−1.93	−6.9
	974.79	−1.87	−13.0
	974.89	0.57	−4.7
	975.79	−1.73	−5.4
	975.91	0.98	−3.5
	976.74	−3.03	−9.4
	976.81	−1.32	−6.0
	976.87	0.10	−13.0
	976.87	0.18	−9.7
	976.92	1.37	2.5
	977.80	−2.63	−7.2
	977.90	0.97	−1.1
	978.78	−1.77	−5.6
	978.79	−1.67	−3.1
	978.91	1.27	−3.0
	980.78	−1.75	0.4
	980.85	0.20	−15.9
	981.78	−1.53	−8.3
	981.83	−0.43	−6.3
	1332.87	−0.57	−12.2
	1332.91	0.58	−18.1
	1336.92	0.88	−9.1
	1336.92	0.93	−8.4
HD 79186			
	979.51	−0.05	−4.2
	979.58	−1.60	6.1
	979.64	2.97	2.7
	981.53	0.65	6.8
	1335.54	0.07	−3.5
	1335.58	1.07	−14.4
	1335.69	3.60	−5.1
HD 106343			
	976.69	1.03	−13.6
	976.76	2.72	−6.2
	976.79	3.53	5.6
	978.64	−0.03	−5.1
	978.77	3.07	−14.8
	1332.70	0.53	−18.8
	1332.75	1.93	−7.5
HD 116119			
	973.76	1.43	−18.4
	973.76	1.57	−1.2
	973.77	1.67	−4.8
	973.77	1.73	−5.4
	1335.71	0.02	−12.6
	1336.70	−0.05	−15.7
	1336.78	1.73	−26.4
	1337.70	−0.08	−8.5
	1337.75	1.08	−9.3
HD 142758			
	976.74	−1.40	−18.9
	976.80	−0.05	−12.6
	976.86	1.43	−12.8
	976.91	2.65	−18.9
	980.70	−2.17	3.8
	980.77	−0.47	−1.8
	980.84	1.20	−11.6
	980.84	1.23	−14.3
	1333.76	−1.55	−15.0
	1333.79	−0.87	−7.4
	1336.79	−0.58	−0.1
	1336.89	1.77	6.8

HD 126053 has also been recently eliminated from the list of "primary standards" and regarded as a "secondary standard" only because of its possibly variable radial velocity (Batten 1983), we decided to eliminate it from our subsequent analysis. The other stars show similar mean values for our primary and secondary standards; the mean square errors are, however, smaller for the former. There is some evidence that the 1979 residuals are larger (smaller in absolute value) than the 1980 residuals.

Figure 2 presents the individual residuals against the mean hour angle during the exposure; symbols are as in Figure 1. Since the image-tube approaches the telescope mounting when observing southern stars to the East of the meridian and separates from it when observing stars near the meridian or to the West, if the cause of the radial velocity errors were the proximity of the image-tube to the mounting this figure should show a correlation similar to the one found in Figure 1. Quite on the contrary, we notice that the distribution is fairly symmetric around zero hour angle. In fact, we derived the best-fitting line and obtained a correlation factor of 0.17

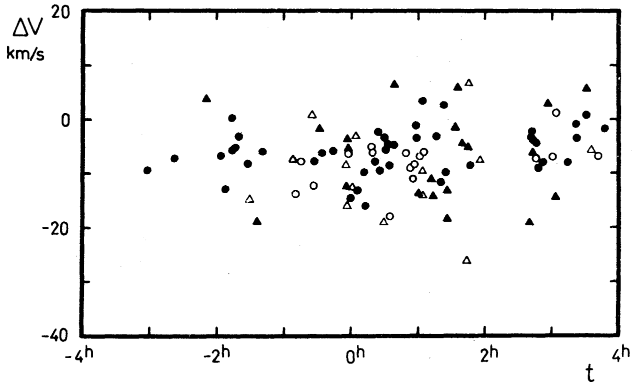

Fig. 2 Individual radial velocity residuals vs. mean hour angle during the exposure. Symbols are as in Figure 1.

which corresponds (according to Student's t-distribution) to a probability of less than 90% that such a value does not arise just from chance. Nevertheless, when we derived the best-fitting line using cos t (i.e., an even function of t), instead of t, as the independent variable we obtained a correlation factor of 0.24 which corresponds to a probability of more than 98% that such a value does not arise just from chance. In other words, although the correlation of the radial velocity residuals with the hour angle is not significant, its correlation with an even function of the hour angle is very significant. Such result cannot be attributed to the proximity of the image-tube to the mounting.

There is, however, a different way to explain the correlation found by Shawl *et al.* (1981). If the radial velocity differences arise from the dispersion of the stellar light in the atmosphere of the Earth, then for

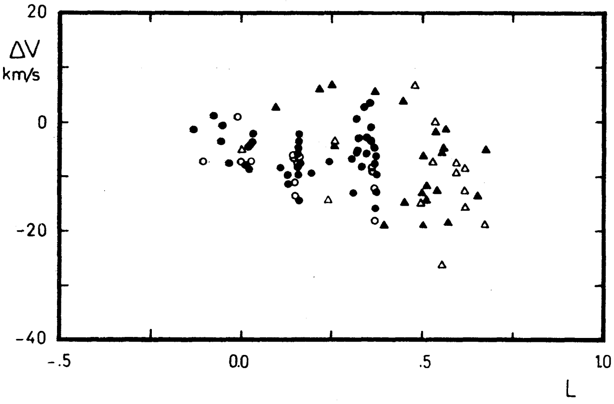

Fig. 3. Individual radial velocity residuals vs. the quantity L defined by formula (1). Symbols are as in Figure 1.

observations made not far from the meridian, there should be a good correlation between the radial velocity differences and the tangent of the difference between the site latitude and the stellar declination (Catchpole *et al.* 1982).

When the star is far from the meridian, however, the slit of the spectrograph and the direction of the dispersion are not normal. If the atmospheric dispersion is the cause of the differences then these should correlate with the value:

$$L = \mathrm{tg}\, z \ \cos q \qquad (1)$$

where z is the zenit distance and q the parallactic angle. We note, incidentally, that the inclusion of the parallactic angle automatically yields the right sign of the correction. That is, the mistake that Catchpole *et al.* (1982) found in the work of Wallis and Clube (1968) is solved without resorting, as they did, to a formula valid only at the meridian.

Let us estimate the amount of this effect in terms of radial velocity. From the technical information provided by RCA one can roughly estimate that the mean wavelength of the sensitivity curve of the RCA 4550 image tube (the one used at the eyepiece) is about 6000 A; the mean wavelength of our spectra is about 4250 A, and that of the spectra of Shawl *et al.* (1981) is about 4675 A. With these values one can derive from the tables of atmospheric refraction given by Allen (1976) that, for a zenith distance of 45°, there is a dispersion effect of about 1″.01 for our spectra and of about 0″.63 for those of Shawl *et al.* According to the properties of the CTIO spectrograph (Smith and Hesser 1977) these differences correspond to displacements of 7.6 and 4.7 μm respectively, on the photographic plate. Considering the dispersions employed we conclude that the atmospheric dispersion effect can easily give rise to errors in radial velocity of about 25 km s^{-1}, and 35 km s^{-1}, respectively, in our observations and in those of Shawl *et al.* (1981) made at the meridian and at a zenith distance of

5°. These are rough estimates only, but they show that ıe predicted amount is fairly large and of the order of ıagnitude of the observed effect.

We computed the correlation factor between the ıdial velocity residuals and the quantity L and we ›und correlation factors of 0.30, 0.27, and 0.35, respec- vely, for all the observations taken together, for the 979 data, and for the 1980 data. They correspond, ›spectively, to probabilities of more than 99.5%, 97%, ıd 94% that such values do not arise just from chance. igure 3 presents the plot of the radial velocity residuals ;ainst the quantity L.

IV. CONCLUSION

The correlations we found for the systematic dif- ›rences in radial velocities obtained with the image-tube ›ectrograph of the 1-m telescope at CTIO agree with ıe qualitative behavior one would expect if they had ıeir origin in the atmospheric dispersion of stellar light; oreover, the differences are of the order of magnitude ıe would expect from the properties of the spectro- aph used and the values of the atmospheric dispersion. his effect, originally found at Radcliffe Observatory, is ‹ely to affect radial velocities obtained at other places well. Although other causes (e.g., flexure) might give se to similar effects, nowadays, that image-tube eye- eces are often used, one should try to match the ›ectral sensitivity of the eyepiece with the spectral gion being photographed in order to reduce the atmos- ıeric dispersion effect. Image-tube eyepieces with large d and infrared sensitivity, on the other hand, increase ıe errors when the blue region of the spectrum is ›served. Our formula (1) is an improvement of the ›rmula of Catchpole *et al.* (1982) useful for spectra ›tained not very near the meridian, and can be used to ›rive from standard stars a correction of the form:

$$\Delta V = a + b\,L \quad , \tag{2}$$

hich will then be applied to the program stars.

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